Towards sustainable energy development: sustainability indicators and stakeholders

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Abstract

Sustainable energy development is a cross-cutting policy objective with the ultimate aim of a sustainable energy future. However, what that future involves and how it can be reached is unclear. The aim of this PhD thesis is to address the question of what a sustainable energy future entails and how stakeholders can track progress towards sustainable energy development. The concept of sustainable energy development is inherently vague, and its meaning has evolved considerably. In this research, two approaches were developed to capture the meaning of sustainable energy development. A general definition of the concept was captured through a comprehensive literature review with citation analysis and a context-specific definition through stakeholder engagement. While these two definitions largely aligned, they also highlighted that sustainable energy development can vary significantly between energy systems. A mixed approach of semi-structured interviews, focus groups, and a Delphi survey was demonstrated as a useful approach to identify opportunities and pressing challenges for energy development within a particular setting.

A thorough review of existing indicators for sustainable energy development and indicator selection methodologies showed that there is room for improvement. Therefore, a new approach to indicator selection rooted in stakeholder engagement was developed. Based on stakeholder input, a context-specific set of indicators for sustainable energy development can be selected that reflects the relevant challenges and priorities. Thereby, stakeholders' ownership and acceptance of the resulting indicators can be increased. A successful set of sustainability indicators can be used to monitor progress, inform actions, and communicate issues. The integration of sustainability indicators, a dynamic model and multi-criteria decision analysis can enable the analysis of alternative energy futures and identification of a desirable development path.

Útdráttur

Sjálfbær orkuþróun er forsenda þess að ná sjálfbærri orkuframtíð. Óljóst er hvað sú framtíð felur í sér eða hvernig skuli ná þangað. Markmið þessarar doktorsrannsóknar var að rýna hvað sjálfbær orkuframtíð hefur í för með sér og hvernig haghafar geta mælt árangur í átt að sjálfbærri orkuþróun. Hugtakið sjálfbær orkuþróun er í eðli sínu óskýrt og skilningur á því hefur breyst og þróast umtalsvert í gegnum árin. Í rannsókninni var tvenns konar nálgun þróuð í þeim tilgangi að fanga merkingu hugtaksins. Yfirgripsmikil rýni á vitneskju sem er til staðar með tilvitnanagreiningu leiddi til almennrar skilgreiningar. Samtal við haghafa leiddi til sértækrar skilgreiningar. Þrátt fyrir að þessum skilgreiningum svipi hvorri til annarrar, sýndi greiningin að sjálfbær orkuþróun fyrir eitt orkukerfi þarf ekki að vera heimfæranleg á annað orkukerfi. Blönduð aðferð af viðtölum, rýnihópum og Delphi könnun getur verið nytsamleg nálgun til að greina tækifæri og aðkallandi áskoranir fyrir orkuþróun í vissu samhengi.

Ítarleg rýni á núverandi vísum fyrir sjálfbæra orkuþróun og aðferðafræði við val þeirra sýndi fram á svigrúm til úrbóta. Því var ný nálgun við val á sjálfbærnivísum þróuð sem byggist á þátttöku haghafa. Mögulegt er að velja sjálfbærnivísa sem endurspegla viðeigandi tækifæri og áskoranir fyrir orkuþróun með samtali við haghafa. Með því er eignarhald og skilningur haghafa á vísunum einnig aukinn. Árangursríkt sett af sjálfbærnivísum getur mælt árangur, upplýst aðgerðir og miðlað mikilvægum upplýsingum. Með samþættingu sjálfbærnivísa, kviks kerfislíkans og rýni á margþættri ákvarðanatöku er mögulegt að greina mismunandi sviðsmyndir og bera kennsl á hverjar þeirra fela í sér sjálfbæra orkuframtíð.

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This doctoral thesis is based on one published paper and three submitted manuscripts to peer-reviewed scientific journals as well as one peer-reviewed conference paper. The articles will be referred to in the text as chapters as follows:

Paper I: Chapter 3

Gunnarsdóttir, I., Davíðsdóttir, B., Worrell, E., Sigurgeirsdóttir, S., 2020. Sustainable energy development: History of the concept and emerging themes. Renewable and Sustainable Energy Reviews. Manuscript under review after major revisions.

Paper II: Chapter 4

Gunnarsdóttir, I., Davíðsdóttir, B., Worrell, E., Sigurgeirsdóttir, S. (2020). Review of indicators for sustainable energy development. Renewable and Sustainable Energy Reviews, 133, 1-22. https://doi.org/10.1016/j.rser.2020.110294

Paper III: Chapter 5

Gunnarsdóttir, I., Davíðsdóttir, B., Worrell, E., Sigurgeirsdóttir, S., 2020. Indicators for sustainable energy development: Discuss, reflect, select. Energy Research and Social Science. Manuscript under review after major revisions.

Paper IV: Chapter 6

Gunnarsdóttir, I., Davíðsdóttir, B., Worrell, E., Sigurgeirsdóttir, S., 2020. Indicators for sustainable energy development: An Icelandic case study. Energy Policy. Manuscript under review after major revisions.

Paper V: Chapter 7

Gunnarsdóttir, I., Davíðsdóttir, B., 2021. Sustainable Energy Development and the Role of Geothermal Energy in Iceland – Stakeholders' View, in Proceedings World Geothermal Congress 2021. Reykjavík, pp. 1-11.

Abbreviations

AESPI	Aggregated Energy Security Performance Indicator
AI	Assessment Index
Bellagio STAMP	Bellagio Sustainability Assessment and Measurement Principles
CSD	Commission on Sustainable Development
DSR	Driving force/state/response
EDI	Energy Development Index
EEA	European Environment Agency
EF	Ecological footprint
EISD	Energy Indicators for Sustainable Development
ESCI	Energy Sustainability Country Index
ESI	Energy Sustainability Index
ESMAP	Energy Sector Management Assistance Program
ETP	Energy Technology Perspectives
ETP	Energy Technology Perspectives
EY	Ernst & Young
GNESD	Global Network on Energy for Sustainable Development
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IEEJ	Institute of Energy Economics Japan
IRENA	International Renewable Energy Agency
ISD	Indicators for Sustainable Development
ISED	Indicators for Sustainable Energy Development
ISED-AT	Indicators for Sustainable Energy Development for Austria
MCDA	Multi criteria decision analysis
MCDA-DEA	Multi-criterion decision analysis-data envelopment analysis
MDGs	Millennium Development Goals
MEPI	Multi-dimensional Energy Poverty Index
OECD	Organisation for Economic Co-operation and Development
PASHMINA	Paradigm Shifts Modelling and Innovative Approaches
RECAI	Renewable Energy Country Attractiveness Index
REES	Risky External Energy Supply
RERII	Renewable Energy Responsible Investment Index
RISE	Readiness for Investment in Sustainable Energy
RISE	Regulatory Indicators for Sustainable Energy
RoMEO	Rights Metadata for Open-Archiving
SALSA	Search, Appraisal, Synthesis and Analysis
SD	Sustainable Development
SDG	Sustainable Development Goals
SE4ALL	Sustainable Energy for All
SED	Sustainable Energy Development
SEDI	Sustainable Energy Development Index

SEW	Sustainable Energy Watch
SISED	Synthetic Index of Sustainable Energy Development
SSEI	Standardized Sustainability Energy Index
TSDI	Taiwan's Sustainable Development Indicators
UESI	Urban Energy Sustainability Index
UN	United Nations
UN DESA	United Nations Department of Economic and Social Affairs
UNDP	United Nations Development Programme
UNFCC	United Nations Framework Convention on Climate Change
UNIDO	United Nations Industrial Development Organization
US	United States
USDD	Index of Sustainable Energy Development
WEA	World Energy Assessment
WEF	World Economic Forum
WEO	World Energy Outlook
WEO	World Energy Outlook
WSSD	World Summit on Sustainable Development

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Preface

The research presented in this thesis is part of a larger project called *Trajectories towards a sustainable energy future*.

Multiple different development paths are possible for sustainable energy development (SED) in Iceland as Icelandic energy resources can be developed and the energy used in diverse ways. For example, the two sectors that still rely on fossil fuels, transportation and the fishing industry, face various possible development trajectories ranging from the use of biofuels to electrification. Each of the trajectories and the policy instruments applied have different sustainability implications. Given the capital intensity and longevity of energy infrastructure and technologies and the complex sustainability implications of different development choices, decision-makers must realize what is considered a desired pathway towards SED, understand the multifaceted sustainability implications of different trajectories, and be equipped to make decisions based on robust analysis.

The aim of the project *Trajectories towards a sustainable energy future* is to:

i) **reveal** what SED in Iceland entails according to stakeholders and to design context-specific indicators that can quantify whether the Icelandic energy system is moving towards SED as seen by stakeholders.

ii) **improve** the understanding of the multidimensional implications of alternative development trajectories of the Icelandic energy system towards SED and carbon neutrality and illustrate the sustainability implications of different development pathways.

iii) **identify** energy system trajectories and associated policy instruments that are robust with respect to multiple sustainability criteria

An integrated system dynamics model of the Icelandic energy system was created to fulfill these objectives. This model was coupled with decision-support tools, i.e., sustainability indicators fed into a multi-criteria decision analysis framework, which enabled the multi-criteria assessment of different trajectories.

The project was divided into five Work Packages; WP1: the development of a systems dynamics model of the Icelandic energy system, WP2: identification of what SED entails in Iceland, selection of sustainability criteria for energy system development, and development of an indicator framework based on stakeholder involvement, WP3: design of an MCDA framework for decision support that incorporates the criteria and indicators revealed in WP2, WP4: the creation of an integrated systems model with sustainability indicators and MDCA framework, and WP5: scenario development and assessment.

This thesis presents the work that was done in WP2 of the *Trajectories* project. Since completing WP2, the indicators developed in this thesis have been simulated into an MCDA framework and used for decision support within Iceland.

The project *Trajectories towards a sustainable energy future* was funded by RANNIS through grant number 163464-051, The national energy company (Landsvirkjun), The Icelandic Road and Coastal Administration (Vegagerðin), and The EU- Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 675153 through the project AdaptEconII (Adaptation to a New Economic Reality). Additionally, specific financing was obtained for WP2 from the Eimskip University fund and the Icelandic national federation of Graduate Women International.

1 Introduction

Energy systems and the services they provide have been found the key to improving economic and social well-being (IAEA et al., 2005). As a result, energy is instrumental in realizing sustainable development. The necessity of energy was recognized when the concept of sustainable development was first formally put forward in 1987 in the UN's Our Common Future report, commonly known as the Brundtland report (World Commission on Environment and Development, 1987). However, initially, energy was mainly mentioned with reducing emissions and increasing energy security (United Nations Sustainable Development, 1992; World Commission on Environment and Development, 1987). In 2000, the concept of sustainable energy development (SED) was first introduced, where the environmental, economic, and social impacts of energy systems were recognized (UNDP et al., 2000). SED was presented as a new development paradigm where the role of energy in achieving sustainable development was highlighted (UNDP et al., 2000). The introduction of the UN's Sustainable Development Goal 7 on affordable and clean energy even further solidified the necessity of energy for sustainable development (United Nations General Assembly, 2015). Over time, SED has become an international cross-cutting policy objective connected with some of the world's major developmental challenges. Gradually, the importance of SED has increased with depleting fossil fuels and rising environmental pressures due to climate change (UNDP et al., 2000).

Sustainable energy development (SED) is a complex and multidimensional concept. When the concept was first introduced in the UN's World Energy Assessment, the relationship between sustainable development and energy production and use was described (UNDP et al., 2000). Firstly, energy is a driver of prosperity and human well-being as sufficient energy services can promote economic and social development. Secondly, energy production and use cannot "exceed the carrying capacity of ecosystems" if energy development is to be sustainable (UNDP et al., 2000). Therefore, environmental sustainability is at the center of SED. This definition of SED recognizes the economic, social, and environmental impacts of energy systems.

A prominent issue in the field of sustainability has been the vagueness and ambiguity of the concept of sustainability (Johnston et al., 2007; Robinson, 2004; Solow, 1991). Some have described sustainability as an "essentially contested concept" where concepts such as sustainable development and SED can be viewed as products of "social, historical, and cultural constructs" (Freeden, 1996; Gallie, 1956; Robinson, 2004). To some extent, sustainability has become an empty buzzword that is often hijacked for political or marketing purposes (Johnston et al., 2007; Robinson, 2004). Both businesses and governments overemphasize the economic dimension of sustainability, while a comprehensive understanding of the social dimension is less developed (Robinson, 2004). Concerning energy, some countries have limited SED to mean low or zero-carbon energy with little consideration of other aspects of sustainability (European Commission, 2019). All over the world, "green deals" are proposed for a green recovery and a more sustainable future, such as The European Green Deal and the Green New Deal in the US (European Commission, 2019; Ocasio-Cortez, 2019). However, while a better understanding of sustainability is still missing, it is difficult to push towards a more sustainable future without the risk of repeating past mistakes. Therefore, there is an urgent need for a clearer and more structured understanding of sustainability and SED.

One way of identifying the relevant sustainability issues is a bottom-up approach where stakeholders in a particular setting are engaged. Thereby, the relevant stakeholders and communities can be actively involved in determining what a desirable future should entail (Robinson, 2004). This approach is particularly appropriate as challenges on the path towards SED can vary significantly from one country to the next (Cherp and Jewell, 2014; Taylor et al., 2017). Therefore, context-specific analysis of SED supports improved and informed decision-making and policy development (Taylor et al., 2017). Furthermore, increased public participation has been shown to increase the effectiveness and general support of actions and policies (Irvin and Stansbury, 2004). It is clear that for SED to be realized, public support of efforts will be vital (UNDP et al., 2000).

Developing ways to monitor progress and inform actions towards SED is important (IAEA et al., 2005). Sustainability indicators have long been used for this purpose (United Nations Sustainable Development, 1992). Multiple different indicators for SED exist that vary in both purpose and quality (Narula and Reddy, 2015; Shortall and Davidsdottir, 2017). These efforts have been stymied by ambiguities in the concept of SED, especially in the local context (Narula and Reddy, 2015; Shortall and Davidsdottir, 2017). Several limitations have been identified in existing SED indicators, such as inconsistent results, a singular perspective, "backward-looking," and overemphasizing economic aspects (Narula and Reddy, 2015; Shortall and Davidsdottir, 2017). Furthermore, disagreement on methodological approaches and whether, for instance, stakeholders should be involved during indicator development has proven challenging (Sovacool, 2012; Taylor et al., 2017). An indicator set measuring progress towards SED needs to adequately capture the different dimensions of SED while considering national circumstances to reflect the context where it will be applied (Taylor et al., 2017).

Research has shown that the involvement of stakeholders during indicator development can result in more robust, representative, and credible indicators while reducing potential bias in selection (OECD and JRC-European Commission, 2008; Pintér et al., 2012). Stakeholder engagement during indicator selection or policy development can increase stakeholders’ feeling of joint ownership, promoting successful implementation (World Economic Forum, 2017). Furthermore, valuable insight can be gained into the sustainability goals and energy-related challenges of the system in question, which can aid in developing context-specific indicators. Stakeholder engagement and context-specific analysis are particularly relevant due to the vague definition of SED. The value of stakeholder engagement is emphasized throughout this thesis to understand what SED entails in a particular setting and aid in developing context-specific indicators. For an indicator set to be useful to decision-makers and stakeholders, it needs to reflect the context in which it will be applied (Shortall and Davidsdottir, 2017). Furthermore, stakeholder engagement can lead to selecting indicators that are valued by stakeholders (Brown, 2009; Schirnding, 2002).

The motivation for this research was to improve the understanding of sustainable energy development and better the development of relevant sustainability indicators. The aim of this study was not to test a hypothesis but to further understanding of the concept of sustainable energy development and improve the methodology for a context-specific analysis of SED and the development of relevant indicators. As described in a preface to this thesis, the research presented here is part of a larger collaborative research project called *Trajectories towards a sustainable energy future.* The work presented in this thesis served the role of identifying what SED entails in Iceland and developing an indicator framework and sustainability criteria for the energy system based on stakeholder input. These outputs have been incorporated into an integrated system dynamics model of the Icelandic energy system to enable the assessment of sustainability implications of different development pathways.

The following overarching research question is addressed in this thesis:

- What does a sustainable energy future entail, and how can stakeholders track progress towards SED?

To address this question, the research objectives of this thesis are:

- Review the literature on the concept of sustainable energy development and, thereby, identify critical issues of concern for assessing the sustainability of energy development.

- Develop a stakeholder engagement approach to enable a context-specific analysis of SED

- Analyze what should be measured to track progress towards SED, how, and why these elements should be measured.

- Review existing methodologies and guidelines for sustainability indicators to identify the characteristics of robust and successful indicator sets.

- Demonstrate the need for a context-specific set of indicators for sustainable energy development based on stakeholder input to inform and monitor actions and policy development.

Each of the papers in this thesis addresses specific research questions that help address the overarching research questions and the above objectives.

1.1 Research focus and structure

This thesis is organized into seven chapters. In this introductory chapter, the topic of the thesis is introduced, the research questions and objectives are presented, a general background of the issues analyzed is provided, and the five academic papers this thesis is comprised of are outlined. These papers constitute chapters 3 – 7 of this thesis.

A clear understanding of the concept of sustainable energy development (SED) and what it entails was thought necessary to carry out the prescribed research objectives. Therefore, this thesis commences in Paper I, where the concept of sustainable energy development and its evolvement over time is analyzed. For this purpose, a systematic literature review was carried out, which included citation analysis to identify highly cited publications that could have shaped the concept. To the best of the author’s knowledge, this is the first comprehensive review of the concept SED and its history based on citation analysis. The analysis carried out in Paper I demonstrates that SED has evolved from being focused mainly on reduced emissions and energy security to being a cross-cutting policy objective, central to sustainable development (UNDP et al., 2000; United Nations General Assembly, 2015; United Nations Sustainable Development, 1992; World Commission on Environment and Development, 1987). This broader understanding includes recognizing the role energy plays in enabling social development and economic growth (Brew-Hammond, 2012). Through a thematic analysis of the most cited publications, the emerging themes of SED are identified as access to affordable modern energy services, sustainable energy supply, sustainable energy consumption, and energy security. The overarching goal of SED is recognized as furthering sustainability. These SED themes and the overarching goal align well with issues highlighted by the *Energy Indicators for Sustainable Development (EISD)* and by the WEC's *Energy trilemma* (IAEA et al., 2005; World Energy Council and Oliver Wyman, 2019). Paper I is concluded by bringing attention to the need for indicators that measure progress towards SED and adequately capture the concept's multidimensional nature.

The necessity of indicators to measure progress towards sustainable development was recognized as early as 1992 in the UN's Agenda 21 (United Nations Sustainable Development, 1992). Multiple efforts have been made to develop indicators that measure progress towards SED or some aspect of it. Most notably, the *Energy indicators for Sustainable Development (EISD)* were created through an interagency effort to enable countries to measure progress towards SED (IAEA et al., 2005). In Paper II, the existing SED indicators are identified, and their suitability to measure progress towards SED is assessed. For this purpose, the characteristics of successful indicator sets are identified by evaluating many different checklists and guidelines for sustainability indicators and their development. These desirable characteristics are used to form indicator set assessment criteria that allow for evaluating indicator sets. During this process, a few publications are found that assessed indicator sets for SED. For example, Shortall et al. (2017) analyzed the suitability of three established SED indicator sets; EISD, Energy Architecture Performance Index (EAPI), and World Energy Trilemma Index (ETI), to measure national energy sustainability. However, none of the studies found attempted to assess as many indicator sets as done in Paper II nor included a clear presentation of the desirable characteristics of an indicator set for SED. In the end, one SED indicator set, the EISD, is found to encompass all of the attributes of a comprehensive and robust indicator set. Nonetheless, numerous flaws of that set are identified, and steps for improvement are suggested. Paper II is concluded by describing valuable steps for developing a successful indicator set for SED.

Based on these proposed steps, a process for indicator selection is developed and introduced in Paper III. An emphasis is placed on presenting a transparent and clear process as most existing SED indicator sets are found unclear and lacking in detail. Stakeholder engagement is put at the heart of the process for multiple reasons. During indicator selection, the involvement of stakeholders has been shown to lead to the development of a more robust and representative set of indicators as numerous different viewpoints are considered (OECD and JRC-European Commission, 2008; Pintér et al., 2012). Having stakeholders define the critical issues and what should be considered for indicator selection reduces the researchers' bias in selection and leads to identifying context-specific energy-related challenges and stakeholder goals (Shortall et al., 2015a). Throughout this thesis, arguments are made for the analysis of SED at the national or even regional level as challenges and actions on the path towards SED can differ significantly. In line with that, context-specific indicators are produced when the proposed indicator selection process is applied, as showcased in Paper IV. The iterative stakeholder engagement approach to indicator selection is used to create a set of indicators for SED of the Icelandic energy system. In Paper IV, the potential policy implications and co-benefits of the process are discussed. A possible policy implication of the approach includes the identification of SED themes for Iceland and stakeholder goals that can provide valuable insight into the creation of energy policy for the country.

Paper V is a clear example of a co-benefit or by-product of the indicator selection process. As part of the process, multiple interviews are conducted in Iceland to identify SED challenges and opportunities in the context. These interviews provide a foundation for indicator selection. In Paper V, these interviews are explored to understand stakeholders' views of geothermal energy and its role in SED in Iceland. This analysis shows that, according to stakeholders, geothermal energy definitely will play a role in Iceland's SED. Furthermore, stakeholders recognize that geothermal energy utilization has played a significant role in the past and was instrumental in an earlier energy transition. A stakeholder goal identified from that analysis with clear policy implications is ensuring the sustainable utilization of resources.

This thesis is wrapped up in chapter two, where overall findings are discussed, recommendations are made, contribution to academic knowledge and potential policy implications are identified, and future research is proposed. Finally, the conclusions of the overall thesis are drawn. Following this concluding chapter, the five papers are presented in chapters 3-7.

1.2 Sustainable energy development

In 2000, the concept of sustainable energy development (SED) was first introduced in the UN's World Energy Assessment (UNDP et al., 2000). SED was put forward as an emerging energy paradigm and was compared to the traditional, fossil-fuel driven one. One of the main differences was that energy production and use were viewed holistically in the new and sustainable energy paradigm. This new energy paradigm entailed considering all possible impacts, whether economic, environmental, or social, and energy services were recognized as drivers for economic and social development. Furthermore, an emphasis was placed on staying within ecosystem boundaries and that our energy systems need to meet current and future needs (UNDP et al., 2000).

The necessity of energy for sustainable development was recognized when the concept was first defined in the UN's *Our common future* report (World Commission on Environment and Development, 1987). It was unclear, however, how energy was supposed to contribute to that future, as evidenced by the following quote from the report: "A safe and sustainable energy pathway is crucial to sustainable development; we have not yet found it" (World Commission on Environment and Development, 1987). Nearly 30 years later, when the UN's Sustainable Development Goal 7 on affordable and clean energy was introduced, the role of energy for sustainable development was further acknowledged and clarified (United Nations General Assembly, 2015). Some of the main issues of SED were highlighted, such as accessibility, affordability, and energy security. The sub-goals of SDG 7 prioritize issues like ensuring access to modern energy services for all, increasing the share of renewables, and improving energy efficiency.

A general understanding of sustainable energy development and the key sustainability challenges facing energy systems worldwide can be captured through a review of the relevant literature and international reports, as is done in Paper I. Shortall et al. (2017) identified eight common themes of SED based on a review of the international policy literature: access and electrification, affordability and equity, security, efficiency, renewables, economic or cost-efficiency, environmentally benign and clean, and contributes to well-being. The aim of a secure and sustainable energy future is mentioned in the IEA's most recent World Energy Outlook (WEO) (International Energy Agency, 2020). The report highlights numerous goals of SED, such as accessible and affordable energy to all, energy security, reliable and secure electricity supply, improved energy efficiency, carbon neutrality, better air quality, and public acceptance. Several actions are mentioned to reach these goals, including clean energy transition through increased utilization of renewables and reduced reliance on fossil fuels, infrastructure improvements, diversification of energy sources and economies, clean energy investment, rapid innovation and deployment of environmentally benign technologies, raising awareness of the negative impacts of energy systems, and behavioral changes (International Energy Agency, 2020).

The goals and actions mentioned in the WEO-2020 reflect the complexity and the multi-dimensional implications of transitioning to a sustainable energy system. An energy transition from fossil fuels towards renewables can, for instance, affect the environment by, e.g., reducing negative impacts from extraction, cutting down global emissions, and improving air quality. The effects of an energy transition on society can range from improving accessibility, affordability, and energy security to better health and reducing geopolitical conflicts. Such a transition would also significantly impact the economy, especially since volatile oil prices would have less influence (UNDP et al., 2000). The exact impacts of an energy transition depend on the energy system in question. Shafiei et al. (2019) showed that completing a transition towards domestic renewables in the transportation sector in Iceland, one of two sectors in the country that still rely on fossil fuels, will significantly reduce GHG emissions, improve air quality, and result in a more secure energy system. However, an energy transition would not improve accessibility because everyone already has access to modern energy services (Statistics Iceland, 2020). Possible social benefits of an energy transition in Iceland could be a better quality of life, reduced health impacts due to decreased air pollution, and behavioral changes (Cabinet of Iceland and Ministry of Industries and Innovation, 2020; Sovacool et al., 2020). In contrast, increased reliance on renewables in a remote community or a developing country through, for instance, distributed or small-scale power development could improve access to affordable modern energy services that could promote both economic and social development (Dincer, 2000; REN21, 2020; United Nations Development Programme et al., 2004).

Nerini et al. (2018) studied the links between energy and all 17 SDGs to show that energy is connected directly and indirectly to 143 out of 169 targets set out in the 2030 Agenda. Energy systems are presented as fundamental for economic and social development and, as such, connected with most of the SDGs. Their analysis demonstrates SED's cross-cutting nature, where impacts are felt within all dimensions of sustainable development; environment, economy, and society (Nerini et al., 2018). The WEO-2020 clearly shows the complexity of SED and the various sustainability challenges facing energy systems.

Uncertainty over the Covid-19 pandemic and its duration even further complicates things and has opened up a “wide range of possible energy futures” (International Energy Agency, 2020). According to the report, “the worst effects are felt among the most vulnerable,” where energy poverty and inequality might be exaggerated even further. However, the opportunities during these uncertain times are also highlighted, where governments can choose a secure and sustainable energy future by leading “the way and providing the strategic vision, the spur to innovation, the incentives for consumers, the policy signals and the public finance that catalyzes action by private actions, and the support for communities where livelihoods are affected by rapid change” (International Energy Agency, 2020). Green investments by governments and others can enable a faster transition to SED and reduce inequality and enhance the social resilience of vulnerable communities by improving access to affordable modern energy services (International Energy Agency, 2020; Modi et al., 2005). For that to happen, the transition towards a sustainable energy system must be a just transition (Jenkins et al., 2018; Sovacool et al., 2019).

The path towards SED and what challenges lie on that path can vary significantly from one country or energy system to the other. For instance, accessibility to affordable modern energy services is a priority in some countries, particularly developing ones. In contrast, other countries have moved their focus to an energy transition towards renewable energy sources and increasing the environmental sustainability of the energy system (Shortall and Davidsdottir, 2017). The reason why the concept of SED and its meaning is still contested is perhaps that the underlying issues vary based on context. Taylor et al. (2017) argue that "countries should be encouraged and supported in interpreting the goal of affordable and clean energy within their national context." Energy systems differ from one to another due to factors such as resource endowments, level of economic or social development, and geographical conditions, which can influence what challenges the system in question is facing (Narula and Reddy, 2015). Clarifying what these challenges are and the desired direction of energy development requires an understanding of the specific socio-technical system in question and the desire of the actors within that system. Therefore, a stakeholder centric approach is necessary when capturing what SED means within a particular context. Identifying general sustainability issues facing energy systems worldwide is useful but not detailed enough to inform decision-making regarding energy development at the national or regional level.

1.2.1 Case study: Iceland

A case study approach is applied for this thesis to allow for a more in-depth analysis of SED and the application of a proposed methodology within a real-life context (Yin, 2009). Iceland is chosen as a case study, and the overarching research question of the thesis is addressed within that context. Stakeholder engagement methods were used for data collection on Iceland’s energy system and its development and are discussed further in Papers III and IV. Stakeholders of the system were engaged through semi-structured individual interviews, focus groups, and a Delphi survey. The aim of this stakeholder engagement was to capture what SED in Iceland involves and identify challenges and opportunities on the path towards a sustainable energy future.

Iceland and its energy system make for an interesting case study for several reasons that will be detailed in the following paragraphs. Iceland is a volcanically active island sitting on top of the Mid-Atlantic ridge. In 2019, the Icelandic population was about 360,000, with 62% living in the capital region (Statistics Iceland, 2019). According to the Human Development Index, Iceland ranks among countries with the highest standard of living in the world (United Nations Development Programme, 2019). The fact that everyone has access to affordable modern energy services contributes to that high living standard (Statistics Iceland, 2020). A study carried out by Jóhannesson et al. (2018) indicated that Iceland's ecological footprint (EF) might be the highest in the world due, to no small extent, to consumption patterns in the country and high energy intensity. However, their research also highlighted inaccuracies with EF calculations for economies with a high degree of specialization, such as the Icelandic one, where results end up being much too high (Jóhannesson et al., 2018). Nonetheless, the study shows clearly that energy development in the country has contributed to a high EF.

The Icelandic energy system is mainly driven by domestic renewable energy, with an 82% share of renewables in total primary energy use in 2018, see Figure 1 (Orkustofnun, 2019a). This share of renewables in primary energy supply is one of the highest in any national energy budget (International Renewable Energy Agency, n.d.). Electricity is generated almost exclusively (99%) from the utilization of domestic renewable energy resources (Orkustofnun, 2019b). The same applies to space heating, where 90% of all houses in Iceland are heated through geothermal district heating and 7% with electricity generated from renewables (Orkustofnun, 2019c). The primary energy sources are geothermal energy and hydropower, and a considerable development potential remains. Other renewable energy resources, such as wind, are not exploited to any real extent, although there are plans to do so in the future (Ministry of Tourism Industries and Innovation, 2018; Orkustofnun, 2019a). Therefore, available renewable resources are only utilized to a limited extent. Fossil fuels account for 18% of total primary energy supply, with oil use in transport and the fishing industry accounting for 16% of that total, and coal in heavy industry accounting for 2% (Orkustofnun, 2019a). Enhancing SED in Iceland would therefore not only focus on a transition towards renewable energy in the sectors that still rely on fossil fuels but also aim to enhance the quality of the energy system and the services it provides. Worldwide transitions to SED are focused on low or zero-carbon energy development and frequently exclude other underlying sustainability challenges of the concept or the various sustainability issues associated with a high reliance on renewable energy (European Commission, 2019). Even though Iceland already has a high share of renewables and ample availability, the country faces many energy-related challenges and tradeoffs on its path towards SED. This is one of the reasons why Iceland and its energy system make for an interesting case study as the nation has already achieved what most countries aspire to but still faces diverse energy-related sustainability challenges. Therefore, this case study analysis highlights that SED encompasses much more than merely a transition towards low- or zero-carbon energy and highlights some of the challenges countries might need to tackle in the future.

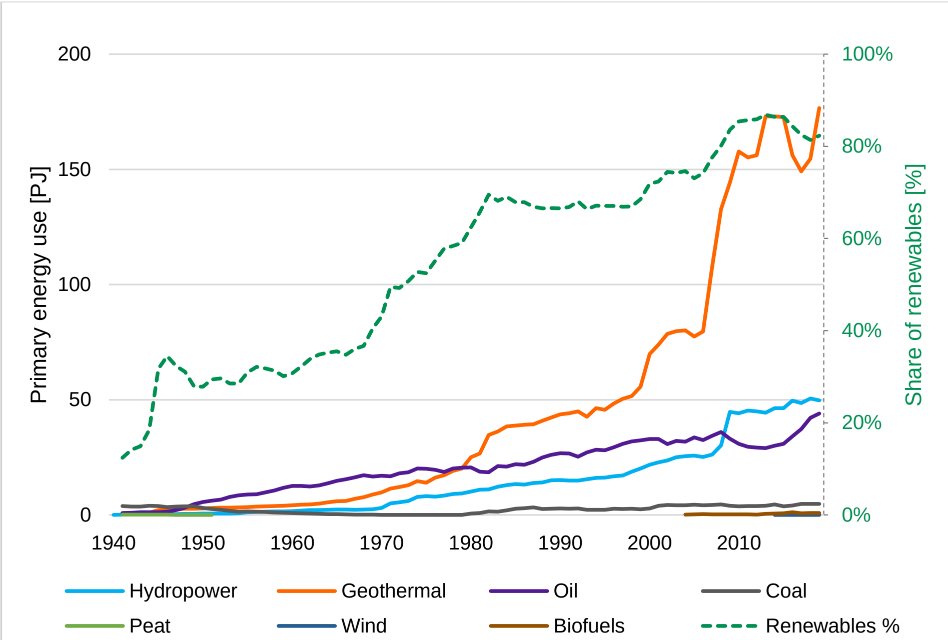

Figure 1: Primary energy use in Iceland by energy source in 2018. The solid lines show the amount of primary energy use by energy source. The dashed line shows the gradually increasing share of renewables in primary energy use in the country (Orkustofnun, 2019a). Graph originally presented in Paper IV of this thesis.

In October 2020, Iceland's Minister of Tourism, Industry, and Innovation proposed a new long-term energy policy for Iceland called "Energy policy to 2050: Sustainable energy future" (Cabinet of Iceland and Ministry of Industries and Innovation, 2020). The policy document, which is yet to be accepted by the parliament, resulted from a two-year effort of a diverse committee that contained representatives of all political parties and selected ministries. The sustainability challenges facing the Icelandic energy system can be identified from this newly proposed energy policy. The policy has five main themes that reflect the main challenges: *Energy security*, *Energy transition*, *Energy efficiency and conservation*, *Environment*, and *Society and economy*. Within the theme of *energy security*, attention was brought to the necessity of improving energy infrastructure and increasing diversity in energy production to ensure a secure and reliable energy supply that fulfills society's energy needs. At present, energy transmission and distribution are less secure in rural areas than in the capital and highly populated areas (Ministry of Industries and Innovation, 2018). In this theme, an emphasis was also placed on increasing the diversity of energy consumers. In 2018, 77% of electricity produced in Iceland was consumed by energy-intensive industries (Orkustofnun, 2019d). Such a heavy reliance on one type of consumer can create vulnerability in the system and, in fact, the country's economy (Statistics Iceland, 2018). In the theme on *Energy transition*, the reliance of the transportation sector and the fishing industry on fossil fuels was highlighted, and the importance of completing a transition towards domestic renewable energy and becoming fully independent of imported fossil fuels was emphasized. This challenge was discussed in the context of improving economic competitiveness, the environment, quality of life, and energy security. Within the theme *Energy Efficiency and Conservation*, the lack of focus on energy efficiency and conservation in the country was emphasized, and the need to utilize better domestic energy resources. These concerns could be addressed by reducing wasteful consumption of heat, promoting smart technologies, and fully utilizing all resource streams. In the theme *environment*, the challenge to develop renewable energy resources while protecting nature and minimizing environmental impact was addressed. Before the pandemic, the most important economic sector in Iceland was the tourism industry, which relies on access to untamed nature. Therefore, the policy stresses the need to develop domestic resources with minimum impact while recognizing the value of protecting areas from energy development. This theme also addresses the challenge of sustainable use and development of energy resources, such as biomass and geothermal resources. Energy resources have not always been utilized sustainably in Iceland, where, for instance, excessive utilization of geothermal resources has led to the temporary depletion of reservoirs (Spittler et al., 2019b). In the theme called *Society and economy*, the urgency of energy equity and equal access to secure energy across the country was highlighted as well as the need for a competitive energy market. Furthermore, an emphasis was placed on ensuring that the nation benefits from its energy resources, both at the local and national level.

Another point of emphasis in the new energy policy is the coordination and integration of decision-making processes and public administration to realize the proposed vision of a sustainable energy future (Cabinet of Iceland and Ministry of Industries and Innovation, 2020). Currently, decision-making regarding energy development is fragmented between numerous ministries, governmental agencies, and municipalities. The situation is further complicated by a diverse group of stakeholders that have diverging views of what is necessary for energy development in the country; for instance, some emphasize the value of untamed nature and nature conservation while others argue for more power development to meet rising demand. Therefore, numerous power centers can impact energy development and contradict each other's actions. This sort of fragmented decision-making system and lack of coordination is widespread in Iceland, particularly for cross-cutting policy objectives such as climate change and sustainable development. As a result, the governance of these objectives is weak and inefficient (Icelandic Climate Council, 2020). According to Shortall et al.'s (2017) analysis, there is a "need for implementing effective and legitimate, socially acceptable decision-making methods for energy planning." The newly proposed policy may address this, but thus far, fragmented pieces of energy policy have been put in place that fall short of providing a clear and comprehensive vision for energy development in the country (Ministry of Industries and Innovation, n.d.). As a result, decisions regarding energy development have been taken on a case-by-case basis with no unified direction and without considering the system holistically or its energy development in the context of sustainability (Minister of industries, 2011). For that reason, an in-depth analysis of the Icelandic energy system and its sustainable development was thought particularly interesting for this research. The proposed energy policy somewhat addresses this and provides the first comprehensive long-term vision for energy development in the country where the entire energy system and different viewpoints are considered (Cabinet of Iceland and Ministry of Industries and Innovation, 2020). Hopefully, the proposed energy policy will coordinate efforts towards SED and cause the different power centers to evaluate their decisions within the larger context of a long-term vision for energy development in Iceland.

An example of an energy-related topic that has been debated in Iceland for years has been the development of new electric power plants in previously undeveloped areas, especially when it is for foreign industrial companies (National Power Company of Iceland, n.d.; Shortall and Davidsdottir, 2017; Thórhallsdóttir, 2007). In 1997, the Icelandic government pledged to start working on a long-term plan for energy production, where sustainable development would be kept as a guiding light (Thórhallsdóttir, 2007). Subsequently, work began on the *Master Plan for Nature Protection and Energy Utilization* to assess the environmental, economic, and social impacts of new individual power plant development options and classify options into three main categories: Energy utilization, On hold, and Protection based on these impacts (Rammaáætlun, n.d.). Essentially, the Master Plan was supposed to be “a tool designed to bridge opposing views and interests regarding land use in areas rich in energy resources in Iceland” (Rammaáætlun, n.d.). Through the Master plan, decision-making on new power plants and areas protected from energy development was moved to a steering committee composed of stakeholders and working groups of the plan. From the beginning, an emphasis was placed on the development of a transparent and robust methodology. Experts within working groups have developed indicators and common metrics to assess the multi-dimensional impacts of power plant options. Multi-criteria decision analysis (MCDA), specifically the Analytical Hierarchy Process, has been used to aggregate the different metrics and allow for the ranking of development options (Rammaáætlun, n.d.). Unfortunately, the implementation of the Master plan has been characterized by conflicts, and, therefore, it has not reached its goal of bridging opposing views. There are several reasons for this. One reason the Master plan has failed is because it has almost solely focused on the environment and nature dimension of energy development and ignored the social and economic dimensions. As a result, the MCDA excluded economic and social criteria. Another reason for the continued conflict is that stakeholders are overlooked in these assessments, e.g., the tourism industry, visitors, and local communities (Burns and Haraldsdóttir, 2019; Sæþórsdóttir and Hall, 2019). Burns et al.’s (2019) analysis of the perspectives of visitors and tourism business operators demonstrated “the need for inclusion of a wide range of stakeholders and interest groups in decision making about land use options.” Therefore, a more comprehensive approach to stakeholder engagement for the Master plan might increase public support. The importance of stakeholder engagement in Iceland’s fragmented decision-making framework for energy development is discussed further in section 1.4.

As detailed in this section, Iceland makes for an interesting case study for several reasons. Iceland’s isolated energy system is unique in several ways. Most prominently due to its high share of domestic renewables in primary energy use from geothermal energy and hydropower utilization. Despite this high share of renewables, the country still faces numerous challenges on the path towards SED. Therefore, this case study highlights that SED is not limited to a transition towards environmentally benign energy and the importance of a common vision beyond that goal. Furthermore, fragmented decision-making regarding energy development in the country and, until recently, the lack of energy policy provides an opportunity for a holistic analysis of a fragmented system.

1.3 Sustainability indicators

The use of indicators to measure progress towards a policy goal, such as sustainable development, is a well-established practice. Indicators for sustainable development were mentioned when the concept of sustainable development was first defined in the UN's *Our common future r*eport (World Commission on Environment and Development, 1987). Five years later, the need for a harmonization of efforts for sustainability indicators was laid out in the UN's *Agenda 21* (United Nations Sustainable Development, 1992). This call for better sustainability indicators led to the development of a significant number of indicators and indices for sustainable development and, more recently, sustainable energy development (UNDP et al., 2000). A recent indicator set developed by the UN measures progress towards the seventeen Sustainable Development Goals (SDGs) (SDSN, 2014). When forming the SDGs, an emphasis was placed on identifying appropriate indicators as soon as possible. Thereby, progress towards the goals could be monitored shortly after their introduction (SDSN, 2014).

In general, an indicator can be defined as "a parameter or a value derived from parameters, which provides information about a phenomenon" (OECD, 1993). Indicators are developed for a specific purpose, where they often capture and simplify complex concepts or policy goals (OECD, 1993; Shortall et al., 2015b). The *Energy Indicators for Sustainable Development (EISD)* were developed to reflect the economic, social, and environmental issues facing energy systems and, thereby, communicate prevalent SED challenges to policymakers and the public (IAEA et al., 2005). The indicators were designed to demonstrate the "interlinkages and trade-offs among various dimensions of sustainable development" (IAEA et al., 2005). That is, this set of SED indicators was designed to recognize the complexities and multi-dimensional impacts of energy development and communicate them effectively to policymakers and general society.

Taylor et al. argue that the inclusion of an indicator can recognize the importance of an underlying issue and act as a catalyst for action (Taylor et al., 2017). To support their point, Taylor et al. compared the UN's Sustainable Development Goals (SDG) to the older Millennium Development Goals, which failed to recognize the role of energy in furthering sustainable and economic development. The inclusion of SDG 7 on affordable and clean energy for all, and the relevant indicators highlighted the importance of energy for sustainable development (United Nations General Assembly, 2015). As Taylor et al. (2017) put it: "The inclusion of energy as an SDG can act as a catalyst for countries and international organizations to redouble their efforts to collect statistics and develop indicators to track progress towards achieving affordable and clean energy for all."

The utilization of indicators allows for the assessment of progress towards a goal and identifying trends (Olafsson et al., 2014). Thus, early warning signs of harmful impacts or lack of progress can be detected, and actions adjusted accordingly. Therefore, indicators should be designed to help decision-makers understand why change is taking place and invite action. The most recent *Tracking SDG7: The Energy Progress Report* communicates progress towards SDG 7 and its underlying targets (IEA et al., 2020). The report demonstrates that "stepped-up efforts towards all targets [are] urgently required if SDG 7 [is] to be met within the coming decade." Such a statement would not be possible without appropriate monitoring of progress towards the targets through sustainability indicators reflecting SDG 7 targets.

Considering the numerous benefits of indicators, they should be embedded within the policy cycle to support better and more informed decision-making and policy development (Shields et al., 2002; Shortall and Davidsdottir, 2017) (see Figure 2). The premise of the policy cycle is that policy is created in an orderly way, i.e., the issue at hand is defined, potential solutions are developed and assessed to formulate a policy, the policy is implemented, its impact is monitored, and, finally, the policy is reviewed (Shields et al., 2002). Shield et al. (2002) argue that indicators that reflect the relevant issues and the policy's objectives allow policymakers to monitor results and "ensure harmony and consistency across sustainability policies." Scientific studies of sustainability issues have highlighted their complexity and multi-dimensionality. However, to some extent, sustainability sciences have fallen short of changing behavior and informing "evidence-based policy" (Pintér et al., 2012). Scientists need to ensure the policy relevance of their research and communicate their results in an appropriate and meaningful way for the audience (Pintér et al., 2012; Shields et al., 2002). Therefore, Pintér et al. (2012) highlighted the need for "better governance mechanisms across all stages of the policy cycle," which includes better measurement tools and practices that reflect the issues at hand and are based on scientific research. As detailed in the paragraphs above, carefully selected indicators based on scientific research can simplify complex concepts and aid with the effective communication of important issues. Furthermore, indicators enable the monitoring of the system in question and identification of development trends.

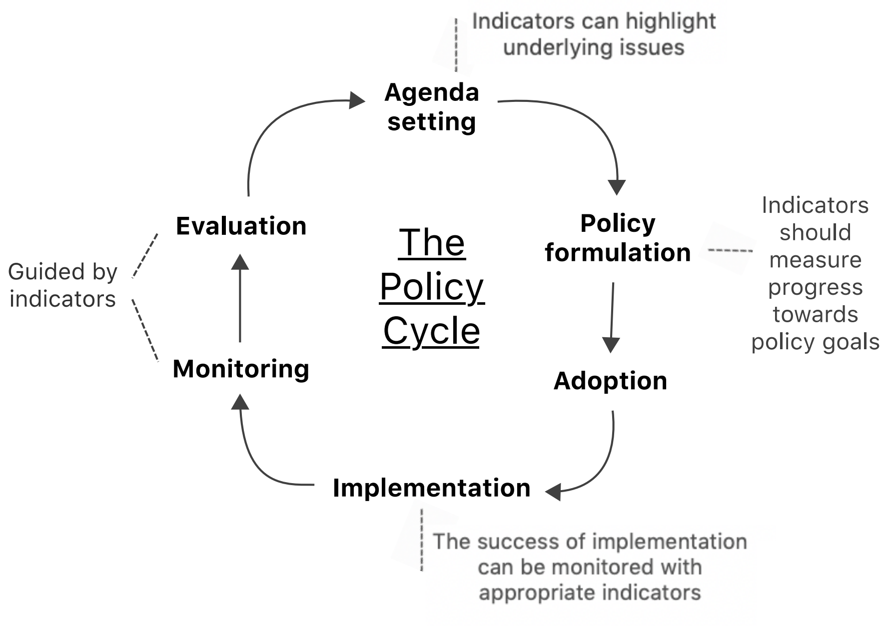

Figure 2: Indicators within the policy cycle. Author's compilation drawing on Shields et al. (2002) and Bridgman and Davis (2003).

Many attempts have been made to develop indicators that measure progress towards SED, both individual indicators and composite indices. Most of these have failed to capture a holistic view of sustainable energy development and the underlying complexities. Existing SED indicator sets have been criticized for oversimplifying SED as only a limited scope of the system is considered, an imbalanced representation of the dimensions of sustainability, inconsistent results, obscure methodology, failure to capture unique national circumstances, and being backward-looking. Narula and Reddy (2015) compared three established indices for SED, namely, *Energy Architecture Performance Index, International Index of Energy Security Risk,* and *Energy Sustainability Index,* to examine the consistency of their results. This comparison revealed that the three indices emphasize different aspects of energy development and, therefore, their results are inconsistent and incomparable. The indices' construction and the underlying indicators reflect what is deemed important by the authors of each index. Narula and Reddy (2015) conclude their analysis by comparing the situation to "three blind men assessing what an elephant is like," where each man feels and describes a different part of the animal resulting in complete disagreement of what it looks like. This analogy demonstrates the importance of a holistic analysis of SED, where the whole picture is considered.

Like Narula and Reddy, Shortall et al. (2017) evaluated three established indicator sets for SED, namely, *Energy Trilemma Index, Energy Architecture Performance Index,* and *Energy Indicators for Sustainable Development* (EISD). Their study involved assessing the usefulness and suitability of the three SED indices to measure national energy sustainability with Iceland as a case study. Their analysis largely came to the same conclusion as Narula and Reddy (2015), the interpretation of SED and its underlying issues varies from one index to the other. The three indices were not thought suitable to measure progress towards SED at the national level as their interpretation of SED does not align with national or regional definitions. The indices were found only "partially relevant" for measuring SED in Iceland as they failed to capture the concerns of policymakers in the country and the unique characteristics of the Icelandic energy system, i.e., "the unique Icelandic energy mix of mainly geothermal and hydropower for electricity and heating; the environmental challenges and the structure and small size of the economy" (Shortall and Davidsdottir, 2017). Additionally, Shortall et al. (2017) brought attention to the fact that most sustainability indices are limited to being "backward-looking" as they reflect the past or, at most, the current situation. Therefore, sustainability indicators should be connected with dynamic models to enable the evaluation of the sustainability implications of alternative future scenarios.

Similarly, Olafsson et al. (2014) evaluated the suitability of four established environmental indices, *Environmental Vulnerability Index, Environmental Performance Index, Ecological Footprint,* and *Happy Planet Index,* in measuring national environmental sustainability performance with Iceland as a case study. Their analysis also demonstrated inconsistencies between the different indices. These general environmental indices were found to only provide a broad picture of the system in question and, therefore, not relevant to national policy. A more holistic and flexible approach was thought necessary that allows for the integration of national specificities, e.g., in the Icelandic case, a consideration of "exceptional renewable energy resources, a small but growing population, a sensitive and geographically isolated environment, and an economy reliant on heavy industry and its fishing" (Olafsson et al., 2014).

The research conducted by both Shortall et al. (2017) and Olafsson et al. (2014) highlight the necessity of sustainability indicators that reflect the system in question and the relevant challenges. The developers of the *Energy indicators for sustainable development* (EISD) stated that "the indicators need to be read in the context of each country's economy and energy resources" (IAEA et al., 2005). Thereby, the indicators are further developed to reflect the context to ensure their usefulness to national policymakers. Stakeholder consultation is recommended to enable this process and the implementation of the EISD (IAEA et al., 2005). By involving stakeholders during indicator development, it is possible to consider diverse viewpoints and identify what SED means in the context (Pintér et al., 2012; Shortall et al., 2015a). Shields et al. (2002) highlight the value of indicators derived from participatory processes that are selected because "they are meaningful to the public and reflect an understanding of their values and objectives." Additionally, stakeholders' ownership of the indicators can be increased, which can aid with their implementation (World Economic Forum, 2017). Nevertheless, it is not common practice to engage stakeholders during indicator development (Shortall and Davidsdottir, 2017).

The Icelandic energy system is unique and faces a different set of energy-related sustainability challenges to most, as discussed in Section 1.2. Shortall et al. (2017) demonstrated that three established SED indices fail to reflect these challenges and the national specificities of the Icelandic energy system and, therefore, do not effectively measure SED progress in the country. Their analysis highlighted the need for a country-specific set of indicators the reflect the context and the relevant SED challenges. A suitable set of SED indicators is important in Iceland due to the fragmented decision-making system for energy development in the country. A comprehensive set of indicators that captures a holistic picture of the system in question and its status could influence the different power centers to rethink their decisions within the larger context of the entire energy system and its sustainable development. When developing such a set of indicators, it is valuable to learn from the mistakes made when the *Master Plan for Nature Protection and Energy Utilization* was developed. For instance, it is essential to consider all dimensions of sustainable development in a balanced way, i.e., the environment, society, and economy. Furthermore, a broad group of stakeholders should be engaged to capture the different views of energy development in the country to select a holistic set of indicators for SED in Iceland.

1.4 Stakeholder engagement

Decision-makers have started to recognize the value of stakeholder engagement for effective decision-making and increasing public acceptance of actions (Irvin and Stansbury, 2004). A catalyst for this recognition was the 1998 *Aarhus Convention on Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters*, where the importance of transparency and public participation in the decision-making process was highlighted (United Nations, 1998). The purpose of public participation in decision-making was to "enhance the quality and the implementation of decisions, contribute to public awareness of environmental issues, give the public the opportunity to express its concerns and enable public authorities to take due account of such concerns" to increase accountability and transparency of decision-making, and strengthening public support (United Nations, 1998). As discussed in Section 1.2, the transition towards a sustainable energy system needs to be fair to succeed, which involves identifying what such a transition entails according to the different stakeholders.

Stakeholder engagement during decision-making and research has been found to build trust and public acceptance, increase comprehensiveness as multiple viewpoints are considered, and enable the identification of pressing issues, thus ensuring relevance (Durham et al., 2014; Reed, 2008). When developing a best practice Stakeholder engagement handbook, the BiodivERsA research team looked into several case studies to demonstrate the benefits and potential pitfalls of stakeholder engagement (Durham et al., 2014). One of those case studies involved assessing the role of fire management and stakeholder participation in protecting biodiversity in different European ecosystems. Their research showed that a high level of stakeholder participation led to a more comprehensive understanding of the systems in question, the identification of potential management solutions, the diffusion of conflict among different groups of stakeholders through constructive dialogue, and stakeholder learning of different views and management approaches across Europe (Durham et al., 2014).

Reed (2008) conducted a literature review to identify and evaluate the benefits and limitations of stakeholder participation in environmental management. Their study demonstrated that public participation “can enhance the quality of environmental decisions,” particularly because it leads to a more comprehensive analysis of the problem in question. However, for stakeholder participation to inform and shape better decision-making, it needs to be designed and done well. Reed (2008) argued that successful stakeholder participation should be viewed as a process with clear objectives from the beginning and highly skilled facilitation, where stakeholders are systematically analyzed and engaged as early as possible. The integration of scientific and local knowledge through stakeholder engagement was thought to lead to a more comprehensive understanding of complex systems and processes (Reed, 2008).

According to the World Economic Forum’s *Global Energy Architecture Performance Index Report 2017,* a transition towards a sustainable energy system will rely on the relevant stakeholders to implement the necessary changes to achieve goals laid out by governments in policies (World Economic Forum, 2017). Therefore, stakeholders should be engaged during policy development both to shape a vision, the policy, and assess its feasibility. Thereby, a sense of joint ownership of the policy and a clear understanding of its goals can be built. In the report, Uruguay was provided as an example of how stakeholder participation led to effective policy design (World Economic Forum, 2017). An “inter-ministerial coordination group” was established to discuss and align goals and develop a successful energy policy. A similar approach was taken to develop the newly proposed energy policy in Iceland, where a diverse committee was established that contained representatives of all political parties and selected ministries (Cabinet of Iceland and Ministry of Industries and Innovation, 2020).

Stakeholder engagement should formally be embedded within the policy cycle to improve decision-making and increase public support of actions (see Figure 3). Furthermore, as detailed before, stakeholder engagement should be conducted while developing indicators to be used in the policy cycle. Incorporating stakeholder consultation within the policy cycle can help formulate policy, whereby stakeholders assist in identifying the pressing issues to set the agenda and the vision and assess the policy’s practicability. Furthermore, stakeholder consultation can improve the success of the adoption, and implementation of policy, especially as it often depends on the stakeholders to achieve the policy’s objectives and push for the necessary changes (World Economic Forum, 2017). Finally, the feedback of relevant stakeholders can be valuable when evaluating the effectiveness of a policy.

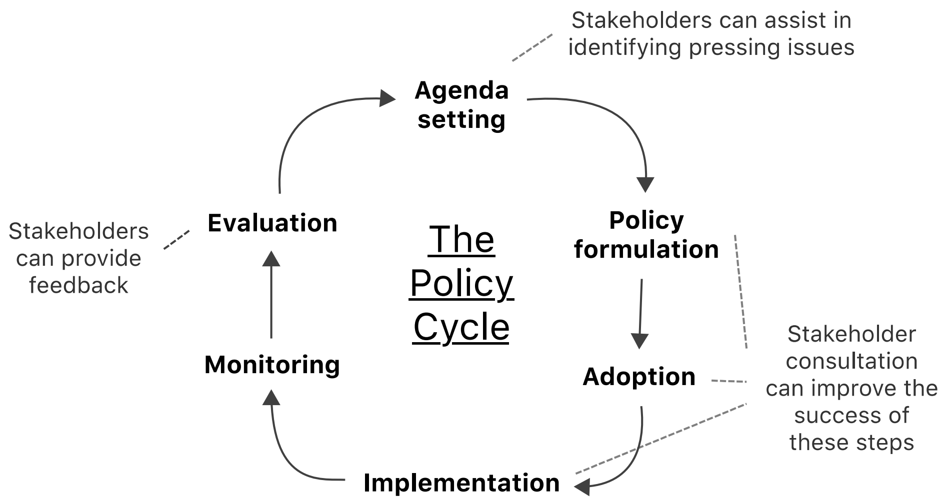

Figure 3: Stakeholder engagement within the policy cycle. Author's compilation drawing on Shields et al. (2002) and Bridgman and Davis (2003).

Similar to policy development and agenda setting, the involvement of stakeholders during indicator selection is valuable or even necessary (Pintér et al., 2012). Sovacool (2012) argued that stakeholder consultation during indicator development allows for the connection of complex concepts to potential metrics, enables a targeted discussion that can produce "insightful knowledge," and leads to the collection of data more recent than can be found in the published literature. A stakeholder-centric approach to indicator development is particularly relevant due to the contested nature of the concept of SED and its varying meaning based on context. Shortall et al. (2017) argued that one of the main hindrances of creating appropriate SED indicators has been ambiguities in what the concept entails, especially within the local context. The sustainability vision, goals of different stakeholders and the underlying themes of complex concepts, such as SED, can be identified through stakeholder engagement. Suitable indicators reflect these stakeholder goals and themes to measure progress (Shortall, 2015). Furthermore, the robustness of the resulting indicators is increased, and the potential for bias in indicator selection is reduced when multiple viewpoints are considered, which in turn enhances the usefulness of indicators in the policy cycle (OECD, 2008).

In light of the Icelandic energy system's uniqueness, context-specific analysis of the relevant sustainability challenges is particularly valuable. Stakeholder engagement can enable such an analysis, resulting in a more comprehensive understanding of complex systems and processes (Reed, 2008). Even though Iceland has a representative democracy, where voting can be a form of stakeholder consultation, public participation in decision-making is still valuable. Nationally representative democracy does not translate to locally representative impact analysis, especially since there has never been anything other than coalition governments in Iceland (Cabinet of Iceland, 2020). Before parliamentary elections, political parties present an array of policy objectives for the coming term.

Generally, energy development does not rank high on this list, if included at all, and, in the past, has not heavily influenced how people cast their vote. In recent years, political instability and repeated short Parliamentary sessions indicate a low level of trust in the Icelandic government, highlighting the value of stakeholder consultation to strengthen public acceptance (Burns and Haraldsdóttir, 2019).

As discussed in Section 1.2.1, decisions regarding energy development in Iceland are taken within a fragmented decision-making system with multiple power centers. A constructive dialogue between these different power centers and relevant stakeholders could lead to more effective decision-making. Iceland's *Master plan* failed to meet its goal of bridging opposing views and, therefore, new power plant options are still a contested topic in the country (Rammaáætlun, n.d.; Sæþórsdóttir and Hall, 2019). A more comprehensive approach to stakeholder engagement that includes all relevant stakeholders could improve the plan and increase public support. Such efforts would involve capturing the opinions of those not included in the current process, i.e., the tourism sector, visitors, and local communities (Burns and Haraldsdóttir, 2019; Sæþórsdóttir and Hall, 2019). In the new energy policy, an emphasis is placed on transparency and public participation during decision-making, which aligns well with some of the main arguments made in this thesis (Cabinet of Iceland and Ministry of Industries and Innovation, 2020). Therefore, the new energy policy recognizes the value and necessity of public acceptance of energy development and relevant decision-making.

1.5 Summary of methods and results

A summary of the objectives, research questions, methods, and results of each Paper is provided in this section.

1.5.1 Paper I

Gunnarsdóttir, I., Davíðsdóttir, B., Worrell, E., Sigurgeirsdóttir, S., 2020. Sustainable energy development: History of the concept and emerging themes. Renewable and Sustainable Energy Reviews. Manuscript under review after major revisions.[1]

Received: October 15th, 2019 / Status: Manuscript under review after major revisions.

Both sustainable development and sustainable energy development have been found vague and ambiguous concepts, as discussed in this introduction. When reviewing the literature, the complexity of sustainable energy development became apparent and how its meaning has changed considerably over time. However, no detailed analysis of the concept itself and its history was found in the literature. Therefore, the motivation for this first paper was to assess the current state of the field concerning the concept of sustainable energy development. This assessment involved an analysis of the concept and its evolution over time.

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[1] The role of the doctoral student (Ingunn Gunnarsdóttir) in this paper was to carry out all of the research activities. Dr. Brynhildur Davíðsdóttir, Dr. Ernst Worrell, and Dr. Sigurbjörg Sigurgeirsdóttir guided the doctoral student during the research activities and writing process.

The objectives of Paper I were as follows:

- examine how the concept of sustainable energy development materialized
- identify emerging themes of the concept

A systematic literature review was carried out to address these objectives. The following research questions were laid out to guide this review:

- How has the concept of sustainable energy development evolved?
- What is sustainable energy development?

The literature review included citation analysis to identify the most cited publications on SED that can be considered to have shaped the concept. Three scientific databases were scoped for the search string "sustainable energy development" to find relevant publications. From this, 1,253 publications were identified. The citations of these publications were extracted to create a long list of relevant references. These citations were then cross-referenced to determine the 34 most-cited publications connected to SED. These most-cited publications were examined further through a thematic analysis to address the Paper's second objective; identify the emerging themes of the concept. During this process, multiple thematic maps were created to improve themes, identify connections, and aid in presenting themes.

The results of this Paper were split into two to address the two objectives. First, the history of the concept, how it emerged and has evolved is reviewed. The review presented in this paper includes an overview of how the role of energy for sustainable development has expanded over time. Initially, energy was mainly mentioned in the context of reducing emissions, improving air quality, and ensuring energy security. Currently, energy and the services it provides are viewed as essential to sustainable development and connected with major developmental issues worldwide. This broader understanding stresses the importance of energy for sustainable development and its cross-cutting influence. In this section, a timeline of the concept was presented where key actors, influential publications, and important events were identified.

Second, the results of the thematic analysis were introduced as key themes of SED, namely, access to affordable modern energy services, sustainable energy supply, sustainable energy consumption, and energy security. These themes were presented in thematic maps to reveal underlying issues and interlinkages between the themes. Furthermore, the overarching goal of SED was identified as furthering sustainability. These results highlighted the multidimensional and cross-cutting nature of SED. Additionally, they emphasized that actions need to be taken now and by all for SED to be possible. Comparing these results with established SED themes showed that the main SED issues were included in the study. Furthermore, the analysis allowed for identifying potential gaps in the literature, where the least discussed topics were the sustainable utilization of resources and sustainable energy consumption.

1.5.2 Paper II

Gunnarsdóttir, I., Davíðsdóttir, B., Worrell, E., Sigurgeirsdóttir, S. (2020). Review of indicators for sustainable energy development. Renewable and Sustainable Energy Reviews, 133, 1-22. https://doi.org/10.1016/j.rser.2020.110294[2]

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From the analysis carried out in Paper I, it was clear that SED has become an international policy objective that has increased in importance over time. For this reason, a suitable set of sustainability indicators is essential to monitor progress and inform actions for SED. The second paper of this thesis was also motivated by the need to assess the current status of the field, this time concerning indicators for sustainable energy development.

The objectives of Paper II were:

- identify what makes an indicator set comprehensive and robust
- provide a comprehensive overview and comparative analysis of existing indicator sets for SED

The related research questions were addressed in the paper:

- What makes an indicator set comprehensive and robust?
- How suitable are existing indicators in measuring progress towards SED?

A first step in addressing these questions was the identification of existing indicator sets for SED. For this purpose, a systematic literature review was done using an adjusted SALSA framework; Search, Appraisal, Snowball technique, Synthesis, and Analysis. This process led to the identification of 57 different indicator sets for SED. The characteristics of robust and comprehensive indicator sets were reviewed to enable a comparative analysis of existing SED indicator sets and address the research questions. Existing guidelines and checklists for indicator development that detailed what is desirable and necessary in an indicator were reviewed for this purpose. This review led to creating six different indicator set assessment criteria thought essential for a robust and comprehensive indicator set, namely, transparency of indicator selection, transparency of indicator application, conceptual framework, representative, linkages, and stakeholder engagement. Thus, theoretically, an indicator set that met all six criteria could be considered comprehensive and robust. In the end, the criteria were used 69 times to assess 57 indicator sets for SED as some indicator sets were applied within different contexts and by various researchers.

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[2] The role of the doctoral student (Ingunn Gunnarsdóttir) in this paper was to carry out all of the research activities. Dr. Brynhildur Davíðsdóttir, Dr. Ernst Worrell, and Dr. Sigurbjörg Sigurgeirsdóttir guided the doctoral student during the research activities and writing process.

This Paper clearly showed the multitude of indicators that have been developed to monitor SED or some part of it. The article also highlighted the varying quality of these indicator sets. A frequent flaw of the indicator sets was a lack of transparency in both indicator selection and application, which significantly impacts both the credibility and replicability of the indicator set. The analysis carried out showed that conceptual frameworks were commonly used for indicator development. However, further analysis of what constitutes an adequate theoretical framework could be done. In line with previous studies, many of the indicator sets did not capture SED appropriately, where, for instance, the social aspect was often undervalued. Linkages between indicators and the underlying issues of SED were only considered by some. Given the multidimensionality and complexity of SED, the consideration of linkages would be beneficial. The final assessment criterion highlighted the value of stakeholder engagement during indicator development. The results of this analysis showed that, most often, stakeholders were not involved in the creation of the existing SED indicator sets.

In the end, only one indicator set, *Energy Indicators for Sustainable Development (EISD)* (IAEA et al., 2005), fulfilled all of the assessment criteria and, thus, could be considered comprehensive and robust. The presentation of the EISDs included a detailed description of how they were selected and should be applied, where the application of a thematic framework, the involvement of experts and stakeholders, and consideration of linkages were mentioned. A more in-depth analysis of the EISDs brought to light some of its flaws, including an imbalanced presentation of SED, lack of institutional indicators, and no consideration of how the indicators and their results should be communicated. These flaws might explain why the indicator set has not been used by many. The paper was concluded by outlining some practical steps in developing a suitable SED indicator set, such as a context-specific analysis of SED based on stakeholder engagement. Additionally, the EISD indicator was suggested as an appropriate starting basket of indicators for further development within the context in question where its flaws could be tackled.

1.5.3 Paper III

Gunnarsdóttir, I., Davíðsdóttir, B., Worrell, E., Sigurgeirsdóttir, S., 2020. It Is Best to Ask: Designing A Stakeholder-Centric Approach to Selecting Sustainable Energy Development Indicators. Energy Research and Social Science. Manuscript accepted with minor revisions. [3]

Received: December 6th, 2019 / Status: Manuscript accepted with minor revisions.

Building on Paper II, this third paper was motivated by the need for an improved methodological approach to indicator selection that produces robust and comprehensive indicators. The article mainly consists of a detailed description of a proposed indicator selection process rooted in stakeholder engagement.

The following two objectives were defined for the third paper of this thesis:

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[3] The role of the doctoral student (Ingunn Gunnarsdóttir) in this paper was to carry out all of the research activities. Dr. Brynhildur Davíðsdóttir, Dr. Ernst Worrell, and Dr. Sigurbjörg Sigurgeirsdóttir guided the doctoral student during the research activities and writing process.

- develop an iterative approach to indicator selection based on stakeholder engagement

- analyze how the proposed indicator selection process enhances the established methodology

The following related research question was addressed:

- How does the proposed indicator selection process enhance established methodology?

A seven-step iterative stakeholder engagement approach to indicator selection was presented in the paper. Detailed descriptions and justifications for each of the steps of the process were provided to ensure transparency and replicability. The first four steps are centered around the engagement of stakeholders through interviews, focus groups, and surveys to identify what SED entails in the context. An emphasis is placed on selecting a diverse group of stakeholders to capture multiple viewpoints. Thereafter, the established qualitative methodology is applied to identify the themes of SED in the context and sustainability goals of stakeholders. These results are then connected with a thematic conceptual framework. In the last three steps of the process, indicators are connected to the identified SED themes and goals to produce a set of context-specific indicators for SED. This process includes reviewing existing indicators for SED, such as those identified in Paper II. Indicator assessment criteria were developed based on existing indicator criteria to ensure the suitability of individual indicators. These criteria are interpretability, trends, grounded in research, data availability and quality, and linkages. The iterative nature of the proposed approach allows for the repetition of steps if deemed necessary, for instance, if there is a lack of saturation in stakeholder views.

If the proposed indicator selection process is followed, the criteria laid out in Paper II for comprehensive and robust indicator sets should be fulfilled. A transparent iterative indicator development process was presented with stakeholder engagement at its heart to ensure that indicators are representative, comprehensive, and useful to stakeholders and to reduce bias in the selection of indicators. In this process, qualitative and quantitative methods are combined to enhance the robustness of the resulting indicators. Stakeholders are engaged multiple times to verify results and even further increase robustness. The results of the first four steps of this process are valuable in themselves; identification of what SED entails in the context and stakeholder goals. These results could have direct policy implications and shape the development of energy policy or an action plan for SED. Even though the approach was presented as a way to select indicators for SED, it could be used for the selection of indicators for other sustainability goals.

1.5.4 Paper IV

Gunnarsdóttir, I., Davíðsdóttir, B., Worrell, E., Sigurgeirsdóttir, S., 2020. Indicators for sustainable energy development: An Icelandic case study. Energy Policy. Manuscript under review after major revisions. [4]

Received: March 24th, 2020 / Status: Manuscript under review after major revisions.

The motivation for this fourth paper was to apply the stakeholder engagement approach to indicator selection presented in Paper III to produce a set of context-specific indicators for SED. It was necessary to demonstrate the usefulness of the process by applying it within a real-life situation. Throughout the paper, the importance of stakeholder engagement for indicator selection and that indicators should reflect the context they are applied in was highlighted.

The objectives laid out in Paper IV were:

- implement the proposed indicator selection process and present indicators for SED in Iceland
- reveal the potential policy implications of the indicator selection process

Iceland and its energy system were chosen as a case study, and an indicator set reflecting the energy-related challenges there was developed. For this purpose, the following research questions were defined:

- What challenges and opportunities are facing the Icelandic energy system on the path towards SED?
- What should be emphasized to reach SED in Iceland?
- What should be measured to track progress towards SED in Iceland?

The methods applied in this study were presented in Paper III and, therefore, will not be detailed further here. Stakeholders of the Icelandic energy system were identified and engaged to address the above research questions. Based on stakeholder input, six main themes of SED in Iceland were recognized; nature conservation, social benefits, energy security, economically efficient energy system, sustainable energy production, and sustainable energy consumption. According to stakeholders, these themes need to be addressed for SED to be realized in Iceland. Indicators were selected to reflect these themes and SED goals discussed by stakeholders. During this process, the review of the existing SED indicator sets carried out in Paper II was used to find useful and suitable indicators. The stakeholder-centric approach to indicator selection resulted in a broad and comprehensive set of context-specific indicators for SED in Iceland. Thereby, the value of the proposed indicator selection process and stakeholder engagement is confirmed.

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[4] The role of the doctoral student (Ingunn Gunnarsdóttir) in this paper was to carry out all of the research activities. Dr. Brynhildur Davíðsdóttir, Dr. Ernst Worrell, and Dr. Sigurbjörg Sigurgeirsdóttir guided the doctoral student during the research activities and writing process.

Multiple different policy implications of the process were revealed to address the second objective of this Paper. Stakeholder engagement led to the identification of multiple concrete policy goals, such as the sustainable utilization of natural resources and an energy transition in transportation. These goals form a foundation for the creation of an energy policy pushing for SED. The resulting sustainability indicators can be used to measure the success of such a policy and monitor progress towards SED. In order to validate the results of the study, the six identified SED themes were compared to an existing draft energy policy. This comparison showed that a comprehensive and complete picture of SED in Iceland was captured. The survey sent to stakeholders showed a high level of agreement among stakeholders on the different SED issues. The only divisive issue was the possibility of a submarine interconnector to the European electricity grid. It is valuable for policymakers to know that stakeholders agree on the importance of SED and the necessary actions towards a more sustainable future.

1.5.5 Paper V

Gunnarsdóttir, I., Davíðsdóttir, B., 2021. Sustainable Energy Development and the Role of Geothermal Energy in Iceland – Stakeholders' View, in Proceedings World Geothermal Congress 2021. Reykjavík, pp. 1-11.[5]

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The motivation for Paper V was to explore further inputs gained from the stakeholder interviews in the indicator selection process carried out for Paper IV. Thereby, a by-product of the approach proposed in Paper III was demonstrated. This demonstration entailed focusing on one aspect of SED in Iceland, geothermal energy, and analyzing how stakeholders discussed geothermal energy in the context of SED in Iceland. Similar to previous papers, the value of stakeholder engagement or public participation during policy development was highlighted.

Two main objectives were defined:

- Present an effective public participation process to engage stakeholders
- Analyze the past and future role of geothermal energy for sustainable energy development in Iceland according to stakeholders

Furthermore, the following research question was considered:

- How do stakeholders view geothermal energy in a sustainable energy future?

[5] The role of the doctoral student (Ingunn Gunnarsdóttir) in this paper was to carry out all of the research activities. Dr. Brynhildur Davíðsdóttir guided the doctoral student during the research activities and writing process.

This study presents a five-step method to public participation, which consists of stakeholder mapping, semi-structured interviews, focus groups, qualitative analysis, and Delphi survey. These steps align with the first four steps of the indicator selection process presented in Paper III. As detailed in Paper IV, the purpose of these interviews was to evaluate what SED in Iceland involves and identify stakeholder goals. A further analysis was carried out of how stakeholders discussed the role of geothermal energy for SED to meet this paper's objectives.

During the interviews, most stakeholders mentioned the lack of comprehensive long-term energy policy in Iceland and discussed how SED could not be achieved without one. As presented in Paper IV, six main themes of SED were identified; nature conservation, social benefits, energy security, economically efficient energy system, sustainable energy production, and sustainable energy consumption. The more in-depth analysis of geothermal energy carried out in this study showed that stakeholders viewed geothermal energy as essential to Iceland's energy future. Five main themes of discussion for geothermal energy and SED were identified: main energy source, is it sustainable?, environmental and social impacts, expertise and learning from mistakes, and foresight and international role model. Stakeholders seemed to recognize the importance of geothermal energy for SED, especially for electricity production and district heating. The negative environmental and social impacts of geothermal utilization, mainly in the form of harmful emissions, were also brought up. Many stakeholders discussed how geothermal energy has played an instrumental role in the past and will continue to do so for the foreseeable future. However, as mentioned by a few, geothermal resources need to be utilized sustainably for that to be possible. In that regard, an emphasis was placed on learning from past mistakes. When discussing the energy transition in the past with geothermal district heating, many stakeholders mentioned that the same kind of foresight and ambition was necessary to push for SED.

Many insights were gained from this analysis that have clear policy implications and can inform future geothermal energy development. For instance, stakeholders emphasized that benefits from geothermal utilization should be felt in the local community to compensate for potential negative impacts. Furthermore, sustainable use of resources should be ensured through, for instance, stepwise development of geothermal power stations.

2 Summary and discussion

2.1 Summary

This research set out to assess what a sustainable energy future entails and analyze how stakeholders can track progress towards that future. The path towards a sustainable energy future involves the sustainable development of energy systems or sustainable energy development (SED). The need for a more structured and clearer understanding of the concept of SED was recognized. For this purpose, the literature was reviewed to analyze what SED entails and identify underlying issues and themes relating to the concept (Paper I). This review led to the identification of four main themes of SED, namely, access to affordable modern energy services, sustainable energy supply, sustainable energy consumption, and energy security, as well as an overarching goal of furthering sustainability. Moreover, the analysis highlighted that the evolvement of the concept of SED has led to a broader understanding of the role of energy, including recognition of its cross-cutting influence. This evolvement of the concept has resulted in SED becoming an international policy objective prioritized by governments worldwide. Actions towards SED can vary significantly depending on the energy-related challenges facing the energy system or country in question. Therefore, it is essential to analyze what SED entails within the context to ensure appropriate and successful actions.

Existing indicators for SED were identified and evaluated to analyze how progress towards a sustainable energy future could be monitored (Paper II). The characteristics of a successful indicator set were identified and formed into six indicator set assessment criteria to enable this evaluation, namely: transparency of indicator selection, transparency of indicator application, conceptual framework, representative, linkages, and stakeholder engagement. Lack of transparency was common, which hindered an accurate assessment of some indicator sets. Only one existing indicator set met all criteria, *Energy indicators for sustainable development*, and can be considered comprehensive and robust. Flaws to this set were identified, such as an imbalanced representation of the different pillars of sustainable development and no consideration of how the indicators should be communicated. Therefore, these indicators were deemed to be an appropriate initial basket of indicators for further development within the context in question. The value of stakeholder engagement to aid in the development of context-specific and representative indicators was highlighted.

The review of existing indicators for SED demonstrated the need for an improved process for indicator development and a better set of indicators for SED. A method for indicator development rooted in stakeholder engagement was developed to meet this need (Paper III). In this process, stakeholders are engaged repeatedly to identify what SED entails in the context. Subsequently, indicators are tied to the underlying issues to enable the monitoring of progress towards a sustainable energy future. By engaging stakeholders during indicator development, the validity and comprehensiveness of resulting indicators are increased, and the researchers' bias in the selection of indicators is reduced. If the steps of this process are followed, the indicator set assessment criteria laid out in Paper II should be met, and a comprehensive and robust indicator set should be produced.

The indicator development process was implemented within a real-life context, Iceland, to demonstrate the usefulness of the proposed approach and reveal its potential policy implications (Paper IV). Initially, the challenges and opportunities for SED in Iceland were identified through stakeholder engagement. Subsequently, indicators were chosen to measure progress towards the relevant sustainability goals and monitor actions addressing the underlying issues. Thus, a set of context-specific indicators for SED in Iceland was produced. These indicators reveal the national priorities for SED in Iceland across all three dimensions of sustainability and enable the assessment of progress towards a sustainable energy future in Iceland. Through stakeholder engagement, multiple concrete policy goals were identified, such as the diversification of energy consumers and sustainable utilization of energy resources. Overall, the results of the stakeholder engagement can provide a base for the development of energy policy in Iceland that pushes for SED and is supported by stakeholders. Furthermore, these results can be explored further to gain a deeper understanding of stakeholder views and assess what a sustainable energy future might entail, for instance, what role geothermal energy might play in that future (Paper V). Even though the approach was demonstrated in Iceland, the study could provide insights into some of the challenges that other countries might face in the future.

The structure of this concluding chapter is as follows. In Section 2.2, the main outcomes and implications of the research are discussed. The contributions of this thesis, both academic and practical, are outlined in Section 2.3. This study's limitations and methodology, and the proposed indicator selection process are identified and discussed in Section 2.4. Additionally, further research is considered in Section 2.4. The following Section, 2.5, includes recommendations to policy- and decision-makers. Finally, a concluding statement for the thesis is provided in Section 2.6.

2.2 Discussion of results

In this section, the results of the six papers will be discussed in terms of:

- Understanding a sustainable energy future
- Measuring progress towards sustainable energy development

2.2.1 Understanding a sustainable energy future

This research aimed to improve understanding of what a sustainable energy future entails and how sustainable energy development can lead to such a future. As discussed in the introduction of this thesis, a challenge within the field of sustainability is how vague some of the relevant concepts are, including sustainability and sustainable energy development (Johnston et al., 2007; Robinson, 2004; Solow, 1991). As a result, these concepts mean different things to different people and are misused accordingly, intentionally or unintentionally (Robinson, 2004). This misuse includes “greenwashing,” where the “sustainable development language is being used to promote what may be unsustainable activities” (Pargman and Raghavan, 2014; Robinson, 2004). In the context of energy, Narula and Reddy (2015) highlight the fact that there are no "universally accepted definitions" of terms such as energy security and energy sustainability. As a result, these terms are "interpreted differently according to the perspective of the user" (Narula and Reddy, 2015). Robinson (2004) states that the concept of sustainability "is more usefully thought of as approach or process of community-based thinking that indicates we need to integrate environmental, social and economic issues in a long-term perspective while remaining open to fundamental differences about the way that is to be accomplished and even the ultimate purposes." Similarly, Narula and Reddy (2015) discuss the "need to start 'listening' to different perspectives" to see the full picture.

The above discussion highlights the need for a clearer and more structured framework for understanding these vague sustainability concepts. In this study, two approaches are taken to capture what SED means. Firstly, the literature is reviewed to assess the current status of the SED field and how the concept has developed over time, as seen in Paper I. In this literature review, a multitude of relevant publications are studied, which aligns with Narula and Reddy's (2015) suggestion of considering "different perspectives. Secondly, a stakeholder engagement approach is taken to assess what SED involves within a particular setting, as discussed in Papers III and IV. This approach aligns with Robinson's (2004) suggestion of having a conversation with the community and Narula and Reddy's advice (2015) of listening to different perspectives. One of the principal values of this study is the approaches developed to understand SED better, as discussed in Section 2.3 Contribution to knowledge. These approaches could also be applied to other sustainability concepts and within other contexts to improve understanding. The results of these two approaches are discussed further in the following paragraphs.

A literature review of the concept of sustainable energy development (SED) was carried out to assess the field's current status, as seen in Paper I. In the sustainable energy development paradigm, the environmental, social, and economic impacts of energy are considered. Furthermore, the role energy plays in promoting human well-being and enabling sustainable development is acknowledged (UNDP et al., 2000). In contrast to this, in the traditional paradigm, energy is viewed primarily as a sectoral issue, its externalities are largely ignored, and energy is not connected to development issues (Shortall and Davidsdottir, 2017). Currently, energy is viewed as integral to sustainable development, as evidenced by the introduction of the UN's Sustainable Development Goal 7 on clean and affordable energy (United Nations General Assembly, 2015). The text of this goal sheds light on what a sustainable energy future should entail: "universal access to affordable, reliable, sustainable and modern energy for all" (United Nations General Assembly, 2015). The current worldwide pandemic due to COVID-19 even further highlights the necessity of access to affordable modern energy services to enable countries to respond effectively to the crisis and provide adequate health services (IEA et al., 2020). In this case, access to energy saves lives. The review presented in Paper I shows how the concept of SED has evolved to include a broader understanding of the cross-cutting influence of energy and its services.

Multiple different themes or topics of SED have been presented that roughly show what needs to be addressed or what goals need to be achieved to reach a sustainable energy future, as discussed in Section 1.2 of this thesis. In this research, four main themes of SED were presented, namely, access to affordable modern energy services, sustainable energy supply, sustainable energy consumption, and energy security, along with an overarching goal of furthering sustainability. A general definition of SED was produced from these themes, which aligns well with existing ones in the literature, as seen in Paper I.

The analysis presented in Paper I highlights how the underlying challenges and actions for SED can vary based on the context and the perspective of the stakeholder (Cherp and Jewell, 2014). While the ultimate goal remains the same, a sustainable energy future, the paths towards it, namely, SED, can differ significantly. There is no one-size-fits-all solution that will push every system or nation towards a sustainable energy future. Therefore, context-specific analysis of SED and energy-related challenges is necessary (IAEA et al., 2005). Engaging stakeholders enables a context-specific analysis of SED and what challenges lie on the path towards a sustainable energy future. This approach aligns with Robinson's (2004) statement that "sustainability is itself the emergent property of a conversation about what kind of world we collectively want to live in now and in the future." The value of stakeholder engagement is recognized increasingly more, especially since the UN's *Aarhus Convention on Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters* (United Nations, 1998). A new stakeholder-centric approach was developed for this research; see Paper III and IV. In this new approach, stakeholders are engaged to identify what challenges and opportunities face the energy system in question and describe a desirable sustainable energy future. Thereby, a context-specific understanding of SED and a sustainable energy future is gained. Decision-makers armed with this knowledge can develop appropriate action plans for SED approved by stakeholders. In this study, Iceland was chosen as a case study, and the stakeholder engagement approach was demonstrated there. Even though the analysis was context-specific, the insights gained could be useful to other energy systems that might face similar challenges.

Thereby, two distinct definitions of SED were produced in this research; one general one based on the literature and another context-specific one based on stakeholder input, see Figure 4. According to both of these definitions, the ultimate goal of energy systems is to further sustainable development. These two definitions align well with each other and broadly cover the same topics. The main difference is that the context-specific definition is focused on the unique challenges facing the Icelandic energy system. Therefore, issues such as access to modern energy services are not included as all Icelanders have it, and the sustainable utilization of energy sources is highlighted due to experience with geothermal utilization. The general definition provides a comprehensive overview of the meaning of SED. However, the context-specific definition is more useful to, for instance, policymakers, as it gives greater insight into the unique SED challenges and opportunities facing a particular energy system. Furthermore, a greater understanding of the social dimension of SED can be gained through stakeholder engagement.

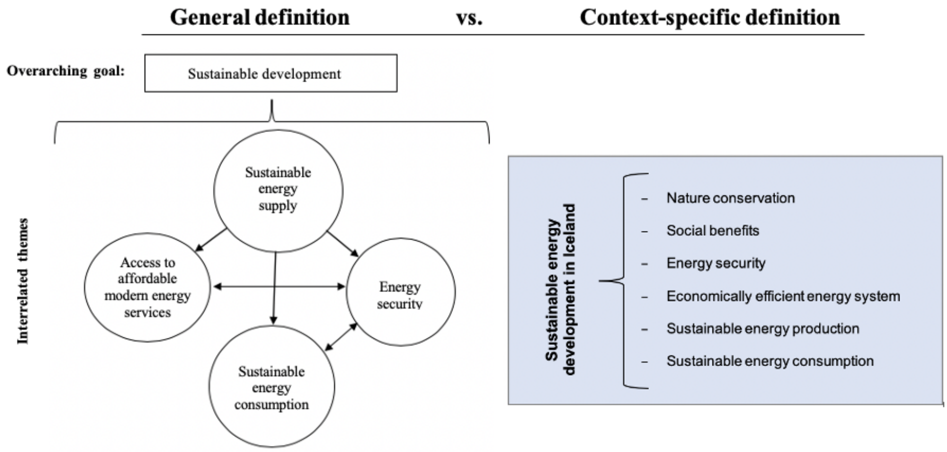

Figure 4: Comparison of the two definitions of sustainable energy development produced in this research. Author's illustration.

The difference between the research presented here and prior work is how the definition of SED and its underlying themes were attained. The author is not aware of any other reviews of the concept of SED and its history that are based on citation analysis. The benefits of this approach are that a comprehensive definition of SED is produced from a study of established and highly cited publications in the field; thereby, the researcher's own bias is minimized. The main downsides are related to citation analysis, such as, lack of analysis of how or why publications were cited, and older publications are favored over newer ones (Bornmann and Daniel, 2008; MacRoberts and MacRoberts, 1989). The value of stakeholder engagement in analyzing concepts such as SED has been established (Robinson, 2004; Sovacool, 2012). What is unique about the approach taken in this research is the combination of stakeholder interviews, Delphi survey, and literature review to capture what SED entails in a particular setting. This combination increases the robustness of the results while minimizing the researcher's own bias. One of the main benefits of the approach is that the views of a broad group of stakeholders are captured to produce a comprehensive and context-specific definition of SED. The main drawbacks are that stakeholder engagement can be time-consuming, and access to stakeholders at various levels is vital.

The final steps of this Ph.D. research coincided with the proposal of a new long-term energy policy in Iceland called "Energy policy to 2050: Sustainable energy future" (Cabinet of Iceland and Ministry of Industries and Innovation, 2020). Therefore, an opportunity presented itself to compare the results of this analysis with the newly proposed energy policy. As discussed in section 1.2.1, the policy has five themes that reflect the main challenges facing the Icelandic energy system on its path towards SED. Furthermore, eight main priority issues for SED in Iceland were presented in the policy. These themes and priority issues are compared to the SED themes and sub-themes identified in this research in Table 1. This comparison demonstrates that a complete picture of the Icelandic energy system and its SED challenges was captured. The research's theme of nature conservation is reflected in the policy as the theme *environment* and priority issue of nature protection and minimizing environmental impacts. The research presented here and the new policy include a theme called *energy security,* which is reflected in priority issues of reliable and secure infrastructure across the country and secure energy supply. The energy security theme developed in the thesis has a broader definition, as it also encompasses the theme of *energy transition* and climate change. The theme of sustainable energy supply is reflected in the policy's themes of *environment* and *energy transition* and the priority issue of renewable energy. The sustainable energy consumption theme corresponds with the *energy efficiency and conservation* theme and the priority issue of energy efficiency, smart technology, and diversity. The social benefits theme aligns well with the priority issue of benefits to the society and consumers and the theme called *society and economy*. The economically efficient energy system theme also corresponds with the *society and economy* theme and priority issue of competition and value creation. This comparison shows that the same challenges and opportunities for SED were largely identified, even though they were organized differently. Thus, the newly proposed energy policy arguably verifies the results of this research. The research presented here goes further than the recently proposed energy policy by connecting indicators with the sustainability challenges facing Iceland's energy system. These indicators allow for the measurement of progress towards a sustainable energy future in Iceland.

Table 1: Comparison of the SED themes in Iceland identified in this research with themes presented in a newly proposed long-term energy policy.

	Proposed energy policy from 2020		Research conducted by Gunnarsdottir et al.	
	Themes	**Priority issues**	**Themes**	**Sub-themes**
Main SED themes in Iceland	Environment	Nature protection and minimizing environmental impacts	Nature conservation	Protect the wilderness Minimize visual pollution
	Energy security	Reliable and secure infrastructure across the country Secure energy supply	Energy security	Sufficient energy reserves Diverse energy sources Strengthen the transmission and distribution system Quality of supply: urban vs. rural Energy independence: domestic energy Energy independence: import dependence Energy independence: risk of imports
	Energy transition	Energy transition and climate change Renewable energy	Sustainable energy production	Energy transitions Carbon neutral energy system Sustainable utilization of resources Minimize impacts on land Minimize emissions
	Energy efficiency and conservation	Energy efficiency, smart technology and diversity	Sustainable energy consumption	Reduce energy consumption Energy efficiency Cleaner fossil fuels Change of attitude
	Society and economy	Benefits to the society and consumers	Social benefits	Public acceptance Benefit from energy development Knowledge creation and technological advancements
		Competition and value creation	Economically efficient energy system	Diversity in income and industries Government expenditure/revenue Economical and profitable energy system Affordable energy prices

2.2.2 Indicators for sustainable energy development

The second half of the overarching research question addressed in this thesis is focused on how progress towards SED should be tracked. The value of indicators to measure progress towards policy objectives has been recognized for some time now. The value of sustainability indicators is reviewed in Section 1.3 in the introductory chapter of this thesis. Multiple indicators and indices have been created to measure progress towards sustainable development or some aspect of it, such as SED (UNDP et al., 2000). Many of these indicators have been criticized for not adequately capturing sustainable development, such as oversimplifying concepts, undervaluing the social dimension, and inconsistent results (Narula and Reddy, 2015; Shortall and Davidsdottir, 2017). Ambiguities in the relevant sustainability concepts could be the cause of these faults. It is challenging to develop a useful tool to measure progress towards a vague goal. Therefore, a better understanding of what SED entails should aid in the development of more effective and representative indicators.

Many attempts have been made to define the necessary steps or characteristics of successful sustainability indicators in the form of criteria, checklists, or guidelines for indicators. One of the earliest ones is the OECD's criteria for selecting environmental indicators from 1993 (OECD, 1993). The different criteria describe many of the same characteristics; for instance, indicators should show trends over time, be relevant to policy, be scientifically sound, and capture a representative picture of the system in question (OECD, 1993; Pintér et al., 2012; Schirnding, 2002). In Paper II, these criteria were reviewed to identify the characteristics of successful indicator sets to enable an assessment of existing SED indicator sets. According to this review, a comprehensive and robust indicator set for SED should have a transparent process for indicator selection and application to ensure the indicator set's credibility and replicability. A conceptual framework should be used to structure the problem in question. The indicators should reflect all dimensions of sustainable development, and the linkages between indicators should be assessed to identify potential correlations and trade-offs. Finally, stakeholders should be engaged to ensure a representative set of indicators. The benefit of defining indicator set criteria is that they enable an assessment and comparison of existing indicator sets in a reasonably straightforward and systematic manner. The downside is that other desirable characteristics that are not included in the criteria might be overlooked, and no in-depth analysis of the topics covered by the indicator set is done.

Most existing indicator sets for SED are developed as national indicators for country comparisons (Graymore et al., 2008; Narula and Reddy, 2015; Shortall and Davidsdottir, 2017). For instance, the WEC's *Energy Trilemma Index* and WEF's *Energy Architecture Performance Index* both monitor the sustainability of national energy systems (World Economic Forum, 2017; World Energy Council and Oliver Wyman, 2019). These indicator sets do not account for national conditions and country-specific energy challenges and, thereby, assume "homogeneity between the characteristics of the energy system of all countries" (Narula and Reddy, 2015). Energy systems and their path towards a sustainable energy future can differ significantly, as highlighted throughout this thesis. A context-specific set of indicators that reflects an energy system's unique characteristics and the relevant energy-related challenges is needed to adequately monitor progress towards SED, inform policy, and communicate the important issues.

The value of context-specific analysis of vague sustainability concepts, such as SED, and stakeholder engagement is emphasized throughout this thesis. A stakeholder-centric approach to indicator development was proposed to capture what SED entails in the context; see Papers III and IV. Thereby, a set of indicators can be selected to reflect the relevant energy-related challenges and reveal national priorities for energy development. The developers of the *Energy Indicators for Sustainable Development* (EISD) also emphasize that indicators should reflect country-specific conditions (IAEA et al., 2005). For indicators to serve their role of monitoring progress and informing decision-making regarding SED, they need to track progress towards national SED goals and reflect the challenges facing that energy system (Shortall and Davidsdottir, 2017). The proposed stakeholder engagement approach to indicator selection can produce a comprehensive and representative set of indicators that reflect stakeholder priorities for energy development in a particular setting. This approach can be applied within any context and at any level, from local to national, to produce context-specific sustainability indicators. The main downside of the process is that it entails repeated stakeholder engagement, which can be time-consuming and, hence, expensive.

The only indicator set that fulfilled all of the indicator set assessment criteria laid out in Paper II and, thus, could be considered comprehensive and robust were the *Energy indicators for sustainable development (EISD)* (IAEA et al., 2005). Nonetheless, these indicators are not used by many. Further analysis of the indicator set revealed some of its faults, such as imbalanced presentation of SED with significantly more economic indicators than social ones and lack of institutional indicators. A comparison with commonly used indicator sets showed that the reason for its lack of use might be because no attention is given to the communication of the indicators. Effective communication of indicators can improve understanding and build trust (Pintér et al., 2012). The Bellagio STAMP principles prescribe the following: "use innovative visual tools and graphics to aid interpretation and tell a story" (Pintér et al., 2012). The usefulness and application of indicators can be increased by communicating them in a transparent and visually appealing way (UN DESA, 2007). Shields et al. (2002) emphasizes that information should be presented "in a way that is meaningful to the lay audience" and states that indicator results need to be "couched in language that resonates with the intended audience." The addition of a final step of communication to the proposed indicator selection approach could be valuable. Effective communication can be a deciding factor for whether an indicator set is used and whether it serves its role of informing policymakers and the public of the critical issues and the status of the system.

Most sustainability indicators are limited to being "backward-looking," as they only reflect the past or, at most, the system's current status (Shortall and Davidsdottir, 2017). It is possible to make indicators "forward-looking" by connecting them with a dynamic model (Zeijl-rozema et al., 2011). Thereby, insight can be gained into the sustainability implications of alternative development trajectories and future scenarios. A review of current energy systems models carried out by Spittler et al. (2019a) showed that current models do not adequately capture the multidimensional implications of SED. To address this, Spittler et al. suggest (2019a) departing "from traditional methodological approaches and ways of thinking and use complementary methods." An improved energy system model that reflects the complexity and multidimensionality of SED could be developed by integrating sustainability indicators, system dynamics, and multi-criteria decision analysis (MCDA). The collaborative research project, *Trajectories towards a sustainable energy* *future*, described in the Preface, aims to do exactly this, i.e., incorporate sustainability indicators and MCDA into a system dynamics model of the Iceland energy system to allow for the identification of desirable development trajectories towards SED.

2.3 Contribution to knowledge

This thesis makes both academic and practical contributions. The most tangible contributions of this research are new approaches to understanding sustainable energy development and developing indicators for SED. The outputs of demonstrating the stakeholder-centric approach in Iceland are a context-specific analysis of SED and a set of indicators reflecting the relevant energy-related challenges and sustainability goals. The multiple academic and practical contributions of this thesis are discussed further in the following section.

2.3.1 Academic research: Contribution to science

This research has made several contributions to academic knowledge. A common problem with sustainable energy development (SED) discourse are ambiguities in the definition of the concept (Narula and Reddy, 2015). A testament to that, when the concept of sustainable development was first formally put forward in 1987 in the *Our Common Future* report by the UN, the role of energy in achieving sustainable development was recognized but not clarified or detailed to any extent (World Commission on Environment and Development, 1987). In this research, the first analysis of the concept of SED based on citation analysis is carried out. This review of the concept shows that it has evolved considerably over time and will most likely continue to do so, responding to changing energy-related challenges and development issues worldwide. The SED themes presented in Paper I contribute to the SED discourse and correlate with recent interpretations of the concept and its underlying issues. Furthermore, potential gaps in the literature or avenues for further research are identified. A thorough review of the concept of SED was thought to be a necessary first step to address the research question of this thesis. The same might apply to other research in the SED field where the analysis presented in Paper I could be useful. Thus, the review of the concept of SED, particularly, the interrelated themes and overarching goal, can inform future SED research, decision-making, and policy development.

In this research, the most comprehensive search and assessment of indicator sets for SED that has ever been done to the author’s knowledge are carried out, thus adding to the existing literature on sustainability indicators. This search and assessment aimed to assess the suitability of existing indicators in measuring progress towards SED. For this purpose, the characteristics of successful indicator sets were identified from existing indicator guidelines to form indicator set assessment criteria. These criteria could be used to assess existing sustainability indicators, not explicitly for SED, as well as guide the development of new sustainability indicators. Transparency in both indicator selection and application is emphasized to ensure the usefulness and replicability of the indicators. The necessity of a conceptual framework for indicator selection is highlighted by one criterion. The brief overview of the different frameworks and their main benefits and shortcomings in the paper can be useful to anyone developing indicators. The results of Paper II highlight the advantages and weaknesses of existing indicator sets for SED, mainly showing that most existing indicators are found lacking. This assessment of the field and the potential pitfalls for indicator development is valuable knowledge. To conclude Paper II, a recommendation is made to use the *EISD* as an initial basket of indicators for further development within the context, which should be useful to both academics and decision-makers. The value of context-specific indicators for SED reflecting national priorities and challenges of energy development is highlighted in this paper. The engagement of stakeholders is recommended to identify energy-related challenges and select representative indicators. Furthermore, the importance of effective communication of indicators and their results is discussed. In this paper, the need for an improved process for indicator development and better indicators for SED is demonstrated.

Building on the indicator assessment criteria and results of Paper II, an iterative stakeholder-centric approach to indicator selection was developed and presented in Paper III. Thereby, the paper adds to a growing research field on sustainability indicators and metrics. What is unique about the proposed indicator development process is that quantitative and qualitative methods are integrated. Qualitative methods are applied during stakeholder interviews and their analysis. These qualitative results are then quantified and verified through a Delphi survey sent to interviewees. The two approaches are thought to complement each other to produce a more robust set of indicators. Stakeholder engagement is put at the center of the process to ensure the development of a comprehensive and representative set of indicators. An emphasis is placed on engaging a diverse group of stakeholders to capture a complete picture of SED in the context. Decision-makers have started to recognize the value of stakeholder engagement or public participation during decision-making and policy development, as discussed in Section 1.4. By engaging stakeholders during indicator selection, the gap between science and policy is bridged. A few valuable products are included in this process, such as a generic map of the stakeholders of an energy system that can be further developed to reflect most energy systems. Another example is indicator assessment criteria that were developed, building on existing criteria for indicator selection. These criteria are used to assess selected indicators to ensure their quality and suitability. Despite its original purpose of SED indicators, the process can be applied within other contexts and to develop indicators for other aspects of sustainable development.

Only taking the first few stakeholder engagement steps of the proposed indicator selection process can be valuable. These steps are presented as an approach to public participation presented in Paper V. The purpose of these steps in the indicator selection process is to capture what SED entails in the context. It is possible to capture what SED or any other vague sustainability concept means in a particular setting through stakeholder engagement. Stakeholder engagement has been found useful to understand better “essentially contested concepts,” such as sustainability and SED (Freeden, 1996; Gallie, 1956). As described by Robinson (2004): “sustainability is itself the emergent property of a conversation about what kind of world we collectively want to live in now and in the future.”

The proposed indicator development process is applied in Iceland to develop indicators for SED in the country, see Paper IV. By implementing the process within a real-life context, the usefulness of the approach is demonstrated. One of the central values of Paper IV are indicators for Iceland’s energy system, both as a significant scientific contribution and a practical tool for stakeholders. The indicators can be used to monitor progress towards SED, which could result in more sustainable utilization of energy resources, increased public acceptance, and facilitate a constructive dialogue among stakeholders. Furthermore, the selection of indicators can sometimes be a catalyst for action (Taylor et al., 2017). The utilization of the indicators could result in a valuable dataset on the Icelandic energy system. As prescribed by the approach, a broad group of stakeholders was engaged several times to identify the challenges and opportunities for SED in Iceland. This stakeholder engagement led to extensive qualitative data collection and analysis of SED in the country, which could be valuable to academics and policymakers. An example of how this data can be further explored is seen in Paper V, where stakeholders' views on the role of geothermal energy in Iceland's SED are evaluated. Throughout this research and the proposed indicator development process, the value and necessity of stakeholder engagement during indicator selection and decision-making are demonstrated.

2.3.2 Applied science: Contribution to policy and practice

Several outputs were produced in this research that have practical value and policy implications. A comprehensive review of the current understanding of sustainable energy development and its evolvement over time is valuable to policy and decision-makers. The review presented in Paper I helps stakeholders understand the main challenges facing current energy systems, what sustainable energy development might entail, and how it could evolve. This review is particularly valuable as ambiguities in the concept have been a prominent issue in the field. The analysis of existing SED indicators presented in Paper II is similarly useful to academics and decision-makers. As discussed earlier, multiple outputs of this research should be of value to anyone developing sustainability indicators, especially for SED. For instance, identifying the characteristics of a successful indicator set and the strengths and weaknesses of existing indicators should valuable. Furthermore, those that are not going to invest in the development of a new indicator set can use the review to find suitable indicators that fulfilled the assessment criteria laid out. The value or necessity of indicators, in particular context-specific ones, to measure progress towards policy goals is demonstrated throughout this research.

The need for better SED indicators and an improved process for indicator development was identified in Paper II. Therefore, a new approach to indicator selection was proposed in Paper III and tested in Paper IV. This proposed methodological approach is one of the central values of this research. In this methodology, stakeholder input provides the foundation for indicator selection – an understanding of SED in a particular setting. Thereby, the indicator selection process can produce a comprehensive and representative set of indicators relevant to policy and accepted by stakeholders. The involvement of stakeholders during indicator selection can improve their understanding of the indicators and increase their sense of ownership, which can be beneficial during implementation. The resulting indicators can act as a catalyst for action or bring about changes that push for the sustainable development of an energy system. Hence, the proposed process and resulting indicators can lead to better policies and action plans. Furthermore, the first few steps of stakeholder engagement can be used as a process for public participation. Thereby, stakeholders' views and goals for any sustainability or policy goal can be identified, as presented in Paper V. The methods presented in this research can be used as a guide for participatory governance as well as the development of indicators.

This research's main policy implications are found in Paper IV, where indicators for SED in Iceland are presented. The proposed process enabled selecting indicators reflecting Iceland's unique energy challenges and national priorities for energy development. As discussed above, the indicator set itself can inform policy and shape actions. Furthermore, the indicators can monitor progress towards SED and communicate relevant issues to stakeholders. Multiple other co-benefits of the indicator selection process with policy implications are identified in Paper IV. These include an identification of the national priorities for SED and what challenges and opportunities face the system, an analysis of stakeholders and their goals for energy development, and a study of the linkages between different indicators or national priorities. As a result, the proposed process helps stakeholders understand what SED entails in the context. The Delphi survey enables the assessment of stakeholders' agreement on the different SED issues. A high level of agreement among stakeholders on the various actions necessary for SED was detected in Iceland. Such knowledge should be useful to policy and decision-makers that rely on public acceptance of actions.

Multiple concrete policy goals are identified from engaging stakeholders in Iceland, such as diversification of energy consumers, sustainable utilization of natural resources, and an energy transition in transportation. In the end, a foundation for the development of energy policy – an action plan and vision of SED – can be gained from applying the proposed indicator selection process within a particular setting. Considering the current lack of accepted energy policy in Iceland, the products of this research should be valuable. This research coincided with the development of a new long-term energy policy in Iceland. A comparison of the newly proposed energy policy and the results of this research in Section 2.2 verified the results of this analysis and their policy relevance. Even though the process was applied in Iceland, the same context-specific outputs should be produced if the methodology is used elsewhere. Furthermore, the insights gained from applying the process in Iceland could be informative to others that are facing or might face a similar set of challenges in the future.

A less tangible practical impact of this research is any potential stakeholder learning and knowledge or ideas sharing during stakeholder engagement. A diverse group of stakeholders was engaged through individual interviews, focus groups, and a Delphi survey, which led to productive discussions on energy development in Iceland. These discussions might have facilitated learning and an exchange of ideas between different stakeholder groups or sectors. Thus, awareness is built, and knowledge is shared, at least among the stakeholders that were engaged.

2.4 Limitations and further research

In this section, the limitations of the literature reviews and the proposed indicator selection approach are discussed. Numerous potential weaknesses have already been identified and discussed in the papers themselves. A broader perspective will be taken in this section, and limitations analyzed at a higher level. Following a discussion on the limitations of this research, avenues for further research are explored.

2.4.1 Methodological limitations of the literature reviews

One of the aims of this research is to improve the understanding of the inherently vague sustainability concept of sustainable energy development. Two different approaches are taken in this research. Firstly, the literature was reviewed to identify prominent SED themes and assess how the concept has evolved. The problem of this approach is that some of the faults of current SED definitions can be carried on, such as lack of consideration and understanding of the social impacts of energy development. Although, this fault of the approach could highlight what is overlooked in the current SED discourse and identify potential gaps in the literature. Secondly, stakeholders were engaged to capture what SED means in a particular setting. Robinson (2004) argues that "sustainability should not be conceived of as a single concept, or even as a consistent set of concepts." According to Robinson (2004), an understanding of sustainability, or in this study, SED, could be gained from a conversation within the community about what a desirable future entails. The stakeholder engagement approach taken in this study aligns well with Robinson's statement.

The sustainability discussion and literature has primarily been shaped by Western researchers and from a Western perspective. As a result, there is a certain level of Western bias in the sustainability discussion. This problem is sometimes referred to as WEIRD in the human behavior and psychology literature where practices have been criticized for a bias towards and overly emphasizing research of Western, educated, industrialized, rich, and democratic (WEIRD) societies (Henrich et al., 2010a, 2010b). Researchers assume their research is universal and also applies to other non-WEIRD societies without necessarily supporting this generalization with evidence (Henrich et al., 2010b). This WEIRD problem is also found within the sustainability literature. To address this problem, some argue that research needs to move beyond these WEIRD societies and start focusing more on other, perhaps underrepresented, societies (Sovacool et al., 2018). This Western bias in research is even further increased when researchers limit their analysis to literature in English, even though there is a clear dominance of the English language in the international scientific literature (Hamel, 2007). The literature reviewed in this study was almost exclusively written in English, and publications written in other languages were mostly excluded. One possible way of reducing Western bias would be to emphasize the analysis of research from all around the world, not only within WEIRD societies, and attempt to translate relevant literature from other languages than English.

The search conducted for both publications on sustainable energy development and relevant indicator sets was primarily restricted to academic databases. Nonetheless, many of the most cited publications were policy documents published by international agencies such as the UN and IEA. Furthermore, multiple indicator sets for SED were not developed by academics but also by established international agencies. Therefore, limiting the search to academic databases could have resulted in the omission of influential publications and indicator sets. An additional search in a non-academic database, for instance, one for grey literature, could enhance the literature reviews. However, no well-functioning database for the grey literature was found.

Six different assessment criteria were selected to allow for the evaluation of existing indicator sets for SED. These criteria reflect characteristics thought to make indicator sets comprehensive and robust and were based on existing indicator guidelines, such as the Bellagio STAMP principles (Pintér et al., 2012). While the criteria enabled the evaluation of a large number of indicator sets, they were in no way an exhaustive list of the desirable characteristics of indicators. Nonetheless, the evaluation was limited to the criteria, and no more in-depth study of the indicator sets was carried out. Therefore, some crucial criteria might have been excluded, such as how well the indicators reflect SED's underlying topics and how effectively indicator results are communicated. Furthermore, some of the criteria were simplified to allow for measurability. An example of this is the “representative” criterion, which was measured by whether economic, social, and environmental indicators were included. A valuable next step would be an in-depth assessment of high-scoring indicator sets, including an analysis of the topics covered by the indicators and how representative they are of SED.

There is always some potential for the researchers’ own bias influencing the study in some way. Sovacool et al. (2018) argue that qualitative research is more vulnerable to the researchers’ bias. This argument applies, for instance, to the thematic review carried out in Paper I. In response to this, Sovacool et al. (2018) suggest that researchers emphasize being “empirically grounded in evidence” to minimize bias. Another example of potential bias is when the decision was made of which indicator sets should be included in the analysis conducted in Paper II. There, the authors’ subjective judgment might have directly affected the outcomes of the study. In the end, it is quite impossible to eradicate a researcher’s own bias in research. The important thing is that researchers are aware of their own biases and attempt to reduce it throughout (Merriam and Tisdell, 2016).

2.4.2 Limitations of the iterative stakeholder engagement approach to indicator selection

One of the main limitations of this study, along with other PhD studies, is that it had to fit the scope of a PhD program. Therefore, the study was limited in both time and funding. This limitation highlights the importance of effective organization to ensure comprehensive and exhaustive data collection and analysis.

A new approach to indicator selection rooted in stakeholder engagement is one of the most valuable outputs of this research. While there are multiple benefits to this new approach, there are also some limitations. A seven-step process for indicator development where stakeholders are engaged repeatedly can be lengthy and labor-intensive. These faults can lead to an expensive process for indicator selection. However, some steps can be taken to address these faults. Considerable time can be saved with excellent organization, especially for stakeholder engagement. For instance, a thorough analysis of stakeholders enables selecting a balanced and representative group of interviewees. Identifying useful contacts that can potentially connect the researcher to other stakeholders can be helpful. Furthermore, the timing of stakeholder engagement is essential; for example, attempting to engage stakeholders during the summer months through either interviews or surveys can be unfruitful. The timing was an issue when the proposed indicator selection process was applied in Iceland, as discussed in Paper VI. Response rates decreased significantly for the second round of the Delphi survey, which was sent to stakeholders during the summer months.

Stakeholder engagement is both one of the main strengths and potential downfalls of this new approach to indicator selection. Access to stakeholders at various levels within the energy system is essential to capture a balanced and comprehensive picture of the system and its sustainable development. Stakeholders are engaged repeatedly to ensure the robustness of results. There is potential for stakeholder fatigue due to this repeated engagement. Therefore, additional efforts might be required to motivate stakeholders to continue participation throughout the process. Finally, there is the possibility that researchers influence interviewees in some way, or their own bias could affect the interpretation of results. Emphasis should be placed on minimizing influence and bias throughout the process by, for instance, demonstrating neutrality and saying as little as possible during stakeholder interviews.

Some problems are associated with the use of a thematic indicator framework. Through this framework, a problem or indicators can be presented in a structured and straightforward manner, and a thematic presentation of indicators also fits well with qualitative analysis. However, using a thematic framework can make it challenging to identify causality and interlinkages, and the dynamics within a problem are not captured (Stanners et al., 2007). These faults can lead to the oversimplification of a problem. To tackle this limitation, the UN has emphasized the consideration of linkages among themes and indicators when applying a thematic framework (IAEA et al., 2005; UN DESA, 2007). Furthermore, since the dynamics within SED are not captured through a thematic perspective, one needs to be careful when interpreting the results of indicators and analyzing causality as "indicators can sometimes show trends that are similar but not linked" (IAEA et al., 2005). In the approach presented in this research, the limitations of thematic frameworks are tackled in a similar way to the UN, by stating that the linkages between themes and indicators need to be considered, see Paper III. However, a better approach is also theorized where a theme-based framework combined with a system dynamics approach could enable an analysis of interlinkages and trade-offs while keeping the multiple benefits of a thematic framework (Nerini et al., 2018).

Effective communication of indicators and their results is vital if indicators are to inform policy and influence actions (UN DESA, 2007). An additional step of connecting indicators with the relevant benchmarks and quantitative policy targets, when possible, would be useful (SDSN, 2014). This lack of connection between indicators and targets makes it difficult for stakeholders to assess the progress being made towards the different targets. Although, for some of the more qualitative indicators, there might not be a quantitative target. More thought could be put into how indicator results are analyzed and presented. For example, innovative visual tools and graphics could be used to communicate the critical issues of SED clearly to stakeholders (Pintér et al., 2012).

One of the main strengths of this process is the potential for multiple by-products with policy implications, such as analysis of stakeholders and their goals, identification of concrete policy goals, and discussion of actions enabling SED and challenges facing the system. However, the process itself is focused on the production of SED indicators. As a result, these potential by-products might not be explored further. It would be wasteful not to take full advantage of all the data collected during this lengthy process. Therefore, this approach should not be limited to the production of indicators but should be viewed as a decision-making tool that enables the context-specific assessment of a sustainability problem, selecting relevant sustainability indicators, scenario building, and informs policy and decision-making.

As discussed in Section 2.2.2, most current sustainability indicators are “backward-looking.” The indicators only show the current and past status of sustainability issues and do not reflect what might happen in the future. This same criticism applies to the indicators produces in this research. While it is important to monitor an energy system's current status, it would also be beneficial to know how the results of indicators might change corresponding to different actions taken or policies implemented.

2.4.3 Further research

Since sustainable energy development is likely going to remain a central policy goal, governments will need to understand what SED means and how progress towards it can be measured. Therefore, the research and methodology presented in this thesis will hopefully remain relevant. While the focus of this research is on SED, the methodologies developed and applied could be used for other aspects of sustainable development or even other policy goals, in particular the approach to public participation.

The concept of SED will continue to evolve, reflecting changing energy and developmental challenges worldwide, as discussed in Paper I. Therefore, a periodic review of the concept, similar to the one conducted in Paper I, would be useful. An up-to-date understanding of the concept and knowledge of how the relevant challenges are evolving is valuable information to any stakeholder of an energy system. While the methods applied in this research have been demonstrated as useful, a more thorough examination of the relevant grey literature would further enhance it. Additionally, an awareness of potential Western bias of the literature and an attempt to minimize that bias is beneficial. To even further improve the review, citing behavior in the field could be analyzed more to, for instance, identify emerging gaps in the literature and assess what kind of publications are cited the most.

A more detailed analysis of high scoring indicator sets that is not limited to the indicator set assessment criteria would be valuable. Furthermore, a review of the topics that these established indicator sets for SED reflect would even further shed light on what the concept entails. A comparison of this sort of analysis with the results presented in Paper I would be interesting. Current indicator sets have been criticized for undervaluing the social aspects of SED (Shortall and Davidsdottir, 2017). This sort of analysis and comparison would clearly show which issues are emphasized by current indicator sets and which ones are not.

Indicators can be viewed as useful tools to communicate important issues to stakeholders (Taylor et al., 2017). Therefore, attention needs to be given to the effective communication of indicators. A criticism of the proposed indicator selection process is the lack of consideration of how the indicators should be communicated to stakeholders. Therefore, further research could be done on what effective communication entails to ensure the indicator set's usefulness and application. For instance, linking indicators with quantitative policy targets or benchmarks can be valuable. Thereby, the indicators are put into the relevant context and clearly show whether progress is being made towards policy objectives.

There remain ample opportunities to utilize the indicators developed in this research and examine their results. If the indicators developed for the Icelandic energy system are used, a valuable dataset for the Icelandic energy system will be created. An analysis of this dataset could support better decision-making regarding energy development in the country. Furthermore, potential linkages between different indicators and their outcomes could be identified. The indicator set should be updated regularly to reflect the gradually changing challenges facing the energy system and to ensure its continued use. This update could be done through an adjusted Delphi survey sent to stakeholders where the relevance of indicators would be assessed, and new areas of concern would be identified.

The value of stakeholder engagement and sustainability indicators is highlighted throughout this research and manifested in a new approach to indicator selection for SED. The current policy cycle could be enhanced with the incorporation of the proposed indicator development process, see Figure 5. Thereby, stakeholders would be engaged to aid with agenda-setting and identify what SED or any sustainability issue means in the context. Stakeholder engagement during policy formulation supports a sense of ownership and improved understanding of actions (World Economic Forum, 2017). The development of indicators reflecting the relevant policy objectives would be emphasized from the start of the policy cycle. These indicators would then enable the monitoring of progress and evaluation of the success of policies and actions.

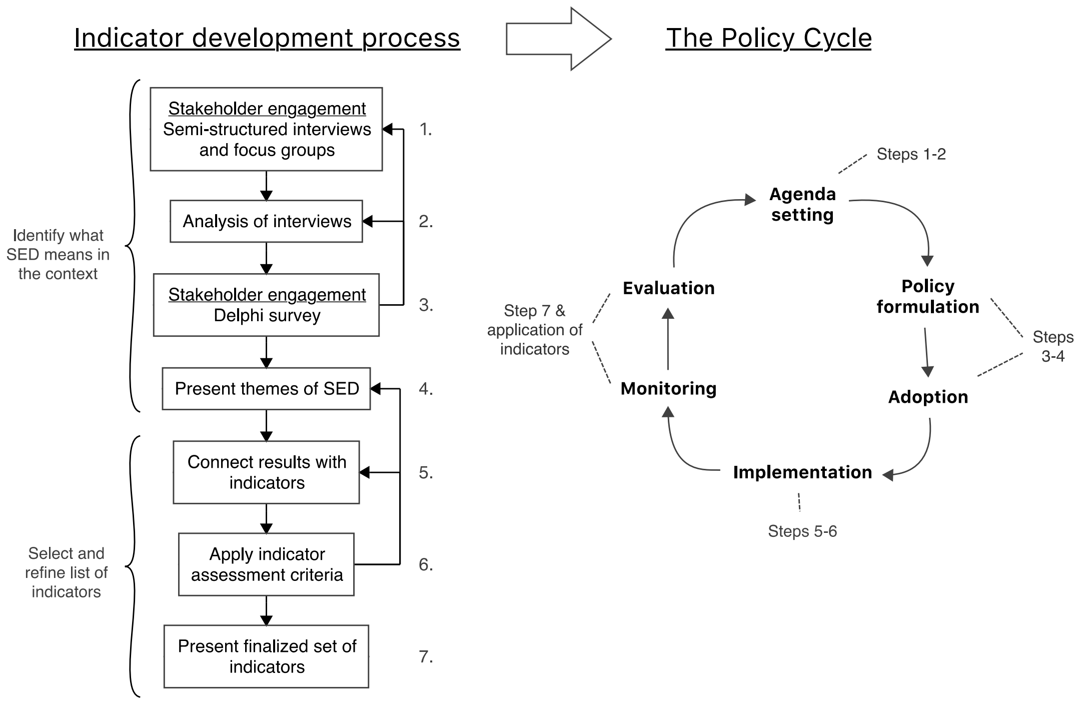

Figure 5: Incorporating the indicator development process and stakeholder engagement within the policy cycle. Author's compilation of the indicator development process and policy cycle drawing on Shields et al. (2002) and Bridgman and Davis (2003).

A valuable decision-support tool could be created by integrating sustainability indicators, an energy system model, and multi-criteria decision analysis (MCDA). Thereby, indicators would become "forward-looking," and the multidimensional sustainability implications of alternative futures could be assessed and compared based on stakeholder preferences through the use of MCDA. This sort of integrated tool for decision support would enable identifying a robust development path towards a sustainable energy future. The knowledge of what actions and policies would push for a desirable pathway towards SED is immensely valuable to decision-makers.

Several opportunities for further research exist if the qualitative data collected through stakeholder engagement in Iceland is analyzed in more detail. Thereby, the previously mentioned by-products of the indicator selection process would be examined further and made more concrete. Stakeholders discussed what a sustainable energy future might entail, what challenges are facing the system on the path towards that future, and their goals for energy development. Based on this input, scenarios for a sustainable energy future could be built. Subsequently, pathways and policy actions that drive the shift towards those sustainable energy future scenarios can be visualized and evaluated through backcasting (Giddens, 2009). This sort of research can inform the creation of energy policy that pushes for SED. Additionally, different aspects of that future and stakeholders' views can be assessed further, as done in Paper V.

Many stakeholders mentioned the foresight and ambition of the Icelandic government when the transition towards geothermal district heating took place. The same kind of political climate was thought necessary to push SED further in the country. It would be interesting to examine what this environment entailed and how it came about, for instance, what factors influenced the government's decision to transition to geothermal energy. Understanding what kind of political climate enables change is useful to push for other necessary changes for sustainable development.

2.5 Recommendations

The following recommendations are made to policy- and decisionmakers based on the outcomes of this thesis:

- A literature review of vague sustainability concepts, such as SED, can be helpful to get a broad idea of what a concept involves, as described in Paper I. However, a more detailed analysis of such concepts within a particular setting is more beneficial and can inform decision making and policy development, as discussed further in Papers III and IV. By engaging stakeholders, concrete policy actions and sustainability goals of stakeholders can be identified. A structured and transparent stakeholder engagement approach, such as the one proposed in this study, can be useful for this purpose.

- Sustainability indicators can be useful tools for monitoring progress and informing policy. It is beneficial to develop context-specific indicators for SED that reflect the energy-related challenges facing a particular energy system. An indicator selection process based on stakeholder input can enable the selection of one-of-a-kind indicators reflecting the unique SED challenges and opportunities within a specific setting, as described in Papers III and IV. When developing sustainability indicators, it is essential to keep in mind that while indicators can be useful, they are just a means to an end and not the goal itself.

- It is beneficial to use the indicator assessment criteria laid out in this study to guide the development of sustainability indicators; see Papers II and III. The credibility and replicability of an indicator set depend on how transparently the process for indicator selection and application is presented. The use of a conceptual framework can aid in structuring complex problems, such as SED. Social, economic, and environmental indicators should be included to measure progress towards a sustainability goal adequately. It is valuable to consider linkages between indicators and, thus, different sustainability issues. The engagement of stakeholders during indicator selection enables the development of a representative and comprehensive set of indicators. The indicators themselves should be simple and easily interpreted, show trends over time, be grounded in research, and be based on good quality data.

- The effective communication of indicators and their results can be a deciding factor for their use, as discussed in Paper II. Therefore, further research could be done on what makes the communication of indicators effective. When developing a new set of indicators, an effort should be put into the communication and presentation of the indicators to ensure their usefulness and use. Thereby, indicators can become tools to communicate important issues to stakeholders.

- Giving ownership of indicators to the relevant governmental body, agency, or organization could be useful, as discussed in Paper II. Thereby, one body would be in charge of collecting data, monitoring, reporting, and updating the indicators periodically.

- The integration of sustainability indicators with an energy system model and MCDA is recommended to create a valuable decision-making framework. Thereby, indicators are made "forward-looking" and used to assess the sustainability implications of different development trajectories. This sort of framework would enable the assessment of alternative energy futures. Thereby, the impact of different decisions and policy actions on the sustainability indicators could be evaluated. Using this framework, desirable trajectories towards a sustainable energy future and the necessary policy actions to enable those trajectories could be identified.

- For policy- and decisionmakers in Iceland, specifically, a recommendation is made to consider the results of this thesis, in particular, Paper IV and Paper V. Based on stakeholder input, a comprehensive overview of what SED involves in Iceland is provided here. Furthermore, a set of indicators for Iceland's SED is presented that reflects national priorities for energy development according to stakeholders. These indicators and the relevant analysis within Iceland compliment the newly proposed energy policy in Iceland and enable the monitoring of progress towards a sustainable energy future in Iceland.

The iterative stakeholder engagement approach to indicator selection developed and applied in this research was demonstrated as a useful approach to capture what SED involves in a particular setting and develop context-specific indicators, as described in Papers III and IV. This approach highlights the value of stakeholder engagement to inform actions and allow stakeholders to buy into the decision-making process. Multiple different strategies for stakeholder engagement or public participation exist that vary significantly both in methods and transparency. The advantage of the approach presented here is its clear structure, where the various steps are laid out, and their purpose is clearly explained. The iterative nature of the approach allows for the repetition of steps when deemed necessary, ensuring the robustness of results. This approach can be applied within other settings and for other vague sustainability concepts to capture a context-specific understanding of the concept and develop appropriate sustainability indicators.

2.6 Conclusions

This thesis set out to explore what a sustainable energy future entails and how progress towards it could be measured. The first step to address this question was to understand better sustainable energy development leading to that future. An analysis of the literature showed that the concept of sustainable energy development (SED) is inherently vague and complex and has evolved considerably over time. Broadly, SED entails improving economic and social well-being while staying within ecosystem boundaries. As such, energy has been found instrumental in realizing sustainable development. As a result, SED has become a central cross-cutting policy objective connected with most major development issues worldwide.

The path towards a sustainable energy future can vary significantly, corresponding to the energy-related challenges and opportunities within a particular setting. The benefits of a context-specific analysis of SED are demonstrated in this thesis. A new stakeholder engagement approach is presented to capture what SED means to stakeholders of the system in question. Through this approach, the sustainability goals of stakeholders and underlying energy issues are identified. Overall, this thesis has advanced understanding of the concept of sustainable energy development, both at a general level through a comprehensive literature review and within a particular setting through the stakeholder engagement approach.

A set of SED indicators and a process for their development was developed to address the latter half of the overarching research question addressed in this thesis. Similar to a context-specific analysis of SED, a tailored set of sustainability indicators is valuable to reflect the relevant energy issues. Sustainability indicators can serve an important role in monitoring progress, informing actions, and communicating issues. However, current approaches to indicator development and existing SED indicator sets have been found lacking. A stakeholder engagement approach to indicator selection resulting in representative and comprehensive indicators could be the way forward. Frequently, the social side of sustainability issues is undervalued. Understanding the potential social impacts of energy development can be captured by engaging with the relevant stakeholders. Integrating the stakeholder engagement approach for indicator selection within the policy cycle could be useful. Thereby, stakeholders could inform the selection of appropriate policy objectives reflecting the relevant sustainability issues, and the indicators would enable the monitoring of progress towards these policy objectives.

The value of sustainability indicators could be increased even further by connecting them with a dynamic model and multi-criteria decision analysis. Thereby, the indicators are made “forward-looking” and used to assess the sustainability implications of alternative futures. Such an integrated model could enable the identification of development trajectories towards a desirable and sustainable energy future. As such, the integrated model could become a powerful decision-support tool. The communication of the results of such a model and the indicators themselves can determine their usefulness and impact. Therefore, further research on how to effectively communicate such issues would be valuable.

The methodologies developed and applied in this research were intended to improve understanding of sustainable energy development and advance relevant indicators. However, these methodologies could also be used to understand other ambiguous sustainability concepts better. Furthermore, the indicator selection process could be applied within different contexts to develop indicators measuring progress towards other sustainability goals. Similarly, while the methodologies developed were demonstrated within the Icelandic energy system, the lessons learned and insights gained could be useful for other energy systems that might face a similar set of challenges in the future.

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Paper I: Sustainable energy development: History of the concept and emerging themes

SUSTAINABLE ENERGY DEVELOPMENT: HISTORY OF THE CONCEPT AND EMERGING THEMES

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Abstract

Sustainable energy development is a complex multi-dimensional concept that can vary in meaning based on the context it is applied in and the perspective of the user. The role of energy in achieving sustainable development was recognized when the concept was first put forward in 1987. However, what that role consisted of was not made clear. Since then, the concept of sustainable energy development has developed to become a prominent policy objective on the international agenda, as evidenced by the introduction of the UN's Sustainable Development Goal 7 on energy. This paper presents an overview of the history of the concept as well as its emerging themes. Through a citation analysis, the most cited open-access publications relevant to the concept were identified. A thematic analysis of these most cited publications led to the identification of four interrelated themes of sustainable energy development; access to affordable modern energy services, sustainable energy supply, sustainable energy consumption, and energy security. The overarching goal of sustainable energy development was defined as furthering sustainability. Equitable access to affordable and reliable modern energy services is integral to sustainable development. A transformation of the current energy system is necessary to reduce its harmful impacts, both on the supply and demand side. This transformation is not possible unless it is economically viable through, for instance, cost-competitive technologies and changes in energy pricing to reflect the external costs of energy.

Highlights

- Sustainable energy development is a young multi-dimensional concept
- Common themes of sustainable energy development are identified
- Access to modern energy services for all is essential to further sustainable development

Keywords

Sustainable energy development; Energy policy; Sustainable development; Literature review; Thematic analysis; Citation analysis

Word Count

10,060

List of abbreviations

CSD – Commission on Sustainable Development
EEA – European Environment Agency
EISD – Energy Indicators for Sustainable Development
ETP – Energy Technology Perspectives
IAEA – International Atomic Energy Agency
IEA – International Energy Agency
IRENA – International Renewable Energy Agency
ISD – Indicators for Sustainable Development
ISED – Indicators for Sustainable Energy Development
MDGs – Millennium Development Goals
RoMEO – Rights Metadata for Open-Archiving
SDG – Sustainable Development Goals
SE4ALL – Sustainable Energy for All
SED – Sustainable Energy Development
UN – United Nations
UN DESA – United Nations Department of Economic and Social Affairs
UNDP – United Nations Development Programme
UNIDO – United Nations Industrial Development Organization
WEA – World Energy Assessment
WEO – World Energy Outlook
WSSD – World Summit on Sustainable Development

1. Introduction

When the concept of sustainable development was first formally put forward in 1987 in the *Our Common Future* report by the UN, the role of energy in achieving sustainable development was recognized [1]. However, what that role consisted of was not made clear. In 2000, the United Nations Development Programme presented a new development paradigm in its *World Energy Assessment* report. There the concept of sustainable energy development was introduced where the impacts of energy development on the economy, society, and environment were considered [2]. In 2001, the IAEA, along with other international organizations and countries presented an initial attempt at developing indicators for sustainable energy development, at the Ninth session of the Commission for Sustainable Development, which further shaped the concept [3]. Sustainable energy development (SED) is a complex and multi-dimensional concept that can vary in meaning based on the context it is applied in and the perspective of the user [4]. The role of energy in achieving sustainable development was further recognized and defined in 2015 with the introduction of goal seven of the United Nation's Sustainable Development Goals, "*Ensure access to affordable, reliable, sustainable and modern energy for all"* [5]. Since the *Our Common Future* report in 1987, the role of energy in sustainable development and what sustainable energy development entails has been further defined. It is now firmly on the political agenda, in particular, due to raised environmental concerns and depleting fossil fuel sources.

Multiple different themes or issues of sustainable energy development exist. These have evolved and changed through time, similar to other issues of sustainable development. Initially, energy was discussed in the context of reducing greenhouse gas emissions and improving air quality [6]. Currently, sustainable energy development is viewed more holistically, where all three pillars of sustainable development are accounted for: economy, society, and environment. Thus, the role energy plays in promoting economic growth and social development is recognized [2]. Considering increasing energy demand and depleting fossil fuel sources, energy efficiency and a transition towards renewable energy sources are emphasized [7]. Environmental degradation with the associated health and social impacts has even further pushed this energy transition [2]. While the topic of energy security has been prominent for some time, it is now viewed as a part of sustainable energy development, which can involve actions such as diversifying energy sources with an emphasis on domestic and renewable resources [8]. None of this is achievable without the necessary political will and policy changes to push a transformation of current energy practices [2].

The objectives of this study are twofold;

1) examine how the concept of sustainable energy development materialized
2) identify emerging themes of the concept

These objectives are met through a review of the relevant literature. The history of the concept of sustainable energy development is examined to analyze how it has become a key policy objective integral to sustainable development. The most influential publications on sustainable energy development are identified through a citation analysis where the most-cited open-access publications are identified. Subsequently, a thematic review is carried out of these publications to identify emerging themes of the concept. To the best of our knowledge, this is the first comprehensive review of the concept of sustainable energy development, its history, and emerging themes based on citation analysis.

2. Method

2.1. Systematic literature review

The study aims to analyze the concept of sustainable energy development, how it has become a prominent policy objective, and what this multi-dimensional concept encompasses. A systematic literature review was carried out to address these objectives. A systematic approach to a literature review increases the comprehensiveness of the search and minimizes potential bias while ensuring rigorous and transparent methods [9,10]. The review consisted of three main steps; literature search, citation analysis, and thematic analysis described in detail in the following paragraphs. An initial pool of publications was identified through the literature search. This search was restricted to openly available publications through either open access publications or self-archiving. Authors often choose to self-archive, i.e., make a free copy of their publication available online, to make their publications more accessible. Despite restricting the literature search to openly available publications, only about 20% of publications were excluded at this step. The citations of these publications were analyzed to identify the most cited publications in the field. Thereafter, a thematic analysis was carried out of these most cited publications to identify emerging themes of SED. It is important to note that while the literature search was limited to openly available publications, the results of the citation analysis were not.

2.2. Literature search

The literature search consisted of three main steps:

1. *Search databases for the search string "sustainable energy development"*

A combination of different databases is recommended for systematic literature reviews to identify all relevant literature [11]. The selection of databases greatly depends on the field of science. As the topic of interest for this analysis was an interdisciplinary topic that rests within numerous disciplines, field-specific databases, such as medical ones, were excluded. When selecting which databases to use, three commonly used non-subscription-based databases were scoped for the search string "sustainable energy development": 1,515 results from ScienceDirect, 521 from Scopus, and 323 from Web of Science. For this study, only publications in English were considered. No time limitation was put on documents to allow for an analysis of the history of SED.

2. Limit search to open access publications

Invariably, citation analyses are preceded with a restricted literature search or selection of relevant publications to determine an initial pool of publications for further study [12,13]. Quental and Lourenço defined “narrow and precise criteria” for their literature search to ensure the retrieval of relevant papers [14]. Generally, these search criteria significantly reduce the number of results found in the literature search. For this study, restricting search results based on relevance was thought to introduce the authors‘ bias of what are important issues of SED. Therefore, a relevance criterion could taint later results, namely, the identification of emerging themes of SED. Instead, the literature search was limited to publications that were readily available to the researchers, such as through open access journals or self-archiving (See Table 1). One of the reasons for this criterion was that some of the search results could not be accessed, such as books that were not available to the researchers. Furthermore, the benefit of this criterion is that it allows for the replication of this analysis by others.

Table 1: RoMEO colors.

The table shows the meaning of different archiving colors [15].

Gold	Open access
Green	Archiving allowed for pre-print and post-print
Blue	Archiving allowed for post-print
Yellow	Archiving allowed for pre-print
White	Archiving not supported

Due to the open-access criterion, some search results, including books, book chapters, conference proceedings, and journal articles, were excluded at this stage. Only journal articles that are made available in either open access journals or repositories were kept. The SHERPA RoMEO archiving colors were used to guide this step [16]. The purpose of the RoMEO (Rights Metadata for Open archiving) project was to analyze the rights of authors to self-archive their research [17]. In this project, a publishing color chart was developed that indicates the archiving policies of peer-reviewed journals [15]. For this study, the web-based SHERPA RoMEO database was used to identify the categorization of journals [16]. Articles published in journals categorized as gold, green, blue, or yellow, see Table 1, proceeded to the next step of the literature review. For these journals, the authors can self-archive some version of their paper. In the end, over 80% of search results were kept despite the open-access search criterion. The majority of journals allow for self-archiving in some form and, therefore, only a small number of journals are classified as white.

3. Integrate results from the different databases and eliminate duplications

In the end, a total of 1,253 publications were identified that met the search criteria laid out. The citations of these publications were analyzed further in the next step of the literature review process. It is important to note that the citation analysis itself was not limited to openly available publications, and, therefore, publications identified as influential could be published in, for instance, a closed or white journal.

2.3. Citation analysis

Citation analysis is the assessment of bibliographic references, which can indicate scientific interaction between researchers within a field [13,18,19]. In 1972, Garfield first proposed that citations could be used as a metric for scientific activity and influence, which eventually led to the creation of the journal Impact Factor [14,20]. According to Garfield, frequently cited publications at least have a high level of utility and are of interest to researchers in the field [21]. The premise of citation analyses is that high-quality work is cited more often than low quality work [22]. Thus, the frequency of citations can be an indicator of the „importance and qualitative value“ of a document [23] or its "research impact" [22]. Furthermore, highly cited publications can represent a central contribution to the field [23] or could be considered influential in shaping it [24].

Citation analyses have been found useful to study the history of a concept or a scientific discovery, which fits well with the goals of this analysis [25,26]. Generally, this approach involves analyzing the citations of a pool of publications found through a literature search to identify the most cited documents [13,24]. Citation analysis can be a lengthy process that involves numerous labor-intensive steps. For this study, five mains steps were taken that are described further in the following paragraphs.

1. Extract citations from publications identified in the literature search

An initial pool of publications for the citation analysis was identified through the above literature search. The first step of the citation analyses involved extracting the references of those publications to create a list of relevant references. Therefore, 1,253 publications were downloaded, and their 55,152 references were manually extracted and transcribed into an Excel sheet. Through this step, an electronic database was created that could be analyzed further [23]. On average, 44 citations were made per publications; however, in some studies, hundreds of references were made. This step was one of the most time-consuming of the citation analysis.

2. Aggregate identical references

Variants of the same references were aggregated to shorten the initial long list down to 48,382. As citations could be formatted differently and could contain, for instance, spelling errors, a combination of author information, title, and date of publication was necessary to enable this aggregation [14].

Citations did not directly align when the list of references was alphabetized, making the aggregation a lengthy process.

3. Count number of times cited

The number of times publications were cited was counted to identify the most cited ones. As the pie chart in Figure 1 shows, the majority of publications were referenced only once. A similar result was produced in Quental and Lourenço's citation analysis of the sustainable development literature, where 87% of publications were cited only once [14]. The number of publications drops steadily with a higher number of times referenced. The most cited document was referenced 63 times.

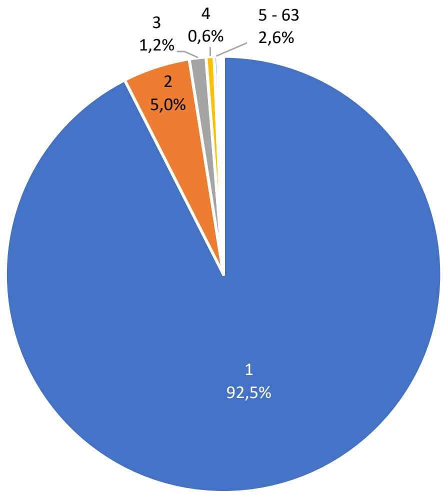

Figure 1: How often were references cited? *Pie chart showing the distribution of how many times references were cited.*

4. Identify the most cited publications

The most common approach to determine the most cited publications is simply to select a specific amount of most cited publications. Citation analyses were found that identified as few as ten most cited publications [27] to as many as to 60 [14], although most studies identified the 20 most cited publications [12,13,19,26]. For this analysis, an approach of identifying the 30 most cited publications was taken, which was deemed an appropriate amount to be influential in the field of sustainable energy development. This approach meant that publications cited at least thirteen times were considered further, which resulted in a total of 34 most cited publications. Appendix A includes a list of these most cited publications.

5. Analyze results

One publication was cited to by far the most often, or 63 times, and that was the UN's *Our Common Future* report, which was also the oldest publications identified as influential [1]. Figure 2 shows the origin of the most cited references, mainly, UN, IEA, and journal articles. The nine most cited references discussed SED at a global level and, thus, applied to many, both UN reports and frequently cited paper in the field. These results are similar to Quental and Lourenço's bibliometric analysis of the sustainable development literature [14]. The topic of 14 of the 34 documents was SED of a single country or region, of which eight analyzed the situation in Turkey and three in Malaysia. An emphasis was placed on examining the concept generally to meet the objectives of this study, and not the specific challenges the country in question was facing.

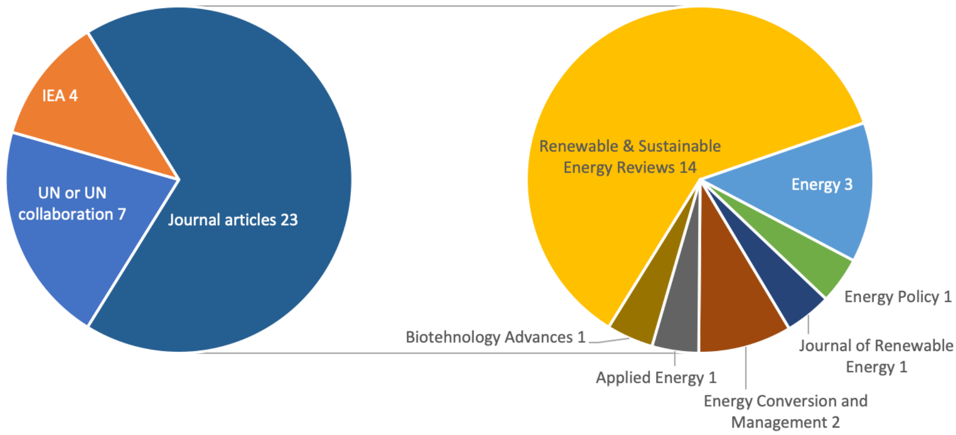

Figure 2: Publishers of most cited publications. *Pie of pie showing where or who published the most cited publications.*

Citation analyses often involve steps of cluster formation and interpretation to identify the main categories of research in the field [13,23,24]. Many of the publications identified as most cited were found too broad to fit within just one cluster, such as the UN‘s Our Common Future report, and the IEA‘s World Energy Outlooks [1,28–30]. Therefore, a thematic analysis of the contents of most cited publications was found more fitting to address the objectives of this study. A similar approach was taken by Liñan and Fayolle, where citation and thematic analysis were combined [24].

2.4. Thematic analysis

The purpose of the thematic analysis of the most cited documents was to identify emerging themes of sustainable energy development and assess the current understanding of the concept. The thematic analysis was rooted in Glaser and Strauss's grounded theory, where ideas and themes were not chosen before the analysis but derived from the data collected and developed throughout the process [31]. This approach is sometimes described as a continuous cycle of data collection and data analysis [32]. A six-step iterative method for the thematic analysis was developed based on an established framework for qualitative research by Braun and Clarke [33,34], described further below:

1. *Familiarization with publications*

The 34 most cited publications were read with a focus on sections relevant to sustainable energy development and not country-specific challenges. Initial ideas about the data and potential patterns were recorded [33].

2. *Generation of codes for each publication*

Each publication was manually coded with the research questions of this study in mind: examine how the concept of SED materialized and identify its emerging themes. Therefore, text in the publications that described, for instance, defining elements of SED, underlying challenges, and necessary actions was coded. According to Boyatzis, codes refer to ‘the most basic segment, or element, of the raw data or information that can be assessed in a meaningful way regarding the phenomenon’ which in this case is SED [35]

3. *Identifying initial themes for each publication*

The constant comparison method was used to identify and refine patterns in the codes [31]. Through this process, similar codes were grouped to form initial categories or themes for SED [32]. As some publications were lengthy, up to 800 pages, it was deemed better and more manageable to code and, subsequently, group codes into potential themes for each publication at a time. No software was used except Excel for the organization of codes.

4. *Integration of themes and codes*

The various themes and codes from each publication were integrated to produce overarching themes of SED. The constant comparison method was also useful during this process [31].

5. *Review themes*

The overarching themes were checked against initial codes. Furthermore, several thematic maps were created to refine themes further and identify connections and overlaps, as suggested by Braun and Clarke [33].

6. *Define and name themes*

A clear definition of each theme was generated [33]. A total of four themes of sustainable energy development were identified along with one overarching goal, further detailed in Chapter 3.2. *Key themes of sustainable energy development.*

3. Results and discussions

3.1. History of sustainable energy development

In this chapter, the first objective of this study is addressed, an examination of how the concept of sustainable energy development materialized. The 34 most cited publications were analyzed with this in mind. Some of these publications did not include information relevant to the history of SED or how the concept emerged. Therefore, these publications were not referenced in this chapter. Similar to Quental and Lourenço’s analysis of the sustainable development literature, references with “a global dimension and large diffusion,” such as the most cited publications from the UN and IEA, were found to influence the evolvement of the concept [14]. The results of the thematic analysis of all 34 most cited publications are presented in chapter 3.2 on the key themes of SED.

The concept of sustainable development and its most commonly used definition was first proposed in 1987 in the UN's *Our Common Future* report, generally referred to as the Brundtland report [1]. This report was the most cited and the oldest publication reviewed in the citation analysis. The role of energy in achieving sustainable development is recognized in the report, although, how is unclear as is evidenced by the following quote: "A safe and sustainable energy pathway is crucial to sustainable development; we have not yet found it" [1]. Since the adoption of *Agenda 21* at the 1992 UN's Conference on Environment and Development (the Earth Summit), sustainable development has been an important policy objective at the global, national, and local levels [36]. Similarly, in Agenda 21, energy development was mentioned in conjunction with sustainable development, mostly in chapter nine on the protection of the atmosphere [36]. The connection between the atmosphere, greenhouse gas emissions, and energy is further highlighted in the UN's Framework Convention on Climate Change in 1992 and the Kyoto Protocol in 1997. Both international treaties called for a new approach to energy development with an emphasis on reducing emissions from energy generation and consumption [6,37]. The concept of sustainable energy development was yet to emerge during this time. Energy was seen as a necessity for sustainable development, although it was mainly associated with climate-related issues as well as energy security and scarcity of fossil fuel resources [1]. Topics such as renewables, energy efficiency, environmental impacts of energy generation (other than atmospheric emissions), and the role of energy in promoting human progress were discussed. However, the concept of an all-encompassing sustainable energy development was yet to be proposed [36]. For instance, renewable energy resources have been utilized for millions of years; nonetheless, the notion of sustainable utilization and management of those resources is relatively new [38].

At the UN's General Assembly in 1997, the necessity of more sustainable energy use patterns was acknowledged for the first time, and the initial steps towards a sustainable energy development agenda were taken [39]. Even though energy development was a recurring theme on the international policy agenda in the 1990s, it was not until 2000 that the concept of sustainable energy development was introduced. It was presented as a new development paradigm and compared to the traditional, fossil-fuel driven, one in the UNDP's *World Energy Assessment* (WEA) report, the third most cited publication [2]. One of the main differences was that energy development and use were viewed more holistically, where all possible impacts were considered, whether they be economic, environmental, or social [39]. An emphasis was placed on a cleaner and more diversified mix of energy resources, increasing equitable energy access and energy efficiency, and, perhaps most importantly, recognizing that energy systems need to meet current and future needs [2]. In the same year, 2000, the UN's *Millennium Declaration* was adopted, and the associated *Millennium Development Goals* (MDGs) introduced [40]. No energy-related targets or no mention of energy and its role in achieving the MDGs were found in the declaration, which shows that SED was still not an established policy topic or recognized as a tool for promoting social development [40]. At the time, energy issues were viewed more in isolation, separated from other development issues. Eventually, the failure of leaving energy out of the MDGs forced a more thorough analysis of what enabled social and economic development and recognition of energy's contribution [41].

Energy for sustainable development was a prominent theme for the first time at a UN meeting at the 9th session of the Commission on Sustainable Development (CSD9) in 2001 [42]. This meeting laid the groundwork for the World Summit on Sustainable Development (WSSD) the following year and highlighted the need for international co-operation to form actions towards a more desirable and sustainable energy future [38,43,44]. At the WSSD, the importance of energy access for poverty reduction and meeting the MDGs was discussed as well as the necessity of changing production and consumption patterns of energy [38,39,44]. Thus, the focus was on two main targets regarding SED: improving energy access and promoting a cleaner energy system [38]. However, no agreement on goals or actions for SED and associated issues was reached at the summit [38]. Spalding-Fecher et al. argued that this was because no international collaboration or central authority existed on energy issues that pushed them forward on the agenda [43]. Therefore, the main result of the WSSD, regarding SED, was further solidifying it on the agenda and bringing attention to the need for an institutional home or interagency mechanism, especially considering the issue's cross-cutting nature [43].

The consequence of this realization was seen over the following years with the establishment of various agencies related to SED within the UN structure and the emergence of energy initiatives within established UN organizations [43]. In 2004, UN-Energy was created as an inter-agency mechanism to aid countries in transitioning to sustainable energy and coordinate efforts on energy within the different UN organizations [45]. The UN's Industrial Development Organization (UNIDO) established an *Energy and Climate Change* initiative, the United Nations Development Programme (UNDP) started thematic evaluations on *Energy and Environment* actions, and the UN Division for Sustainable Development pushed for the sustainable development of energy systems [24, 25]. Most recently, in 2009, the International Renewable Energy Agency (IRENA) was founded by 75 different states as an intergovernmental agency to promote the adoption and sustainable use of renewable energy [48]. The establishment of these various agencies and initiatives are evidence of the fact that SED was becoming more recognized as a crucial topic on the international agenda. Furthermore, their establishment recognized the growing role of energy in meeting various sustainable development issues and the importance of changing current consumption and production patterns.

Another critical initiative shaping the concept was the development of indicators for sustainable energy development. Indicators can provide more clarity and a deeper understanding of a concept and its underlying themes and interlinkages [39]. The need for indicators to track progress towards sustainable development was laid out in Agenda 21 [36]. In response to this, the United Nations Department of Economic and Social Affairs (UNDESA) introduced a set of 134 indicators for sustainable development (ISD) in 1996 [49]. Over the following decade, this initial set was revised and reduced to 96 indicators, of which six were energy-related measuring energy access, energy use, and transportation [50]. In 1999, the International Atomic Energy Agency (IAEA), in co-operation with numerous other international agencies, began developing indicators for sustainable energy development (ISED) to complement the ISD set [39,51]. In 2005, the IAEA, UNDESA, IEA, Eurostat, and the European Environment Agency collaborated to produce the interagency report *Energy Indicators for Sustainable Development: Guidelines and Methodologies,* which was the second most cited publication of the citation analysis [52]. The interagency effort aimed to create a core set of indicators for energy development to aid in decision-making and the development of effective energy policies at the national level. In the report, a set of 30 energy indicators for sustainable development (EISD) was presented and arranged into the three dimensions of sustainable development; social, economic, and environmental. The dimensions were categorized into themes and sub-themes, such as equity, health, security, atmosphere, and more [52]. The EISD set represented the most pressing energy issues globally at the time [39]. These themes, sub-themes, and the indicators themselves indicated a broader understanding of SED than earlier where, for instance, social issues were directly linked to energy development.

Ten years after the introduction of the, previously mentioned, Millennium Development Goals (MDGs), in 2010, a follow-up resolution was adopted where energy was presented as necessary in achieving the goals. The access, efficiency, and sustainability of energy, all elements of SED, were emphasized in particular [53]. Ban Ki-moon, former Secretary-General of the UN, pushed the topic further on the agenda with his vision statement introducing the Sustainable Energy for All (SE4ALL) initiative in 2011 [7]. He also highlighted the importance of addressing energy issues to achieve the MDGs, eliminate poverty, and save the planet. As the name indicates, the overarching goal of the SE4ALL initiative is to provide sustainable energy for all by 2030 with an emphasis on energy access, energy efficiency, and sustainable energy sources [7]. In 2015, the 2030 Agenda for Sustainable Development and the associated Sustainable Development Goals (SDG) was ratified [5]. The goals of the SE4ALL initiatives were adapted into the seventh SDG: "*Ensure access to affordable, reliable, sustainable and modern energy for all"* [5]. With the introduction of SDG7, energy was recognized as necessary in achieving sustainable development, and the concept of sustainable energy development was rooted firmly within that discussion.

In 1977, the International Energy Agency (IEA) published the first World Energy Outlook (WEO) report [54]. The WEOs aim is to provide long-term global energy projections and analysis by assessing energy markets, technology development, policies, and emerging issues [55]. Three different

WEO reports, 2008-2010, were identified as most cited in the citation analysis, which sheds light on the importance of these publications [28–30]. The sustainability of the current energy system, especially regarding energy security, was questioned in the WEO-2004 [56]. In the report, a steep trajectory of increasing energy demand was shown, and fossil fuels were presented as the dominant energy source despite concerns of rising emissions and scarcity. The importance of expanding modern energy services was emphasized as well as the need for policies to transform the current energy system and promote sustainable energy development [56]. In 2006, the IEA released the first Energy Technology Perspectives (ETP), which, to an extent, are focused on the role that energy technology can play to address the issues mentioned above [54,57]. Several vital steps and different development pathways towards a sustainable energy future are laid out in the annual ETPs [57]. Since 2006, WEOs and ETPs have highlighted the importance of a cleaner, more technologically advanced, and sustainable energy future with affordable energy prices and effective energy policies [57,58]. Responding to increased climate concerns, WEOs have started to include different climate scenarios, such as the *450 Scenario*, where greenhouse-gas concentration is kept at 450 parts per millions of CO2 equivalent, and climate change is limited to below 2 degrees Celsius [28]. In the WEO-2017, a *Sustainable Development Scenario* was first presented where the necessary energy-related actions to meet the *2030 Agenda for Sustainable Development* were analyzed [59]. In the same year, the necessity of an energy technology transformation towards clean energy technologies was highlighted in the ETP-2017 [60]. The progress of topics analyzed in the IEA's WEOs and ETPs corresponds to the evolvement of the concept of sustainable energy development through time.

As can be seen from the above discussion, the concept of sustainable energy development has evolved considerably over the last few decades. In the late 1980s and early 1990s, a narrow view was taken of energy development where the focus was mainly on reduced emissions and energy security. Furthermore, energy issues were viewed in isolation and not connected to other development issues. Over time, a broader perspective of energy development has been taken where the potential social and economic impacts are considered and not just the environmental ones. Currently, the necessity of energy in advancing social and economic development is recognized. Furthermore, the need to change current production and consumption patterns is emphasized increasingly more with raised awareness of the severity of climate change and its potential impacts globally. Issues such as accessibility, affordability, energy transition towards renewables, and energy efficiency are topics discussed by most, if not all, governments worldwide. Hence, the concept of SED has gradually both grown to have a more comprehensive definition and increased importance. A more detailed analysis of the current understanding of sustainable energy development can be read in the following section. The themes and underlying issues of SED will continue to evolve, corresponding to development and energy issues worldwide. For instance, access to modern energy services is planned to become a reality for all one day. Once that happens, perhaps issues relating to, e.g., the selection of energy sources and their sustainable utilization, will become even more prominent.

This analysis shows that the role of energy has evolved from being embedded within the concept of sustainable development to becoming an independent concept in itself. This evolvement stresses the importance of energy for sustainable development. On the one hand, a strength of this broader understanding of SED is that the cross-cutting influence of energy is recognized. Nerini et al. analyzed linkages between energy and all 17 SDGs to assess the role of energy for sustainable development. Their study showed that "energy systems are a foundation of social and economic development, and affect delivery of outcomes across all SDGs" [61]. Furthermore, their analysis highlighted the complex dynamics between energy systems and sustainable development issues. On the other hand, a potential weakness of the broader approach is that energy will be given too much credit and connected with too many issues. For instance, improving access to modern energy services does not guarantee social development and economic growth. Although energy services have been described as fundamental to both [62]. Therefore, it will be important to critically analyze how and why energy contributes or not towards different sustainable development issues. A timeline for the concept of sustainable energy development and how it has embedded itself within the international policy discourse can be seen in Figure 3 below.

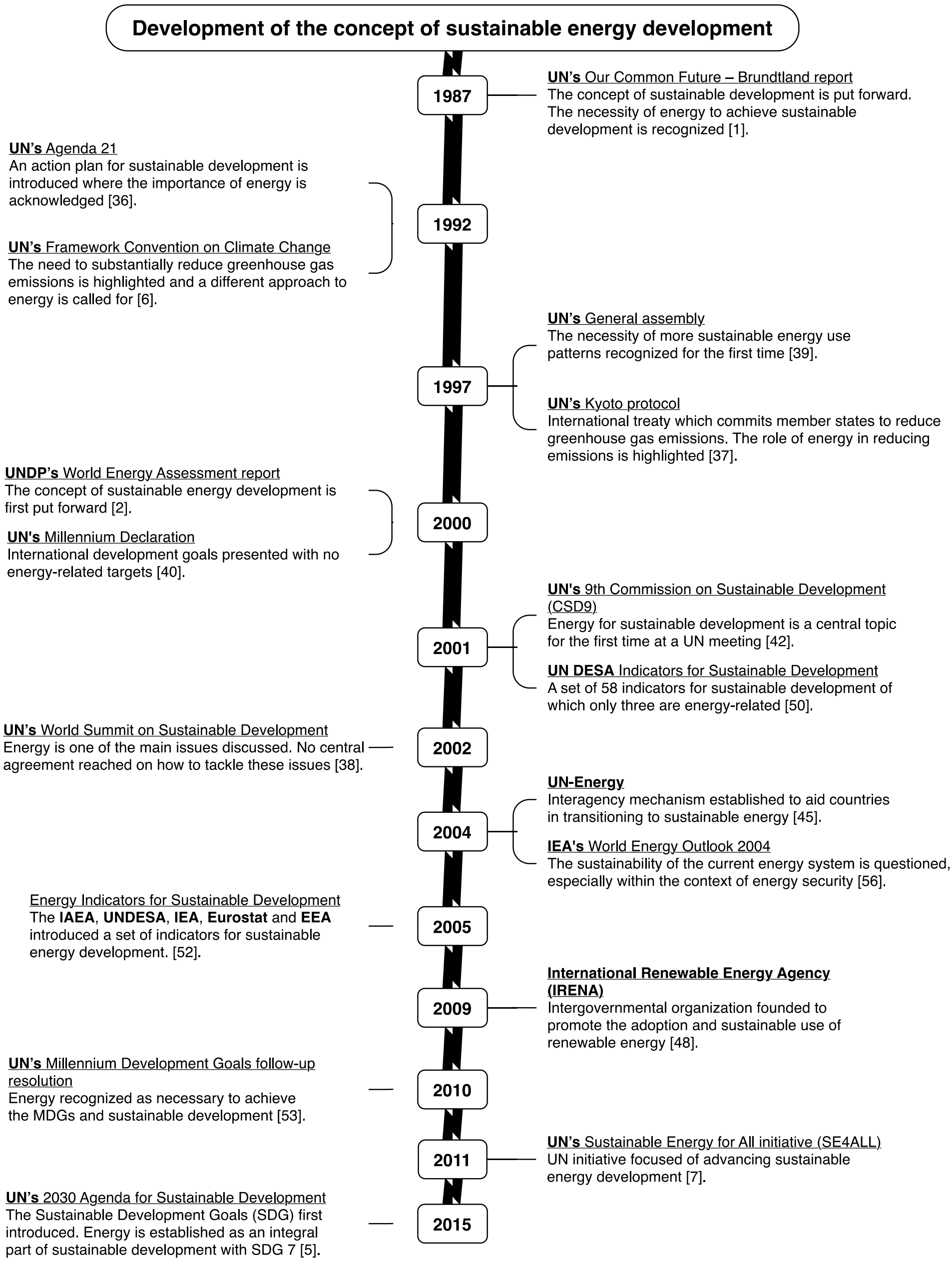

Figure 3: Timeline of sustainable energy development*. Timeline showing the main events and publications that contributed to shaping the concept of sustainable energy development and how it become recognized as integral to sustainable development. Key actors are bolded in the text.*

3.2. Key themes of sustainable energy development

It is apparent from the above analysis that sustainable energy development has evolved to become an essential international policy objective and that energy is integral to sustainable development. One of the aims of this study is to identify the emerging themes of the concept. For this purpose, a thematic analysis was carried out of the most cited publications relevant to the concept. Four themes of sustainable energy development were established, along with one overarching goal. Sustainable development was defined as the overarching goal for the evolvement of energy systems. The four identified themes are essentially sub-goals of SED: access to affordable modern energy services, sustainable energy supply, sustainable energy consumption, and energy security. This categorization can be seen in Figure 4 and is detailed further in the following sections. The order of the themes does not reflect their importance as they are all necessary to SED.

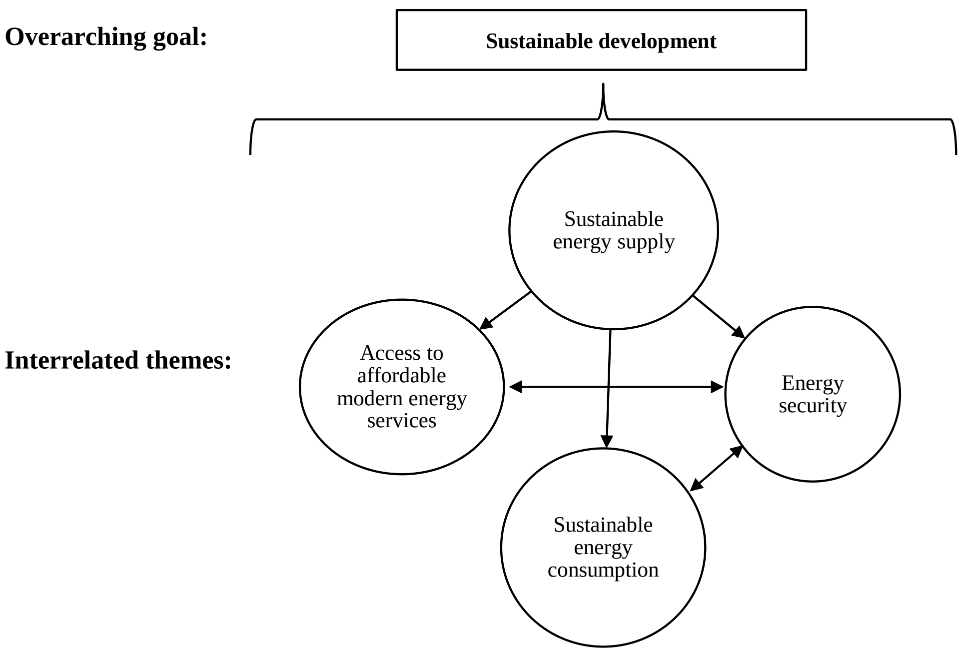

Figure 4: Key themes of sustainable energy development*. Thematic map showing the overarching goal and interrelated themes of sustainable energy development. The arrows illustrate connections between the different themes. The direction of the arrows indicates whether a theme enables another theme.*

Some overlap and linkages between the different themes of SED, indicated by arrows in Figure 4, are inevitable. This claim is evidenced by, for instance, the UN's efforts to develop indicators for both sustainable development and SED [50,52]. For the last two decades, the UN has organized its sustainability indicators into the main themes and sub-themes. A thematic approach was thought better to capture the relevant policy issues than prior approaches and assist policy and indicator development at the national level [50]. In this approach, an emphasis has been placed on accounting for thematic linkages to consider "the multi-dimensional and integrated nature of sustainable development," and the same applies to SED [50]. For instance, some of the Energy Indicators for Sustainable Development are placed within more than one category to reflect interlinkages between the themes and show that some issues are cross-cutting [52]. In the end, themes are simply tools to make complex concepts, such as SED, more easily understandable.

3.2.1 Overarching goal

Sustainable energy development can differ considerably between countries and energy systems [4]. The energy-related problems facing developing countries as compared to developed ones can vary drastically if only because of different energy needs. Furthermore, the availability of energy resources in a country can be a determining factor for energy development. Nonetheless, the purpose of energy systems is to improve human well-being by providing services that promote economic growth and social development while minimizing environmental and health costs [2]. Moreover, energy is essential in achieving the desirable social, environmental, and economic goals of sustainable development, as confirmed by the introduction of SDG7 [2,5,39,44,50,62–65]. Therefore, despite the different circumstances and energy-related challenges, the ultimate goal of sustainable energy development remains the same, to promote sustainability at all levels [65,66].

3.2.2. Themes

Theme 1: Access to affordable modern energy services

Long before the concept of sustainable energy development emerged, access to energy services has been a topic on the energy policy agenda. Access to energy services is seen as vital to economic growth and promoting social well-being, which makes it essential to sustainable development [2,39,44,50,52,63–65]. Access to energy services refers to the physical availability of energy through the necessary infrastructure and geographic positioning, as well as being affordable to all. A lack of access to energy services has been connected with some of the main challenges of sustainable development, such as poverty, lack of opportunities for women, and environmental degradation [2,39,44]. Therefore, energy poverty needs to be reduced to address some of the main challenges of sustainable development [39,44,52,56]. Moreover, providing everyone access to modern energy services addresses some of the current inequalities of the world [2,5,36,39,44].

Over time, the topic has become more complex and developed into access to modern energy services, which is energy in the form of mechanical power or electricity that is used to fulfill the needs of society [50]. Therefore, having access to modern energy services includes having access to, for instance, electricity for cooking, lighting, or income generation [2]. In developing countries, many households still lack access to modern energy services and, as a result, use charcoal or traditional biomass for cooking and heating. Utilizing these non-commercial fuels can lead to worsened air quality and adverse effects on health [28,39,44]. This addition of the word modern addresses some of the environmental and health impacts associated with the utilization of non-commercial fuels [50,52]. Although some energy sources utilized to provide modern energy services can also have negative environmental and health impacts, such as fossil fuels.

Modern energy services need to be both accessible and affordable to all, as indicated in SDG 7 [5]. Energy services need to be equitably accessible and affordable to everyone while contributing to human well-being and raising living standards [39,44,52,65–67]. For instance, when improving access to modern energy services in developing countries and rural communities, the affordability of energy needs to be ensured [2,5,39,44,52]. Increased access to affordable modern energy services supports economic growth and social development [2,65,68].

One of the main challenges within this theme is providing energy services in remote rural areas [2,44]. By expanding and improving infrastructure, it is possible to provide access to more people. However, often, it is infeasible or too expensive to connect these areas to the grid. Therefore, local solutions through decentralized generation can fit better and enable rural electrification [44]. To ensure the success of these actions, the involvement of stakeholders in decision-making and innovative financial schemes is necessary [44]. The utilization of renewables on a small-scale is often appropriate, which promotes an energy transition from conventional fuels [44,62]. By transitioning to modern renewables, access to environmentally-sound energy services is provided, and the harmful environmental and health impacts of energy utilization in these areas are reduced or avoided [28,39,44]. Additionally, distributed generation can make energy more affordable in remote areas as it reduces transmission costs and the infrastructure investments that would have been necessary for a grid connection [44].

For any of this to be possible, political will is necessary to push this on the agenda and develop national energy policies that promote access to modern energy services. These actions include removing market barriers, providing the necessary financing, and supporting research and technological advancements for innovative supply-side technologies [44,64,66,67,69].

The main reasons why access to affordable modern energy services is necessary for sustainable energy development and how this theme should be addressed were identified and presented in a thematic map seen in Figure 5. The prominence of the theme and underlying topics within the most cited publications can be seen in Table 2.

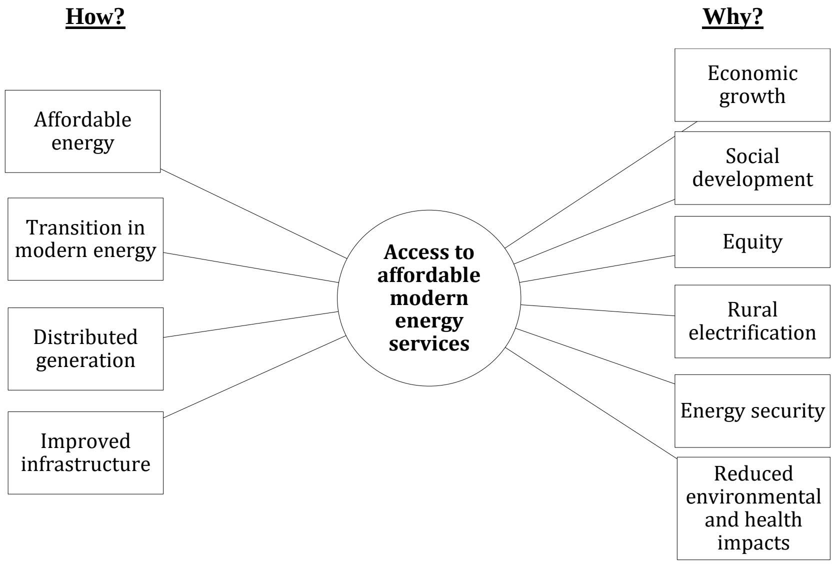

*Figure 5: **Access to affordable modern energy services.** Thematic map showing how and why access to affordable modern energy services is part of sustainable energy development.*

Table 2: Theme 1 within the most cited publications
Analysis of references made to theme 1, access to affordable modern energy services, and its underlying issues in the 34 most cited publications.

Topic	References	Count
Access to affordable modern energy services	[1,2,50,52,62–64,66,70–73,8,74–77,28–30,36,37,39,44]	24
How?		
Affordable energy	[1,2,62,64,66,67,70,71,74,75,77,28–30,36,39,44,50,52]	19
Transition in energy generation	[1,2,50,52,62,63,70–75,8,76,77,28–30,36,37,39,44]	22
Distributed generation	[1,2,70,71,73,76,77,8,28–30,36,44,62,63]	15
Improved infrastructure	[2,28,72–75,29,30,36,44,52,63,64,71]	14
Why?		
Economic growth	[1,2,62–67,70–73,28,74–79,29,30,36,39,44,50,52]	26
Social development	[1,2,52,62–67,70–72,8,73–81,28–30,36,39,44,50]	29
Equity	[1,2,66,70,73–76,28–30,36,39,44,50,52]	16
Rural electrification	[1,2,62,64,70–73,76,77,8,28–30,36,39,44,52]	18
Energy security	[2,8,67,70,72–75,82,28–30,39,44,52,62,66]	18
Reduced environmental and health impacts	[1,2,50,52,62–64,66,67,69–71,8,72–77,80,28–30,36,37,39,44]	27

Theme 2: Sustainable energy supply

The environmental impacts of current energy systems, from production to consumption, are felt in the air, water, land, biodiversity, human health, and more [2,39,52,62,65,83,84]. The importance of staying within ecosystem boundaries or carrying capacity regarding energy development was emphasized when the concept of sustainable energy development was first introduced in 2000 [2]. With increased awareness of climate change and the harmful environmental impacts of energy systems, the necessity of decreasing the environmental footprint of the energy system is becoming apparent to most [36,52]. If energy development has harmful environmental or health impacts, it is not adequately serving its ultimate purpose of improving human well-being [2]. Current energy practices are not sustainable and need to be changed, especially considering depleting conventional fossil fuel sources [28,44,66,69,73]. Therefore, a transition in energy generation towards low-carbon and more environmentally-friendly sources, such as renewable sources, is necessary [28,37,71,78,79,85–87,44,50,52,62–64,67,69]. The fact that initiatives to promote renewables are taking place all over the world shows that the necessity of sustainable energy supply is becoming apparent to most [69].

The choice of energy sources and their mix largely depends on what is available in the country in question [86]. Less desirable energy sources include low-quality biomass and nuclear energy with the associated health, safety, and waste issues [68,88]. Renewable energy sources include solar, biomass, geothermal, wind, tide, and hydropower [2,29,75]. Some of these renewables show more promise than others [80], although the purpose of this study is not to assess the different energy sources. Electricity generation from hydropower has played and still plays a significant role in furthering SED worldwide. However, the environmental costs of large scale hydroelectric dams can be high [2,77]. Intermittency is a considerable problem with energy generation from solar or wind power [63,81,87]. Utilizing those renewables involves “designing integrated energy system solutions,” where other flexible energy technologies are added to ensure a constant supply of energy [87]. In response to the intermittency problem, efforts are being made to improve energy storage technologies that can complement these renewables [63,81]. The sustainable utilization of renewable energy sources is necessary, such as efficient management of geothermal energy and biomass sources to hinder overexploitation [38,62,82,89].

Sustainable energy supply involves having an economically viable supply of energy [1]. A transition to sustainable energy supply is not possible if energy options are not cost-competitive and economically viable [69,81]. Several actions can be taken to make environmentally sound technologies more cost-competitive, such as correct energy pricing, provide innovative financing schemes, and support research [1,28,68,69,81,90,29,30,39,44,62,64,66,67]. Current energy pricing does not adequately reflect the real costs of energy; for instance, the harmful environmental and health impacts of fossil fuels [1,44,62,66,81]. As a result, conventional fossil fuels are favored over new options. Although fluctuating and rising fossil fuel prices and falling prices of renewables make them a more attractive option [78]. Governments need to incentivize desirable behavior by internalizing the negative costs of energy systems and removing market distortions, such as fossil fuel subsidies [39,44,64]. Such actions would promote energy efficiency and increase the competitiveness of renewables [44,69]. Often, research and technological advancements are aimed at improving the cost-effectiveness of technologies and, thus, make new options more desirable [91]. Based on the theories of Schumpeter, one can say that invention and innovation are not enough for technological advancements. The diffusion of innovations through investment has to take place as well [92]. Therefore, investments in the deployment of new technologies are also needed [28,56,73,84,93].

This transition towards sustainable energy supply is sometimes referred to as the "energy transition challenge" [94], which highlights some of the associated difficulties, including the necessary systemic changes and infrastructure development to address challenges such as the intermittency of some renewable energy sources [63,87,94]. According to the WEO-2004: "a truly sustainable energy system will call for technological breakthroughs that radically alter how we produce and use energy" [56]. Therefore, research to accelerate the development and deployment of better energy technologies should be supported [2]. In some cases, this will involve facing the costs of the early retirement of existing capital stock [28,56]. Significant efforts have been made to increase renewables in the energy mix with a SE4ALL goal of doubling its share by 2030 [5,7]. Despite improved technologies and reduced prices of energy generation for most renewables, the share of renewables still needs to be increased considerably [95]. Therefore, the theme is expected to stay firmly within the energy policy discourse as highlighted by SDG 7.2: "By 2030, increase substantially the share of renewable energy in the global energy mix" [5].

A thematic map illustrating why a transition towards a sustainable energy supply is necessary for sustainable energy development and how this should be enabled can be seen in Figure 6 below. The prominence of the theme and underlying topics within the most cited publications can be seen in Table 3.

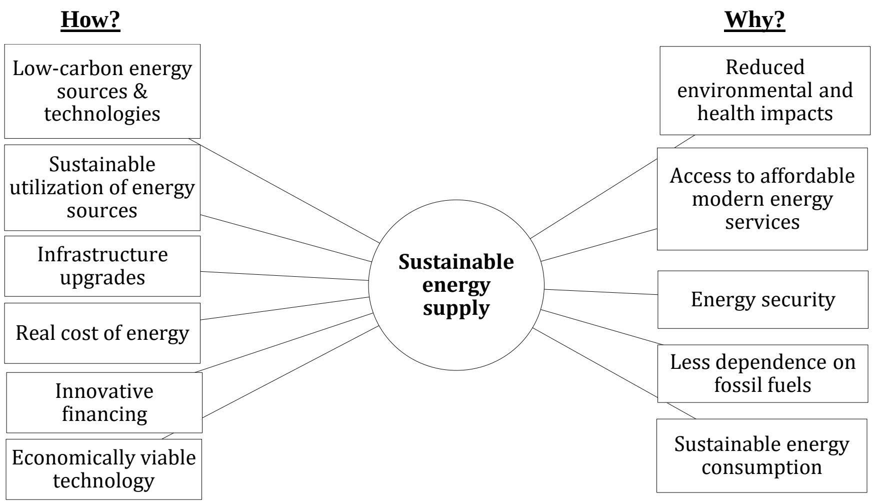

Figure 6: *Sustainable energy supply.* *A thematic map illustrating the main reasons how and why a sustainable energy supply is necessary for sustainable energy development.*

Table 3: Theme 2 within the most cited publications

Analysis of references made to theme 2, sustainable energy supply, and its underlying topics within the most cited publications.

Topic	References	Count
Sustainable energy supply	[1,2,50,52,62–67,69,70,8,71–80,28,81,85–87,29,30,36,37,39,44]	34
How?		
Low-carbon energy sources & technologies	[1,2,50,52,62–67,69,70,8,71–80,28,81,85–87,29,30,36,37,39,44]	34
Sustainable utilization of energy sources	[1,36,39,52,62,67,71,75,79,81]	10
Infrastructure upgrades	[2,28,67,69,71–75,78,87,29,30,36,39,44,52,63,64]	19
Real cost of energy	[1,2,66,69,71,75,76,8,28–30,36,39,44,52]	15
Innovative financing	[1,2,65–67,69,71,73,75,78,79,8,28–30,39,44,62,64]	19
Economically viable technology	[1,2,63–67,69–73,8,74–81,85,28–30,36,39,44,62]	29
Why?		
Reduced environmental and health impacts	[1,2,50,52,62–67,69,70,8,71–80,28,81,85,86,29,30,36,37,39,44]	33
Access to modern energy services	[1,2,50,52,62,64,70–75,8,76,77,28–30,36,37,39,44]	22
Energy security	[2,8,66,67,69–75,78,28,79,81,86,29,30,39,44,50,52,62]	23
Less dependence on fossil fuels	[1,2,52,62–64,66,67,69–72,8,73–79,81,85,86,28,87,29,30,36,39,44,50]	32
Sustainable energy consumption	[1,2,52,62,66,67,69,71–73,78,8,28,30,36,37,39,44,50]	20

Theme 3: Sustainable energy consumption

If access to modern energy services is to be expanded to all, it seems inevitable that demand for energy will grow rapidly around the world, especially in developing countries and those where access is not universal yet [2,30,62,63]. Without a swift transition in energy generation towards environmentally benign energy sources, this will result in increased emissions and harmful environmental impacts as well as greater competition for finite natural resources [1,63,96]. By increasing energy efficiency and conservation, this growing demand can be combated to some extent [2,65,67]. An essential objective of sustainable development is to decouple economic growth from energy use, which means a decoupling of economic activities and increased environmental pressures in most cases [50,52]. Therefore, current energy generation and consumption patterns need to be transformed to be able to provide access to all while sustaining supply and minimizing harmful environmental impacts [2,28].

It is generally acknowledged that increased energy efficiency and conservation is an integral part of sustainable energy development [1,38,44,63,65,66,81,87]. The importance of energy efficiency was highlighted in Agenda 21, where the necessity of improving the efficiency of energy production, distribution, and consumption was mentioned [36]. In the WEO-2009, energy efficiency even is presented as the greatest tool to reduce emissions [29]. Improved energy efficiency is vital, considering increasing energy demand and depleting fossil fuel sources [2,67]. Aside from energy efficiency just making economic sense since energy costs are cut, improved efficiency also leads to a reduction in the harmful environmental impacts of energy production [2,28]. Therefore, the goal of "doubling the rate of improvement in energy efficiency" by 2030 is put forward in the UN's SE4ALL initiative and SDG7 [6,4]. The inclusion of energy efficiency measures in the energy policy directives of many countries highlights its importance [97].

Experience has revealed that sometimes there is a rebound effect in response to efforts to increase energy efficiency [2]. By increasing energy efficiency, the costs and price of energy and its services can drop. Thus, improved energy efficiency can result in increased total energy demand that offsets potential energy savings [2,29,30]. The direct rebound effect refers to increased consumption of energy due to lower energy expenditures. The indirect rebound effect refers to the increased consumption of other energy-intensive goods and services that indirectly leads to an increase in energy consumption [98]. Sorrell et al. found that in the long-run, the direct rebound effect is „likely to be less than 30%“ of the expected savings [98]. Furthermore, their analysis argued that the direct rebound effect „is expected to decline in the future as demand saturates and income increases“ [98]. Nevertheless, decision-makers need to be aware of the rebound effect when developing energy efficiency policies and, for instance, control energy pricing appropriately [30].

Energy pricing can be a valuable tool to incentivize both sustainable energy consumption and a transition in energy generation [39,44,64]. Changing energy pricing by removing fossil-fuel subsidies and internalizing the real costs of energy promotes a transition towards environmentally-friendly energy and increased energy savings [1,2,8,30,39,44,62,66,81]. The necessity of changing current energy pricing was recognized as early as 1992 in Agenda 21; "Without the stimulus of prices and market signals that make clear to producers and consumers the environmental costs of the consumption of energy, materials and natural resources and the generation of wastes, significant changes in consumption and production patterns seem unlikely to occur in the near future" [36].

A change in current consumption patterns is necessary for sustainable energy development [1,39,44]. Educating consumers and making them aware of the harmful impacts of current energy practices can push for a change in behavior [36,62]. These efforts also should promote the efficient use of energy by teaching energy-saving techniques and advocating for energy-efficient appliances [36,62,96]. Promoting the use of improved stoves in developing countries can reduce emissions that cause health problems and contribute to climate change [2,83,90]. Education and training are vital to the success of an energy transition, especially in remote communities with less access to technical support. Furthermore, informing the local community of actions and having them involved increases the likelihood of social acceptability [64]. An energy transition cannot be sustained unless the local community is on board and given the necessary training and technical know-how to maintain the system [2,36,38,62,68,90,91]. These efforts also result in better energy management and less wasteful consumption [38].

The main reasons how and why sustainable energy consumption is vital to SED are shown in Figure 7. The prominence of the theme and underlying topics within the most cited publications can be seen in Table 4.

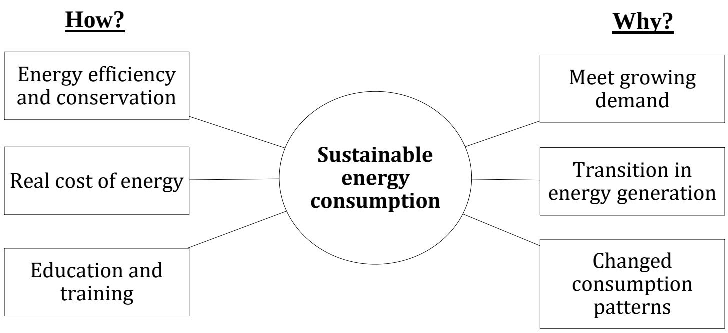

Figure 7: Sustainable energy consumption. *A thematic map highlighting how sustainable energy consumption can be achieved and why it contributes to sustainable energy development.*

Table 4: Theme 3 within the most cited publications

Analysis of references made to theme 3, sustainable energy consumption, and its underlying issues in the most cited publications.

Topic	References	Count
Sustainable energy consumption	[1,2,50,52,62,66,67,69,71–73,76,8,87,28–30,36,37,39,44]	21
How?		
Energy efficiency and conservation	[1,2,50,52,62,63,65–67,69–71,8,72–81,28,87,29,30,36,37,39,44]	31
Real cost of energy	[1,2,66,69,71,75,76,8,28–30,36,39,44,52]	15
Education and training	[1,2,73,28,29,36,37,44,62,67,69]	11
Why?		
Meet growing demand	[1,2,65,67,69–74,76,77,8,78,79,28–30,36,44,62,63]	23
Transition in energy generation	[1,2,50,52,62,66,67,69,71–74,8,75,76,78,79,87,28–30,36,37,39,44]	25
Changed consumption patterns	[1,2,62,66,67,69,71–73,87,8,28,30,36,39,44,50,52]	18

Theme 4: Energy security

Energy security is a well-established theme of sustainable energy development and has been historically in the energy policy discourse [2,39,44,65,66,99]. A reliable supply of energy is the basis for economic activity and social development [39,52,69]. Generally, energy security refers to the low vulnerability of vital energy systems, which can include energy's reliability, availability, and resiliency [4,65]. The four As of energy security are often used as a basis for discussion on the concept, namely; availability, affordability, accessibility, and acceptability [4]. In the UNDP's World Energy Assessment, energy security was described as "the availability of energy at all times in various forms, in sufficient quantities, and at affordable prices" [2]. Therefore, there are clear linkages between this theme and the first two on access to affordable modern energy services and sustainable energy supply.

Numerous efforts can be taken to enhance energy security, as shown in Figure 8. Diversification of energy sources involves not relying on a single form of energy or supplier that can impact energy security [2,38,52,67]. Diversification efforts should aim at increasing the share of domestic energy sources and renewables as well as reducing dependence on a small number of suppliers or sources [39,52,69,93]. Geographical hindrances and geopolitics generally make domestic fuels more secure than imported ones [2,39,44,66,90]. Furthermore, the stability of energy prices is improved when countries are not highly dependent on fuels potentially imported from or through politically volatile areas [1]. Considering the current depletion rate of conventional fuels such as fossil fuels, increasing the share of renewable sources enhances energy security in the long-term [77]. A transformation of the current energy system and reducing dependence on fossil fuels is necessary to increase energy security and combat climate change [29,44]. However, for renewable energy sources to contribute to energy security in the long-run, they need to be utilized sustainably and not be overexploited [38,62,82,89]. Diversifying a country's energy supply towards domestic and renewable energy sources should not only increase energy security if properly managed but also reduce harmful environmental impacts of the energy system and have positive social impacts such as job creation [2,39,44,52].

For sustainable development to be possible, a sustainable supply of energy is required [39]. Therefore, energy infrastructure upgrades should be aimed at making the system both more efficient and resilient to disruptions, such as natural disasters or terrorist attacks [65,93]. Distributed or decentralized generation, often with renewables, can increase the resilience of a system by emphasizing local solutions and reduce dependence on the grid [38,93]. Furthermore, a greater share of renewables and low-carbon energy sources will secure energy supply for future generations [62,76,95].

Energy prices need to be affordable and stable for energy to promote economic and social development [36,39,67]. Both affordability and accessibility are often mentioned in conjunction with energy security. An example of how affordability can affect energy security can be seen from historical trends of oil prices and the resulting consequences [67,78]. Links between accessibility and energy security are, for instance, geopolitical factors and geographical hindrances that can hinder both [44]. Some of the actions mentioned above, such as increased distributed generation, reduced dependence on imported fossil fuels, and infrastructure upgrades, can increase both energy security and access to modern energy services while promoting a transition towards a sustainable energy supply.

In Figure 8, the main ways how energy security can be increased and why it is vital to sustainable energy development are shown. The prominence of the theme and underlying topics within the most cited publications can be seen in Table 5.

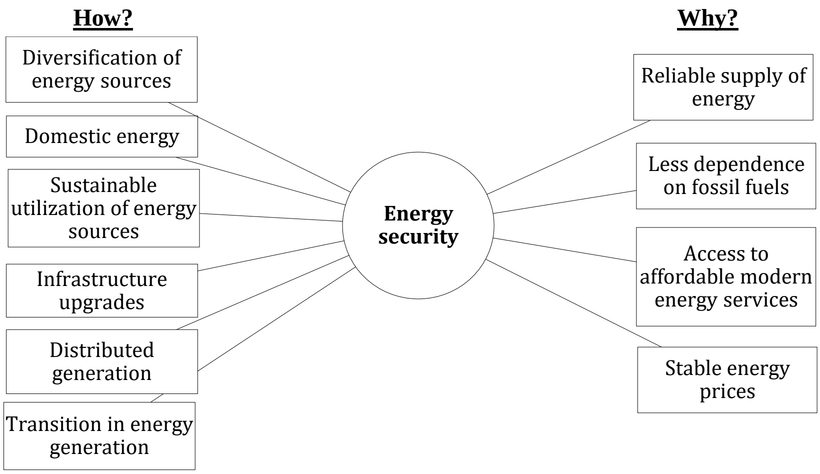

Figure 8: Energy security. *A thematic map showing why energy security is integral to sustainable energy development and how it can be increased.*

Table 5: Theme 4 within the most cited publications
Analysis of references made to theme 4, energy security, and its underlying topics in the most cited publications.

Topic	References	Count
Energy security	[2,8,63–67,69–73,28,74–76,78,79,81,86,29,30,39,44,50,52,62]	27
How?		
Diversification of energy sources	[2,8,63,66,67,69–74,78,28–30,36,39,44,50,52]	20
Domestic energy	[2,8,67,69–76,78,28,86,29,30,39,44,52,64,66]	21
Transition in energy generation	[2,28,64–67,69–74,29,75,78,79,86,30,39,44,50,52,62,63]	27
Distributed generation	[2,8,73,76,28,29,44,62,63,69–71]	12
Infrastructure upgrades		16
Sustainable utilization of energy sources	[39,52,62,67,71,75,79,81]	8
Why?		
Reliable supply of energy	[2,8,63,65–67,69–72,74,75,28,76,78,81,29,30,39,44,50,52,62]	23
Less dependence on fossil fuels	[2,8,63–67,69–73,28,74–76,79,81,86,29,30,39,44,50,52,62]	27
Access to affordable modern energy services	[2,8,63,66,70–75,28–30,39,44,50,52,62]	18
Stable energy prices	[2,28,77–79,29,30,36,63,67,69,73,74]	15

3.2.3 Assessment of themes

The most frequently discussed theme by the highest number of publications was identified by analyzing Tables 2 to 5 above, see Table 6. Arguably, this analysis shows which theme is most prominent within the SED literature. Furthermore, it highlights which themes were mentioned less often, which might indicate a gap in the literature on these topics or highlight potential avenues for further research. The importance of sustainable energy supply was discussed to some extent in all 34 publications. The least discussed theme was sustainable energy consumption indicating that more analysis could be done on how this theme could be addressed, for instance, how training and education can promote a change in consumption patterns. When looking at the sub-topics of each theme in Tables 2-5, the least discussed topic was the sustainable utilization of energy resources, both within the context of sustainable energy supply and energy security. Even though everyone discussed the necessity of sustainable energy supply, only a few directly addressed the vitality of utilizing resources sustainably and the possibility of depleting resources considered renewable, specifically stock-based renewables like geothermal and biomass energy.

Table 6: Most referenced theme within the most cited publications
Analysis of references made to theme 1, access to modern energy services, and underlying issues.

Goal and themes	Reference count
Sustainable development	26
Access to affordable modern energy services	24
Sustainable energy supply	34
Sustainable energy consumption	21
Energy security	27

To further assess the above themes, they were compared to three existing SED themes or classification schemes. The World Energy Council's Energy Trilemma emphasizes energy security, energy equity, and environmental sustainability of energy systems [100]. These align well with the themes of this study, where energy equity broadly covers the same topics as *access to affordable modern energy services* and environmental sustainability corresponds to *sustainable energy supply* and *sustainable energy consumption*. The Energy Indicators for Sustainable Development (EISD) are organized into the three dimensions of sustainable development: social, economic, and environmental [52]. Within those dimensions, both themes and sub-themes of SED are defined, see Table 7. The first theme of this study fits well with topics within the social dimension. The second theme belongs to the environmental dimension. *Sustainable energy supply* and *energy security* correspond to themes within the economic dimension of the EISDs. A recent study by Shortall et al. defined eight main themes of sustainable energy development: access & electrification, affordability & equity, security, efficiency, renewables, economic or cost-efficiency, environmentally benign & clean, and contributes to well-being [101]. The first two themes correspond to the first theme of this study. Security and this study's *energy security* theme cover the same SED issues. Efficiency is discussed within the theme of *sustainable energy consumption*. The second theme on *sustainable energy supply* includes both renewables and environmentally benign & clean themes of their study. Economic or cost-efficiency is discussed to some extent within the second and third themes of this study. Finally, the overarching goal of promoting sustainable development lines up with their final theme of contributing to well-being. This comparison shows that the results of this study align well with existing SED themes, which verifies the value of the methods chosen in this study. That is, the comparison demonstrates that the analysis of the 34 most cited publications in the SED literature led to comprehensive and complete coverage of the underlying issues of SED.

Table 7: Themes of EISD
Organization of the *Energy indicators for sustainable development* showing SED themes and sub-themes

Dimension	Theme	Sub-theme
Social	Equity	Accessibility
		Affordability
		Disparities
	Health	Safety
Economic	Use and production patterns	Overall use
		Overall productivity
		Supply efficiency
		Production
		End use
		Diversification (fuel mix)
		Prices
	Security	Imports
		Strategic fuel stocks
Environmental	Atmosphere	Climate change
		Air quality
	Water	Water quality
	Land	Soil quality
		Forest
		Solid waste generation and management

3.3 Potential limitations of this analysis

There are a few potential weaknesses to this analysis and the methodology chosen. First, there is a possible bias in the selection of databases utilized for the literature search. A choice was made to focus on general databases and not field-specific ones. This choice could have resulted in the omission of publications that were influential in the development of the concept of sustainable energy development. A limitation of this analysis is, for instance, the fact that no well-functioning database for grey literature was found and included.

Second, the literature review was limited to publications in English. According to Hamel, scientific literature has shifted towards an apparent “dominance of English” [102]. The same cannot be said as definitively about public documents, evidenced by the fact that a few highly cited publications were omitted from further analysis as they were not available in English. Furthermore, the literature search was limited to openly available publications, which could have resulted in the omission of influential publications on SED. Even though this criterion omitted only about 20% of initial search results, it could still influence the results of this analysis. However, the citations of these publications were not filtered based on whether they were open access or not. Therefore, the resulting most cited documents in the field did not have to meet this initial criterion for the literature search.

Third, while a citation analysis can be a useful approach to identify the most cited and influential literature, it is not without faults. The main criticism of citation analysis is the lack of analysis of why or how a source is cited, such as whether a publication might be referenced because it is incorrect or controversial [22,103]. Responding to this criticism, Garfield discussed the “reluctance of scientists to go to the trouble of refuting inferior work” [21]. Some argue that citations are “a function of many variables besides scientific impact,” such as time, field, journal, article type, availability of publication, and technical problems [22]. For instance, recent research is cited rather than older, and frequently cited publications are more likely to be referenced even more [22]. This fault was demonstrated by the fact that the newest most cited publications were published in 2011. Technical problems with citations include differences in formatting that can complicate and delay a citation analysis as well as the fact that references, typically, are not available outside of the publication itself. Furthermore, incorrect citations are “unfortunately far from uncommon” [22]. Finally, self-citations can skew a citation analysis, even though self-citations are a standard and reasonable procedure against self-plagiarism [21,103,104]. In response to this criticism, Garfield argued that a “high publication count could be achieved only if the person had a lot to say that was at least marginally significant“ [21]. This flaw is illustrated in this study by the fact that two prolific authors wrote a few of the most cited papers on Turkey’s energy situation. These papers were found to analyze various SED issues comprehensively and did not merely reflect issues relevant to Turkey.

Fourth, only the 34 most cited publications were identified, which might seem like a low number. However, identifying a relatively small number of most cited publications in citation analyses is a common practice [12,13,19,26,27]; see discussion in section 2.3. above. Furthermore, the results of the thematic analysis showed that saturation was reached with regards to the topics of SED. Reaching data saturation means that the same themes and patterns present themselves repeatedly, and reading more publications would not reveal new themes or data. Therefore, reaching saturation confirms the validity and comprehensiveness of chosen methods. Evidence of this saturation is that the themes identified in this study align well with the results of other studies, as discussed in Section 3.2.3. Therefore, including 34 publications covered the development and themes of SED adequately to allow for an in-depth analysis of the concept.

Fifth, as with any research, especially of qualitative nature, there is always some potential for the authors‘ bias that might influence the study in some way. During the thematic analysis, the authors' subjective judgment can influence the interpretation of the text, coding, and generation of themes. One way to address this is by being aware of one's own bias when collecting and analyzing the data [32]. Furthermore, comparing the resulting themes to the original text or initial codes to ensure a match is valuable [33].

4. Conclusions

This study has reviewed the concept of sustainable energy development and its transformation through time. The concept of sustainable energy development has evolved to become an important policy objective addressed by governments around the world. Initially, energy was viewed narrowly in conjunction with emissions and air quality. Now, energy is considered to be a necessary enabler for social and economic development and, consequently, sustainable development. As a result, energy issues are no longer viewed in isolation and are instead connected to other development challenges. This broader understanding of SED and the cross-cutting influence of energy highlights both its importance and multi-dimensionality. However, this more comprehensive understanding could also lead to too many issues being associated with SED. Energy and the services it provides are vital to sustainable development, but sustainable development will not be reached solely through SED.

The overarching goal of the development of energy systems is to further sustainable development according to the analysis presented here. Four interrelated themes of SED were identified: access to affordable modern energy services, sustainable energy supply, sustainable energy consumption, and energy security. According to these themes, energy development should increase international equity by providing modern energy services to all. Energy services need to be equitably accessible and affordable to everyone while contributing to human well-being and raising living standards. A transformation of the current energy system, both in generation and consumption, will be required to address this challenge. This transformation calls for a transition to a sustainable energy supply with efficient low-carbon and environmentally-sound energy generation and increased utilization of renewable energy sources. A transition is only feasible if modern technologies and renewables are economically viable. Sustainable energy consumption will involve increased energy efficiency and awareness of the negative impacts of the current energy system, as well as the positive implications of an energy transition. Changes in consumption patterns can, for instance, result in increased electricity demand for transportation and heating. A secure and reliable supply of energy is necessary for the sustainable development of a society. Linkages between these SED themes are inevitable as, for instance, some actions address multiple themes.

A comparison of these themes with existing SED themes shows that the main issues of SED were identified in this study. These results confirm that the methodological approach chosen was suitable and of value. Over time, these themes of SED will continue to evolve, responding to global development issues. Hopefully, access to modern energy services and wasteful consumption patterns will be less pressing issues, and emphasis will be placed on the sustainable utilization of environmentally sound resources and technologies.

According to this analysis, the most prominent theme of SED is a sustainable energy supply, which was discussed to some extent in all 34 most cited publications. The least discussed theme was sustainable energy consumption, which brings attention to a potential gap in the literature and avenues for further research. The least discussed sub-topic of the themes was the sustainable utilization of energy resources, both concerning energy security and sustainable energy supply. This highlights that more attention could be given to the sustainable management of, for instance, stock-based renewables to prevent their depletion. Further analysis of citing behavior within the SED literature could lead to the identification of more gaps in the literature. Such an analysis could also highlight which types of publications are cited most often and within which fields those publications lie. The majority of the most cited publications were those with a global and broad reach that were published by established international agencies, such as the UN and IEA. The topic of several of the publications identified as influential in shaping the concept was indicators for SED. It is vital that indicators, tracking progress towards SED, capture the concept accurately.

Future research and actions towards SED need to take account of this more comprehensive definition and the role of energy in promoting sustainable development. Multiple different steps and pathways can be taken toward sustainable energy development. The purpose of this analysis was not to present a list of actions towards SED but to analyze what SED entails. When developing an action plan towards SED, the analysis performed here, and the interrelated themes of the concept should be considered as well as the overarching goal of furthering sustainability.

Acknowledgments

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Appendix A: Most cited publications on sustainable energy development

	Most cited publications	**# of times cited**
1	World Commission on Environment and Development. Our Common Future. New York: 1987. [1]	63
2	International Atomic Energy Agency, United Nations Department of Economic and Social Affairs, International Energy Agency, Eurostat, European Environment Agency. Energy indicators for sustainable development: Guidelines and methodologies. Vienna: 2005. [52]	47
3	Lund H. Renewable energy strategies for sustainable development. Energy 2007;32:912–9. [87]	33
4	United Nations Development Programme, United Nations Department of Economic and Social Affairs, World Energy Council. World Energy Assessment: Energy and the Challenge of Sustainability. New York: 2000. [2]	32
5	International Energy Agency, OECD/IEA. World Energy Outlook 2010. Paris, France: 2010. [30]	26
6	United Nations. Kyoto Protocol to the United Nations Framework Convention on Climate Change. United Nation 1998. [37]	21
7	Wang JJ, Jing YY, Zhang CF, Zhao JH. Review on multi-criteria decision analysis aid in sustainable energy decision-making. Renew Sustain Energy Rev 2009;13:2263–78. [65]	21
8	Vera I, Langlois L. Energy indicators for sustainable development. Energy 2007;32:875–82. [39]	21
9	International Energy Agency, OECD/IEA. World Energy Outlook 2009. Paris, France: 2009. [29]	20
10	Yuksek O, Komurcu MI, Yuksel I, Kaygusuz K. The role of hydropower in meeting Turkey's electric energy demand. Energy Policy 2006;34:3093–103. [70]	19
11	Ahmad S, Kadir MZAA, Shafie S. Current perspective of the renewable energy development in Malaysia. Renew Sustain Energy Rev 2011. [69]	18
12	Dincer I. Renewable energy and sustainable development: A crucial review. Renew Sustain Energy Rev 2000. [62]	17
13	Hashim H, Ho WS. Renewable energy policies and initiatives for a sustainable energy future in Malaysia. Renew Sustain Energy Rev 2011. [67]	16
14	International Energy Agency, OECD/IEA. World Energy Outlook 2008. Paris,	16

	France: 2008. [28]	
15	United Nations Development Programme, United Nations Department of Economic and Social Affairs, World Energy Council. World Energy Assessment: Overview 2004 Update. New York: 2004. [44]	16
16	Afgan NH, Carvalho MG. Multi-criteria assessment of new and renewable energy power plants 2002;27:739–55. [80]	15
17	Kaygusuz K, Kaygusuz A. Renewable energy and sustainable development in Turkey. Renew Energy 2002;25:431–53. [71]	15
18	Kaygusuz K, Sarı A. Renewable energy potential and utilization in Turkey. Energy Convers Manag 2003;44:459–78. [72]	15
19	United Nations Sustainable Development. Agenda 21. Rio de Janeiro: United Nations; 1992. [36]	15
20	Bilgen S, Keles S, Kaygusuz A, Sari A, Kaygusuz K. Global warming and renewable energy sources for sustainable development: A case study in Turkey. Renew Sustain Energy Rev 2008;12:372–96. [73]	14
21	Evans A, Strezov V, Evans TJ. Assessment of sustainability indicators for renewable energy technologies. Renew Sustain Energy Rev 2009;13:1082–8.[81]	14
22	International Energy Agency. Energy Policies of IEA Countries: Turkey 2005. Paris, France: 2005. [74]	14
23	Kaygusuz K, Kaygusuz A. Geothermal energy in Turkey: The sustainable future. Renew Sustain Energy Rev 2004;8:545–63. [75]	14
24	Shafie SM, Mahlia TMI, Masjuki HH, Andriyana A. Current energy usage and sustainable energy in Malaysia: A review. Renew Sustain Energy Rev 2011;15:4370–7. [78]	14
25	United Nations Department of Economic and Social Affairs. Indicators of Sustainable Development: Guidelines and Methodologies. 3rd Edition. New York: 2007. [50]	14
26	Demirbas MF, Balat M, Balat H. Potential contribution of biomass to the sustainable energy development. Energy Convers Manag 2009;50:1746–60. [79]	14
27	Akpinar A, Kömürcü MI, Kankal M, Özölçer IH, Kaygusuz K. Energy situation and renewables in Turkey and environmental effects of energy use. Renew Sustain Energy Rev 2008;12:2013–39. [8]	13
28	Balat H. A renewable perspective for sustainable energy development in Turkey: The case of small hydropower plants. Renew Sustain Energy Rev 2007;11:2152–65. [76]	13
29	Chisti Y. Biodiesel from microalgae. Biotechnol Adv 2007;25:294–306. [85]	13

30	Connolly D, Lund H, Mathiesen B V., Leahy M. A review of computer tools for analysing the integration of renewable energy into various energy systems. Appl Energy 2010;87:1059–82. [86]	13
31	Nautiyal H, Singal SK, Varun, Sharma A. Small hydropower for sustainable energy development in India. Renew Sustain Energy Rev 2011;15:2021–7. [77]	13
32	Streimikiene D, Ciegis R, Grundey D. Energy indicators for sustainable development in Baltic States. Renew Sustain Energy Rev 2007;11:877–93. [66]	13
33	Baños R, Manzanp-Agugliaro F, Montoya FG, Gil C, Alcayde A, Gómez J. Optimization methods applied to renewable and sustainable energy: a review. Renew Sustain Energy Rev 2011;15:1753–66. [63]	13
34	Zhang P, Yanli Y, Jin S, Yonghong Z, Lisheng W, Xinrong L. Opportunities and challenges for renewable energy policy in China. Renew Sustain Energy Rev 2009;13:439–49. [64]	13

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Review of indicators for sustainable energy development

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ABSTRACT

Sustainable energy development has become an international policy objective and an integral part of sustainable development. It is necessary to develop a robust and comprehensive set of indicators to monitor progress towards sustainable energy development. This analysis aimed to assess established indicator sets for sustainable energy development. The characteristics of a comprehensive and robust indicator set were identified to enable such an assessment and used as a basis for six assessment criteria; transparency of indicator selection and indicator application, conceptual framework, representative, linkages, and stakeholder engagement. A total of 57 indicator sets were found that monitor progress towards sustainable energy development or some aspects of it. All but one of these indicator sets were found to be lacking in some aspect, especially regarding a lack of transparency and consideration of linkages between indicators, presentation of an imbalanced picture, and no involvement of stakeholders during indicator development. The only indicator set that met all criteria were *Energy Indicators for Sustainable Development* developed jointly by multiple international agencies. Nonetheless, several flaws in this set were identified. The *Energy Indicators for Sustainable Development* could be considered as an initial basket of indicators for further refinement in the context where they will be applied to ensure their policy relevance and usefulness. The refinement process would benefit from more stakeholder input to take into account the specific context and make sure that there is a balance in the representation of the three dimensions of sustainable development.

1. Introduction

The importance of energy in achieving sustainable development was recognized when the concept was first introduced in the UN's *Our common future* report [1]. In 2000, the concept of sustainable energy development (SED) was put forward in the UN's *World Energy Assessment* (WEA) report with the introduction of a development paradigm where the economic, social, and environmental impacts of energy development were considered [2]. Since then, SED has become an international policy objective reflecting the various challenges facing modern energy systems, such as depleting fossil fuel sources, increasing energy consumption, and climate change. SED was solidified as an integral part of sustainable development with the introduction of goal seven of the UN's Sustainable Development Goals (SDG), "*Ensure access to affordable, reliable, sustainable and modern energy for all*" [3].

The challenges and actions towards SED can differ significantly from one country or energy system to the next. Generally, SED promotes social and economic well-being while ensuring sustainable utilization of resources and a clean environment [4]. In the UN's WEA report, an emphasis was placed on not "exceeding the carrying capacity of ecosystems" when producing and consuming energy to ensure the sustainability of energy development. Furthermore, the necessity of secure and reliable energy supply at an affordable price was highlighted [2].

Developing ways to track progress towards SED and assess whether policies are furthering desirable development is essential. The need for sustainability indicators was clearly defined in the UN's Agenda 21, which called on countries, as well as organizations, to develop indicators of sustainable development that can inform decision-making at all levels [5]. Carefully selected sustainability indicators can provide valuable information to monitor progress and inform policy. Multiple different indicators or indices have been developed in the context of SED. These vary greatly based on their purpose and what they are set out to measure [6]. Numerous challenges have hindered these efforts, such as uncertainties in what various terminology should entail, disagreement on methodological approaches, and whether stakeholders should be included in indicator development [7]. Research on established sustainability indicators for energy development has highlighted some of

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Abbreviations

AESPI	Aggregated Energy Security Performance Indicator
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AI	Assessment Index
Bellagio STAMP	Bellagio Sustainability Assessment and Measurement Principles
DSR	Driving force/state/response
EDI	Energy Development Index
EEA	European Environment Agency
EISD	Energy Indicators for Sustainable Development
ESCI	Energy Sustainability Country Index
ESI	Energy Sustainability Index
ESMAP	Energy Sector Management Assistance Program
EY	Ernst & Young
GNESD	Global Network on Energy for Sustainable Development
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IEEJ	Institute of Energy Economics Japan
ISED	Indicators for Sustainable Energy Development
ISED-AT	Indicators for Sustainable Energy Development for Austria
ISUD	Index of Sustainable Energy Development
MCDA-DEA	Multi-criterion decision analysis-data envelopment analysis
MEPI	Multi-dimensional Energy Poverty Index
MEPI	Multidimensional Energy Poverty Index
OECD	Organisation for Economic Co-operation and Development
PASHMINA	Paradigm Shifts Modelling and Innovative Approaches
RECAI	Renewable Energy Country Attractiveness Index
REES	Risky External Energy Supply
RERII	Renewable Energy Responsible Investment Index
RISE	Readiness for Investment in Sustainable Energy
RISE	Regulatory Indicators for Sustainable Energy
SALSA	Search, Appraisal, Synthesis, and Analysis
SD	Sustainable Development
SDG	Sustainable Development Goals
SED	Sustainable Energy Development
SEDI	Sustainable Energy Development Index
SEW	Sustainable Energy Watch
SISED	Synthetic Index of Sustainable Energy Development
SISED	Synthetic Index of Sustainable Energy Development
SSEI	Standardized Sustainability Energy Index
TSDI	Taiwan's Sustainable Development Indicators
UESI	Urban Energy Sustainability Index
UN	United Nations
UN DESA	United Nations Department of Economic and Social Affairs
UNDP	United Nations Development Programme
UNFCC	United Nations Framework Convention on Climate Change
US	United States
WEA	World Energy Assessment
WEF	World Economic Forum

their limitations [6]. Current indicators have been criticized for their limited scope and perspective, lack of transparency, and not adequately capturing SED [8].

Several studies have evaluated the suitability and usefulness of one or more indicator sets for SED, e.g., Shortall and Davidsdottir's study of how to measure national energy sustainability performance [8], and Narula and Reddy's review of energy security and sustainability indices [6]. However, no one study has analyzed and compared all existing indicator sets for SED to the authors' knowledge. This study aims to assess the suitability of current indicator sets to measure progress towards sustainable energy development. For this purpose, the following objectives are laid out:

- identify what makes an indicator set comprehensive and robust
- provide a comprehensive overview and comparative analysis of existing indicator sets for SED

Indicator set assessment criteria are created based on existing guidelines for sustainability indicators. These criteria reflect characteristics or actions thought to make indicator sets comprehensive and robust. Different from prior studies of SED indicators, these criteria enable the assessment of a large number of indicator sets. A rating of current indicator sets for SED, and identification of sets that could be considered suitable is valuable. Progress is made by building on existing knowledge; in this case, insights on how indicator sets for SED could be improved. Therefore, this study is of value to decision-makers and stakeholders of energy systems as well as researchers in the field.

The paper is structured as follows: Section 2 briefly reviews the concept of SED, problems of existing indicator sets, and frameworks for indicator selection. Section 3 presents the methodology used to find and, subsequently, assess established indicator sets for SED. Section 4 lays out the results of the assessment of indicator sets. A discussion on the suitability and flaws of current indicator sets is provided in Section 5. Furthermore, the potential limitations of this study and future research guidelines are considered in the section. The paper is concluded in section 6, where the next steps are proposed.

2. Background

2.1. Sustainable energy development

Ever since the introduction of sustainable development on the international policy agenda, the role of energy in promoting sustainable development has been increasingly more recognized [1]. Initially, energy development often was put in context with climate change and reducing greenhouse gas emissions, for instance, in the international treaties: Framework Convention on Climate Change and Kyoto Protocol [9–11]. Energy issues were viewed in isolation and not robustly connected to other development issues [11]. In 2000, the United Nations Development Programme (UNDP), in its World Energy Assessment (WEA) report, put forward a new development paradigm where the economic, environmental, and social impacts of energy development were considered, which forms the basis of SED [2]. In the WEA report, the importance of access to energy to promote economic growth and social equity were highlighted as well as the necessity of staying within the "carrying capacity of ecosystems" to ensure the sustainability of energy systems [2]. The need for energy to promote sustainable development was acknowledged with the introduction of the UN's SDG 7 on affordable and clean energy [3]. Over the past three decades, SED has evolved to become a comprehensive and essential policy objective worldwide [9].

The underlying challenges and actions towards SED can differ significantly between countries and energy systems [11,12]. Nonetheless, it is possible to identify common themes and goals of SED. The history and emerging themes of SED were analyzed by Gunnarsdóttir et al., in 2020 [11]. According to their study, the overarching goal of SED is to advance sustainability [11]. Furthermore, four inter-related themes of SED were presented: sustainable energy supply, access to affordable modern energy services, energy security, and sustainable energy consumption [11]. These inter-related themes broadly show what needs to be addressed and accomplished with SED. A diagram of SED can be seen in Fig. 1.

These four themes touch on the environmental, social, and economic aspects of energy development [11]. SED cannot be achieved without equitable access to affordable modern energy services, which is vital to promote economic and social growth [2–4,11,13]. Without a secure supply of energy, sustainable development is not possible [2,11,13,14]. A transformation of the current energy system towards a sustainable energy supply is necessary to reduce its harmful environmental and health impacts [2,5,11,13,14]. This transformation will include a transition in energy generation towards environmentally sound technologies and modern renewables that are managed sustainably [2,10,11,15–17]. These technologies will have to become cost-competitive, and energy pricing needs to reflect the external costs of energy for this transformation to be realized [1,2,5,13,14]. A change in consumption patterns towards sustainable energy consumption will also be necessary, which will involve efforts to increase awareness of the potentially harmful impacts of current energy systems and to promote energy efficiency [1,2,5,11,13,14,16,18]. Actions towards SED need to be taken now by everyone at all levels [11].

2.2. Limitations of sustainability indicators

Ever since the UN's Agenda 21, where the need for indicators was laid out, it has become increasingly more common to use indicators to track and inform actions [5]. Yet, there is no standardized way of selecting indicators. Many attempts have been made to develop indicators to track progress towards SED, as this study highlights. These vary from a single indicator to a long list of indicators that give a detailed picture of the energy system in question [6]. These efforts have made a case for the usefulness and necessity of indicators. However, they have also highlighted some of the challenges associated with creating sustainability indicators and the limitations of existing indicators. These limitations include ambiguities in the definition of SED, failure to capture unique national circumstances, an imbalanced representation of the dimensions of SD, inconsistent results, obscure methodology, and lack of stakeholder engagement. An identification of the potential downsides of current indicators and their methods can aid with the design of more effective sustainability indicators, which is one of the motivations behind this study [8].

Ambiguities, in the definition of SED and, similarly, sustainable development (SD), especially in the local context, have hindered efforts towards creating suitable sustainability indicators [6,8]. While the ultimate goal of SED remains the same, the path towards it and challenges on that path can vary, which highlights the necessity of context-specific indicators [19]. The premise of indicators is that they should be relevant to policy and inform better decision-making [20]. As policies are usually implemented at the national or regional level, indicators should ideally reflect issues within that context [8,21]. Nevertheless, some of the most prominent indicator sets for SED, e.g., the *Energy Trilemma Index (ETI)* and *Energy Architecture Performance Index*, are designed as national indicators for country comparisons without accounting for national conditions [8,19]. Narula and Reddy argue that with country comparisons, "homogeneity between the characteristics of the energy system of all countries" is assumed [6]. However, it is well known that energy systems can vary significantly, for instance, with regards to size, availability of natural resources, and level of industrialization [6]. A comparative assessment carried out by Narula and Reddy showed that the scores of three different energy indices are inconsistent and incomparable [6]. According to their evaluation, this inconsistency can be credited to the fact that the indices emphasize various aspects of SED and might not give a complete picture of the system by themselves.

Some indicator sets have been criticized for oversimplifying SED or presenting an imbalanced picture of SED. These faults have been connected with the aggregation of indicators into a single score, the number of indicators, and the omission of qualitative issues [7,21]. Even though the measurability of qualitative topics can often be challenging, it does not justify their exclusion from an indicator set. Shortall et al. evaluated three established indicator sets for SED, namely, *Energy Trilemma Index, Energy Architecture Performance Index, and Energy Indicators for Sustainable Development (EISD)* [8]. According to their analysis, the qualitative issue of wellbeing, arguably the ultimate goal of sustainable development, was neglected by the three indicator sets [8]. Connected to this, Narula and Reddy [6] discussed how most indices overly emphasize economic aspects of SED while overlooking social and environmental ones, thus presenting an imbalanced presentation of SED.

The engagement of stakeholders has been suggested to aid with the development of context-specific indicators that are relevant to policy and acceptable to stakeholders [7,8]. Thereby, a broad range of

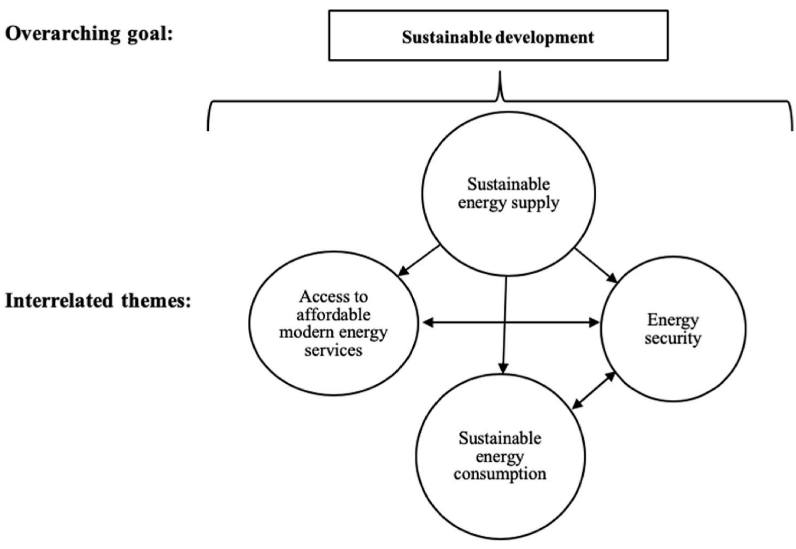

Fig. 1. Themes of sustainable energy development. Thematic map showing the overarching goal and interrelated themes of sustainable energy development. The arrows illustrate connections between the different themes. The direction of the arrows indicates whether a theme enables another theme. Diagram originally presented by Gunnarsdóttir et al. [11].

perspectives can be considered, ideally resulting in a more balanced and representative set of indicators. Sovacool argued that semi-structured interviews lend themselves well to a discussion on complex concepts, such as energy security and SED [7]. Additionally, he explained that through targeted discussions, it is possible to determine what a concept means in the context, including its qualitative issues [7]. Shortall et al. [8] stated that "the design of indicators requires the input of multiple actors, and should include local and lay knowledge. Such indicators need not be identical between each locality but should cover essential themes of sustainable energy development and should lend themselves to being used in models and multicriteria evaluations. Hence both qualitative and quantitative indicators are possible."

A lack of methodological transparency, both regarding indicator selection and their application, is a common criticism of current indicators [8]. The legitimacy and credibility of indicators are heavily dependent on the transparency of their methods [8]. The developers of the *EISD* emphasized the transparency of methods to ensure the usefulness of indicators and, for instance, consistent data collection [4]. Shortall et al. argued that a lack of methodological transparency could hinder the connection of indicators with dynamic models and thereby the ability to look at the sustainability implications of alternative futures [8]. Thus, indicators are limited to being backward-looking.

2.3. Frameworks for indicator selection

Conceptual frameworks are often used to structure and understand complex problems and are considered the theoretical underpinnings of indicator sets [22]. At the most basic level, a framework provides a checklist for what issues should be considered and how they should be organized [23]. The benefits of frameworks are multiple, such as increased comparability, transparency of indicator selection, and minimized bias [24]. Numerous frameworks have been developed that vary on diverse elements, such as interpretation of sustainable development, the structure of the economy or society, and indicator selection and aggregation [25].

Three main types of frameworks have been utilized for the development of indicator sets for SED: causal chain, thematic, and system dynamics ones. In the early 2000s, causal chain frameworks were commonly used when developing sustainability indicators [25]. However, due to complexities and ambiguities in their application, they were abandoned for thematic frameworks [26]. Currently, most indicator sets are developed within thematic frameworks as it provides more flexibility than many prior frameworks and can be applied within different contexts. The main criticism of thematic frameworks is that inter-linkages or dynamic interactions of themes can be undervalued [27]. A system dynamics approach to indicator development has gained popularity where an entire energy system and dynamics within it are analyzed. A further description of the different types of frameworks is presented below in chronological order:

- Causal chain frameworks are all organized similarly, as cause and effect relationships (i.e., causal chains). Numerous causal chain frameworks exist which differ in the number of steps recognized in the chain, e.g., pressure-state-response, driving force-state-response, and driving force-pressure-state-impact-response [26]. By using a causal chain framework, it is possible to structure a problem into causality relationships and, thus, identify drivers and outcomes. The main criticism of them is difficulty in their application as they lack flexibility, and issues need to be relatively simple to be captured through a linear causal chain [4]. Furthermore, the interlinkages of problems were not adequately captured through causal chain frameworks [25]. These weaknesses resulted in the over-simplification of issues and unclear indicator selection [26]. In 2002, the IAEA presented its *Indicators for Sustainable Energy Development (ISED)* that were based within a causal chain framework [28].
- Thematic frameworks are those that group indicators into different issues or themes of sustainability. These types of frameworks are commonly used and often linked with policy targets, such as in the development of national indicator sets [25]. Following national testing, the *Expert Group on Indicators of Sustainable Development* decided to move away from causal chain frameworks to thematic ones to represent policy issues better and make the indicator selection process clearer at the national level [25]. A thematic framework was thought to "better assist national policy decision-making and performance measurement" [29]. Therefore, three years after the *ISED* indicators were put out, the *Energy Indicators for Sustainable Development (EISD)* were presented, which contained the same core set of indicators organized within different themes of SED [4].
- System dynamics frameworks consider the entire energy system and dynamics within it, which are often presented as stocks, flows, and feedback loops. Through systems thinking, it is possible to break down and understand complex problems, which has made it popular across different fields of study [30]. Nerini et al. argued that "a systems perspective is crucial to understanding the practical complexity of energy provision and use, and facilitates effective intervention strategies" [31]. Through a systems approach, it was possible to investigate the complex dynamics of SED and highlight that "energy systems … affect delivery of outcomes across all SDGs" [31]. Kettner et al. used a systems approach to develop indicators for SED for Austria (ISED-AT) [32]. Thus, they were able to illustrate the Austrian energy system through the energy services the system provides, which served as a basis for indicator selection [32].
- A mixed approach is the combination of different frameworks, usually a thematic framework mixed with some other method. By combining two different frameworks, it is possible to address the weaknesses of individual frameworks and enhance the approach to conceptualizing the problem. Keirstead argued that a "combination framework should be developed to link key features" [33]. Therefore, Keirstead chose to combine systems dynamics and thematic framework when developing sustainability indicators for urban energy systems. Thus, the linkages between different indicators and issues were captured while the presentation of the framework was transparent through the various issues [33].

3. Methods

3.1. Literature search – SALSA framework

A literature review was conducted to identify what indicators for SED exist. The main criterion for search results to be included was that indicator sets for SED were either presented in the publication or discussed in a literature review that could be used as a basis for the snowballing method. Due to the multidimensionality of SED, the objectives of identified indicator sets ranged from measuring SED and energy policy to assessing energy poverty and energy security. Some of these indicator sets enabled an evaluation of progress towards SED while others allowed for the assessment of the sustainability of the energy sector or its subsectors. While the emphasis was placed on finding indicator sets for SED, indicator sets measuring other aspects of SED; e.g., energy security, were included when found. Therefore, the list of indicator sets for the different underlying issues of SED is, most likely, not exhaustive. Furthermore, time and geographical scope did not limit this search. Nonetheless, it is important to note the difference between sustainability assessments of the energy sector and an assessment of the SED of a country, where the latter is much broader. The level of sustainability assessment is also critical, which can range from national to industry-specific or sub-sectors of the energy system.

Publications that only presented a single indicator for energy or SED or no indicators at all were not considered further. To limit the number of search results further, indicator sets that exclusively focused on energy sources were excluded, i.e., to select between different energy sources or assess the sustainability of a particular energy source. These indicator sets were often mainly focused on measuring the efficiency of an energy source, which is not the focus of this study.

A systematic search and review of the literature were carried out through the application of the **Search, Appraisal, Synthesis, and Analysis** (SALSA) framework [34,35]. According to Grant et al., a systematic search and review consist of a comprehensive search process and a critical review that results in a 'best evidence synthesis' [34]. The steps of the SALSA framework enable a robust analysis of the existing literature while minimizing the potential for bias [35]. A 'snowballing' method was applied between the Appraisal and Synthesis steps to ensure an exhaustive search, similar to Malinauskaite et al.'s review of *Ecosystem services in the Arctic* [36], as seen in Fig. 2.

The first step of the SALSA framework is a **search** for the relevant literature. Three different academic databases were searched: Science Direct, Web of Science, and Google Scholar, along with a general Google search as some indicator sets might not be found within the scientific literature. Three search keywords were defined: "indicators," "index," and "sustainable energy development," which resulted in the Boolean search string (("Indicators" OR "index") AND ("sustainable energy development")). Initially, a large amount of results was found: Science Direct (n = 698), Web of Science (n = 54), Google scholar (n = 7050) and Google (n = 264.000). Results were presented in order of relevance. All results found through the Web of Science and the first 100 search results of Science Direct, 60 of Google scholar, and 60 of Google were scoped to determine whether they should be analyzed further. The number of search results scoped was determined by whether search results were still found relevant past a certain number. The majority of initial search results were deemed not within the scope of this research as either no indicator set was presented, or SED was not the focus.

The second step of the SALSA framework, **appraisal**, involved further assessing whether search results fulfilled the above inclusion and exclusion criteria. For this purpose, the abstracts of identified papers and reports were read and, subsequently, the entire publication browsed. A total of 220 publications were scoped from the databases. Many results appeared in more than one search engine but were only counted where they first appeared. The resulting publications found appropriate for further analysis were 19 from Science Direct, 19 from Web of Science, six from Google Scholar, and nine from Google.

As mentioned above, to identify more relevant indicator sets, a step of '**snowballing'** was added to the SALSA framework [36]. The 'snowballing' approach involves using the references and citations of papers to identify more relevant literature. Review papers and background sections of publications found through the initial search served as a basis for snowballing to find more indicator sets. Through this method, 39 additional papers or reports were identified that were snowballed from nine different publications.

The results of the first three steps of the modified SALSA framework were indicators sets for SED presented in papers published in peer-reviewed journals and reports from international or national agencies and research institutes. A total of 82 relevant publications were found, where 57 different indicator sets were presented or applied. Out of the 82 publications, 54 were journal articles, and 28 were reports, as seen in Fig. 3.

Following the identification of relevant papers and reports, a step of **synthesis** was done. The identified publications were read and analyzed with an emphasis on the indicator sets and their methodology. Indicator sets presented in the different journal articles and reports were categorized based on their stated purpose or what they were set out to measure. Furthermore, the indicator sets were grouped based on their geographical scope, see Appendix A.

3.2. Assessment of indicator sets

For the final step of the SALSA framework, **analysis**, a methodology for the assessment of indicator sets was developed; indicator set assessment criteria. For this purpose, many different guidelines and checklists for indicators and their selection were reviewed [24,25,37–39]. These often include a list of characteristics desirable in an effective indicator to ensure that the indicator can serve its purpose, such as informing policy and showing trends [40]. This analysis entails assessing established indicator sets and their development, as opposed to an individual indicator, which involved identifying characteristics found to make a set of indicators comprehensive and robust.

Most current checklists for indicators are focused on assessing individual indicators, not indicator sets. The only guidelines found to fit our purposes well were the *Bellagio Sustainability Assessment and Measurement Principles (Bellagio STAMP principles)*, see Fig. 4 [41,42]. These principles consist of eight good-practice guidelines for developing ways to measure progress towards sustainable development [41,42]. An emphasis is placed on selecting a robust and representative set of indicators as opposed to being focused on the characteristic of individual indicators [41]. Therefore, the Bellagio STAMP principles were used as a basis for the development of the indicator set assessment criteria applied here.

A few of the Bellagio STAMP principles did not fit this analysis and, therefore, were not included in the indicator set assessment criteria. Firstly, two of the Bellagio STAMP principles were not found to be measurable in an unbiased manner and, thus, were excluded: Principle 6: Effective communication and Principle 8: Continuity and capacity [41]. Secondly, two of the principles, 1: Guiding vision, and 3: Adequate scope, were excluded from the start as the criteria for the literature search already addressed them [41]. Since the literature search aimed to find indicator sets for SED, then, arguably, they should all meet the first principle of having a "guiding vision" [41]. The third principle of "adequate scope" emphasizes having an appropriate time scale and geographical scope. An "appropriate time horizon" depends on the objective of the indicator set, which was not a limitation of the above literature search [41]. It is both difficult to define and measure an appropriate time horizon, which is why it was not included in this analysis. The literature search was limited to indicator sets that measured the SED of an energy system or country, which addresses the geographical scope to some extent. Based on the four remaining Bellagio STAMP principles, the indicator set assessment criteria were developed.

The indicator set assessment criteria consist of six elements considered essential when developing a robust and comprehensive indicator set, see Table 1. All six criteria are weighted equally with a total score of one for each. An indicator set that meets all the criteria would receive a perfect score of 6 and, thus, could be thought comprehensive and robust. The transparency of an indicator set was assessed first as a lack of

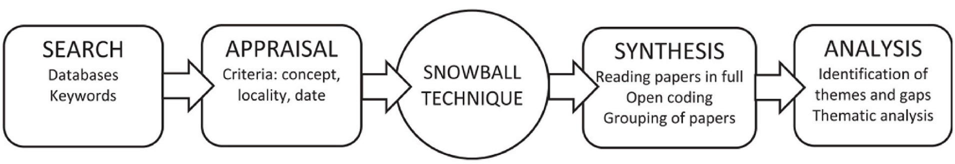

Fig. 2. Modified SALSA framework. The framework used for a systematic literature search and review; a modified SALSA framework with an additional step for snowballing. Diagram originally presented in Malinauskaite et al.'s study [36].

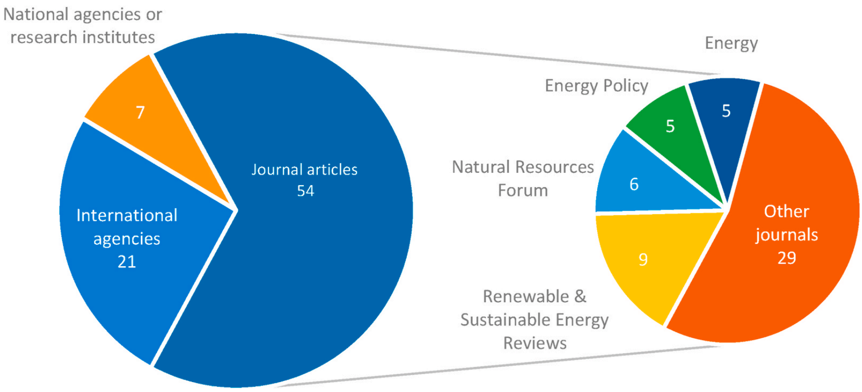

Fig. 3. Sources of indicator sets. Pie of pie showing where the 82 publications analyzed were published or by whom.

Bellagio STAMP principles

1. **Guiding vision**
   Measure progress towards sustainable development
2. **Essential considerations**
   Consider all three dimensions of SD and their interactions, the governance structure, current trends & drivers of change, risks & uncertainties, and potential impact for decision making
3. **Adequate scope**
   Both consider long- and short-term effects and range from local to global
4. **Framework and indicators**
   Based on a conceptual framework, recent and reliable data, standardized measurement methods, and compared to benchmarks and targets.
5. **Transparency**
   Data, data sources, indicators, methods, and results are accessible to all. Rationale is provided for assessments and funding and potential conflicts are disclosed.
6. **Effective communication**
   Use clear and plain language and present results objectively through innovative visual tools and graphics, if possible.
7. **Broad participation**
   Reflect the views of stakeholders and engage with potential users of the assessment.
8. **Continuity and capacity**
   Demand repeated measurements, show changes over time, investments to allow for regular revisions and improvements.

Fig. 4. Bellagio STAMP principles. Overview of the Bellagio STAMP principles based on publications by Bakkes [39] and Pintér et al. [38].

transparency hinders a further evaluation. The following criteria are listed in the order that they are usually met during indicator development and are all considered essential to capture a comprehensive, balanced, and unbiased picture of SED.

The first assessment criterion highlights the importance of transparency in indicator selection based on the fifth Bellagio STAMP principle. The credibility and legitimacy of an indicator set are increased through transparency in methodology [8]. If choices and assumptions made during indicator selection are not made clear, the indicator set can be misused or misinterpreted [41]. For this analysis, the transparency of indicator selection is assessed by whether the individual indicators of an indicator set, and the methodology for indicator selection were made available. Adequate transparency includes an explanation of the indicator selection process and the different steps involved. The two sub-criteria are considered equally important and given half a point each. If neither sub-criteria are met, it is difficult to assess the indicator set as the necessary information is not made available.

The second criterion is also rooted in the fifth Bellagio STAMP principle, where the value of transparency in indicator application is emphasized [41]. The usefulness of an indicator set depends on this criterion as it is not possible to apply the set or replicate results without the necessary information [23]. The majority of indicator criteria emphasize that indicators should be simple and easy to both interpret and apply to ensure the utility of the indicators to potential users, stakeholders, and decision-makers [24,25,40,41,43]. Multiple established indicator guidelines highlight the importance of using high-quality data that is readily available or collected [24,41,43]. Similar to the first assessment criterion, the transparency of indicator application is assessed by whether two different sub-criteria are met; inclusion of the methodology for indicator application and data sources. The methods for indicator application is considered transparent if, for instance, the mathematical formulas for the individual indicators are provided. Disclosing data sources entails naming where data were found or how data should be collected. The two criteria were given an equal weight of half a point each.

The third criterion is the application of a conceptual framework for indicator selection and organization, which is largely the fourth Bellagio STAMP principle of "Frameworks and indicators" [41,42]. The Bellagio STAMP principles highlight the importance of theoretical frameworks to determine and adequately capture the problem or system in question

Table 1
Indicator set assessment criteria. Compiled by authors.

Criteria	Rationale	Bellagio STAMP principle	Measurability
1. Transparency of indicator selection	It is necessary to make the methodological choices for indicator selection and the underlying indicators of an indicator set available to ensure the credibility and legitimacy of an indicator set.	Principle 5: Transparency	1/2 - Individual indicators 1/2 - Methodology for indicator selection 0 - Neither of the above and no further analysis
2. Transparency of indicator application	The usefulness of an indicator set relies on disclosing the necessary information for indicator application and data sources.	Principle 5: Transparency	1/2 - Methodology for indicator application 1/2 - Data sources 0 - Indicator set not easily calculated again
3. Conceptual framework	The application of a theoretical framework helps structure the problem and can increase comprehensiveness. The transparency of indicator selection can be improved, and bias minimized.	Principle 4: Framework and indicators	1 - Conceptual framework 0 - No apparent framework
4. Representative	The indicator set needs to be representative of sustainable energy development, which includes the consideration of economic, social, and environmental dimensions.	Principle 2: Essential considerations	1/3 - Economic 1/3 - Social 1/3 - Environmental 0 - None of the above
5. Linkages	To further enhance an indicator set, the linkages of individual indicators should be considered to show a complete picture and eliminate correlated indicators.	Principle 2: Essential considerations	1 - Regression analysis of indicators or causal chain or systems framework or presentation of connected indicators or stated that linkages were considered 0 - Not considered
6. Stakeholder engagement	Stakeholder engagement during indicator selection increases the robustness and representativeness of an indicator set. It increases stakeholder acceptance and reduces the potential for bias in selection.	Principle 7: Broad participation	1 - Stakeholders or external experts engaged 0 - No, not clear if was done

[41]. Transparency can be increased with the application of a conceptual framework as the methodology and selection of indicators is made more explicit. This criterion is simply measured by whether a conceptual framework is applied or not. The different theoretical frameworks are not evaluated directly in this analysis. However, as conceptual frameworks guide the selection of indicators and what aspects of the system are captured, these frameworks are indirectly assessed by the next two criteria described.

The fourth criterion underscores that indicator sets need to be representative of what they are set out to measure, which is similar to the second Bellagio STAMP principle. Multiple different indicator guidelines prescribe that indicators should provide an unbiased, representative picture of the system in question and its sustainable development [24,25,43]. For simplification, the three dimensions of sustainable development, economic, social, and environmental, are used as a basis for how this criterion is measured. This simplification corresponds to the overarching goal of SED, sustainable development, as presented in section 2.1. above. An incomplete picture of SED is captured if an indicator set does not include indicators representing all three dimensions, where each dimension is given a third of a point. Some interpretation is required in the assessment of this criterion. For example, an indicator set is thought to consider the social dimension if it includes indicators measuring the accessibility of energy, the economic dimension if the affordability of energy is measured, and the environmental dimension if the environmental impacts of energy are measured. If all three dimensions are considered, the indicator set is thought to be representative of SED and receives a score of 1.

The fifth criterion highlights the consideration of linkages within an indicator set. The second Bellagio STAMP principle, "essential considerations," states that the "system as a whole and the interactions among its components" should be considered [41]. Indicators can be meaningful on their own as well as together with other indicators of the set [43]. A single indicator only shows a partial picture, and the interpretation of two or more indicators together can shed more light on a problem [40]. By considering the linkages of indicators, it is also possible to identify overly correlated indicators. The inclusion of correlated indicators can result in overvaluing one aspect of the problem. According to the OECD's *Checklist for building a composite indicator,* the linkages of indicators should be identified through a regression analysis that works as an alarm bell to identify correlated indicators. However, this approach does not capture causal relations [23]. By using a causal chain or systems framework, the dynamics and interconnections within a problem are considered from the start. As with other criteria here, how to measure whether linkages within an indicator set were considered is challenging. To determine whether this criterion was met, the following actions were searched for: correlation or regression analysis during indicator development, the application of a causal chain or systems framework, or explicitly stated that linkages were considered. The criterion was deemed to be met if one of these actions was done.

The sixth criterion is the engagement of stakeholders during the development of an indicator set based on the seventh Bellagio STAMP principle. By involving stakeholders, it is possible to identify and take into account multiple viewpoints, which significantly increases the robustness and representativeness of an indicator set [23]. Furthermore, it reduces the potential for the researchers' bias in the selection of indicators. The process of involving stakeholders provides valuable insight into the sustainability goals and objectives that the various stakeholders find essential for SED. These goals dictate what should be measured and, thereby, what indicators should be selected [44]. Indicator sets need to be acceptable and of interest to stakeholders and the public for them to be applied [40,43]. Two main approaches for stakeholder engagement were considered; a participatory approach where stakeholders are engaged and expert approach where the opinion of external experts is considered [33]. This criterion is simply measured by whether stakeholders or experts were engaged or not during indicator development. If the criterion is met, the indicator set receives a score of one, the same as other criteria.

4. Results

A total of 57 indicator sets for SED or some aspect of it were found from 82 different publications. Some indicator sets were applied more than once within different contexts and by various researchers or institutions. Therefore, the indicator set assessment criteria were used 69 different times. Sometimes several publications were searched to assess an indicator set, which explains why the number of publications included exceeds the number of indicator sets. Four main categories of indicator sets were created based on what they were set out to measure, see Fig. 5. A sub-category within the general SED category was included, which encompassed 11 indicator sets and 25 studies based on the *Energy Indicators for Sustainable Development* (EISDs) or its precursor *Indicators for Sustainable Energy Development (ISED)*.

The identified indicator sets were found in journal articles and reports published from 1997 to February 2019. Out of the 82 publications analyzed, 43 were published after 2010 and 19 after 2015. The average number of indicators was 25 and ranged from 2 to 372 indicators. Out of

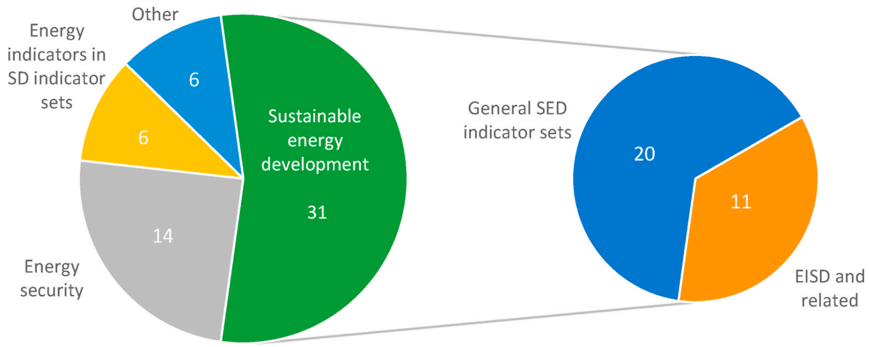

Fig. 5. Categories of indicator sets. The 57 identified indicators sets for SED were categorized into four groups based on their stated purpose or what they were set out to measure. A sub-group within indicator sets for SED was created for those connected to the Energy Indicators for Sustainable Development [4].

the 69 different assessments done, 47 contained fifteen or fewer indicators. The geographical scope was used to sort the indicator sets further within each category. The majority of indicators were developed at the national level, either for country comparison or specific to a country context. About a third of the indicator sets were designed for other scales or could be applied at various levels. Indicator sets that were developed to reflect a particular context or country did not allow for a comparison with other countries or systems. The different geographical scopes and their distribution can be seen in Table 2. Out of the 57 indicator sets identified, 27 of them were aggregated in some way to form an index or composite indicator. A complete list of the indicator sets for SED along with their source publication and other general information can be found in Appendix A.

An analysis of these indicator sets was enabled through the application of the indicator set assessment criteria presented in Table 1. The following sections are organized in the order of assessment criteria applied. It is important to note that a lack of transparency could have led to an inaccurate assessment, as enough information was not made available.

4.1. Transparency of indicator selection

The first criterion was focused on the transparency of indicator selection. A review of identified indicator sets showed that all of them made their underlying indicators available. The same transparency was not found regarding the methodology for indicator selection, where only 21 of the 69 assessments included a description of how indicators were developed. The results of this criterion can be seen in Fig. 6.

The indicator sets that were considered to have a transparent methodology for indicator selection often included an explanation and justification for the steps taken during indicator selection and sometimes even a diagram, e.g., *Sustainable Energy Development Index* by Iddrisu and Bhattacharyya, *Energy Sustainability Index (ESI)* by Mainali et al., *Aggregated Energy Security Performance Indicator (AESPI)* by Martchamadol and Kumar, and *Sustainability indicators for urban energy systems* by Keirstead [26,33,45,46]. Most of the studies that did not meet the sub-criterion lacked the necessary detail to be considered transparent, and some included no explanation at all of how indicators were selected. For instance, the original *ISED* did not meet the sub-criterion of a transparent methodology [28]. The only description of the indicator selection process included was that a causal chain framework was used to frame the problem, experts were brought together to review indicators, and indicator criteria developed by the UN were used [28]. There was no description of the different steps of the process, what decisions were made, or rationale for the selection of the final indicator set. A more detailed description of how the *ISED* were updated into the *Energy Indicators for Sustainable Development (EISD)* and what the indicator selection process entailed was provided in later publications, which is why the *EISD* were thought to meet this criterion fully [4,47].

Table 2
The various geographical scopes of SED indicator sets.

Geographical scope	#
For comparison	
National	30
National or regional	2
National, regional or local	1
Regional	1
Local	1
Rural	2
Cities	3
Urban areas	1
Households	1
Energy system	3
Variable	1
Not for comparison	
National	17
National and household level	1
Local	1
Residential sector	2
Energy system	2

4.2. Transparency of indicator application

Two sub-criteria measured the transparency of indicator application: availability of a methodology for indicator application, and data sources used. The primary assessment of the prior sub-criterion was that enough information was provided so that indicator calculation could be

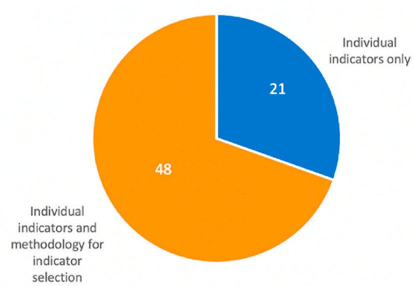

Fig. 6. Transparency of indicator selection. Either only the individual indicators were provided or both the indicators and methodology for indicator selection. No indicator set fulfilled neither sub-criteria.

replicated. Even if all of the identified indicator sets presented their underlying indicators, the clarity of the indicators varied significantly. The second sub-criterion was simply whether the necessary data sources were disclosed. The results of this criterion can be seen in Fig. 7.

General descriptions of data sources such as the following: "Datasets are based on publicly available or purchased data, EY analysis or adjustments to third-party data" did not fulfill the criterion [48]. For some of the identified indicator sets, information on indicator application and data sources was included in methodological addendums or appendices of reports. A methodological addendum to the 2017 report for the *Energy Architecture Performance Index* included indicator metadata, which entailed detailed information on the indicators and their application, relevant data sources, and "technical notes" [49]. Another example is the *Energy Trilemma Index,* where only the names and categorization of indicators are included in their annual report. A reference was made to a "Methodology document" available on their website. However, this document was nowhere to be found and, thus, the indicator set was thought to lack transparency in indicator application [50]. In some cases, the data source sub-criterion was not met because the publication only presented an indicator set and not the use of said indicator set. Therefore, it might depend on the context that the indicator set is applied where the necessary data is found. For example, Keirstead presented an approach to measure the sustainability of urban energy systems that requires a wide range of data sources. These data sources were not listed in his study as the purpose of his paper was to present an approach to indicator selection rather than a finalized set of indicators [33].

4.3. Conceptual framework

The third criterion was simply measured by whether a conceptual framework was used during indicator development or not. An assessment was made of whether a particular theoretical framework was mentioned in the publications, SED was structured, or indicators categorized per a framework. For instance, if indicators were categorized into the economic, social, and environmental dimensions or underlying issues of SED, it was assumed that a thematic framework was used. Out of the 69 indicator set assessments made, 60 were thought to have been developed through some conceptual framework.

The analysis of the indicator sets included identification of what conceptual frameworks were used, see Table 3. The thematic framework was by far the most popular choice as it was used for 55 different indicator sets, either by itself or mixed with another framework. The reason for this is perhaps because of the way the criterion was assessed. Indicators that were organized into the dimensions of sustainability or issues of SED were considered developed through a thematic framework.

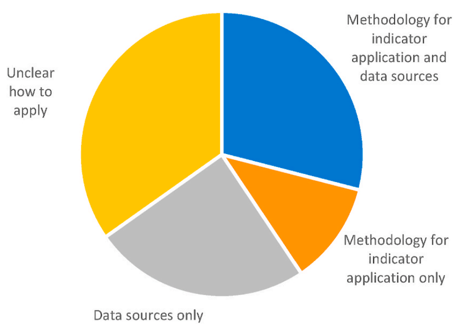

Fig. 7. Transparency of indicator application. Only 20 indicator sets included both the methodology for indicator application and data sources, and 25 sets included one of the two. The application of indicator sets that included neither was thought unclear.

Table 3
Conceptual frameworks used.

Conceptual framework	#
Thematic	43
Causal chain	3
Systems dynamics	1
Mixed approach	13
N/A	9
Total that used a framework	**60**

The few times some other conceptual approach was selected, it was clearly stated.

Variations of the causal chain approach were used eleven times by itself or mixed with another framework. The most recent application of the causal chain approach found was in the development of a *Sustainable Energy Development Index* (SEDI) in 2015 [26]. The results indicate that the causal chain approach has been abandoned for thematic frameworks or, more recently, systems dynamics ones. As mentioned earlier, the UN chose to move towards thematic frameworks due to complexities and ambiguities in the application of causal chain frameworks. In the development of *Indicators for Sustainable Energy Development for Austria (ISED-AT)*, Kettner et al. chose a combined thematic and systems approach [32]. The systems approach was used to structure the problem of SED in Austria based on energy services. The thematic framework was used to categorize indicators into the different dimensions of the problem, e.g., social, economic, and ecological dimensions of households. Through this combined approach, Kettner et al. were able to structure the issue in question clearly while capturing interactions between the different dimensions [32].

4.4. Representative

The fourth criterion was an assessment of how representative the indicator set was, whether economic, social, and environmental indicators were included. In most cases, the evaluation of this criterion was reasonably straightforward, especially when indicators were categorized into the three dimensions already. Sometimes, an assessment had to be made of what dimensions indicators reflected. For instance, indicators measuring the affordability and accessibility of energy were thought to be social ones. Out of the 69 assessments made, 45 were found to consider all three dimensions of sustainable development. The rest of them only presented a partial picture where one or more dimension was not included, see Fig. 8. Only two indicator sets did not include economic indicators, 19 did not consider the social dimension, and 10 excluded environmental indicators. These results confirm Narula and Reddy’s criticism that many energy indices lean towards the economic aspects of sustainable development while undervaluing the environmental and social ones [6].

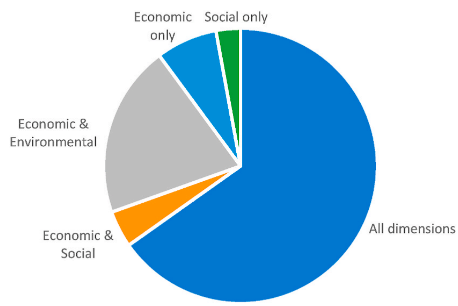

Fig. 8. Representative. Most indicator sets considered all three dimensions of sustainable development, although some only considered a partial picture and were not considered representative of SED.

As is the case with most indicator sets for sustainable development, indicators representing the social dimension were fewer than the other two. An example of this is the application of the *EISD* indicators to analyze energy development in the Baltic States [51]. The indicators used in the analysis were only those that reflected priority areas of energy development in the area, which resulted in the elimination of all social indicators from the *EISD* set [51]. Surprisingly, two indicator sets only measured the social side of energy development. Nussbaymer et al. developed the *Multidimensional Energy Poverty Index (MEPI)* to measure energy poverty, which is a social issue within SED [52]. The *Occupational Entropy and Mind Indicators for Sustainable Energy Development* were developed to measure behavioral changes towards energy sustainability and thought of as an addition to the *ISED* [53].

4.5. Linkages

The fifth assessment criterion assesses the consideration of linkages within an indicator set. This criterion was met if the correlation of indicators was analyzed, a causal chain or systems frameworks were applied, or if it was stated that interconnections were examined. Despite the explicit assessment method, it was found quite challenging to assess this criterion. According to this approach, linkages were considered in 41 of the 69 studies, see Fig. 9. To meet this criterion, Doukas et al. [54] emphasized the importance of uncorrelated indicators in the development of an *Energy Sustainability Index,* and Neves et al. [55] made sure to eliminate repetitions of indicators when selecting *Local energy sustainability indicators*. HELIO International's *Sustainable Energy Watch* and the WEC's *ETI* were thought to consider linkages as the trade-offs between indicators were analyzed [50,56]. The original *ISEDs* were developed through a causal chain framework and, thus, were thought to consider linkages of indicators [28]. A thematic framework was used for the development of the subsequent *EISDs.* However, it was explicitly stated the interlinkages within the set were considered and, therefore, the criterion was met [4].

4.6. Stakeholder engagement

The final criterion was simply whether stakeholders or external experts were engaged during indicator development or not. This criterion was met the least often, where the inclusion of stakeholder or expert opinion to inform indicator development was only mentioned 20 times, see Fig. 10. Sovacool met this criterion when developing an *Energy Security Index*, as energy security and its underlying dimensions were defined based on semi-structured interviews, a survey, a workshop, and a literature review [57]. Consultation with stakeholders and relevant agencies is encouraged in the development of *EISDs* to fit the national context, which is why the indicator set met the criterion. The process is believed to increase the relevancy of the indicator set for national policies and coordinate efforts in data collection [4]. In the development and review of the *Energy Architecture Performance Index*, experts and stakeholders were interviewed to inform the selection of weights and identify areas for improvement, which was found sufficient to meet the criterion [49].

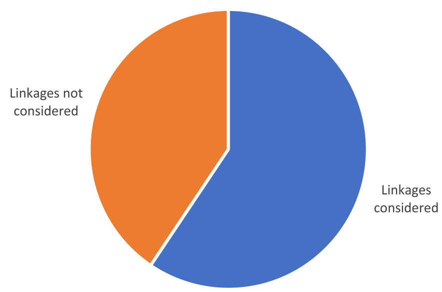

Fig. 9. Linkages. Just over half of the indicator sets considered linkages and interconnections between indicators within a set.

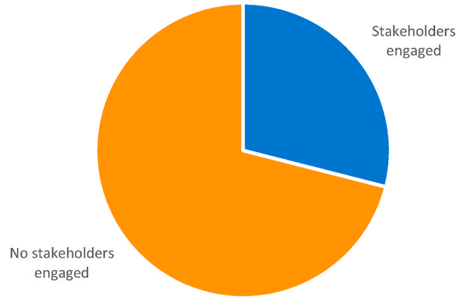

Fig. 10. Stakeholder engagement. No stakeholders were engaged during indicator selection for the majority of indicator sets. A lack of transparency for some indicator sets might affect these results.

4.7. Comprehensive and robust indicator set for sustainable energy development

The indicator set assessment criteria consist of six elements or characteristics considered essential in an indicator set for SED. Thus, a comprehensive and robust indicator set should receive a perfect score of six. The results of this analysis show that one indicator set for SED exists that meets all the criteria; the *Energy Indicators for Sustainable Development (EISD)* developed by the IAEA, UN DESA, IEA, Eurostat, and EEA [4]. The *Energy Architecture Performance Index* received a 5,5 as it only lacked transparency in indicator selection [49,58] Thirteen different indicator sets received a score of 5 with all but two in the sustainable energy development category. The average score was 3,69, with a minimum score of 1,66 and maximum, the previously mentioned, 6. The lowest score was given to four different indicator sets that all showed a partial picture, lacked transparency, did not consider linkages or stakeholder opinion: *Urban Energy Sustainability Index* by Marquez-Ballesteros et al., *Indicators for sustainable energy development in Chinese Villages* by Mortimer and Grant, *Energy Security Indicators* by the Asia Pacific Energy Research Center and *Indicators of long-term energy supply* security by Jansen et al. [59–62]. The distribution of scores can be seen in Table 4, and the scores for each indicator set can be seen in Appendix B.

The identified indicator sets were split into five categories according to their stated purpose. The average scores between the different categories varied significantly, see Table 5. The indicator sets that were derived from the *ISEDs* or *EISDs* received the highest average score, which is logical considering the *EISDs* received a perfect score. Energy security indicator sets received the lowest average score. They were often found to present a partial picture as all dimensions of sustainable

Table 4
Distribution of indicator set scores.

Score range	# of indicator sets
<1	0
$1 \leq x < 2$	7
$2 \leq x < 3$	9
$3 \leq x < 4$	21
$4 \leq x < 5$	17
$5 \leq x < 6$	14
6	1
Average	3,69
Max	6,00
Min	1,66

Table 5
Average scores by indicator set category.

Category	Total Score
Sustainable energy development	3,71
sub-category: EISD and indicator sets based on EISDs	4,20
Energy Security	2,95
Energy indicators in general SD indicator sets	3,89
Other	3,42

development were not considered, especially the social side. Energy security is sometimes defined more narrowly than SED.

5. Discussion

The implications of this study are an identification of the desirable characteristics of indicator sets as well as a comprehensive assessment of existing indicator sets for SED. According to the analysis carried out, the suitability of existing indicator sets varies considerably. One indicator set fulfilled all of the assessment criteria laid out and, therefore, could be considered comprehensive and robust – The *Energy Indicators for Sustainable Development.* The *EISD* were thought to be transparent since a detailed description of how indicators were selected and should be applied was provided. A thematic framework was used in its development, which ensured that all three dimensions of sustainable development were accounted for, and the indicator set was representative of SED. Linkages between the different indicators and themes were considered, apparent by the fact that some indicators were within more than one theme. Finally, experts and stakeholders were consulted during the development of both the original *ISED* and, the subsequent, *EISD.* Thus, the *EISDs* met all the assessment criteria and can be considered a comprehensive and robust indicator set [4].

The *EISD* aim to enable countries to assess their progress towards SED, not necessarily to compare their progress to other countries. Shortall and Davidsdottir did not find the *EISD* to adequately capture the Icelandic context with its unique energy mix and emphasized that indicators need to reflect the national conditions to be useful to policymakers and stakeholders [8]. The *EISD* are described as "a recommended rather than complete core set of energy indicators" [4]. Therefore, stakeholder engagement is encouraged to refine the *EISDs* further to fit the national context and coordinate efforts in data collection [4]. This refinement must not result in the omission of too many indicators or entire dimensions, as was the case with the application of the *EISD* in the Baltic States [51]. Therefore, the *EISD* could be considered as a robust and comprehensive building block for further development that shapes that the indicator set to reflect the context and make it useful to stakeholders.

The *EISD* are not flawless, despite receiving a perfect score in this study. The indicator set has been criticized for, e.g., capturing an imbalanced picture of SED, and having demanding data requirements [8,26]. However, perhaps one of the main weaknesses of the indicator set is that it does not seem to be used by many, which might be because of its lack of effective communication. The use of other, lower scoring, indicator sets for SED, e.g., *Energy Trilemma Index (ETI),* is much more widespread. The *ETI* has become an established measurement tool within the energy field despite lacking rationale for indicator selection and application and only receiving a score of 3,5. If a criterion on effective communication of indicators and their results had been included in this study, the *EISD* would not have received a perfect score, and the *ETI* would have scored better. The flaws of the *EISD* and potential reasons for its lack of use are discussed in the following paragraphs.

A quick analysis of the *EISD* indicator set reveals that the dimensions of sustainable development are not balanced as there are four social indicators, sixteen economic indicators, and ten environmental ones [4]. Shortall and Davidsdottir [8] found the *EISD* indicators to be more comprehensive and better capture the various issues of SED than the WEC's *ETI* and the WEF's *Energy Architecture Performance Index*. However, they argue that none of these three established indicators sets for SED adequately account for human wellbeing or capture impacts on a smaller scale, such as the local level [8]. A suitable indicator set accounts for all dimensions of sustainable development and the interlinkages between the different goals to capture a representative picture of SED.

Iddrisu and Bhattacharayya further criticized the *EISD* indicators for demanding data requirements due to the large number of indicators that make them impractical and difficult to interpret [26]. The *EISDs* are not aggregated, which is frequently done with indicator sets and thereby remain multi-dimensional [4]. In this analysis, 27 of the 57 identified indicators were aggregated in some way, often to form an index. The aggregation of indicators can be a complicated process. Assigning weights and, thus, quantifying the relative significance of indicators is a politically sensitive and value-laden process that can lead to subjectivity [63]. An aggregated index reports the status of an entire system while it might not reflect the health of the different dimensions of the system and hinders an in-depth analysis [64]. That is, through aggregation, a lot of information can be lost due to the "information iceberg" effect unless data for underlying indicators are shown as well [65].

The most visible difference between the *EISD* and the *ETI* is their presentation. The *EISD* are presented as a list of indicators organized within dimensions, themes, and sub-themes of SED [4]. The *ETI* are presented as three core elements of a sustainable energy system – energy security, energy equity, and environmental sustainability, see Fig. 11 [50]. The results of the *ETI* are presented within the triangle. Countries are ranked on an A-B-C scale for each element based on the results of aggregated underlying indicators. The presentation of the *ETI* is much more visually appealing and easier to understand at a glance than the *EISD*, despite the lack of methodological transparency. This difference in presentation might be the deciding factor for why the *ETI* is used much more than the *EISD*. The developers of the *EISD* do not discuss how the indicators should be presented, and their results reported. Effective and transparent communication of indicators can ensure their application and usefulness [25]. The OECD highlights the significance of visualization of the results as it can influence interpretability [23]. Graphics of results can be useful to stakeholders as opposed to raw data that might be technical [43]. It is beneficial to accompany these graphics by short summaries or explanations for general stakeholders, while decision-makers could receive more detailed descriptions when appropriate [43].

The *EISD* were developed as a pool of indicators for SED to be "read in

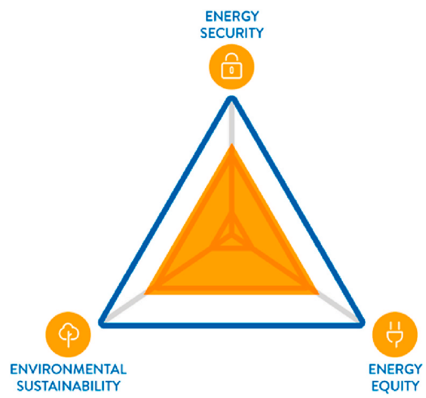

Fig. 11. The Energy Trilemma. Presentation of one of the most commonly used energy indicator sets, the Energy Trilemma Index, within the energy trilemma - energy security, environmental sustainability, and energy equity [48].

the context of each country's economy and energy resources" [4]. While detailed descriptions are provided of the methodology for each indicator, more guidance might be needed on how the EISD should be "read in the context" [4]. For instance, stakeholder consultation is recommended; however, no further guidance is given on how, which, or why stakeholders should be engaged. Establishing a coordinating mechanism to "liaise with all of the relevant organizations in the country and to coordinate their activities with the EISD effort" is suggested [4]. Issues covered by the *EISD* are likely connected to multiple agencies and organizations and, therefore, such a mechanism is undoubtedly necessary. However, ownership of the *EISD* is similarly important, although never mentioned in the *EISD* guidelines. The responsibility for refining the *EISD* to reflect the context, collecting data from the various sources, reporting the indicators, and updating them periodically could be given to one governmental body, and not be shared among multiple agencies and organizations. In comparison, the *ETI* is managed by the WEC, which collects data annually from the relevant national agencies. Thereby, the WEC bears all the responsibility, and national agencies only have to provide them with data.

Another fault of the *EISD* is the absence of institutional indicators [4]. Vera et al. [47] stated that "institutional indicators assess the availability and adequacy of the institutional framework necessary to support an effective and efficient energy system." Therefore, institutional indicators measure issues vital to the realization of SED, such as the effectiveness of policies and action plans, the level of investment in capacity building, education, and research and development [4,47]. The developers of the *EISD* explained that it can be challenging to measure institutional issues as they can be qualitative or relate to the future, which is why no institutional indicators were included [4]. Nonetheless, an attempt could be made to measure progress towards these crucial aspects of SED. A fitting first institutional indicator would be ownership of the *EISD*.

There are a few potential weaknesses to this study, particularly regarding the indicator set assessment criteria. Creating a system for measuring these criteria was challenging. The literature was reviewed to identify what actions or characteristics were though to enable each criterion, which made up the different sub-criteria. The number of criteria and sub-criteria was kept to a minimum to address this, and only criteria based on the most important attributes to develop a robust indicator set were included. For simplification, all the criteria were weighted equally, which could have resulted in some criteria being over- or under-valued. A lack of transparency in either indicator selection or application could have hindered an accurate assessment in some cases, which even further highlights the importance of transparency.

A few aspects of a successful indicator sets were not included in the criteria. Two Bellagio STAMP principles were not considered, namely, principle 6 on effective communication and principle 8 on continuity and capacity [41,42]. The necessity of effective communication of indicators is highlighted in the above discussion. The continuity of an indicator set refers to repeated measurements and regular revisions of indicators. However, it was challenging to measure what effective communication and the continuity of an indicator set would entail.

Although the necessity of taking account of the national context is highlighted throughout this paper, a more detailed analysis of how representative of SED the indicator sets were remains for further analysis. Representativeness includes taking account of the national context to ensure policy relevance and usefulness to stakeholders. Furthermore, the scope or level of different indicator sets is identified, but no assessment is made related to this.

The following steps and considerations for the development of an indicator set for SED are suggested to set future research guidelines. It is beneficial to keep transparency as a guiding light throughout the process. The usefulness of indicators or an approach to indicator selection is entirely dependent on how effectively they are presented and whether stakeholders and policymakers can apply them. An effective and transparent presentation includes disclosing the relevant formulas and data sources as well as methodology for indicator selection. Furthermore, reporting indicator results in a visually appealing way can aid with understanding. The *EISD* can serve as an appropriate starting basket of indicators for any context. However, to increase the usefulness and policy relevance of the indicator set and take account of multiple viewpoints, stakeholders and experts could be engaged for the further refinement of the indicator set. The final set of indicators should represent all three dimensions of sustainable development; economic, social, and environmental, and consider the underlying issues of SED. It is valuable to examine the interconnections between issues and indicators for SED. A mixed approach of a thematic and systems framework seems to be a useful way to capture the multi-dimensional problem that SED is, although this requires further research. The analysis presented here, and the steps outlined can be used to form a comprehensive and robust indicator set for SED within any context.

Giving the responsibility of reporting and maintaining the resulting indicators to one governmental body is advantageous. Indicators connected to the relevant policy goals, both national and international, are valuable to measure progress towards those targets and ensure policy relevance. For instance, the indicators could be connected with the SDGs as energy relates to some extent to all 17 SDGs [31]. Additionally, the indicators could be connected to a country's particular SED goals. To further add relevance to the indicator set, the developers of the *EISD* recommend linking the indicators to dynamic models [20]. Thereby, the indicators are not limited to being backward-looking but can also be used to create scenarios, assess the potential implications of different policy actions, and identify development trends. Finally, as stated by Taylor et al. [66], it is good to keep in mind that "while goals and indicators can be very useful tools to support government policymaking and to assist the public in holding those governments to account, they are just that — tools — and their blind pursuit should not become an end in itself."

6. Conclusion

This study aimed to assess the suitability of existing indicator sets for SED. For this purpose, the study identified established indicator sets for SED, and developed indicator set assessment criteria based on characteristics found to make an indicator set comprehensive and robust. Multiple different SED indicator sets exist for various purposes and of variable quality. All but one of the 57 indicator sets were found to be lacking in some aspect. A common issue was a lack of transparency in both indicator selection and application. Most indicator sets were developed through some conceptual framework; although, further analysis could be done of what framework works best for a SED indicator set. The indicator sets often presented an imbalanced picture of SED with emphasis on the economic impacts of energy developments and less or no recognition of environmental or social ones. Some considered linkages and interrelations of indicators; however, further attention could be given to how this can be done well. Stakeholder engagement in decision-making and the development of indicators to ensure policy relevance and stakeholder acceptance is increasingly more recognized. Nevertheless, most indicator sets were developed without any stakeholder input whatsoever.

The only indicator set that met all criteria and, therefore, could be considered comprehensive and robust were the *Energy Indicators for Sustainable Development*. The *EISD* were transparent and clear, based within a conceptual framework, representative of SED, considered interconnections within the set, and based on stakeholder input. Yet, this set is used by few, and the use of other, lower scoring, indicator sets is much more widespread. Several flaws to the *EISD* were identified that require further improvement to the set. No attention is given to the communication of the indicators and their results, which may be the reason for its lack of use. Effective communication of indicators can influence interpretability and aid with understanding. The *EISD* have been criticized for capturing an imbalanced picture of SED, where economic implications are overemphasized and social issues undervalued. Additionally, no institutional indicators measuring vital aspects of SED, such as the effectiveness of policies and action plans, are included. Clear guidance on how to implement the set at the national level, including giving ownership of the indicators to the relevant agency, seems to be missing as well. Data requirements of the *EISD* have been found burdensome, which can make the indicator set less attractive and useful to stakeholders and decision-makers.

It is valuable to keep in mind what the purpose of an indicator set is. If the indicator set is supposed to measure progress towards SED and inform decision-making and policy development at the national level, the indicator set must reflect the national context and goals set in the country as revealed through stakeholder engagement. The *EISD* could be used as a comprehensive and robust initial pool of indicators for further development, not as a finalized set of indicators. It is beneficial to keep the identified flaws of the *EISDs* in mind and tackle them when the set is updated. In this study, future research guidelines on the development of indicators for SED are laid out. A logical next step would be to develop an indicator set based on these guidelines in addition to a more in-depth analysis of high scoring indicator sets. This more thorough analysis would include, for instance, an assessment of how representative an indicator set is of SED in a particular context and how effectively results are communicated.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Identified indicator sets for sustainable energy development

Category	Name of the indicator set	Authors	Paper	Year	Scope	# of indicators	Aggregation	Conceptual framework
Sustainable energy development	Sustainable Energy Development Index (SEDI)	Iddrisu, Bhattacharyya	Sustainable Energy Development Index: A multi-dimensional indicator for measuring sustainable energy development [26]	2015	National (for country comparisons)	11	Yes	Causal chain (Process cycle) & issue-or theme-based
	Indicators for assessing sustainable energy development scenarios	Papadaki, Siskos et al.	Assessing different scenarios for sustainable energy supply in the island of Crete [67]	2001	National (not for country comparisons)	11	No	Issue- or theme-based
	Synthetic Index of Sustainable Energy Development (SISED)	García-Álvarez, Moreno, Soares	Analyzing the sustainable energy development in the EU-15 by an aggregated synthetic index [68]	2016	National (for country comparisons)	33	Yes	Issue- or theme-based
	Energy sustainability indicators	Latin American Energy Organization et al.	Energy and Sustainable Development in Latin America and the Caribbean: Approaches to energy policy [69]	1997	National (for country comparisons)	8	No	Issue- or theme-based
			Energy and Sustainable Development in Latin America and the Caribbean: Guide for Energy Policymaking [70]	2000				
		Sheinbaum-Pardo, Ruiz-Mendoza et al.	Mexican energy policy and sustainability indicators [71]	2012				
	Sustainable Energy Watch (SEW)	HELIO International	Sustainable Energy Watch (SEW) Indicator Selection and Rationale [56]	2000	National (for country comparisons)	10	No	Issue- or theme-based
		Spalding-Fecher	Indicators of sustainability for the energy sector: A South African case study [72]	2003				
		Hossain, Tamim	Energy and Sustainable Development in Bangladesh [73]	2006				
		Rezaei, Chaharsooghi, Abbaszadeh	The Role of Renewable Energies in Sustainable Development: Case Study Iran [74]	2013				
	Energy Architecture Performance Index	World Economic Forum	Global Energy Architecture Performance Index Report 2017 [58]	2017	National (for country comparisons)	18	Yes	Issue- or theme-based
			The Global Energy Architecture Performance Index Report 2017:					

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Category	Name of the indicator set	Authors	Paper	Year	Scope	# of indicators	Aggregation	Conceptual framework
			Methodological addendum [49]					
	Regulatory Indicators for Sustainable Energy (RISE)	World Bank, ESMAP, Sustainable Energy for All	RISE Readiness for Investment in Sustainable Energy - A tool for policymakers [75]	2014	National (for country comparisons)	27	Yes	Issue- or theme-based
		World Bank, ESMAP, Climate Investment Funds, Sustainable Energy for All	Regulatory indicators for sustainable energy - A global scorecard for Policy Makers [76]	2016				
			Policy Matters - Regulatory Indicators for Sustainable Energy [77]	2018				
	Energy indicators for sustainable development through policy	Hannan, Begum, Abdolrasol et al.	Review of baseline studies on energy policies and indicators in Malaysia for future sustainable energy development [78]	2018	National (not for country comparisons)	14	No	Issue- or theme-based
	Assessment Index (AI) (precursor for energy trilemma)	World Energy Council	World Energy and Climate Policy: 2009 Assessment [79]	2009	National (for country comparisons)	46	Yes	Issue- or theme-based
	Energy Sustainability Country Index (ESCI) (precursor for energy trilemma)	World Energy Council	Pursuing sustainability: 2010 Assessment of country energy and climate policies [80]	2010	National (for country comparisons)	21	Yes	Issue- or theme-based
	Energy Trilemma Index	World Energy Council	World Energy Trilemma Index 2018 [50]	2018	National (for country comparisons)	35	Yes	Issue- or theme-based
	Energy Development Index (EDI)	International Energy Agency	World Energy Outlook 2010 [81]	2010	National or regional (for comparison)	4	Yes	N/A
		Mandelli, Birgieri, Mattarolo, Colombo	Sustainable energy in Africa: A comprehensive data and policies review [82]	2014				
	Regional Sustainable Energy Development Evaluation Indicator System	Yu, Zhao, Chen	Construction of Regional Sustainable Energy Development Evaluation Indicator System [83]	2010	Regional (for comparison)	24	No	Causal chain (DSR) & Issue or theme-based
	Local energy sustainability indicators	Neves, Leal	An exploratory study on energy sustainability indicators for local energy planning [84]	2009	Local (for comparison)	18	No	Issue- or theme-based
			Energy sustainability indicators for local energy planning: Review of current practices and derivation of a new framework [55]	2010				
	Indicators for sustainable energy development in Chinese Villages	Mortimer, Grant	Evaluating the prospects for sustainable energy development in a sample of Chinese villages [60]	2008	Local (not for comparison)	2	No	N/A
	Energy Sustainability Index	Doukas et al.	Assessing energy sustainability of rural communities using principal component analysis [54]	2012	Rural (for comparison)	9	Yes	N/A
	Energy Sustainability Index (ESI)	Mainali, Pachauri et al.	Assessing rural energy sustainability in developing countries [45]	2014	Rural (for comparison)	13	Yes	Issue- or theme-based
	Urban Energy Sustainability Index (UESI)	Marquez-Ballesteros, Mora-López et al.	Measuring urban energy sustainability and its application to two Spanish cities: Malaga and Barcelona [59]	2019	Cities (for comparison)	12	Yes	Issue- or theme-based
	Sustainable energy indicators for cities	Zen, Lima, et al.	Sustainability, Energy and Development: A Proposal of Indicators [85]	2012	Cities (for comparison)	26	No	Issue- or theme-based
	Sustainability indicators for urban energy systems	Keirstead	Selecting sustainability indicators for urban energy systems [33]	2007	Cities (for comparison)	42	No	Systems dynamics & issue- or theme-based
EISD and indicator sets	Indicators for sustainable energy	IAEA, and IEA	Indicators for Sustainable Energy Development [28]	2002	National (not for country comparisons)	41	No	Causal chain (DSR) & issue or theme-based

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Category	Name of the indicator set	Authors	Paper	Year	Scope	# of indicators	Aggregation	Conceptual framework
based on EISDs	development (ISED) (precursor for EISD)							
	Application of ISEDs in Brazil	Schaeffer, Szklo et al.	Indicators for sustainable energy development: Brazil's case study [86]	2005	National (not for country comparisons)	53	No	Causal chain (DSR) & issue or theme-based
	Application of ISEDs in Cuba	Pérez, López, Berdellans	Evaluation of energy policy in Cuba using ISED [87]	2005	National (not for country comparisons)	35	No	Causal chain (DSR) & issue or theme-based
	Application of ISEDs in Russia	Aslanyan, Molodtsov, Iakobtchouk	Monitoring the sustainability of Russia's energy development [88]	2005	National (not for country comparisons)	15	No	Causal chain (DSR) & issue or theme-based
	Application of ISEDs in Lithuania	Streimikiene	Indicators for sustainable energy development in Lithuania [89]	2005	National (not for country comparisons)	12	No	Causal chain (DSR) & issue or theme-based
	Application of ISEDs in Thailand	Todoc, Todoc, Lefevre	Indicators for sustainable energy development in Thailand [90]	2005	National (not for country comparisons)	36	No	Causal chain (DSR) & issue or theme-based
	Energy indicators for sustainable development (EISD)	IAEA, UN DESA, IEA, Eurostat, and EEA	Energy Indicators for Sustainable Development: Guidelines and Methodologies [4]	2005	National (not for country comparisons)	30	No	Issue- or theme-based
		Vera, Langlois, et al.	Indicators for sustainable energy development: An initiative by the International Atomic Energy Agency [47]	2005				
		Vera, and Abdalla	Energy Indicators to Assess Sustainable Development at the National Level: Acting on the Johannesburg Plan of Implementation [91]	2006				
		Vera, and Langlois	Energy indicators for sustainable development [13]	2007				
	Application of EISDs in the Baltic States	Streimikiene, Ciegis, and Grundey	Energy indicators for sustainable development in Baltic States [51]	2007	National (not for country comparisons)	12	No	Issue- or theme-based
	Application of EISDs in Brazil	Pereira Jr. Soares et al.	Energy in Brazil: Toward sustainable development? [92]	2008	National (not for country comparisons)	30	No	Issue- or theme-based
	Application of EISDs in Thailand	Shoram, Hirunlabh et al.	Critical analysis of Thailand's past energy policies towards the development of a new energy policy [93]	2018	National (not for country comparisons)	3	No	Issue- or theme-based
	Application of EISDs in Africa	Mandelli, Birgieri, Mattarolo, Colombo	Sustainable energy in Africa: A comprehensive data and policies review [82]	2014	National (not for country comparisons)	17	No	Issue- or theme-based
	Energy indicators in the EU sustainable development strategy	Streimikiene, Ciegis	Framework of indicators for monitoring implementation of interrelated targets of the EU Sustainable Development Strategy [94]	2007	National (for country comparisons)	12	No	Issue- or theme-based
	Sustainable energy development indicators for EU energy policy 1	Streimikiene, Sivickas	The EU sustainable energy policy indicators framework [95]	2008	National (for country comparisons)	15	No	Issue- or theme-based
	Sustainable energy development indicators for EU energy policy 2	Streimikiene	Impact of environmental taxes on sustainable energy development in Baltic States, Czech Republic and Slovakia [96]	2015	National (for country comparisons)	7	No	Issue- or theme-based
	Sustainable energy development indicators for EU energy policy 3	Siksnelyte, Zavadskas, Bausys, Streimikiene	Implementation of EU energy policy priorities in the Baltic Sea Region countries: Sustainability assessment based on neutrosophic MULTIMOORA method [97]	2019	National (for country comparisons)	17	No	Issue- or theme-based
	Sustainable energy index	Zhou, Ang, and Poh	A mathematical programming approach to constructing composite indicators [98]	2007	National (for country comparisons)	3	Yes	Issue- or theme-based
		Wang	A generalized MCDA–DEA (multi-criterion decision analysis–data envelopment analysis) approach to construct slacks-based composite indicator [99]	2015				

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Category	Name of the indicator set	Authors	Paper	Year	Scope	# of indicators	Aggregation	Conceptual framework
		Wang, Zhou, and Wang	Constructing slacks-based composite indicator of sustainable energy development for China: A meta-frontier nonparametric approach [100]	2016				
	Aggregated energy security performance indicator (AESPI)	Martchamadol, Kumar	An aggregated energy security performance indicator [46]	2013	National (for country comparisons)	25	Yes	Issue- or theme-based
	Indicators for sustainable energy development (PASHMINA)	Kettner, Kletzan-Slamanig et al.	PASHMINA – Paradigm Shifts Modelling and Innovative Approaches Development. Indicators for Sustainable Energy Development - The PASHMINA Approach [101]	2012	Energy system (for comparison)	40	No	Systems dynamics & issue- or theme-based
	Composite index for sustainable energy development				Energy system (for comparison)	40	Yes	Systems dynamics & issue- or theme-based
	Sustainability assessment indicators for energy systems	Zolfani, Saparauskas	New application of SWARA method in prioritizing sustainability assessment indicators of energy system [102]	2013	Energy system (for comparison)	14	Yes	Issue- or theme-based
	Indicator for Sustainable Energy Development for Austria (ISED-AT)	Kettner, Kletzan-Slamanig, and Köppl	Indicators for sustainable energy development for Austria: Residential Buildings and Electricity and Heat Supply [32]	2015	Residential sector (not for comparison)	71	No	Systems dynamics & issue- or theme-based
	Sustainable energy development index for Austria				Residential sector (not for comparison)	19	Yes	Systems dynamics & issue- or theme-based
Energy Security	Supply-demand S/D index	Scheepers et al.	EU standards for energy security of supply- updates on the crisis capability index and the supply/demand index quantification for EU-27 [103]	2007	National (for country comparisons)	20	Yes	Systems dynamics
	Crisis capability index				National (for country comparisons)	66	Yes	Issue- or theme-based
	Energy Security Indicators	Asia Pacific Energy Research Centre	A quest for Energy Security in the 21st Century Resources and, Constraints [61]	2007	National (for country comparisons)	5	No	N/A
	Energy Security Matrix	Kisel, Hamburg, et al.	Concept for Energy Security Matrix [104]	2016	National (for country comparisons)	27	No	Issue- or theme-based
	Energy Security Assessment Model	Murakami, Motokura, Kutani - Institute of Energy Economics, Japan (IEEJ)	An analysis of major countries' energy security policies and conditions – quantitative assessment of energy security policies [105]	2011	National (for country comparisons)	14	No	Causal chain (Supply chain)
	Energy Affinity Index	Marín Quemada and Muños Delgado	Affinity and Rivalry: Energy Relations of the EU [106]	2011	National (for country comparisons)	5	Yes	N/A
	The U.S. Energy Security Risk (Index)	Global Energy Institute - U.S. Chamber of Commerce	Index of U.S. Energy Security Risk: Addressing America's Vulnerabilities in A Global Energy Market - 2018 edition [107]	2018	National (not for country comparisons)	37	Yes	Issue- or theme-based
	International Index of Energy Security Risk		International Index of Energy Security Risk: Assessing Risk in A Global Energy Market - 2018 edition [108]	2018	National (for country comparisons)	29	Yes	Issue- or theme-based
	Risky External Energy Supply (REES) index	Le Coq and Paltseva	Measuring the security of external energy supply in the European Union [109]	2009	National (for country comparisons)	7	No	N/A
	Electricity generation security of supply indicators	Portugal-Pereira and Esteban	Implications of paradigm shift in Japan's electricity security of supply: A multi-dimensional indicator assessment [110]	2014	National (not for country comparisons)	9	No	Issue- or theme-based
	Simple and Complex Energy Security Indicators and Metrics	Sovacool and Mukherjee	Conceptualizing and measuring energy security: A synthesized approach [111]	2011	Variable (for comparison)	372	No	Issue- or theme-based
	Energy security index 1	Sovacool, Mukherjee et al.	Evaluating energy security performance from 1990 to	2011	National (for country comparisons)	20	Yes	Issue- or theme-based

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Category	Name of the indicator set	Authors	Paper	Year	Scope	# of indicators	Aggregation	Conceptual framework
			2010 for eighteen countries [57]					
	Energy security index 2	Sovacool	An international assessment of energy security performance [112]	2013	National (for country comparisons)	20	Yes	Issue- or theme-based
	Indicators of long-term energy supply security	Jansen et al.	Designing indicators of long-term energy supply security [62]	2004	National or regional (for comparison)	4	No	N/A
	Energy Security Indicators	Asian Institute of Technology, Global Network on Energy for Sustainable Development (GNESD)	Energy Security in Thailand [113]	2010	National and household level (not for comparison)	9	No	N/A
Energy indicators in general SD indicator sets	Indicators for Sustainable Development Goal 7	United Nations	A/RES/71/313 Resolution adopted by the General Assembly on Work of the Statistical Commission pertaining to the 2030 Agenda for Sustainable Development [114]	2017	National, regional or local (for comparison)	6	No	Issue- or theme-based
		UN DESA Statistics Division	Metadata for each indicator [115]	2016				
	EU sustainable development indicators - energy	Streimikiene, Mikalauskiene, Mikalauskas	Comparative assessment of sustainable energy development in the Czech Republic, Lithuania and Slovakia [116]	2016	National (for country comparisons)	4	No	Issue- or theme-based
	Energy indicators in Taiwan's Sustainable Development Indicators (TSDI)	Tsai	Energy sustainability from analysis of sustainable development indicators: A case study of Taiwan [117]	2010	National (not for country comparisons)	2	No	Causal chain (PSR)
	Energy indicators from the German sustainability strategy	German Federal Government	Perspectives for Germany - Our strategy for sustainable development [118]	2002	National (not for country comparisons)	15	No	N/A
	Index of Sustainable Energy Development (ISUD)	Schlör, Fischer, Hake	Methods of measuring sustainable development of the German energy sector [119]	2013	Energy system (not for comparison)	15	Yes	Issue- or theme-based
	Standardized sustainability energy index (SSEI)				Energy system (not for comparison)	15	Yes	Issue- or theme-based
Other	Occupational Entropy and Mind Indicators for Sustainable Energy Development	Pop-Jordanov, Markovska, et al.	Occupational Entropy and Mind Indicators for Sustainable Energy Development [53]	2004	National (for country comparisons)	3	No	Causal chain (PSR)
	Renewable Energy Country Attractiveness Index (RECAI)	Ernst & Young	recai May 2018 - From black gold to green power [120] Ernst & Young website – RECAI methodology [48]	2018 2019	National (for country comparisons)	15	No	Issue- or theme-based
	Renewable Energy Sustainability Index	Cirstea, Moldovan-Teselios et al.	Evaluating Renewable Energy Sustainability by Composite Index [121]	2018	National (for country comparisons)	23	Yes	Issue- or theme-based
	Renewable Energy Responsible Investment Index (RERII)	Lee, Zhong	Construction of a responsible investment composite index for renewable energy industry [122]	2015	National (for country comparisons)	17	Yes	Issue- or theme-based
	Multi-dimensional Energy Poverty Index (MEPI)	Nussbaumer, Bazilian, and Modi	Measuring Energy Poverty: Focusing on What Matters [52]	2012	Households (for comparison)	6	Yes	Issue- or theme-based
	Sustainable Mobility Indicators	Nicolas, Pochet et al.	Towards sustainable mobility indicators: application to the Lyons conurbation [123]	2003	Urban areas (for comparison)	22	No	Issue- or theme-based

Appendix B. Analysis of indicator sets for energy development

Category	Name of indicator set	Indicator set assessment criteria						Total score
		Transparency of indicator selection	Transparency of indicator application	Conceptual framework	Representative	Linkages	Stakeholder engagement	
		1/2 - Individual indicators (a) 1/2 - Methodology for indicator selection (b) 0 and no further analysis - Neither of the above	1/2 - Methodology for indicator application (a) 1/2 - Data sources (b) 0 - Unclear how to apply indicators	1 - Framework used 0 - No apparent framework used	1/3 - Economic (a) 1/3 - Social (b) 1/3 - Environmental (c) 0 - None of the above	1 - Linkages considered 0 - Not considered	1 - Stakeholders or experts engaged 0 - No, not clear if was done	
Sustainable energy development	Sustainable Energy Development Index (SEDI) [26]	a, b = 1	a, b = 1	1	a, b, c = 1	1	0	**5**
	Indicators for assessing sustainable energy development scenarios [67]	a = 1/2	0	1	a, b, c = 1	0	0	**2,5**
	Synthetic Index of Sustainable Energy Development (SISED) [68]	a = 1/2	a, b = 1	1	a, c = 2/3	1	0	**3,16**
	Energy sustainability indicators [69–71]	a = 1/2	0	1	a, b, c = 1	1	0	**3,5**
	Sustainable Energy Watch (SEW) [56,72–74]	a = 1/2	a = 1/2	1	a, b, c = 1	1	0	**4**
	Energy Architecture Performance Index [49,58]	a = 1/2	a, b = 1	1	a, b, c = 1	1	1	**5,5**
	Regulatory Indicators for Sustainable Energy (RISE) [75–77]	a, b = 1	a, b = 1	1	a, b, c = 1	0	1	**5**
	Energy indicators for sustainable development through policy [78]	a = 1/2	0	1	a, b, c = 1	0	0	**2,5**
	Assessment Index (AI) (precursor for energy trilemma) [79]	a = 1/2	b = 1/2	1	a, b, c = 1	1	0	**4**
	Energy Sustainability Country Index (ESCI) (precursor for energy trilemma) [80]	a = 1/2	0	1	a, b, c = 1	1	0	**3,5**
	Energy Trilemma Index [50]	a = 1/2	0	1	a, b, c = 1	1	0	**3,5**
	Energy Development Index (EDI) [81,82]	a = 1/2	a, b = 1	0	a, b, c = 1	0	0	**2,5**
	Regional Sustainable Energy Development Evaluation Indicator System [83]	a = 1/2	0	1	a, b, c = 1	1	0	**3,5**
	Local energy sustainability indicators [55,84]	a, b = 1	0	1	a, b, c = 1	1	1	**5**
	Indicators for sustainable energy development in Chinese Villages [60]	a = 1/2	b = 1/2	0	a, b = 2/3	0	0	**1,66**
	Energy Sustainability Index [54]	a, b = 1	a = 1/2	0	a, c = 2/3	1	1	**4,16**
	Energy Sustainability Index (ESI) [45]	a, b = 1	a, b = 1	1	a, b, c = 1	1	0	**5**
	Urban Energy Sustainability Index (UESI) [59]	a, b = 1	0	1	a, c = 2/3	0	0	**2,66**
	Sustainable energy indicators for cities [85]	a = 1/2	0	1	a, b, c = 1	0	1	**3,5**
	Sustainability indicators for urban energy systems [33]	a, b = 1	0	1	a, b, c = 1	1	1	**5**
EISD and indicator sets based on EISDs	Indicators for sustainable energy development (ISED) (precursor for EISD) [28]	a = 1/2	0	1	a, b, c = 1	1	1	**4,5**
	Application of ISEDs in Brazil [86]	a = 1/2	b = 1/2	1	a, b, c = 1	1	1	**5**
	Application of ISEDs in Cuba [87]	a = 1/2	b = 1/2	1	a, b, c = 1	1	1	**5**

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Category	Name of indicator set	Indicator set assessment criteria: Transparency of indicator selection	Transparency of indicator application	Conceptual framework	Representative	Linkages	Stakeholder engagement	Total score
		1/2 - Individual indicators (a) 1/2 - Methodology for indicator selection (b) 0 and no further analysis - Neither of the above	1/2 - Methodology for indicator application (a) 1/2 - Data sources (b) 0 - Unclear how to apply indicators	1 - Framework used 0 - No apparent framework used	1/3 - Economic (a) 1/3 - Social (b) 1/3 - Environmental (c) 0 - None of the above	1 - Linkages considered 0 - Not considered	1 - Stakeholders or experts engaged 0 - No, not clear if was done	
	Application of ISEDs in Russia [88]	a = 1/2	0	1	a, c = 2/3	1	1	**4,16**
	Application of ISEDs in Lithuania [89]	a = 1/2	b = 1/2	1	a, b, c = 1	1	1	**5**
	Application of ISEDs in Thailand [90]	a = 1/2	b = 1/2	1	a, b, c = 1	1	1	**5**
	Energy indicators for sustainable development (EISD) [4,13,47,91]	a, b = 1	a, b = 1	1	a, b, c = 1	1	1	**6**
	Application of EISDs in Baltic States [51]	a = 1/2	a = 1/2	1	a, c = 2/3	1	0	**3,66**
	Application of EISDs in Brazil [92]	a = 1/2	b = 1/2	1	a, b, c = 1	1	0	**4**
	Application of EISDs in Thailand [93]	a = 1/2	0	1	a, b, c = 1	0	1	**3,5**
	Application of EISDs in Africa [82]	a = 1/2	a = 1/2	1	a, b, c = 1	1	0	**4**
	Energy indicators in the EU sustainable development strategy [94]	a = 1/2	0	1	a, b, c = 1	1	0	**3,5**
	Sustainable energy development indicators for EU energy policy 1 [95]	a, b = 1	b = 1/2	1	a, c = 2/3	1	0	**4,16**
	Sustainable energy development indicators for EU energy policy 2 [96]	a, b = 1	b = 1/2	1	a, c = 2/3	1	0	**4,16**
	Sustainable energy development indicators for EU energy policy 3 [97]	a, b = 1	a, b = 1	1	a, b, c = 1	1	0	**5**
	Sustainable energy index [98–100]	a = 1/2	a, b = 1	1	a, c = 2/3	0	0	**3,16**
	Aggregated energy security performance indicator (AESPI) [46]	a, b = 1	a, b = 1	1	a, b, c = 1	1	0	**5**
	Indicators for sustainable energy development (PASHMINA) [101]	a = 1/2	0	1	a, b, c = 1	1	0	**3,5**
	Composite index for sustainable energy development [101]	a = 1/2	0	1	a, b, c = 1	1	0	**3,5**
	Sustainability assessment indicators for energy systems [102]	a = 1/2	0	1	a, b, c = 1	0	1	**2,5**
	Indicator for Sustainable Energy Development for Austria (ISED-AT) [32]	a = 1/2	b = 1/2	1	a, b, c = 1	1	0	**4**
	Sustainable energy development index for Austria [32]	a = 1/2	b = 1/2	1	a, b, c = 1	1	0	**4**
Energy Security	Supply-demand S/D index [103]	a = 1/2	b = 1/2	1	a, c = 2/3	1	0	**3,66**
	Crisis capability index [103]	a = 1/2	0	1	a = 1/3	0	0	**1,83**
	Energy Security Indicators [61]	a = 1/2	a = 1/2	0	a, c = 2/3	0	0	**1,66**
	Energy Security Matrix [104]	a = 1/2	0	1	a, b = 2/3	0	0	**2,16**
	Energy Security Assessment Model [105]	a = 1/2	a, b = 1	1	a = 1/3	1	0	**3,83**
	Energy Affinity Index [106]	a = 1/2	a, b = 1	0	a = 1/3	0	0	**1,83**
	The U.S. Energy Security Risk (Index) [107]	a, b = 1	b = 1/2	1	a, b, c = 1	0	0	**3,5**
		a = 1/2	b = 1/2	1	a, c = 2/3	0	0	**2,66**

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Category	Name of indicator set	Indicator set assessment criteria: Transparency of indicator selection	Transparency of indicator application	Conceptual framework	Representative	Linkages	Stakeholder engagement	Total score
		1/2 - Individual indicators (a) 1/2 - Methodology for indicator selection (b) 0 and no further analysis - Neither of the above	1/2 - Methodology for indicator application (a) 1/2 - Data sources (b) 0 - Unclear how to apply indicators	1 - Framework used 0 - No apparent framework used	1/3 - Economic (a) 1/3 - Social (b) 1/3 - Environmental (c) 0 - None of the above	1 - Linkages considered 0 - Not considered	1 - Stakeholders or experts engaged 0 - No, not clear if was done	
	International Index of Energy Security Risk [108]							
	Risky External Energy Supply (REES) index [109]	a, b = 1	a, b = 1	0	a = 1/3	0	0	**2,33**
	Electricity generation security of supply indicators [110]	a, b = 1	a = 1/2	1	a, c = 2/3	0	0	**3,16**
	Simple and Complex Energy Security Indicators and Metrics [111]	a, b = 1	0	1	a, b, c = 1	0	1	**4**
	Energy security index 1 [57]	a, b = 1	a, b = 1	1	a, b, c = 1	0	1	**5**
	Energy security index 2 [112]	a, b = 1	a = 1/2	1	a, b, c = 1	0	1	**4,5**
	Indicators of long-term energy supply security [62]	a = 1/2	a = 1/2	0	a, b = 2/3	0	0	**1,66**
	Energy Security Indicators [113]	a = 1/2	a, b = 1	0	a, b, c = 1	0	0	**2,5**
Energy indicators in general SD indicator sets	Indicators for Sustainable Development Goal 7 [114]	a = 1/2	a, b = 1	1	a, b, c = 1	0	1	**5**
	EU sustainable development indicators – energy [116]	a = 1/2	a, b = 1	1	a, c = 2/3	0	0	**3,16**
	Energy indicators in Taiwan's Sustainable Development Indicators (TSDI) [117]	a = 1/2	a, b = 1	1	a, c = 2/3	1	0	**4,16**
	Energy indicators from the German sustainability strategy [118]	a = 1/2	b = 1/2	0	a, b, c = 1	1	1	**4**
	Index of Sustainable Energy Development (ISUD) [119]	a = 1/2	0	1	a, b, c = 1	1	0	**3,5**
	Standardized sustainability energy index (SSEI) [119]	a = 1/2	0	1	a, b, c = 1	1	0	**3,5**
Other	Occupational Entropy and Mind Indicators for Sustainable Energy Development [53]	a = 1/2	0	1	b = 1/3	1	0	**2,83**
	Renewable Energy Country Attractiveness Index [120]	a = 1/2	0	1	a = 1/3	0	0	**1,83**
	Renewable Energy Sustainability Index [121]	a, b = 1	b = 1/2	1	a, b, c = 1	1	0	**4,5**
	Renewable Energy Responsible Investment Index (RERII) [122]	a, b = 1	b = 1/2	1	a, b, c = 1	1	0	**4,5**
	Multidimensional Energy Poverty Index (MEPI) [52]	a, b = 1	a, b = 1	1	b = 1/3	0	0	**3,33**
	Sustainable Mobility Indicators [123]	a = 1/2	a, b = 1	1	a, b, c = 1	0	0	**3,5**

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Paper III: It Is Best to Ask: Designing A Stakeholder-Centric Approach to Selecting Sustainable Energy Development Indicators

It Is Best to Ask: Designing a Stakeholder-Centric Approach to Selecting Sustainable Energy Development Indicators

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Abstract

Sustainable energy development is a complex and multi-dimensional concept that is integral to sustainable development. This paper offers an approach to selecting comprehensive and robust indicators to monitor progress towards this international policy objective. Numerous weaknesses in current indicator sets for sustainable energy development have been identified, e.g., lack of transparency, imbalanced representation of the pillars of sustainable development, and absence of stakeholder engagement during development. Currently, no standardized approach to indicator selection exists. In this paper, an iterative process to indicator selection for sustainable energy development is presented. This process is rooted in stakeholder engagement to ensure a representative indicator set and reduce the potential for bias in indicator selection. A diverse and balanced group of stakeholders should be engaged through interviews and a Delphi survey to capture stakeholders' views of sustainable energy development within a particular setting. Based on stakeholder input, the main themes of sustainable energy development are identified, which corresponds to a thematic conceptual framework for indicator development. These results are connected to established indicators to produce a preliminary set of indicators. Subsequently, a set of indicator assessment criteria are applied to assess the quality of indicators and eliminate overly correlated indicators. In the end, a comprehensive and robust set of indicators for sustainable energy development is produced that reflects the context in question. To ensure the usefulness of the indicator set to decision-makers and stakeholders, information such as the necessary formulas and data sources should be provided.

Keywords

Sustainable energy development; Sustainability indicator; Energy indicator; Indicator development; Stakeholder engagement; Interdisciplinary research

Highlights

- Robust indicators are needed to track progress towards sustainable energy development
- Most current indicators for sustainable energy development are found lacking
- No standardized approach to indicator selection exists
- A stakeholder engagement approach to indicator selection is presented
- Transparency in indicator selection is vital to ensure their usefulness

1. Introduction

In 2000, a new energy paradigm was introduced, where the economic, social, and environmental impacts of energy development were considered [1]. This paradigm was called sustainable energy development (SED) and highlighted energy's role in achieving sustainable development. The necessity of energy for sustainable development was further recognized with the introduction of the UN's Sustainable Development Goal (SDG) 7 on affordable and clean energy [2]. In an increasingly energy-intensive world with depleting fossil fuels and increasing environmental pressures, SED's importance is evident. This development involves improving access to modern energy services to advance well-being [3]. One of the main challenges of SED is to improve access and affordability while ensuring environmental sustainability and staying within "the carrying capacity of ecosystems" [1]. Currently, SED is viewed as a cross-cutting policy objective connected to some of the major social, economic, and environmental challenges the world is facing. Similar to sustainable development, SED is a complex and inherently vague concept [4]. Therefore, a clearer framework for what SED means is needed and how progress towards it can be measured.

Energy systems vary from one to another due to factors such as geographical location, availability of natural resources, and level of industrialization [5]. As a result, challenges on the SED path and actions for a sustainable energy future can differ significantly between energy systems. Therefore, context-specific analysis of SED is appropriate [6,7]. Stakeholder engagement can be beneficial to understand better what sustainability concepts entail within a particular setting. Robinson recommends a discussion with the relevant stakeholders and communities to identify what a desirable and sustainable future could involve [4]. National priorities for energy development can be identified through context-specific analysis with stakeholder engagement and, thus, inform decision-making and policy development [8].

Tools to inform actions and monitor progress towards a desirable and sustainable energy future are valuable [3]. Sustainability indicators have long been used for this purpose. The usefulness and necessity of indicators to inform decision making and raise awareness were highlighted in the UN's Agenda 21 in 1992, which led to a substantial push for new indicators in the following years [1,9]. Despite this, there is no standardized approach to selecting sustainability indicators [10]. Numerous efforts have been made to develop indicators that measure one or more aspects of SED [1,11]. Many of these have been criticized for limitations, such as lack of transparency and presenting an imbalanced picture of SED [6,11]. Some have argued that a context-specific set of indicators for SED, reflecting the relevant challenges and national priorities, is necessary for it to be useful to decision-making and policy development [3,6,11]. Therefore, stakeholder engagement can be beneficial during indicator development to capture what a sustainability concept, such as SED, involves within a particular setting [8]. Decision-makers have started to recognize the weight of stakeholder engagement and public participation for effective decision making and to increase public acceptance [12]. Nevertheless, it is not common practice to formally engage stakeholders during indicator development [11].

In this paper, a new methodological approach to indicator development is proposed based on a theoretical study of current methods. Stakeholder engagement is at the heart of this process, where stakeholder input provides a base for indicator selection. It is possible to capture a comprehensive and robust picture of what SED might entail within a particular setting by engaging stakeholders. Thereby, a context-specific set of indicators can be selected that reflects the relevant SED challenges and opportunities. An indicator set for SED can be produced through further refinement and comparison with the literature and established indicator sets. In the proposed methodological approach, an emphasis is placed on transparency to ensure usefulness and validity.

The objectives of this paper are twofold;

1) present an iterative approach to indicator selection based on stakeholder engagement
2) analyze how the proposed indicator selection process enhances established methodology

The paper is structured as follows: Section 2 briefly reviews the concept of sustainable energy development. The methodology of the literature review of existing indicators for SED is described in the third section. The results of that review and a proposed methodology for indicator development is presented in section 4. The value of this proposed approach is analyzed further in section 5. Finally, the paper is concluded in section 6, where the implications of this study and the next steps are presented.

2. Background

2.1 Sustainable energy development

The role of energy systems is to improve human well-being and raise living standards by providing modern energy services that advance social and economic development [1]. One of the most critical challenges facing the world is how to deliver energy services to all while minimizing the related environmental and health costs [1]. In general, sustainable energy development aims to address this challenge; advance sustainable development while minimizing negative environmental, social, and economic impacts [13]. To address that challenge, the current energy system, both on the supply and demand side, needs to be transformed [14]. The role of energy in furthering sustainable development was highlighted with the introduction of the UN's SDG 7: "Ensure access to affordable, reliable, sustainable and modern energy for all" [2]. SED is a complex and multi-dimensional concept with the ultimate aim of a sustainable energy future. However, what lies on the path towards such a future can vary based on context; for instance, the energy-related challenges facing developing countries compared to developed ones can differ significantly [6,8]. Some argue that SED and other sustainability concepts can be viewed as “essentially contested concepts”, as their interpretations can vary and they are products of “social, historical, and cultural constructs” [15,16]. Similarly, Heaslip and Fahy [17] state that “communities’ perceptions and understandings of energy are complex and place-based and situated in cultural and political contexts.”

Gunnarsdóttir et al. analyzed the concept of SED and presented four common interrelated themes; sustainable energy supply, energy security, sustainable energy consumption, and access to affordable modern energy services [13]. According to their analysis, the overarching goal of SED is to promote sustainable development. To do so, everyone should have access to modern energy services at an affordable price. These energy services have to be secure and reliable for them to advance social and economic development. In 2018, 789 million people did not have access to electricity, and 2.8 billion did not have access to clean cooking [18]. Even though these numbers have improved in recent years, social inequality regarding energy access is evident. To ensure environmental sustainability, a transition towards a sustainable energy supply with increased utilization of renewable energy sources and environmentally benign technologies is necessary, as highlighted by the second sub-goal of SDG7. For this to be feasible, these technologies have to become economically viable, which can be encouraged through, for example, innovative financial schemes, energy pricing reflecting external costs, and increased support for research and development [19]. The importance of international collaboration and financial support of clean and renewable energy, particularly in developing countries, is highlighted by one of SDG 7's sub-goals [2]. For SED to be realized, current consumption patterns need to change and become more sustainable through, for instance, increased energy efficiency and raised awareness of the negative impacts of energy production and consumption [11]. In recent years, global primary energy intensity has fallen to about 5.0 MJ/USD in 2017, indicating improved energy efficiency [18]. Nonetheless, a significantly faster improvement rate will be required to meet the goal of doubling the global rate of improvement in energy efficiency laid out in the 2030 Agenda for Sustainable Development [2,18]. Everyone needs to take action to push for more sustainable energy systems [13].

Multiple attempts have been made to measure SED progress through metrics and sustainability indicators that vary both in purpose and quality [5,6,11]. Sustainability indicators can serve an essential role in assessing a system's current status and monitoring progress towards a goal. Thereby, the indicators can inform decision-making and improve actions [10]. Indicators can be used to simplify complex concepts, such as SED, and communicate the critical underlying issues to policymakers and the public [8,20]. Additionally, complex interactions and key relationships within an energy system can be identified through the use of indicators [5]. Indicators measuring progress towards SED should take account of its complexities and underlying themes. One of the main challenges for the creation of appropriate SED indicators has been ambiguities in what the concept of SED encompasses, especially within the local context [5,6]. A situated analysis of the concept within a particular setting, especially when involving stakeholders, can further understanding and lead to a socially acceptable definition [7]. A context-specific set of indicators might be appropriate since the challenges and opportunities on the SED path can vary significantly between energy systems [21]. A more thorough review of existing indicators for SED and the desirable characteristics of such an indicator set is provided in section 4.

3. Methods

An essential first step when conducting research is to assess the current state of the field and build on existing knowledge. For this study, a review of existing SED indicators and the methods for their selection was thought necessary. Such a review was conducted by Gunnarsdóttir et al. in the paper *Review of indicators for sustainable energy development* [11]. This study and proposed approach to indicator selection primarily builds on the results of that review. Gunnarsdóttir et al. 's study involved a comprehensive literature review to identify existing SED indicator sets. A so-called SALSA framework was applied to ensure a systematic search and review of the literature, where steps of Search, Appraisal, Synthesis, and Analysis (SALSA) were taken and an additional step of snowballing [22,23]. This search led to the identification of 82 relevant publications that included 57 different indicator sets for SED.

Gunnarsdóttir et al. [11] developed a set of assessment criteria to enable comparative evaluation of the indicator sets. These criteria were based on existing guidelines and checklists for indicator development, particularly the Bellagio STAMP principles [24]. Generally, the criteria reflect characteristics or actions thought necessary to develop a comprehensive and robust indicator set. The six indicator set assessment criteria were the following: transparency of indicator selection, transparency of indicator application, conceptual framework, representative, linkages, and stakeholder engagement. Transparency was thought essential to justify both methodological choices and enable the use of the indicators. The use of a conceptual framework aids in selecting balanced and representative indicators and can improve their organization. A set of sustainability indicators can only be representative if it reflects all three dimensions of sustainability by including economic, social, and environmental indicators. It is important to assess linkages within an indicator set to consider dynamics within the indicator system and eliminate overly correlated indicators. Stakeholder engagement has been found beneficial to capture the relevant issues and develop a representative and comprehensive indicator set.

The results of Gunnarsdóttir et al. 's [11] study show that there is room for improvement regarding the development of indicators for SED. In their research, the necessary steps for developing comprehensive and robust indicators are described. Furthermore, the strengths and limitations of current indicators are identified. Therefore, it is appropriate to create a more suitable approach to indicator selection for SED that builds on these results. A more thorough analysis of Gunnarsdóttir et al. 's results and a new approach to indicator selection are provided in the fourth section of this paper.

4. Results

4.1 Review of indicators for sustainable energy development

The importance of transparency of both indicator selection and application was highlighted in Gunnarsdóttir et al. 's study [11]. An indicator set's credibility and clarity depend on how much information is provided on the indicators themselves, how they were selected, and how they should be applied [6]. A lack of transparency makes it difficult to replicate or use an indicator set and, thus, affects its usefulness [6,11]. For instance, indicators can be misused or misinterpreted without sufficient information and guidance on how they should be applied [24]. The fifth Bellagio STAMP principle revolves around transparency and underscores the necessity of making information and data accessible to ensure that the public understands the indicators and their methodology [24]. Gunnarsdóttir et al. [11] considered an indicator set transparent if their presentation included the underlying indicators of a set, the approach to indicator selection, the methodology for indicator application including the relevant formulas, and data sources. Their review showed that a lack of transparency in both indicator selection and application is common for existing SED indicator sets. For instance, no justifications were provided for the selection of the IAEA's Indicators for Sustainable Energy Development (ISED) or information on how they should be calculated in their original presentation [25]. However, a later version of these indicators, with the updated name of Energy Indicators for Sustainable Development (EISD), included a detailed description of how the indicators were selected and how they should be applied [3]. Transparency was a guiding light when developing the indicator selection approach presented in this study, as detailed in section 4.2. Therefore, arguments are provided for the methodological choices made for the approach, and an emphasis is placed on providing a detailed methodology for indicator application.

Often, conceptual frameworks are used when developing indicators to structure the problem in question [26]. Through a framework, it is possible to organize and make sense of complex issues such as SED [27,28]. These frameworks provide theoretical underpinnings and guide the way indicators are selected [26]. The application of a conceptual framework during indicator development is thought to increase the transparency of the process, minimize potential bias, and increase how representative indicators are of the problem [29]. Four main types of frameworks have been used in the development of SED indicators: causal chain, issue- or theme-based, system dynamics, or a mixed approach of frameworks [11]. These vary mainly in how they structure and interpret SED [11,30]. Some version of a conceptual framework, most often a thematic one, was used to develop almost all of the SED indicator sets assessed by Gunnarsdóttir et al. [11]. Their analysis showed that causal chain frameworks had been abandoned mostly for thematic or system dynamics frameworks. These are more flexible and can capture the complexities and interconnections within SED [11,31]. To use the same examples as above, the original ISED were developed through a causal chain approach, while a thematic framework was used in the development of the later and improved EISD [3,25].

Thematic frameworks are flexible in structure and can capture the multi-dimensional nature of SED [32]. Their main criticism is that inter-linkages or dynamic interactions of different issues or themes are not captured adequately, leading to the over-simplification of complex problems [33]. To tackle this limitation, the UN has emphasized the importance of considering linkages among themes and indicators when applying a thematic framework [3,32]. This recommendation, a thematic framework accompanied by the consideration of linkages, was incorporated into the approach presented below.

Gunnarsdóttir et al. 's [11] fifth assessment criterion emphasized the consideration of linkages within an indicator set. Thereby, the interactions among indicators or components of an energy system can be identified, and overly correlated indicators can be eliminated [11,24]. Similarly, the second Bellagio STAMP principle highlights an analysis of the "system as a whole and the interactions among its components" [24]. Ideally, indicators should be meaningful on their own and together with other indicators of the set [34]. According to Gunnardóttir et al. 's analysis [11], more than half of the SED indicator sets were thought to consider linkages to some extent. They also stated that a more thorough assessment is needed of how this should be done well [11]. Indicator sets developed through a causal chain or system dynamics frameworks were thought to consider linkages between indicators, such as the original ISED [25] and Keirstead's Sustainability indicators for urban energy systems [35]. Other indicator sets that were thought to consider linkages were those that explicitly stated they did (e.g., EISD [3]), evaluated the correlation of indicators to eliminate overly correlated indicators (e.g., Doukas et al. 's Energy Sustainability Index [36]), and analyzed trade-offs between indicators (e.g., HELIO International's Sustainable Energy Watch [37] and the WEC's Energy Trilemma Index [38]). The consideration of linkages among indicators is recommended in the sixth step of the proposed approach to indicator selection.

Sustainable energy development is a complex and multi-dimensional concept, as discussed in the background section above. In its simplest form, SED involves considering the impacts energy development has on society, economy, and environment [1]. An incomplete picture of SED is captured if one or more dimension of sustainability is not represented. Gunnarsdóttir et al. [11] assessed whether social, economic, and environmental indicators were included in the set to analyze how representative indicator sets were of SED. According to their analysis, about 2/3 of existing SED indicator sets had indicators representing all three dimensions, while the remaining third excluded one or more dimensions. The economic aspects of SED were considered by most. In contrast, the social aspects often were not accounted for adequately, e.g., García-Álvarex et al. 's Synthetic Index of Sustainable Energy Development (SISED) [39] and Doukas et al. 's Energy Sustainability Index [36]. Gunnarsdóttir et al. [11] state that a more thorough analysis could be carried out of how representative indicator sets are of SED, including assessing whether an indicator set adequately reflects the contexts where it is applied. While SED's ultimate goal remains the same, actions and challenges on the path towards a sustainable energy future can vary considerably between energy systems, as discussed in the introduction and background section. In his review of the World Bank’s Regulatory Indicators for

Sustainable Energy (RISE), Urpelainen [21] argues that “the World Bank should replace the pursuit of one-size-fits-all best practices and instead focus on generating knowledge about the contextual fit of different policy approaches.” Therefore, a context-specific set of indicators that reflects the relevant challenges and opportunities for SED within a particular setting would be valuable [11]. The proposed indicator selection approach aims to develop context-specific indicators to ensure their representativeness and usefulness to policymakers.

By involving stakeholders during indicator development, it is possible to get valuable insight into the sustainability goals and objectives of different stakeholders and capture a comprehensive and representative picture of the system or problem in question [4]. A discussion with those affected by or who can affect the system in question, i.e., stakeholders, can be particularly useful for analyzing abstract concepts such as SED, especially considering that SED's meaning can vary based on context [4,7,8]. Multiple different benefits of stakeholder engagement have been identified, for instance, building trust and acceptance, increasing comprehensiveness, reducing bias by considering numerous viewpoints, and increasing the relevance and applicability of research [12,40,41]. Shortall et al. argued that: "stakeholder engagement is important in developing tools for assessing sustainability since there tends to be an absence of scientific consensus on the components of sustainable development" [42]. Furthermore, Shortall et al. argued that stakeholders' sustainability goals should dictate what is measured and, thereby, what indicators are selected [43]. By basing indicator sets on stakeholder input, they should be acceptable and of interest to stakeholders, which, hopefully, increases their usefulness and application [11,34,44,45]. Sovacool also recognized the value of stakeholder engagement during indicator development as it enables an analysis of complex concepts concerning metrics, allows for a targeted discussion that can present "insightful knowledge," and leads to the collection of data more recent than can be found in the published literature [46,47].

Gunnarsdóttir et al. 's [11] review shows that the involvement of stakeholders during indicator development has not become standard practice. Stakeholders or experts were engaged in developing only 1/3 of existing SED indicator sets [11]. For instance, it is unclear whether stakeholders were involved in the development of, e.g., Iddrisu and Bhattacharyya’s Sustainable Energy Development Index [31], Global Energy Institute’s International Index of Energy Security Risk [48] and US Energy Security Risk [49], and Marquez-Ballesteros et al.’s Urban Energy Sustainability Index [50]. Nonetheless, stakeholder engagement is becoming more popular with increased recognition of its value [11]. Various approaches to stakeholder engagement during indicator development have been taken. For instance, Sovacool conducted semi-structured interviews, a survey, and a workshop when developing an Energy Security Index [51], experts and relevant stakeholders were interviewed during a review process of the Energy Architecture Performance Index [52,53], and the World Bank's Regulatory Indicators for Sustainable Energy (RISE) are based to some extent on interviews with experts and their answers to a questionnaire [54,55]. For further development of EISDs at the national level, stakeholder consultation is encouraged, although no particular approach to this consultation is prescribed [3]. An overview of which indicator sets did or did not involve stakeholders and whether they met the other assessment criteria described above can be seen in Gunnarsdottir et al. 's paper [11].

Before engaging with stakeholders, it is valuable to consider what strategy fits the purpose of the activity. Multiple different approaches exist for stakeholder engagement, and new methods are being continuously developed [41]. Generally, stakeholder engagement methods can be split into either participatory (two-way engagement) or informative (one-way) [41]. For the process presented here, a participatory approach is appropriate as the aim of the stakeholder engagement is to get an insight into what stakeholders believe SED entails. Three general approaches to participatory stakeholder engagement are identified from the literature on qualitative methodology and stakeholder engagement, as seen in Table 1. Mixed methods or a multi-method approach to stakeholder engagement appropriate, where one or more methods are chosen that complement each other [56–58]. A mixed-method approach is applied in this study's indicator selection approach to ensure comprehensive data collection.

Table 1
A general overview of approaches to participatory stakeholder engagement

Approach	Brief description	References
Individual interviews	One-on-one, often semi-structured interviews with open-ended questions that allow for an in-depth analysis of stakeholder views. Multiple interviews are required to capture the opinion of all stakeholder groups, which can be time-consuming and expensive.	[41,57]
Focus groups	The opinion of a diverse group of stakeholders is captured through open-ended questions asked in, for instance, focus groups, workshops, and advisory groups. These are often also semi-structured. Focus groups can lead to constructive discussions among stakeholders, albeit, generally, a less in-depth analysis of individual stakeholder opinion. Not an appropriate approach for topics that can be sensitive or personal.	[41,57,59,60]
Surveys and questionnaires	A more structured approach to stakeholder engagement, usually, with closed-ended questions that can be used to capture the opinion of many stakeholders. It can be more fitting in the later stages of a project, such as to validate the initial analysis, assess whether results are generalizable, and to quantify qualitative results. Often, a cost-effective approach.	[41,57]

According to Gunnarsdóttir et al. 's [11] analysis, the only indicator set that fulfilled all six assessment criteria were the *Energy Indicators for Sustainable Development* (EISD) [3]. The *EISDs* were thought to be "transparent and clear, based within a conceptual framework, representative of the problem in question, consider interconnections within the set, and based on stakeholder input" [11]. Despite being the highest-scoring SED indicator set, the EISD do not seem to be used by many. Gunnarsdóttir et al. [11] argued that the lack of consideration of how the indicators and their results should be communicated could explain its unpopularity. Effective communication can involve a visual presentation of indicators, storytelling, and transparency, improving the indicators usefulness and interpretability [28,32,34]. Furthermore, some flaws in the EISD were identified. These include overemphasizing the economic impacts of energy development while undervaluing social ones, demanding data requirements, and lacking institutional indicators [3,6,11,31,61]. The developers of the EISD emphasize that the indicators need to be "read in the context of each country's economy and energy resources" [3]. To an extent, the EISD set is not fully developed until it has been implemented at the country level to reflect country-specific conditions. A "national coordinating mechanism" is suggested to assess the circumstances and identify national priorities that make "use of the widest possible consultation and participation of all stakeholders involved" [3]. Gunnarsdóttir et al. [11] conclude their study with a similar recommendation stating that the EISD set should be used as an initial basket of indicators for further refinement through stakeholder engagement and critical analysis. This recommendation aligns well with the proposed indicator selection approach.

4.2 Overview of the indicator development process

The objective of this study is to present an improved approach to indicator development that builds on established methodology and is rooted in stakeholder engagement. Transparency and clarity of the proposed approach are emphasized as current SED indicators have been criticized for a lack thereof [6,11]. This indicator development process is based on stakeholder input to ensure the relevancy and usefulness of the indicators. Thus, the output of this process is a set of context-specific indicators for SED. Considering the characteristics and objectives within a particular setting during indicator development adds significant value to the indicator set and captures elements missed in global or national-level indices [62]. The main downside of context-specific indicators is that they do not necessarily allow for comparisons of country performances. However, according to van Zeij-Rozema et al., it is possible to compare different indicator sets, even if they are context-specific, when indicators are selected and developed through the same process [62]. Finally, even though the proposed approach is designed for SED indicators, it can be used to select indicators for other aspects of sustainable development and capture what abstract sustainability concepts entail within a particular setting.

The indicator development process presented here consists of seven main steps, as illustrated in Figure 1. The first step of the process involves engaging stakeholders through semi-structured interviews and focus groups to determine what SED involves in that context. In the second step, the interviews are analyzed according to established qualitative methodology to identify emerging themes, stakeholders' sustainability goals, and potential indicators. In the third step of the process, interviewees are engaged again through a Delphi survey to verify the identified results. In the fourth step, these verified results are presented as SED's main themes in the context, which corresponds to an issue- or theme-based conceptual framework. In the fifth step, results are connected to established indicators to produce a preliminary set of indicators. Pre-determined indicator assessment criteria are applied in the sixth step of the process to ensure the suitability and quality of indicators and eliminate unsuitable ones. This sixth step includes considering the interrelation of indicators and, thus, preventing overly correlated indicators. The seventh and final step involves presenting a finalized set of indicators with enough detail to ensure their usefulness and easy application. Therefore, a mixed-method approach is taken in this process where quantitative and qualitative methods are combined [58].

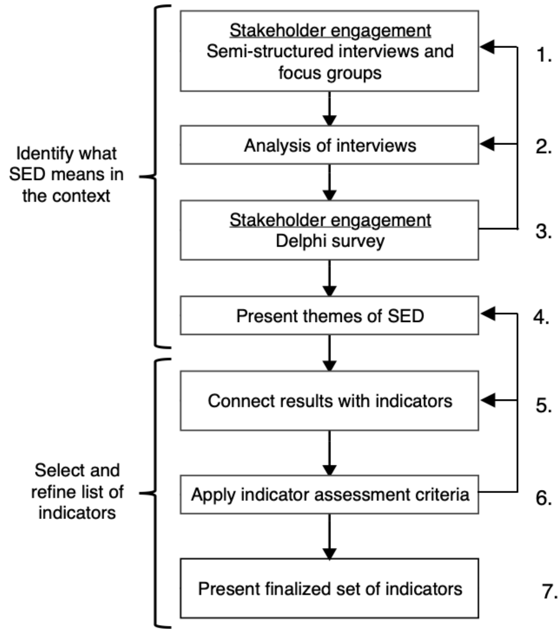

Figure 1: Diagram of the indicator development process and its seven main steps. Arrows shows the progression of the process and indicate that steps can revisited if necessary. Diagram generated by authors based on approach presented by Shortall et al. [43].

The purpose of the stakeholder engagement is to determine what sustainable energy development means to the different stakeholders and, thereby, what it entails in the context. Thus, the indicators can reflect the relevant issues. A combination of stakeholder engagement methods, i.e., semi-structured interviews, focus groups, and Delphi survey, is proposed to capture diverse viewpoints that can provide the most holistic and comprehensive picture of the energy system as possible. The aim is not to reach a consensus among the different stakeholders, but rather capture different perspectives and get input from every interviewee. The robustness of results is increased by engaging interviewees several times to verify results, albeit, this also increases the likelihood of stakeholder fatigue.

The proposed approach is an iterative process that allows for the repetition of steps if deemed necessary, as indicated by arrows in Figure 1. For instance, the first couple of steps, stakeholder interviews and qualitative analysis, might need to be revisited if the Delphi survey results indicate a lack of saturation in stakeholder views. A more thorough analysis of what SED entails might be required if there is a considerable lack of agreement in stakeholders' answers, and multiple new aspects are added in the survey. This iterative nature of the process even further increases the robustness of results.

Each step of the indicator development process is described in detail in the following sections, along with methodological justifications for choices.

Step 1: Semi-structured interviews and focus groups

A necessary first step to stakeholder engagement is to identify the stakeholders. Freeman defined stakeholders as "groups and individuals who can affect, or are affected by, the achievement of an organization's mission" [63]. For the approach presented here, stakeholders affect or are affected by the energy system where the indicator development process is applied. Several different methods can be used to identify stakeholders, such as mind mapping, brainstorming, generic stakeholder lists, value chain, and life cycle approaches [41]. For this process, top-down analysis of the system is suggested. A combination of mind mapping and a value chain approach is used to identify the main stakeholder groups. After a trial-and-error period, this combination of methods was thought to have a broader scope and include more stakeholder groups than one single approach did. For instance, if only a value-chain approach is chosen, influential stakeholders of the system, such as international and national-level decision-makers, are not necessarily included. A generic initial mind-map of the stakeholders of an energy system can be seen in Figure 2. There, stakeholders are split into two main groups. Firstly, the "value chain" that captures the supply and demand side of the energy system. Secondly, "value chain influencers & enablers," representing those that can affect or are affected by the system but are not part of its value chain. This mind-map should be further expanded to include more specific sub-groups that reflect the energy system in question and, if necessary, update over-arching groups.

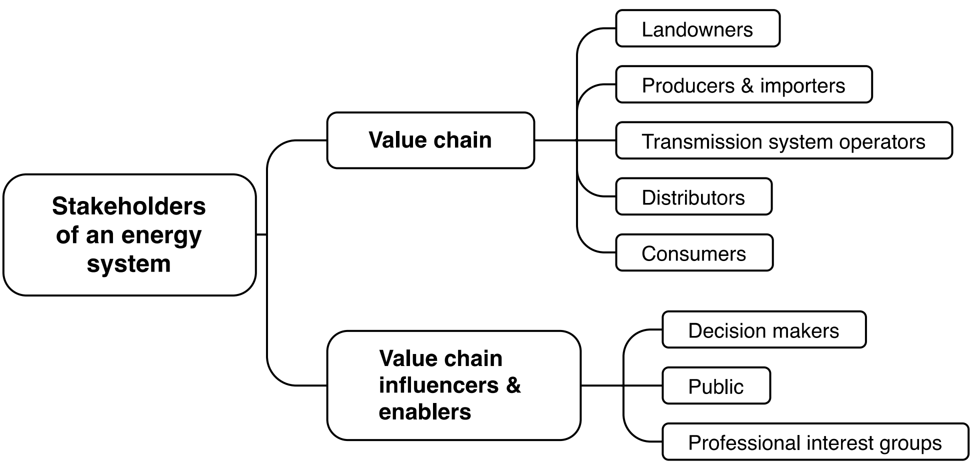

Figure 2: A generic mind-map of the stakeholders of an energy system. This mind-map should be further developed to reflect the energy system in question.

In this approach, purposeful sampling is carried out with maximum variation to ensure the selection of a diverse group of stakeholders that can provide a comprehensive and balanced picture of the energy system [41,57]. An attempt should be made at having an equal gender ratio and interviewees of a variable age range. A stakeholder map can aid in the selection of a balanced group of interviewees that represent the different stakeholder groups. In this approach, stakeholders representing each of the sub-groups of the "value-chain" and "value chain influencers & enablers" should be engaged, see Figure 2.

Generally, more informed stakeholders of the system that are more directly involved in the workings of an energy system are found within other sub-groups than the public. By interviewing more informed stakeholders individually, a greater emphasis is placed on their expert knowledge than the input of stakeholders with perhaps less understanding of the system. Representatives of all sub-group except the one for the public are considered experts of the system and interviewed through semi-structured individual interviews. The public's opinion is captured through focus group interviews, both at locations where energy development has directly affected the local community and where impacts are less direct.

Group interviews have been found to lend themselves well to exploring topics that are not necessarily well understood by participants as group dynamics can aid with a discussion [16]. When selecting participants for the focus groups, a community-based participatory approach is suggested where a member or organization of the community is involved in finding participants for focus groups [64]. Thus, a representative group of the community is engaged, the researcher's bias in selecting participants is reduced, and financial costs are minimized [64].

Before stakeholders are engaged, an interview guide is developed consisting of open-ended and non-leading questions that start a conversation on SED [65]. The individual interviews and focus groups should be semi-structured to allow for the flexibility to clarify the interviewee's answers and delve further when deemed necessary and of particular value [57]. The purpose of these interviews is to assess what SED means in the context in question, which involves asking about the current status of the energy system and identifying the main challenges and opportunities for SED. If the opportunity arises, it is also possible to invite stakeholders to reflect on potential indicators.

The output of these interviews gives an insight into what the stakeholders believe to be essential for SED and what challenges or uncertainties are facing the energy system – enabling a situated study of SED [7]. No more interviews are needed once a representative from each stakeholder group has been engaged, and saturation in interviewees' responses has been reached where no new ideas or perspectives are being introduced. The outcome of the process, indicators for SED, should reflect stakeholders' sustainability goals identified from these interviews [43]. Before interviews, the interviewees' permission to record the interview should be obtained to allow for a transcription of interviews. During stakeholder engagement, one needs to be aware of the interviewer's influence on interviewees or stakeholders and the interviewer's own bias when collecting and analyzing the data [57].

Step 2: Analysis of interviews

A grounded theory approach is proposed for the analysis of interviews. Grounded theory is a systematic methodology for social research with the central aim of discovering theories from qualitative data [66]. The methods prescribed by this approach were considered suitable for the indicator development process as they are flexible enough for the researcher to be able to adapt their data collection approach if necessary. Furthermore, this approach enables a systematic analysis of qualitative data. A combination of maximum variation sampling with a grounded theory approach has been found useful as: "any common patterns that emerge from great variation are of particular interest and value in capturing the core experiences and central, shared dimensions of a setting or phenomenon" [66,67].

The main steps of the grounded theory approach for data collection and analysis are seen in Figure 3 below. The central research question presented here is, "what do stakeholders believe SED entails?" This question should be kept in mind throughout the stakeholder engagement process. According to grounded theory, data collection and analysis should be a "simultaneous process," as indicated by the circle in Figure 4 and iterative arrow in Figure 2 [57,66]. Therefore, interviews should be transcribed as soon as possible. Thus, the remaining data collection can be guided by prior interviews' successes or failures and, for instance, used to try out emerging themes or ideas on interviewees [57]. Transcribed interviews are coded and, subsequently, similar codes are grouped to construct initial categories or themes [57,68]. Through the constant comparison method, patterns in the data are found, and themes are further refined [66]. Thus, frequently mentioned issues are translated into codes and themes. Eventually, the grounded theory process leads to the generation of theory [66].

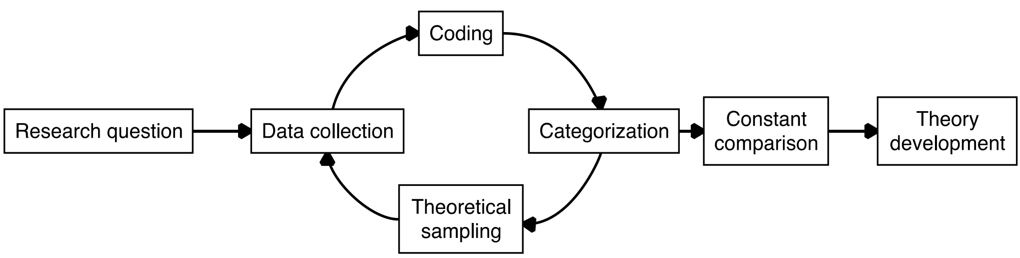

Figure 3: Diagram showing the main steps of qualitative data collection and analysis according to grounded theory. Diagram generated by authors based on methodology by Glaser and Strauss [66] *and Strauss and Corbin* [68].

For this process, the generation of a theory is not necessary. The purpose of this analysis is to identify what stakeholders believe SED should entail in the context. An emphasis is placed on identifying the various goals and necessary actions needed to realize SED according to stakeholders. Shortall et al. argued that sustainability goals serve as a suitable first building block for indicator development [43]. Therefore, identifying themes that correspond to stakeholder goals and associated actions suffices in this approach, and a theory is not needed.

Step 3: Delphi survey

Following a qualitative analysis, a Delphi survey is developed to verify the identified themes further. While the semi-structured stakeholder interviews served as a comprehensive collection of stakeholder input, the Delphi survey aims to reduce and refine qualitative results. The Delphi survey technique is a structured stakeholder engagement method consisting of two or more rounds of anonymous surveys with controlled feedback between rounds. The premise of Delphi surveys is that a structured group of individuals is more accurate than individuals or unstructured groups [69]. The technique is widely used in various fields to obtain the opinion of diverse stakeholders or experts, generally to reach a consensus among the group [69,70]. For instance, the Delphi technique can be used as a forecasting method for scenario building based on expert or stakeholder input [71]. Several examples can be found where a Delphi survey is used in the development of sustainability indicator, for instance; Shortall et al. for a sustainability assessment framework for geothermal energy projects [43], Jónsson et al. for soil indicators for sustainable development [72], and Lim et al. for indicators for Australian road infrastructure projects [73].

For this process, the purpose of the Delphi survey is to get interviewees to verify identified themes and, potentially, add missing elements of SED that might not have been mentioned during the interviews. If potential SED indicators were mentioned during the interviews, it is possible to get stakeholder feedback on those through the Delphi survey. Two rounds of a structured online survey are sent to interviewees, where they are asked to assess the importance of the themes and sustainability goals for SED on a Likert scale from 1-5. A minimum average score of importance for themes or indicators to pass between rounds needs to be determined before sending out the survey. The first round of the Delphi survey allows for the suggestion of missing SED elements. Before the second round, the overall results of the first round are sent to participants. Feedback between rounds is an essential feature of a Delphi as it allows participants to reassess their initial responses with the knowledge of the opinion of others [71]. The second round includes updated themes according to results from the first round and comments from interviewees. For instance, themes that do not reach the pre-determined minimum score of importance and, thus, are not considered significant for SED in this context could be deleted between rounds. The average rating of importance should not only be considered but also whether answers vary significantly. Shortall et al. suggested that the standard deviation of responses could serve as a measure of agreement in the participants' answers [43].

The results of the Delphi survey are verified themes of SED according to stakeholders. These results serve as the basis for the selection of sustainability indicators to measure progress towards SED. The researcher might need to revisit previous steps of stakeholder engagement if multiple new elements are in the first round of the survey which indicates a lack of saturation in stakeholders' views or if there is a significant lack of agreement in the participants' answers, as indicated by iterative arrows in Figure 1.

Step 4: Themes of SED

The fourth step of the process involves presenting the themes of SED as analyzed from the interviews and verified in the Delphi survey. These verified themes and stakeholder goals align with a thematic conceptual framework for indicator development, where the main issues of a topic are organized into its underlying themes or issues [30]. Conceptual frameworks are found to clarify and increase the transparency of indicator selection [11,32]. When using a thematic framework, problems are often grouped into the three pillars of sustainable development; economic, social, and environmental. As mentioned in section 4.1, the main criticism of thematic frameworks is that linkages between issues are often not considered, leading to oversimplification [10]. Linkages between indicators and underlying issues of SED are considered in step 6 of this process to address this flaw. A thorough analysis of what SED means in a particular context based on stakeholder input minimizes bias in selecting indicators and makes the indicator set more representative of the problem. The SED themes presented in this fourth step of the process have been validated. Therefore, no previous actions need to be revisited, as indicated by a lack of iterative arrows in Figure 1.

Step 5: Connect results with indicators

The primary purpose of this fifth step is to produce an initial set of indicators. Some potential indicators might have been suggested during stakeholder engagement that can be used as a starting point. In this step, results are connected to established indicators that can measure progress towards the identified themes and sustainability goals. To find suitable indicators, an analysis of the multitude of different indicators and indices for SED that exist is necessary. The review of existing SED indicator sets carried out by Gunnarsdóttir et al. [11] is useful during this step to find high-scoring and potentially valuable indicators. As described earlier, the EISD can serve as a good starting point for further refinement through stakeholder engagement to reflect the context in question [3,11]. Indicators that lack clarity on what they are set out to measure and how that should be done are not useful [11].

If no established indicators represent a particular theme or sustainability goal appropriately, an attempt should be made to develop a new indicator. Multiple different indicator criteria exist to aid in developing indicators, as discussed in the following step of this process. These criteria can be used to guide the development of a new indicator. The need to develop new indicators is expected to be minimal since such a vast number of indicators for SED exist.

Step 6: Apply indicator assessment criteria

At this point, multiple indicators have been connected to the themes and sustainability goals, but their quality has yet to be assessed robustly. This sixth step of the process involves refining the preliminary list of indicators to ensure the quality of individual indicators and consider how representative the indicator set is of the problem in question. This step will lead to the elimination of indicators based on the below pre-defined criteria. Additionally, it might identify gaps in representation where new indicators need to be added to the set.

Numerous criteria or checklists exist that enable a systematic analysis of the suitability of indicators, e.g., Bellagio STAMP principles and OECD's criteria for indicator selection [24,74]. These often consist of characteristics found common in useful indicators and, thus, deemed necessary to ensure an indicator can serve its purpose [44]. A review of existing indicator criteria allows for the identification of common themes and the creation of more robust indicator assessment criteria. The best and most suitable indicators can be identified using such a framework, and indicators missing the necessary characteristics can be adjusted or eliminated. The indicator assessment criteria proposed for this process can be seen in Table 2. These criteria should be used to assess the initial set to ensure the quality and suitability of indicators. In the end, all indicators of the set need to meet these criteria.

Table 2
Indicator assessment criteria based on commonly used criteria for indicator selection

Criteria element	Brief description	References
Interpretability	Simple, easily interpreted and applied.	[6,24,29,34,44,74–77]
Trends	Sensitive to changes and shows trends over time.	[24,29,34,44,74,75]
Grounded in research	Theoretically sound and measured based on standardized measurement methods that enable international comparison of indicators.	[6,24,34,44,74–76,78]
Data availability and quality	Based on data of good quality that are available or readily collected. Data are collected regularly and reported with a minimal time lag to report current information.	[6,24,78,79,28,29,34,44,74–77]
Linkages	The interrelation of indicators should be considered to eliminate correlated ones. Indicators should be meaningful on their own as well as together with other indicators of the set	[11,24,28,34,44,80]

A few common criteria for indicator selection are not included in this list, such as whether indicators are representative, relevant to policy, acceptable and of interest to stakeholders, and whether a transparent methodology and conceptual framework were used in their development. The process proposed here should produce indicators that already meet these criteria.

If an indicator is found unsuitable or overly correlated with another one, it might be necessary to revisit previous steps. For instance, step 4 - themes of SED to recall what exactly the indicator was supposed to capture and step 5 to review how and why a particular indicator was chosen. The iterative arrows in Figure 1 show this possibility.

Step 7: Finalize set of indicators

If this process is followed, it should produce a comprehensive and context-specific indicator set for SED. As discussed in section 4.1, the communication of indicators and their results is important to ensure their usefulness and application by stakeholders [32,75] [11]. Effective communication includes disclosing the methodology for both indicator selection and application, such as underlying indicators of the set, the necessary formulas, and data sources [11]. According to the Bellagio STAMP principles, effective communication is enabled through: "use of clear and plain language, present information fairly and objectively that helps to build trust, use of innovative visual tools and graphics to aid interpretation and tell a story, and make data available in as much detail as is reliable and practicable" [24]. The OECD, similarly, highlights the significance of visualization of indicator results as it can influence interpretability [28]. Graphics of the results can be useful to a larger group of stakeholders instead of raw data that might be too technical [34]. These graphics should be accompanied by short summaries or explanations for general stakeholders, while decision-makers or key influencers could receive more detailed descriptions when appropriate [34]. The utilization of a thematic framework helps with organizing the indicators and connecting them with relevant issues. Furthermore, a thematic presentation of indicators lends itself well to being connected with relevant policy processes and goals [32].

A periodic review of indicators is necessary to ensure that the indicator set captures the most pressing SED issues at the time. The 8th Bellagio STAMP principle highlights this point, which states that an indicator set should be "subject to continuous review and revision" [24]. SED is a relatively young concept that is still evolving to some extent, highlighting the necessity of a regular review of an indicator set [13]. This review could involve reiterating some prior steps of the above process, such as a repetition of the Delphi survey, to ensure the indicator set's continued relevance. Periodic stakeholder engagement and repeated data collection could enable a longitudinal study of stakeholders' views of energy development [58].

5. Discussion

If the proposed approach for indicator selection for SED is followed with rigor and consideration, the six criteria for indicator set assessment laid out by Gunnarsdóttir et al., and discussed in section 4.1 above, should be met [11]. The transparency of indicator selection should be ensured by using the process itself. The clarity of the indicator application should be sufficient since the necessary indicator methodology and data sources are provided, as instructed in the seventh step of the process. In the fourth step of the process, qualitative results in the form of SED themes are connected to a thematic framework and, thus, a conceptual framework is used to frame the problem. In the same step through the conceptual framework, the representation of the social, economic, and environmental impacts of SED should be examined. Linkages are considered in the sixth step of the process, as one of five indicator assessment criteria to ensure the suitability of indicators. Finally, the entire process is built on stakeholder input. A diverse group of stakeholders is engaged three different times through both interviews and a survey to ensure the robustness of results. Hence, if the steps of the proposed approach to indicator selection are followed, a comprehensive, robust, and context-specific indicator set for SED should be produced.

What is unique about the proposed process is the fact that both quantitative and qualitative methods are used. First, qualitative data is collected through interviews that, subsequently, is quantified through the Delphi survey. In the end, qualitative methods are used to produce a quantitative tool – indicators. Generally, these two research approaches are not mixed, sometimes referred to as the "quantitative-qualitative divide" [81,82]. Nonetheless, some have started to recognize the value of integrating the two for a more robust analysis or "to fully understand their phenomenon of interest" [81]. For instance, a theory can be developed through qualitative research, especially when using the grounded theory approach, and then this theory can be tested through quantitative methods [81]. The argument made here is that the two approaches, quantitative and qualitative, complement each other to produce a more robust set of indicators.

One of the main strengths of this process compared to the established methodology for indicator selection is the increased transparency of indicator selection, where all the underlying steps are laid out and justified. A common criticism of current approaches is the lack thereof [11]. Increased transparency of indicator selection builds credibility and legitimacy while reducing the researcher's bias in the process [6]. Furthermore, the usefulness and potential application of the methodology is increased [24]. The iterative nature of the process where steps can be revisited if necessary, such as a lack of saturation of stakeholder views, even further increases the robustness of the process.

Another strength of this process is the structured stakeholder involvement. Multiple benefits of increased stakeholder engagement have been identified, as discussed in section 4.1 above. Many argue for the necessity of stakeholder engagement during indicator development; nonetheless, this has not become standard practice [11,34,44]. In this process, stakeholders are engaged from the beginning to evaluate what SED means within a particular setting and provide a base for indicator selection. Then, stakeholders are engaged again to verify the identified results. This approach is particularly useful in the analysis of complex and multi-dimensional concepts such as SED. The process promotes the selection of a representative and comprehensive indicator set while reducing the potential for the researcher's own bias in both the qualitative analysis and indicator selection. A diverse group of stakeholders is engaged to capture different perspectives of SED. Thereby, stakeholders' trust in the process is built, which might eventually lead to the application of the indicator set and consideration of its results by many different stakeholders. For indicator sets to be used, they need to be acceptable and of interest to stakeholders and the public [34,44].

The stakeholder engagement in this process can lead to multiple by-products of the indicator selection process. For instance, a thorough analysis of the relevant stakeholders, their opinions regarding energy development, and an understanding of what SED involves within the context can be valuable. These by-products can inform decision-making and the development of energy policy towards SED that is acceptable to stakeholders. Through the Delphi survey, it is possible to determine the level of agreement among stakeholders on the different underlying issues of SED. It can be useful to policy- and decision-makers to know whether stakeholders agree on, for instance, the necessity of a particular action or if there are some controversial topics related to energy development.

The indicator selection approach presented in this study is fairly generic and could be applied to develop indicators for other topics related to sustainable development. The only adjustments that would have to be made are a new version of the stakeholder map and a review of the relevant existing sustainability indicators. A process rooted in stakeholder engagement is useful to further understanding of abstract sustainability concepts, such as SED [83]. The first four steps of the proposed process can be taken solely if the goal is only to capture what a sustainability concept involves within a particular setting and not develop relevant indicators. Therefore, the generalizability of the proposed approach is considerable, both for the development of any sustainability indicators and a context-specific analysis of whatever abstract sustainability concept. Scherhaufer et al. [84] highlight that there is “a need for integrated ways of cooperation between stakeholders, policy-makers and researchers in order to produce knowledge which is usable in both a scientific and practical context.” The approach presented in this study could meet that need to some extent.

When applying this process, researchers should watch out for a few potential pitfalls of the process. Seven indicator development steps are outlined, which can lead to a lengthy and costly process. Stakeholder engagement is both one of the main strengths and potential downfalls of the presented method. Depending on the approach, stakeholder engagement can be a time consuming and expensive. Therefore, researchers need to spend time before stakeholder engagement to carefully select a balanced and diverse group of interviewees, ideally with stakeholders representing multiple stakeholder groups. The number of interviews necessary can be reduced through careful planning, and saturation in interviews might be reached more quickly. Furthermore, engaging the same stakeholders several times can lead to stakeholder fatigue [85]. The fifth step of the process, where results are connected to established indicators, can also be time-consuming. By looking at reviews of indicator sets such as the one done by Gunnarsdóttir et al., this process can be sped up by, for instance, eliminating indicator sets that lack the necessary transparency from further analysis [11]. In this process, an attempt is made to reduce any potential for the researcher's own bias in selecting indicators. Nonetheless, there is always some opportunity for this. Researchers should be aware of their own bias throughout the process, particularly in the final steps where stakeholders do not reaffirm results.

One step that is not included in this process, but perhaps should be, is to connect indicators with policy targets or benchmarks. This process is always more complicated for qualitative indicators that might not have a quantitative goal. Nevertheless, when possible, it would be beneficial to compare indicator values to the relevant targets and benchmarks [24]. Sometimes, indicators can also lead to the creation of targets and baselines [34]. As mentioned above, one of the strengths of a thematic framework is that a thematic presentation of indicators or a problem lends itself well to being linked with policy processes and targets [32]. Identifying and connecting relevant targets and benchmarks with the indicators would require some additional analysis that is not included in the process presented here.

This indicator selection process does not necessarily lead to the creation of an index that can be presented as a single score. Creating an index requires assigning weights to indicators and evaluating the significance of indicators in relation to each other. Weighting can be politically sensitive and lead to subjectivity, especially when indicators are qualitative and quantitative [86]. However, presenting the results of an indicator set or index as a single score can be of value. For instance, the status of complex and multi-dimensional problems such as SED can be communicated clearly to decision-makers and stakeholders and allow for comparisons between energy systems [28]. However, when reporting a composite index, the status of an entire system often is shown, but not its underlying dimensions [72]. A lot of information can be lost through aggregation due to the "information iceberg" effect [87]. Therefore, if a composite index is created, the underlying indicators and their scores should be provided to allow for further analysis.

As discussed in section 3, the approach to indicator selection proposed in this study is based on a review of existing SED indicator sets carried out by Gunnarsdóttir et al. [11]. Several limitations to that study were identified. These are related mainly to the indicator set assessment criteria applied in the study, including how they were evaluated and that some important criteria were missing, such as effective communication. Furthermore, there is always the possibility that some existing indicator sets for SED were not found through the literature review. These faults of the review could have affected the development of the proposed indicator selection process.

6. Conclusions

Comprehensive and robust indicators are needed to track progress towards sustainable energy development. The aim of this study was to present an approach to the development of indicators for SED. A transparent iterative indicator development approach was proposed with stakeholder engagement at its heart to ensure that indicators are representative, comprehensive, and useful to stakeholders, and to reduce bias in the selection of indicators. A mixture of qualitative and quantitative approaches to get the best of both worlds even further enhances the process. Through this process, the emerging issues of SED and stakeholders' objectives are identified, which can shape the development of sustainable energy policy. The monitoring of such policy and relevant actions would be enabled then through the resulting indicator set. Therefore, the methods presented here should be of practical value to policy and decision-makers. The importance of transparency and stakeholder engagement for indicator selection is highlighted throughout this process. The same applies to sustainable energy policy development or policy development in general. Public participation is essential, if only to increase the relevance of policy actions and promote stakeholder acceptance. Even though the process presented here is linked to SED, it could be applied to develop indicators for any abstract sustainability concept. The first few steps of the process could also only be taken to further understanding of a sustainability concept within a particular setting. A natural next step is to implement the process somewhere for the development an indicator set for SED and, thereby, demonstrate its usefulness.

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Paper IV: Indicators for sustainable energy development: An Icelandic case study

Indicators for sustainable energy development: An Icelandic case study

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Abstract

Sustainable energy development is a complex and global policy objective. What needs to be emphasized to reach the objective, varies based on context corresponding to different energy-related challenges. A robust set of context-specific indicators is needed to measure progress towards sustainable energy development. Sustainability indicators enable the monitoring of progress towards policy goals and can inform actions and decision-making. Indicators often reflect the critical issues or challenges that lie ahead. In this study, an iterative stakeholder approach to indicator development is implemented within Iceland. The approach highlights the importance of stakeholder engagement for indicator selection and that indicators need to be context specific. The product of this is a set of indicators for sustainable energy development of the Icelandic energy system. These indicators, based on stakeholder input, reflect national priorities for energy development. Multiple products with policy implications come out of the process; indicators, analysis of stakeholders and their views, a definition of sustainable energy development in the context, a roadmap towards it, and identification of linkages between indicators. Thus, the process can provide a base for energy policy, an action plan towards sustainable energy development that is supported by stakeholders.

Keywords

Sustainable energy development; Sustainability indicators; Energy indicators; Indicator development; Stakeholder engagement; Energy policy

Word Count

8,243

Highlights

- Sustainable energy development is a policy goal that needs robust indicators

- Stakeholder engagement during indicator selection is valuable
- Context-specific indicators are needed as countries face different challenges
- Indicators, based on stakeholder input, reflect national priorities
- The process can provide a base for an energy policy supported by stakeholders

1. Introduction

The purpose of energy systems is to provide (energy) services that improve human well-being and promote economic growth and social development (UNDP et al., 2000). Consequently, energy plays a fundamental role in making sustainable development possible. This role is often referred to as sustainable energy development (SED) and was recognized with the introduction of the UN's Sustainable Development Goal (SDG) 7 on affordable and clean energy (United Nations General Assembly, 2015). The concept of SED has evolved from being focused narrowly on energy security and the role of energy in reducing emissions to becoming a cross-cutting policy objective. Currently, SED is connected to some of the major environmental, social, and economic challenges facing the world (Gunnarsdóttir et al., n.d.; United Nations General Assembly, 2015; World Commission on Environment and Development, 1987). Consideration of the environmental, social, and economic impacts is necessary for SED to be realized (United Nations Development Programme et al., 2000). SED is a complex and contested concept, and actions towards it vary corresponding to diverse energy-related problems facing energy systems or countries (Cherp and Jewell, 2014; Gallie, 1956; Taylor et al., 2017). Therefore, tailored actions towards SED are necessary.

Sustainability indicators can monitor progress towards policy goals and inform actions and decision-making. Indicators often reflect the critical issues or challenges that lie ahead. In a data-driven world, the usefulness of indicators is generally acknowledged. Numerous criteria for indicator selection have been developed; nonetheless, no standardized approach to indicator selection exists (Taylor et al., 2017). Multiple efforts have been made to create indicators for SED or parts of it (Gunnarsdóttir et al., 2020; Narula and Reddy, 2015; Shortall and Davidsdottir, 2017; Taylor et al., 2017). These have been criticized for lack of transparency, imbalanced representation of the pillars of sustainable development, lack of stakeholder involvement, and burdensome data requirements (Iddrisu and

Bhattacharyya, 2015; Narula and Reddy, 2015; Shortall and Davidsdottir, 2017; Sovacool, 2012; Taylor et al., 2017). Indicators for SED need to reflect the context by taking account of the energy-related challenges of a particular energy system to be useful to policy-makers and stakeholders (Shortall and Davidsdottir, 2017; Taylor et al., 2017).

Stakeholder engagement in decision-making, policy development, and indicator selection is progressively more recognized (Irvin and Stansbury, 2004; Pintér et al., 2012; United Nations, 1998). Nevertheless, it is not common practice to involve stakeholders during indicator development (Gunnarsdóttir et al., 2020). Stakeholder engagement during indicator selection makes it possible to take into account diverse viewpoints, thus increasing validity and comprehensiveness, while also reducing potential bias in indicator selection. A process based on stakeholder input can result in a representative set of indicators that is acceptable to stakeholders (Pintér et al., 2012; Sovacool, 2012). Furthermore, stakeholder engagement is useful when analysing "essentially contested concepts," such as sustainability and SED (Freeden, 1996; Gallie, 1956).

Gunnarsdóttir et al. developed an iterative stakeholder engagement approach to indicator selection for SED (Gunnarsdóttir et al., n.d.). Throughout their process, stakeholders are involved repeatedly to recognize the challenges and opportunities for SED in the context and develop representative indicators. The objectives of this study are to:

- implement this indicator selection process and present indicators for SED in Iceland
- reveal the potential policy implications of the indicator selection process

The Icelandic energy system is chosen as a case study, and an indicator set is developed, reflecting the challenges facing that system. The following research questions are addressed: What challenges and opportunities are facing the Icelandic energy system on the path towards SED? What should be emphasized to reach SED in Iceland? What should be measured to track progress towards SED in Iceland? Stakeholders of the system are engaged to answer these questions.

The paper is structured as follows: Section 2 contains a review of the concept of sustainable energy development, the relevant indicators, and the Icelandic energy system. The indicator selection process is outlined in the third section. In the fourth section, the results of the study are presented. These results are discussed in the fifth section. In the sixth section, the policy implications are revealed, and the paper is concluded.

2. Background

2.1 Sustainable energy development and relevant indicators

The concept of sustainable energy development (SED) was first put forward in 2000 as a new development paradigm where the impacts of energy development on the environment, economy, and society were considered (UNDP et al., 2000). The importance of not endangering "the quality of life of current and future generations" and staying within ecosystem boundaries was highlighted in this new paradigm. The role of energy in furthering sustainable development was recognized from the start; that is when a definition of sustainable development was presented in the Brundtland report (World Commission on Environment and Development, 1987). However, what that role consisted of was unclear and, initially, was narrowly restricted to reducing emissions and ensuring energy security (World Commission on Environment and Development, 1987). Recognition of the importance of energy in enabling sustainable development has grown, especially since access to modern energy services is now seen as a vital driver for economic growth and social development (UNDP et al., 2000). One of the main challenges for SED is providing energy access to all while limiting the associated negative environmental and health costs (UNDP et al., 2000).

For this to be possible, a transformation of the current energy system is necessary (IEA, 2008).

Similar to sustainable development, SED can be viewed as an "essentially contested concept," where interpretations of the concept can vary, and its meaning is still contested to some extent (Gallie, 1956). The contested nature of the concept of SED has resulted in ambiguities in its definition, which highlights the importance of a context-specific analysis (Taylor et al., 2017). Nonetheless, the ultimate goal of SED is to support sustainable development. Shortall et al. (2017) identified eight SED themes from a review of the policy literature: access & electrification, affordability & equity, security, efficiency, renewables, economic or cost-efficiency, environmentally benign and clean, and contributes to well-being. Gunnarsdóttir et al. (n.d.). similarly identified four common interrelated SED themes, described below:

- *Access to affordable modern energy services* is vital for economic growth and promoting social well-being. A lack of modern energy services is connected with some of the main challenges of sustainable development, such as poverty, lack of basic health care, and environmental degradation (UNDP et al., 2000). Energy services need to be affordable to all if they are to be accessible and promote sustainable development.
- *Sustainable energy supply:* A transformation of current energy systems involves a transition to environmentally-sound energy options and sustainable utilization of renewable energy sources. This transition is only possible if those options are economically viable and cost-competitive (Gunnarsdóttir et al., n.d.).
- *Energy security:* A secure supply of energy is necessary for sustainable development, which includes a reliable transmission and distribution system and sustainable utilization of energy resources (UNDP et al., 2000).

- *Sustainable energy consumption* involves increased energy efficiency and awareness of the negative impacts of the current energy system that will lead to a change in current consumption patterns (United Nations, 2002).

Multiple different indicators have been developed to measure progress towards SED or some aspect of it. Most of these have been found lacking in some regard, such as non-transparent methods, and disproportionally emphasizing economic aspects (Narula and Reddy, 2015; Shortall and Davidsdottir, 2017; Sovacool, 2012). A challenge to indicator development for SED has been ambiguities of the concept and its varying meaning within different contexts (Narula and Reddy, 2015; Shortall and Davidsdottir, 2017). Shortall et al. (2017) demonstrated the need for context-specific indicators for SED to inform decision-making at the national or regional level. Nonetheless, the majority of current SED indicator sets are general and do not take account of the context (Gunnarsdóttir et al., 2020; Shortall and Davidsdottir, 2017). For instance, the *Energy Trilemma Index* and the *Energy Architecture Performance Index,* well-established SED indicator sets, are designed as national indicators for country comparisons with no flexibility to consider national conditions (Graymore et al., 2008; Shortall and Davidsdottir, 2017). The *Energy Indicators for Sustainable Development (EISD)* are similarly developed as national indicators (IAEA et al., 2005). However, flexibility in the set and guidance on how to update it to reflect the context makes the indicators more suitable. Streimikiene et al. (2007) applied the *EISD* to analyse energy development in Baltic States, which included updating the indicators to reflect priority areas in the region. However, this update resulted in the omission of all social indicators, thus making the indicator set imbalanced and less suitable (Streimikiene et al., 2007). Tsai (2010) developed sustainable development indicators for Taiwan, which included energy indicators. However, these indicators, similar to Streimikiene's study, did not consider the social dimension of SED (Tsai, 2010).

The engagement of stakeholders during indicator development has been recommended to develop representative SED indicators and account for a broad range of perspectives (Shortall and Davidsdottir, 2017; Sovacool, 2012). Stakeholder engagement during indicator selection is found to increase validity and comprehensiveness and reduce bias in selection (Irvin and Stansbury, 2004; Reed, 2008). Furthermore, stakeholder acceptance of the resulting indicators can be increased (Brown, 2009; Schirnding, 2002). Sovacool (2012) found semi-structured interviews appropriate for a discussion on complex concepts, such as energy security and SED. When developing an energy security index, Sovacool was able to determine what energy security means in the context through targeted discussions with stakeholders. Similarly, stakeholder and expert interviews were conducted to identify areas of improvement and inform the selection of weights for the *Energy Architecture Performance Index* (World Economic Forum, 2017). Nonetheless, stakeholders were not involved in the development of most existing SED indicators (Gunnarsdóttir et al., 2020).

More recent and widely used indicators that measure progress towards SED are those connected to the UN's SDG 7 on affordable and clean energy. These indicators assess progress towards the global objectives prescribed in the goal, such as universal access to energy services and increasing the share of renewables (SDSN, 2014). However, these indicators only consider limited aspects of SED and do not capture the multi-dimensionality of the concept (Nerini et al., 2018). The entire SDG indicator set is more comprehensive and, arguably, captures some of the missing SED issues. Taylor et al. (2017) argue that the SDG7 indicators should be complimented by national-level indicators and, thus, measure progress where the decisions and policy actions are taken.

2.2 Case study: Icelandic energy system

In this research, the Icelandic energy system is analysed as a case study. A case study approach allows for an in-depth analysis of a "contemporary phenomenon" within a "real-life context" (Yin, 2009). In this study, the phenomenon studied is SED within the Icelandic energy system. Iceland makes an interesting case study, as its energy system is unique in many ways. The country is rich in renewable energy resources that are used to a limited extent, such as hydro, geothermal, and virtually unutilized wind power. These contribute to a high share of renewables in Iceland's primary energy use (82% in 2018) and electricity generation (99% in 2018) (Orkustofnun, 2019a, 2019b). Therefore, the challenges facing the Icelandic energy system on the path towards SED are perhaps different from many countries. However, Iceland's energy system is where many countries want to be, and therefore, other countries might catch up and face a similar set of challenges eventually. While the case study chosen may be less representative from the perspective of technological energy systems, it is considered a good choice to implement the approach for indicator development as the organization of Iceland’s energy system can be viewed as more or less representative.

Iceland has one of the highest shares of renewables in primary energy use in any national energy budget (International Energy Agency, 2019). The development of primary energy use by energy source can be seen in Figure 1. The dashed line in the graph shows the gradually increasing share of renewables. In 2018, geothermal energy supplied 62% of primary energy and hydropower 19% (Orkustofnun, 2019a). Hydropower accounts for 70% of electricity production, while geothermal accounts for 30% (Orkustofnun, 2019b). The main use of geothermal power is for space heating, which heats 90% of all houses in Iceland (Orkustofnun, 2019c). Other renewable energy sources, such as wind, have been utilized marginally but could become a significant energy source in the future (Ministry of Tourism

Industries and Innovation, 2018). Increasing the diversity of energy sources is often thought to strengthen a country's energy security (IAEA et al., 2005).

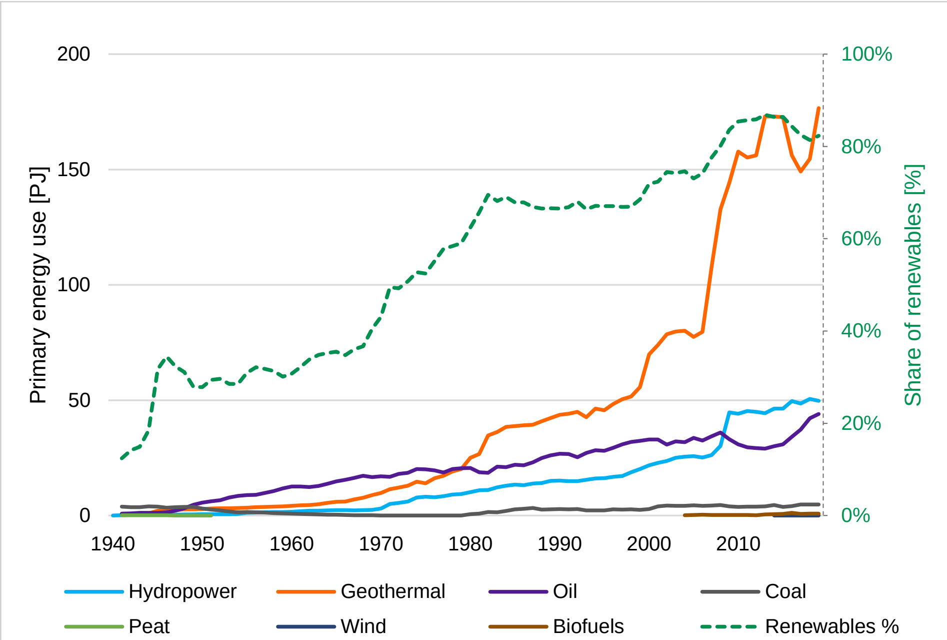

*Figure 1:**Primary energy use in Iceland by energy source in 2018.** The solid lines show the amount of primary energy use by energy source. The dashed line shows the gradually increasing share of renewables in primary energy use in the country (Orkustofnun, 2019a).*

In 2018, the last 18% of non-renewables in primary energy use were 16% fossil fuels and 2% coal (Orkustofnun, 2019a). Fossil fuels were 80% used in transportation, and 17% by the fishing industry (Orkustofnun, 2019d). Coals are not used as an energy source, but utilized in industrial processes, primarily in aluminium smelting as anodes. A challenge facing the Icelandic energy system is the transition of these last 18% towards a 100% renewable system. Multiple benefits of this transition can be recognized, such as reduced emissions, better air quality, and 100% domestic energy generation leading to increased energy security (Shafiei et al., 2019).

Iceland has one of the highest rates of electricity production per capita in the world (IEA, 2019). In 2018, 19.8 TWh of electricity were produced in the country (Orkustofnun, 2019e). This high production rate is due to energy-intensive industries in the country, principally aluminium smelters. In 2018, heavy industries consumed 77% of electricity produced in the country, see Figure 2 (Orkustofnun, 2019e). This reliance on one type of consumer creates vulnerability in the system. It is important to note that, in a sense, (embodied) energy is one of the main exports of Iceland and a pillar of the Icelandic economy (Statistics Iceland, 2018).

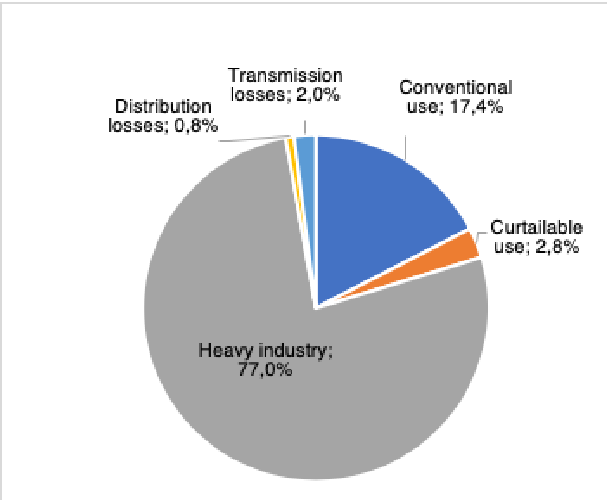

*Figure 2: **Breakdown of electricity consumption in Iceland in 2018.** Graph shows clearly the dominance of heavy industries in the country's electricity consumption (Orkustofnun, 2019c).*

When looking at the indicators for SDG7, the Icelandic energy system seems sustainable due to its high share of renewables and access to modern energy services for all (SDSN, 2014; Statistics Iceland, 2020). Nonetheless, various challenges face the system on the path towards SED. Energy resources need to be sustainably utilized to ensure energy security. For instance, excessive production in a geothermal field can lead to a temporary depletion of a geothermal reservoir (Spittler et al., 2019). The transmission and distribution system needs to be improved to increase energy security across the country further as well as to ensure energy equity. Currently, the system is more secure around the capital and highly populated areas and less so in sparsely populated regions of the country (Ministry of Industries and Innovation, 2018). Furthermore, the efficiency of the system can be improved, both on the supply and demand side (Minister of industries, 2011). By improving the efficiency, the need for increased energy production with the associated environmental costs could be reduced.

SED in Iceland may lead to a carbon-neutral energy system due to an energy transition towards renewables as well as increased carbon sequestration efforts. The CarbFix project, where carbon is permanently stored in the subsurface through mineral carbonation, was pioneered in Iceland (Snæbjörnsdóttir et al., 2020). Technological breakthroughs such as that one and their implementation can push the system towards increased SED.

Thus far, energy policy containing a long-term vision for energy development has not been established in Iceland. Bits and pieces of such a policy have been created that fail to capture a comprehensive picture for energy development in the country (Ministry of Industries and Innovation, n.d.). Currently, work is underway to develop such a policy. An emphasis is placed on public participation in the creation of this new energy policy. The policy aims to push for SED and address the various challenges that the Icelandic energy system currently faces (Ministry of Industries and Innovation, 2018).

3. Methodology

An iterative stakeholder engagement approach was applied for the development of SED indicators for Iceland. This approach was presented originally in the paper *It Is Best to Ask: Designing A Stakeholder-Centric Approach to Selecting Sustainable Energy Development Indicators* (Gunnarsdóttir et al., n.d.). Therefore, the methodology is only briefly explained here. This approach is not limited to SED as it could be used for the development of indicators for other aspects of sustainable development.

The indicator development process consists of seven steps seen in Figure 3. Stakeholder engagement is at the heart of the process, and their input provides a foundation for indicator selection. The first four steps of the process involve identifying what SED entails in the context. Initially, a diverse group of stakeholders is engaged once through semi-structured individual interviews or focus groups to determine stakeholder goals regarding energy development. A grounded theory approach is applied for the analysis of these interviews to identify prominent themes of SED in the context (Glaser and Strauss, 1967).

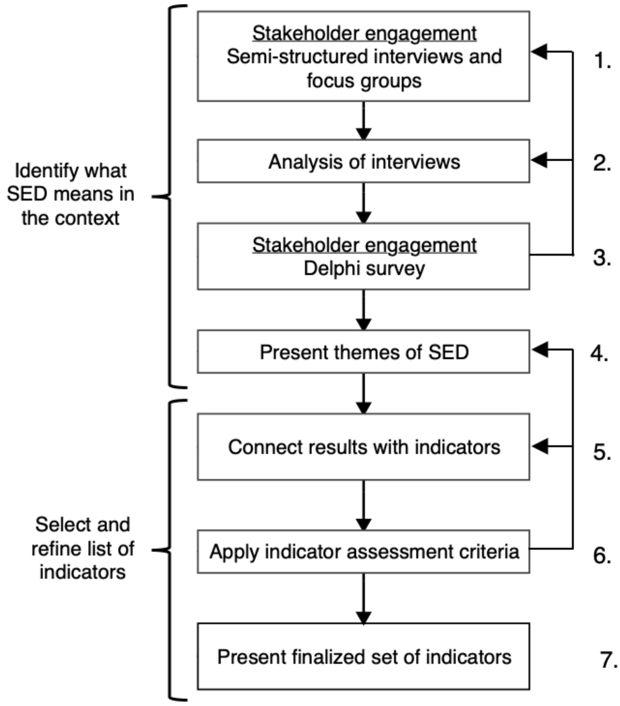

Figure 3: ***Iterative stakeholder engagement approach for indicator development.*** *The seven steps of the process and their purpose is shown. The iterative nature of the process is indicated by arrows in the diagram. Approach and diagram originally presented by Gunnarsdóttir et al. (Gunnarsdóttir et al., n.d.).*

Thereafter, two rounds of a Delphi survey are sent to interviewees. The purpose of the survey is to get stakeholder feedback on identified SED themes. Thereby, stakeholders can verify prior results and add topics that might have been overlooked in the interviews. In this approach, the standard deviation of answers can be a measure of stakeholders‘ agreement on the different sustainability goals (Shortall et al., 2015). Stakeholders were asked to assess the importance of the identified themes and goals for SED, see Table 1 below. Three was chosen as a minimum mean score of importance for a topic to pass between rounds of the survey. Topics that did not meet this criterion were deemed unimportant and eliminated from further analysis. More details on the Delphi survey can be seen in Appendix B.

Table 1: Likert scale of importance for the Delphi survey

Score	**Definition**
5 – Very important	Has a direct impact and must be resolved. Priority task.
4 - Important	Has an impact and is relevant. Not a priority task.
3 – Moderately important	May have an impact and is somewhat relevant. Can be a determining factor.
2 - Insignificant	Has little impact and insignificantly relevant. Not a determining factor.
1 – Not important	Has no impact or relevance. Should not be considered further.

The results of the stakeholder engagement are presented as themes of SED and organized within a thematic conceptual framework. The following steps involve connecting indicators with these identified themes and sustainability goals to produce a preliminary list of indicators and, subsequently, refining that list of indicators. Initially, established SED indicators are considered, namely, those analysed by Gunnarsdóttir et al. (2020) in a review paper of indicators for SED, as well as indicators developed for Iceland. The aim is to find indicators that can measure progress towards the identified SED themes and goals. Novel indicators are created when no indicators are found that fit a specific goal. Subsequently, indicator assessment criteria are applied to ensure the suitability and quality of indicators, see Table 2. These criteria are based on commonly used checklists for assessing the suitability of indicators, such as the Bellagio STAMP principles, and the OECD's criteria for indicator selection (OECD, 1993; Pintér et al., 2012). The final result of the process is a set of context-specific indicators for SED.

Table 2
Indicator assessment criteria based on commonly used criteria for indicator selection. The original version of the table presented by Gunnarsdóttir et al. (n.d.).

Criteria element	Brief description
Interpretability	Simple, easily interpreted and applied.
Trends	Sensitive to changes and shows trends over time.
Grounded in research	Theoretically sound and measured based on standardized measurement methods that enable international comparison of indicators.
Data availability and quality	Based on data of good quality that are available or readily collected. Data are collected regularly and reported with a minimal time lag to report current information.
Linkages	The interrelation of indicators should be considered to eliminate correlated ones. Indicators should be meaningful on their own as well as together with other indicators of the set

The iterative nature of the process allows for the repetition of previous steps if necessary, as shown by the arrows in Figure 3. For instance, if the results of the Delphi survey indicate a lack of saturation in stakeholder views where multiple new topics are added. Then, stakeholder interviews and qualitative analysis might need to be revisited for a more thorough examination. The iterative nature of the process increases the robustness of results.

3.1 Stakeholders of the Icelandic energy system

For this study, the relevant stakeholders were "those that affect or are affected by the [Icelandic] energy system" (Gunnarsdóttir et al., n.d.). Multiple different approaches to stakeholder identification exist, e.g., brainstorming, mind-mapping, stakeholder consultation, and life-cycle analysis (Durham et al., 2014). As suggested by Gunnarsdóttir et al. (n.d.), stakeholders were identified through a top-down analysis of the system with a combined value chain and mind-mapping approach. Stakeholders of the energy system were split into two groups; the value chain of the system and those that influence or enable that value chain. This combined approach was found to be inclusive and more comprehensively capture the system in question than the different approaches did on their own (Gunnarsdóttir et al., n.d.).

A stakeholder map of the Icelandic energy system can be seen in Figure 4. This map expands into more detail, as indicated by the numbers on the right, which signify sub-groups. Purposeful sampling was carried out to select stakeholders of maximum variation (Merriam and Tisdell, 2016). Thereby, diverse opinions and a comprehensive picture of the system could be captured. Maximum variation sampling complements a grounded theory approach well as: "any common patterns that emerge from great variation are of particular interest and value in capturing the core experiences and central, shared dimensions of a setting or phenomenon" (Glaser and Strauss, 1967; Patton, 2015). For this study, this involved selecting stakeholders that represented each group within the "value chain" and "value chain influencers & enablers" groups. Some stakeholders belonged to more than one group; for instance, the focus groups captured the opinion of both "consumers" and "public." Additional considerations were selecting stakeholders associated with the different primary energy sources (i.e., hydro, geothermal, and fossil fuels), attempting an equal gender ratio of interviewees, and reaching stakeholders of different ages. Stakeholder groups that might have been underrepresented are, e.g., public service providers, international organizations, and financial service providers.

In this study, sixteen individual interviews were carried out and two focus groups, one in the local community of recent energy development and one in the capital region where energy development is more out of sight. For the focus groups, a community-based participatory approach was used, where a member of the community was involved in finding participants (Makosky Daley et al., 2010). No additional interviews were carried out since qualitative analysis showed a saturation in interviewees' responses, where no new ideas were being introduced (Gunnarsdóttir et al., n.d.). Following a qualitative analysis of the interviews, interviewees were sent two rounds of a Delphi survey to verify prior results. The Delphi survey also confirmed the saturation of data.

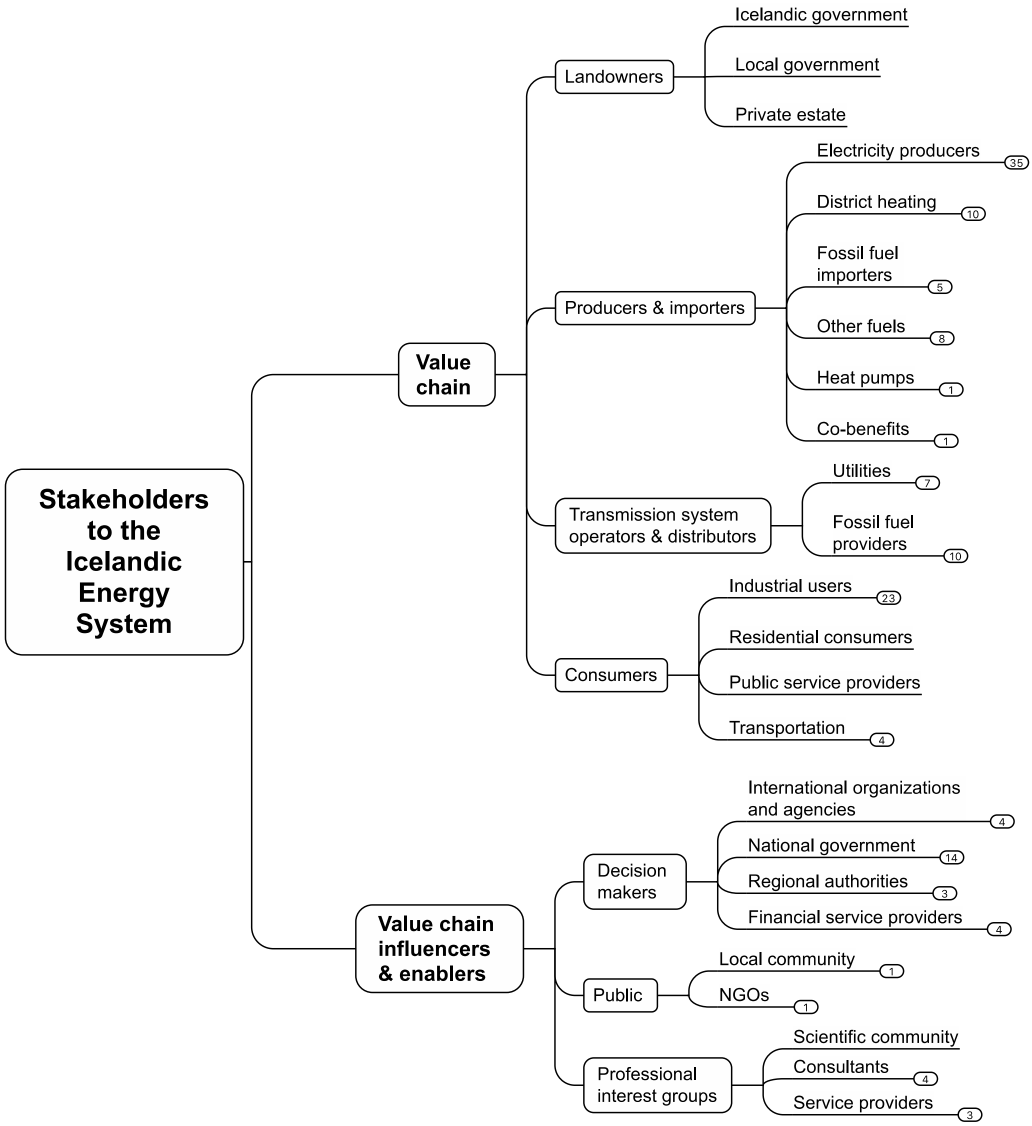

*Figure 4:**Stakeholder map of the Icelandic energy system.** Map expands into more detail as indicated by numbers on the right, which signify the number of sub-groups. Diagram based on an approach presented by Gunnarsdóttir et al. (n.d.).*

4. Results

4.1 Sustainable energy development in Iceland

A picture of what a sustainable energy future in Iceland might entail was captured by engaging stakeholders of the energy system. Stakeholders were asked to discuss the current state of the system, what a sustainable energy future might entail, and what steps would further SED. This stakeholder engagement and qualitative analysis led to the identification of SED themes. These themes overlap, interrelate, and reflect the sustainability goals of stakeholders. The results of this stakeholder engagement are only briefly described here as the objective of this study is to present SED indicators for Iceland.

The Delphi survey served the purpose of verifying results of stakeholder interviews and allowing stakeholders to add topics potentially missed in the interviews. In the first round of the survey, no themes or sustainability goals received a mean score below three, and, therefore, none were eliminated. However, ten goals were reworded or split up based on stakeholders‘ comments and high standard deviation of answers for some goals. The standard deviation of answers reduced significantly between rounds of the survey, which indicates a higher level of agreement among stakeholders in the second round of the survey, see Appendix B. In the second round, two goals received a mean score below three, indicating that stakeholders did not find them important. However, stakeholders did not seem to agree on the importance of these goals, as indicated by the high standard deviation of answers. Both of these goals were related to a submarine interconnector to Europe, either as a way of increasing energy security or economic efficiency by making energy an export. The results of the Delphi survey are integrated into the discussion below. The anonymity of the Delphi survey hinders the researchers from knowing the answers of different stakeholder groups and who changed their opinion during the process. Details on the Delphi survey can be seen in Appendix B.

Based on stakeholder engagement, the overarching goal was determined to be the sustainable development of the Icelandic energy system. Six main themes of SED for Iceland were identified, as seen in Figure 5. All of these themes need to be addressed for SED to be realized in Iceland.

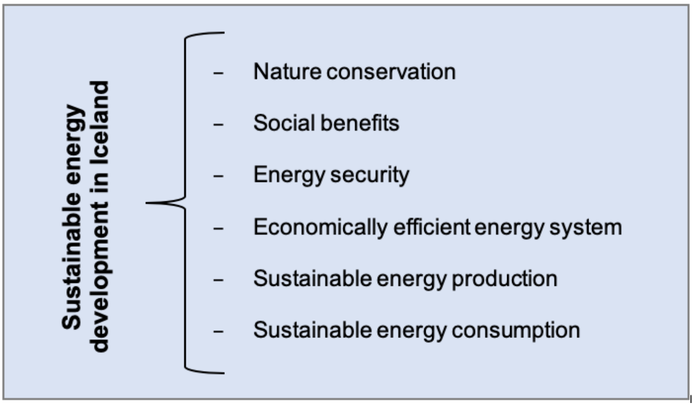

Figure 5: SED themes for Iceland. *An overarching goal of sustainable energy development and themes there under identified from stakeholder engagement and qualitative analysis.*

The first theme of nature conservation was highlighted to some extent by all stakeholders. This theme reflects the goal of protecting Iceland's untouched nature and wilderness from future energy development, both from energy production and distribution. The environmental impact of energy development should be minimized, and the visual pollution of the energy system reduced. Several stakeholders discussed how visual pollution from energy development could have negative impacts on tourism, and effective design could reduce the energy system’s impact area. A potential solution mentioned was increasing the share of subterranean transmission lines. Stakeholders agreed on the importance of minimizing environmental impact as the goal received the highest mean score in the second round of the Delphi while having the lowest standard deviation.

The second theme reflects the goal of ensuring that society benefits from energy development, whether it be in the local community or at a higher level. Some highlighted that benefits from energy development should be felt in the local community in the long run, such as job creation, socially beneficial initiatives, and infrastructure upgrades. Public acceptance of actions was deemed necessary. Increased public participation and informed debate on energy-related decision-making and policy development were thought to increase public acceptance. Stakeholders agreed on the importance of increased public participation and more informed debate with the highest mean score and lowest standard deviation in the second round of the Delphi. This theme also included topics such as knowledge creation, innovation, and technological advancements that were recognized as necessary enablers of SED.

Stakeholders acknowledged the necessity of increased energy security. Several actions were mentioned to reach this goal, such as increasing the diversity of energy resources utilized, ensuring the sustainable utilization of resources, and strengthening the transmission and distribution system, particularly in rural areas. Furthermore, most mentioned an energy transition, mainly in transportation, from imported fossil fuels towards domestic renewables to increase energy independence and energy security. This energy transition towards a fully renewables-based system was also thought to be one of the main challenges facing the system. An energy transition was the highest-scoring goal in the first round of the Delphi and one of the highest in the second round. One of the lowest scoring goals in both rounds of the Delphi was distributed energy generation related to energy security.

An economically efficient energy system was recognized as part of SED. According to stakeholders, the supply side of the energy system needs to be economical and profitable to be sustainable. Some stakeholders thought the profitability of energy supply could be increased through appropriate investments and technological advancements. A few thought a combination of public and private investments in the system was necessary. The possibility of the government implementing a carbon tax, removing fossil fuel subsidies, or applying other economic tools to further SED, in particular, an energy transition, was mentioned. The lack of diversity in energy consumers, mainly energy-intensive industries, was highlighted as a risk. These energy-intensive consumers with long-term power purchase agreements are all in the same sector and, thus, subject to the same economic influences. In this context, the possibility of a submarine interconnector to Europe and, thereby, making energy an Icelandic export was mentioned. The Delphi showed that stakeholders were not in agreement on the importance of such a connector, where a low mean score in the second round indicated that most were against it. Furthermore, the importance of affordable energy prices to households across the entire country was discussed.

The fifth theme reflects the goal of sustainable energy production. This theme was one of the most prominent ones. Sustainable energy production was thought to involve minimizing the environmental impact of production. Therefore, emissions from energy production, both carbon dioxide and other air pollutants, need to be reduced, and the impact area of power plants minimized. One stakeholder mentioned the ultimate goal of a carbon-negative energy system made possible with increased carbon sequestration efforts. The goal of reducing emissions from the energy system was one of the highest-scoring ones in the second round of the Delphi survey as well as having a low standard deviation. Some discussed past mistakes concerning the use of geothermal resources and emphasized the sustainable utilization of energy resources.

The sixth theme pertains directly to all stakeholders of the system and reflects the goal of making the consumption of energy more sustainable. To reach this goal, stakeholders mentioned that overall energy consumption needs to decrease, and energy efficiency needs to increase. These two sub-goals received the highest scores of the second round of the Delphi survey. Many discussed the need for increased awareness of the harmful impacts of current energy systems and a change of attitude towards a more environmentally conscious one. A change of attitude was discussed as an essential catalyst for an energy transition. Stakeholders talked about how the government should lead by example as well as apply economic tools to, for instance, promote energy efficiency and an energy transition. A couple of stakeholders argued that cleaner fossil fuels should be mandated with more stringent quality requirements.

A definition of SED for Iceland can be derived from these themes. All three pillars of sustainable development, economic, environmental, and social, need to be considered for SED to be realized in Iceland. The future economic prosperity of the energy system is ensured through sustainable utilization, more diverse consumers, and necessary investments. The Icelandic energy system becomes more environmentally friendly with an energy transition, sustainable energy production, nature conservation, and change of attitude of its stakeholders. The ultimate aim is a carbon-neutral or negative energy system. The social aspect of SED entails increased public participation, ensuring social benefits of development, affordable and equitable energy, and more environmentally conscious consumers. SED cannot be reached without a secure energy system. The necessary technological advancements and knowledge creation will push the system further towards SED.

According to stakeholders, a critical challenge for SED in Iceland was the lack of comprehensive long-term energy policy. Due to the lack of energy policy, there has been no clear direction for energy development, and decisions have been taken on a case-by-case basis. All-encompassing long-term energy policy should include a roadmap towards SED, which addresses all of the above themes.

4.2. Indicators for sustainable energy development in Iceland

Indicators were selected to measure progress towards the sustainability goals discussed by stakeholders and, as such, assess SED in Iceland. A comprehensive and flexible set of indicators was chosen, which can be used in different ways depending on the purpose of the analysis. For instance, some sub-themes are linked to a few indicators that were thought equally good but might not all need to be analysed. In tables 3-8, indicators for each of the six SED themes can be seen. A more detailed description of the indicators and their methodology can be seen in Appendix A.

4.2.1 Nature conservation

Table 3
Indicators for the theme of nature conservation

Theme	Sub-theme	Indicator	Reference
Nature conservation	Protect the wilderness	Total impact area of power plants	1
	Minimize visual pollution	Subterranean share of transmission and distribution system	Original
		Total impact area of power plants	1

1.Steering committee, 2016,

4.2.2 Social benefits

Table 4
Indicators for the theme of social benefits

Theme	Sub-theme	Indicator	Reference
Social benefits	Public acceptance	Public participation in energy-related policymaking	2, 4
		Transparency of government policymaking	3
	Benefit from energy development	Socially beneficial initiatives	2
		Job creation	4-6
	Knowledge creation and technological advancements	Total R&D expenditure within the energy sector	5, 11
		Number of patents in the energy sector	3,5
		FDI & technology transfer	3
		Capacity for innovation	3
		University-industry collaboration in R&D index	3

2. Austurbrú, n.d., 3. World Energy Council and Wyman, 2017, 4. Neves and Leal, 2010, 5. Sovacool and Mukherjee, 2011, 6. Shortall et al., 2015, 11. SDSN, 2014

4.2.3 Energy security

Table 5
Indicators for the theme of energy security

Theme	Sub-theme	Indicator	Reference
Energy security	Sufficient energy reserves	Total primary energy supply	5,6,9,11,19
		Dynamic reserve / production ratio	5,12–15,19–21
		Critical surplus	9
	Diverse energy sources	Diversity-index for energy supply by type	3,5,7,14–16,21
	Strengthen the transmission and distribution system	Government investments in energy infrastructure development	5
		Efficiency of energy conversion and distribution	3,12–15,20
		Subterranean share of transmission and distribution system	Original
	Quality of supply: urban vs. rural	Frequency of electric power grid	5
		Frequency and duration of blackouts	5
	Energy independence: domestic energy	Total domestic generation and share by type	21
		Proportion of domestic energy sources in TPES	3,21,22
	Energy independence: import dependence	Proportion of imported energy in TPES	3,9,15,20,21
	Energy independence: risk of imports	Share of imports coming from politically unstable countries	5,7, 14
		Degree of transportation risk management	17
	Energy transitions	Number of fast-charging spots and other eco-friendly multi-fuel stations	10
		Share of passenger cars by fuel type	8
		Energy consumption for transportation by fuel	5,8
		Proportion of renewable fuels in total fuel for ships	10
		Number of planes that use land connected electrical charging	10

3. World Energy Council and Wyman, 2017, 5. Sovacool and Mukherjee, 2011, 6. Shortall et al., 2015, 7. Asia Pacific Energy Research Centre, 2007, 8. Eurostat, 2017, 9. García-Álvarez et al., 2016, 10. UAR, 2018, 11. SDSN, 2014, 12. Sovacool et al., 2011, 13. Sovacool, 2013, 14. Martchamadol and Kumar, 2013, 15. International Atomic Energy Agency et al., 2005, 16. World Economic Forum, 2017, 19. Helio International, 2000, 20. Yu et al., 2010, 21. Global Network on Energy for Sustainable Development (GNESD) and Asian Institute of Technology, 2010

4.2.4 Economically efficient energy system

Table 6
Indicators for the theme economically efficient energy system

Theme	Sub-theme	Indicator	Reference
Economically efficient energy system	Diversity in income and industries	Diversity-index for energy consumption by sector	7
	Government expenditure/revenue	Government revenue from energy sales	5
		Tax revenue of carbon tax and fossil fuels	5,8-10
		Government expenditure on fossil fuel subsidies	5,11-13
		Government investments in infrastructure development	5
	Economical and profitable energy system	Investment in the energy sector	3
		Energy intensity by sector	3,5,11–19
		Average levelized cost of electricity	Original
		Proportion of energy use covered by long-term contracts	Original
	Affordable energy prices	Share of household income spent on energy	4,5,9,15,19
		Energy price volatility by type	5,12,13

3. World Energy Council and Wyman, 2017, 4. Neves and Leal, 2010, 5. Sovacool and Mukherjee, 2011, 7. Asia Pacific Energy Research Centre, 2007, 8. Eurostat, 2017, 9. García-Álvarez et al., 2016, 10. UAR, 2018, 11. SDSN, 2014, 12. Sovacool et al., 2011, 13. Sovacool, 2013, 14. Martchamadol and Kumar, 2013, 15. International Atomic Energy Agency et al., 2005, 16. World Economic Forum, 2017, 17. Murakami et al., 2011, 18. Global Energy Institute and US Chamber of Commerce, 2018, 19. Helio International, 2000

4.2.5 Sustainable energy production

Table 7
Indicators for the theme of sustainable energy production

Theme	Sub-theme	Indicator	Reference
Sustainable energy production	Carbon neutral energy system	Total generation and share by type	3,8,16,23,24
		Share of renewables in TPES	4-9,12–14,19,20,22,25–27
		Amount of carbon sequestration by energy industry	1,2
	Sustainable utilization of resources	Dynamic reserve / production ratio	5,12–14,19–21
	Minimize impacts on land	Total impact area of power plants	1
	Minimize emissions	Net emissions from energy production and utilization For: GHG, NOx, CH4, SO2, H2S, and PM2,5 Per capita, over GDP, by sector, or by TPES	2-6,8,9,12-15,18,20,22–24,26
		Ambient concentrations of air pollutants in urban areas	15

1. Steering committee, 2016, 2. Austurbrú, n.d., 3. World Energy Council and Wyman, 2017, 4. Neves and Leal, 2010, 5. Sovacool and Mukherjee, 2011, 6. Shortall et al., 2015, 8. Eurostat, 2017, 9. García-Álvarez et al., 2016, 12. Sovacool et al., 2011, 13. Sovacool, 2013, 14. Martchamadol and Kumar, 2013, 15. International Atomic Energy Agency et al., 2005, 16. World Economic Forum, 2017, 18. Global Energy Institute and US Chamber of Commerce, 2018, 19. Helio International, 2000, 20. Yu et al., 2010, 21. Global Network on Energy for Sustainable Development (GNESD) and Asian Institute of Technology, 2010, 22. Iddrisu and Bhattacharyya, 2015, 23. European Environment Agency, 2014, 24. Scheepers et al., 2007, 25. Doukas et al., 2012, 26. Schlör et al., 2013, 27. Lee and Zhong, 2015

Note: Indicators calculated on an annual basis

4.2.6 Sustainable energy consumption

Table 8
Indicators for the theme of sustainable energy production

Theme	Sub-theme	Indicator	Reference
Sustainable energy consumption	Reduce energy consumption	Total energy consumption (primary or final) By type, per capita, over GDP, or by sector	3,4,9,12–15,19,20,22,23
	Energy efficiency	Energy intensity by sector	3,5,11–19
		Ratio of final over primary consumption	19
		Load factor for gross electric capacities	24
		Average age of cars and ships	23
	Cleaner fossil fuels	Emission factor of fossil fuels	5,19
	Change of attitude	Share of different forms of transportation chosen	1,4
		Share of passenger cars by fuel type	8
		Energy consumption for transportation by fuel	5,8

1.Steering committee, 2016, 3. World Energy Council and Wyman, 2017, 4. Neves and Leal, 2010, 5. Sovacool and Mukherjee, 2011, 8. Eurostat, 2017, 9. García-Álvarez et al., 2016, 11. SDSN, 2014, 12. Sovacool et al., 2011, 13. Sovacool, 2013, 14. Martchamadol and Kumar, 2013, 15. International Atomic Energy Agency et al., 2005, 16. World Economic Forum, 2017, 17. Murakami et al., 2011, 18. Global Energy Institute and US Chamber of Commerce, 2018, 19. Helio International, 2000, 20. Yu et al., 2010, 22. Iddrisu and Bhattacharyya, 2015, 23. European Environment Agency, 2014, 24. Scheepers et al., 2007

5. Discussions

5.1 Sustainable energy development in Iceland

Overall, stakeholders agreed on the necessity of furthering SED, especially considering the increasing threat of climate change. A high level of agreement was detected among the different stakeholder groups on what needs to be done to reach SED. One of the only controversial topics was the possibility of a submarine electricity interconnector from Iceland to continental Europe, where strong arguments were made for and against the connector. An energy transition towards domestic renewables was thought to be one of the most pressing issues. Surprisingly, a representative of fossil fuel importers even discussed an “inevitable energy transition” and how their business model needed to change accordingly.

A comparison of the six SED themes for Iceland to global SED issues shows that they broadly align (IAEA et al., 2005; Shortall and Davidsdottir, 2017; UNDP et al., 2000). One of the most pressing energy development issues worldwide is access to modern energy services (United Nations General Assembly, 2015). Access to energy does not seem to be a topic in Iceland, which is logical as all Icelanders have access to electricity (The World Bank, n.d.). However, the affordability of energy was discussed to some extent, notably concerning differences in energy prices for urban and rural areas and energy prices to industries.

Globally, there is a push for reducing the harmful environmental impacts of energy production and increasing the share of renewable energy resources (Lund, 2007). Iceland already has a high share of renewables in its primary energy use and has ample availability of more renewables. Therefore, the issues facing Iceland regarding sustainable energy production differ from most countries worldwide. Issues mentioned included completing an energy transition towards a fully renewable system and ensuring the sustainable utilization of renewable resources. Due to an abundance of renewable energy resources, wind power has yet to be utilized to any real extent in Iceland (Orkustofnun, 2019a). This luxury of only utilizing available renewable resources to a limited extent is unique. Generally, stakeholders thought wind power would be a viable option for future energy generation in the country.

Energy consumption behaviour in Iceland seems to differ from other countries around the world, perhaps due to an abundance of available renewable energy resources (Sovacool, 2017). A few stakeholders discussed how energy efficiency has not been a topic in the country, and, as a result, Icelanders tend to be wasteful in their energy consumption.

Stakeholders discussed how attitude needs to change towards more sustainable energy consumption.

Emissions from energy production can threaten human health and well-being (UNDP et al., 2000). Harmful emissions seem to be less of a threat in Iceland since renewable energy resources are utilized. The only health-related impacts mentioned were those associated with geothermal power plants and emissions of hydrogen sulphide. Some discussed the necessity of minimizing emissions from geothermal power plants and cleaning hydrogen sulphide from emissions.

One of the main attractions of Iceland is its pristine and untouched nature (Íslandsstofa - Promote Iceland, 2019). Nature protection is particularly important, considering that tourism has become a pillar of the Icelandic economy (Sutherland and Stacey, 2017). Therefore, stakeholders highlighted the value of Iceland's nature and the necessity of minimizing both the environmental and visual impact of future energy development.

5.2. Indicators for sustainable energy development in Iceland

Multiple issues discussed, such as the lack of comprehensive energy policy, were binary, something that has been done or not. An indicator measuring progress towards binary objectives does not show incremental progress over time, apart from just ticking a box when it is done. Most guidelines for indicator selection prescribe that indicators should be sensitive to changes and show trends over time (Jain and Tiwari, 2017; OECD, 1993). Therefore, the indicators did not reflect these binary issues and instead tracked progress towards other non-binary objectives mentioned. The addition of a to-do list with the binary objectives mentioned by stakeholders would complement the indicator set.

Both the themes and the selected indicators overlap and interrelate. Therefore, some indicators are situated within more than one theme. For instance, the indicator "total impact area of power plants" is within two themes; nature conservation and sustainable energy production and connected to three different sustainability goals; protect the wilderness, minimize visual pollution, and minimize impacts on land. It is beneficial to identify potential linkages between indicators to assess a complete picture of SED and eliminate overly correlated indicators. Linkages between indicators can be seen in Appendix A.

The indicators are meaningful on their own but should also be analysed as a part of a set. An analysis of the entire set gives a complete picture of the status of the system. Furthermore, a change in one indicator could affect another. For instance, the utilization of energy-intensive technologies for carbon sequestration would register as a positive development in the "amount of carbon sequestration by industry." However, this could result in a negative change in indicators for energy consumption and efficiency. Interactions such as this one are the reason why the indicator set was not aggregated. Because of the "information iceberg" effect, much information can be lost with the aggregation of an indicator set (Molle and Mollinga, 2003).

A broad set of indicators was selected to allow for some flexibility. Thereby, indicators that fit the purpose of the study can be assessed. For instance, five different indicators measuring knowledge creation and technological advancements are presented that might not all need to be analysed. Indicators that were thought equally good were not eliminated based on the preference of the authors. Some of the indicators might only be considered when looking at specific development scenarios. For example, indicators assessing the risk of energy imports could be considered when the impacts of war and blocked transportation routes on Iceland's energy security would be evaluated.

A common criticism of existing indicators for SED is the lack of a detailed methodology to allow for the application or calculation of the indicators (Gunnarsdóttir et al., 2020). In this study, an emphasis was placed on providing sufficient information on indicator methodology to allow for their application, as seen in Appendix A.

The indicators presented in this paper are context-specific and reflect SED in Iceland. Therefore, they differ to some extent from established SED indicator sets, such as EISDs and indicators for SDG7. Broadly, the same issues are covered by all three sets. This indicator set has over fifty indicators, while there are thirty EISDs, and six connected to SDG7. This difference indicates that the presented indicator set captures a much more detailed picture of what SED entails in Iceland. Furthermore, some of the indicators in both the EISDs and SDG7 were deemed irrelevant for Iceland. These indicators were not topics of discussions for stakeholders and, thus, not issues for SED in the country. An example of this would be indicators measuring accessibility to modern energy services or clean cooking fuels. These differences highlight the value of context-specific indicators.

5.3. Iterative stakeholder engagement approach for indicator development

The seven-step indicator selection process implemented in this study was found to produce a comprehensive and representative set of indicators. As the name of the process indicates, *iterative stakeholder engagement approach*, it relies heavily on the input of stakeholders. Through stakeholder mapping, a diverse and balanced group of interviewees was selected. As a result, multiple viewpoints were considered, which provided a complete picture of the energy system and its SED. The same stakeholders were engaged three different times, once through an interview and twice through a Delphi survey. The semi-structured nature of the interviews was found to lead to fruitful discussions with stakeholders. In general, stakeholders stayed on the topic during the interviews. In the rare cases that conversation went off-topic, pre-determined questions were used to steer the conversation back in the right direction. As with any qualitative research, the interviewers had to be aware of their own bias and attempt to say as little as possible during the interviews.

The results of the Delphi survey indicate that stakeholders agreed with the results of the analysis. No goals or themes were eliminated between rounds of the survey. The only topic that did not meet the minimum score criteria in the second round of the survey was the possibility of a submarine interconnector to the European power grid. However, the high standard deviation of answers implied that stakeholders were split on the issue. The Delphi survey was found to be an appropriate way of verifying results and strengthening the process overall. A benefit of the Delphi survey was that it allowed stakeholders to reflect on the analysis and, in a way, communicate with each other as results are shared between rounds (Lim and Yang, 2009). The main criticism of the Delphi survey in this study was the decreasing response rates, with only 11 people responding to the second round of the survey, see Appendix B.

While stakeholder interviews are flexible and allow for a broad discussion, topics can be entirely overlooked based on the direction the interview takes. This combination of interviews and a Delphi survey was found to ensure that a complete picture was captured while minimizing the researchers' own bias. The choice of a thematic conceptual framework fits well with the stakeholder engagement and grounded theory approach. Conceptual frameworks can serve an important role in constructing complex problems, such as SED, and increasing the transparency of indicator selection (Jain and Tiwari, 2017; United Nations Department of Economic and Social Affairs, 2007). Thematic frameworks are flexible and can capture the relevant policy issues, which has made them popular (Gunnarsdóttir et al., 2020; UN DESA, 2007). The main flaw of thematic frameworks is that problems can be oversimplified, where connections between issues can be overlooked (Iddrisu and Bhattacharyya, 2015; Stanners et al., 2007). When using a thematic framework, the UN has emphasized the consideration of linkages between themes and indicators (UN DESA, 2007). Linkages are considered in Appendix A.

A multitude of established SED indicators exists that were reviewed while connecting indicators with identified themes and goals. Review papers, such as the one by Gunnarsdóttir et al. (n.d.), are useful during this step and can reduce the amount of work involved significantly. Numerous established indicators were eliminated due to a lack of transparency in their purpose and methodology. The following step of applying assessment criteria to assess the suitability of indicators was sometimes challenging. The criteria selected were found quite broad and, at times, difficult to evaluate, especially since no data was connected to the indicators. More detailed criteria with clearly defined parameters would be more useful. Additionally, many indicators were found equally good. In the end, a choice was made to select a broader and more flexible set of indicators rather than eliminating indicators based on the authors' preferences.

The benefits of the chosen approach were demonstrated through its implementation in Iceland. The value of both stakeholder engagement and context-specific indicators is highlighted throughout. As described in the background section, most current indicator sets for SED are neither context-specific nor based on stakeholder engagement. Although recent studies have started to recognize the advantages of both. What is novel about this approach is the integration of qualitative and quantitative methods. Initially, qualitative data is collected through stakeholder interviews. Subsequently, these qualitative results are verified and quantified through the Delphi survey. These results are then compared with the SED literature when indicators are connected with sustainability goals. This combination of qualitative and quantitative methodology is found to produce a well-rounded and comprehensive set of indicators that is accepted by stakeholders. Numerous steps of verification ensure the robustness of the resulting indicator set. A completely different set of indicators would have been selected if only the literature had been reviewed and no stakeholder had been involved. Indicators reflecting the unique conditions of Iceland, such as subterranean share of the transmission and distribution system and proportion of energy use covered by long-term contracts, would not have been included. Transparency is ensured with detailed descriptions of the different steps involved and methodology for each indicator (see Appendix A).

This stakeholder engagement approach is found particularly relevant due to the contested nature of the concept of SED. Sustainable development and SED can be viewed as “essentially contested concepts” as they are products of "social, historical, and cultural constructs" (Freeden, 1996; Gallie, 1956). There is no universally accepted definition of these concepts. One of the main hindrances of creating appropriate sustainability indicators has been ambiguities in what these concepts encompass, particularly in the local context (Narula and Reddy, 2015; Shortall and Davidsdottir, 2017). Therefore, stakeholder engagement is appropriate to evaluate what SED means in the context and to identify local shared values.

Even though the main objective of the process is to produce a set of indicators, many different by-products can be identified. At the beginning of the process, the system in question, and its stakeholders are analysed thoroughly. Subsequently, the sustainability goals of different stakeholder groups are identified. Based on this, a definition of what SED entails in the context can be presented. This definition consists of the different goals and actions laid out by stakeholders that will push for a more sustainable energy system. The opportunities and challenges facing the system on the path towards SED are identified as well. Public acceptance of actions is valuable to ensure their success, as mentioned by stakeholders during interviews. Therefore, an analysis of the relevant stakeholders and their views is valuable for the policy and decision-making process. Furthermore, the process promotes public participation and transparency in the decision-making process. This analysis can be used to explore scenarios of a sustainable energy future. Through a backcasting approach, pathways, and necessary policy actions towards those scenarios can be evaluated (Börjeson et al., 2006).

Some potential drawbacks of the process were identified during implementation. The process can be quite labour-intensive and time-consuming. Effective organization, especially concerning stakeholder engagement, can save considerable time. Access to stakeholders is necessary, which could be a challenge in some places. Identifying useful contacts that can connect researchers with other stakeholders can be helpful. Since stakeholders are engaged several times, there is potential for stakeholder fatigue (Gramberger et al., 2014). While stakeholders were open to an interview, participation in the survey decreased gradually. The timing of stakeholder engagement was found to be influential. The second round of the Delphi survey was sent in late summer, which might have contributed to decreased participation.

A few more lessons were learned during implementation. Firstly, the topic of indicators could be introduced earlier in the process. The stakeholder engagement was entirely focused on identifying what SED means in the context. Indicators were never discussed apart from researchers' mentioning that the ultimate goal was SED indicators for Iceland. An exploratory discussion with stakeholders on potential indicators could be valuable. Although the main focus of the stakeholder engagement should remain the same, capture the meaning of SED in the context. Secondly, it would be beneficial to add a final step of communication of the indicators and their results to the process. Effective communication can be a deciding factor for why an indicator set is used or not (Gunnarsdóttir et al., 2020; Pintér et al., 2012). Indicators and their results should be communicated in a transparent and visually appealing way to ensure their usefulness and application (UN DESA, 2007). Thirdly, a periodic update of the indicator set is important (Pintér et al., 2012). This update could be done every few years through a Delphi survey sent to stakeholders. Then the purpose of the survey would be to reassess the relevance of the selected indicators and sustainability goals as well as identify new topics of concern.

6. Conclusion and policy implications

In this study, an iterative stakeholder engagement approach was applied to produce context-specific indicators for SED in Iceland. These indicators reflect sustainability goals for the Icelandic energy system, according to its stakeholders. If the same approach were applied within a different context, a different set of indicators would be produced, reflecting the challenges facing that energy system. The approach shows the value of stakeholder engagement for indicator selection and context-specific indicators, especially when measuring progress towards a contested and complex concept such as SED. A strength of the approach is the integration of qualitative and quantitative methodology where multiple steps of stakeholder engagement and verification ensure a comprehensive and robust set of indicators. Without stakeholder input, one-of-a-kind indicators reflecting Iceland’s unique SED challenges would not have been included in the set.

Generally, indicators reflect the underlying issues of a goal and can highlight what changes are needed. As such, the choice of indicators can act as a catalyst for action. An example of this is the inclusion of an energy goal in the UN's SDGs that, thus, recognized the importance of energy for sustainable development. The indicators presented in this study can serve the dual role of monitoring and communicating important SED issues in Iceland. These indicators reveal the national priorities for SED in Iceland. The numerous by-products of the process, analysis of stakeholders and their views, the definition of SED in the context, SED roadmap, and identification of linkages between indicators, can shape energy policy.

Potential policy implications of applying the indicator selection process in Iceland include the identification of concrete policy goals like ensuring sustainable utilization of resources, increasing the diversity of consumers, and completing an energy transition. Most of the identified stakeholder goals can have direct policy implications and shape SED in Iceland. This study is particularly valuable due to the current lack of energy policy in Iceland.

A draft of such a policy exists that was never implemented (Minister of industries, 2011). A comparison of the draft energy policy with the results of this study shows that a complete picture of the Icelandic energy system was captured. A testament to that is the fact that the SED themes presented here align almost perfectly with the titles of the chapters in the draft energy policy, see Table 9. The policy priorities for SED in Iceland are revealed in this table.

Table 9: A comparison of the results of this analysis with a draft energy policy in Iceland

SED themes of this study	Chapters of the draft energy policy
Nature conservation	- Respect for the environment, nature, and specialties
Social benefits	- The nation enjoys dividends from resources - Education, research, and international cooperation
Energy security	- Energy need met in a secure manner
Economically efficient energy system	- Maximizing macroeconomic efficiency - Development of a diverse economy
Sustainable energy production	- Respect for the environment, nature, and specialties
Sustainable energy consumption	- Reduce the consumption of fossil fuels - Education, research, and international cooperation

The highest scoring sustainability goals of the Delphi survey highlight some of the more specific and concrete policy implications of this study. Stakeholders agreed that an energy transition towards domestic renewables, especially for transportation, is a pressing issue. An energy transition would both increase energy security as well as reduce harmful emissions of the system. Reducing GHG emissions and improving air quality is of concern, where the ultimate goal is a carbon-neutral system. Stakeholders emphasized raising awareness to promote more sustainable energy consumption and, thereby, enable an energy transition and improve energy efficiency. Stakeholders believed that minimizing the environmental impact of energy development, e.g., through effective design, should be a guiding light for SED in the country. Social acceptance of actions was thought vital to realize SED in Iceland, which is enabled through public consultation during decision-making and more informed debate.

One of the most surprising results of this study was the high level of agreement among stakeholders on what is important to achieve SED in Iceland, apparent from both the interviews and the Delphi survey. On the surface, energy development seems to be a disputed topic. However, this analysis shows that the different stakeholder groups all aim towards a more sustainable energy future and largely agree on what actions need to be taken to reach that future. It is valuable to know that stakeholders are on board with furthering SED. Ultimately, this study provides a base for energy policy, an action plan towards SED, that is supported by stakeholders.

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Appendix A: Methodology of indicators

Table 10
The methodology of indicators for the theme of nature conservation

Theme	Sub-theme	Indicator	Explanation	Metric	Unit	Linkages	Data source
Nature conservation	Protect the wilderness	Total impact area of power plants	The impact area of a power plant is both the sq. km for the plant, as well as the surrounding area that is impacted in some way. The methodology for this indicator is quite complex and varies somewhat based on the type of energy sources. Parameters considered are, for instance, impacts on hydrology, geology, ecology, and tourism.	Total impact area of power plants in Iceland in sq. km over total number of power plants in Iceland	sq. km / plant	NC - Minimize visual pollution SEP - Minimize impacts on land	NEA
	Minimize visual pollution	Subterranean share of transmission and distribution system	A higher share of subterranean power lines leads to less visual pollution. Subterranean power cables are less sensitive to extreme weather conditions.	km of system subterranean over total km of system	%	ES - Strengthen transmission and distribution system	NEA, Landsnet
		Total impact area of power plants	See above	Total impact area of power plants in Iceland in sq. km over total number of power plants in Iceland	sq. km / plant	NC - Protect the wilderness SEP - Minimize impacts on land	NEA

Note: Indicators calculated yearly
NEA = National Energy Authority,

1. Steering committee, 2016

Table 11
The methodology of indicators for the theme of social benefits

Theme	Sub-theme	Indicator	Explanation	Metric	Unit	Linkages	Data source
Social benefits	Public acceptance	Public participation in energy-related policymaking	This indicator involves sending an annual opinion poll to stakeholders of the system, both local and national, to assess public acceptance, public participation, and the availability of information on energy-related policymaking.	Survey	% or qualitative		Survey
		Transparency of government policymaking	This indicator assesses how easily businesses can access information on changes to government policies and regulations that might affect their practices.	Survey	# and country rank		WEF
	Benefit from energy development	Socially beneficial initiatives	This indicator involves sending an annual opinion poll to stakeholders of the system, both local and national, to assess socially beneficial initiatives.	Survey	% or qualitative		Survey
		Job creation	Reflects the benefits of energy development in a community and can be measured locally or at a larger scale. Direct, indirect, and induced jobs associated with energy projects are considered.	Ratio of energy-related jobs over population	%		SI
	Knowledge creation and technological advancements	Total R&D expenditure within the energy sector	This indicator accounts for both public and private expenditure on generating new knowledge through basic and applied research as well as the application of new knowledge and experimental development.	Total research expenditure (public & private) over GDP	%	EEES - Government expenditure/revenue & Economic and profitable energy system	SI, FJS
		Number of patents in the energy sector	Indicates the level of research and development in the energy sector. Measured on a national level.	Total number of patents	#	EEES - Economic and profitable energy system	WIPO, WB

		FDI & technology transfer	This indicator shows to what extent foreign direct investment brings new technology. FDI is a key source of new technology.	Scale of 1-7 (1 = not at all; 7 = to a great extent)	# and country rank		WEF
		Capacity for innovation	Indicates the capacity of businesses to innovate.	Scale of 1-7 (1 = not at all; 7 = to a great extent)	# and country rank		WEF
		University-industry collaboration in R&D index	Measures to what extent universities and businesses collaborated on research and development.	Survey. Scale of 1-7 (1 = not at all; 7 = to a great extent)	# and country rank		SI, WEF

Note: Indicators calculated yearly

WEF = World Economic Forum, SI = Statistics Iceland, WIPO = World Intellectual Property Organization, WB = World Bank, FJS = The Financial Management Authority

Table 12
The methodology of indicators for the theme of energy security

Theme	Sub-theme	Indicator	Explanation	Metric	Unit	Linkages	Data source
Energy security	Sufficient energy reserves	Total primary energy supply	This indicator measures the amount of available energy in the country as primary energy, both domestic and imported.	Sum of domestic and imported primary energy	TWh	SEP - Carbon neutral energy system	NEA
		Dynamic reserve/production ratio	Indicator measures the availability of energy reserves and the sustainability of utilization. The indicator is calculated from current production levels, estimated potential, and energy demand forecasts.	Reserves (current and estimated potential) over production (current and future demand)	Ratio	SEP - Sustainable utilization of resources	NEA, MP
		Critical surplus	Another indicator measuring the amount of available energy by comparing total supply with total demand.	Total supply over total demand	Ratio	SEP - Carbon neutral energy system SEC - Reduce energy consumption	NEA

Diverse energy sources	Diversity-index for energy supply by type	Diversity in energy supply promotes energy security and independence. This indicator is calculated in primary energy by fuel type.	Modified Shannon-Wiener or HHI diversity index for primary energy supply by fuel type	%	SEP - Carbon neutral energy system	NEA
Strengthen the transmission and distribution system	Government investments in infrastructure development	To maintain a strong energy system, investments in energy infrastructure are necessary.	Total investments over GDP	ISK / GDP	EEES - Government expenditure/revenue	SI, FJS
	Efficiency of energy conversion and distribution	Indicates the efficiency of the system, which is associated with reduced energy needs and emissions. Improvements in efficiency lead to more effective utilization of resources and reduce environmental impacts.	Average the efficiency of power generation and rate of electricity T&D losses	%	Energy needs & emissions	NEA, LN
	Subterranean share of transmission and distribution system	See above in Table 7	km of system subterranean over total km of system	%	NC - Minimize visual pollution	LN
Quality of supply: urban vs. rural	Frequency of electric power grid	These indicators compare the quality of electricity distribution in urban and rural areas. Measures the equity of the system.	Frequency of electricity in urban and rural areas	Hz	SB - Benefit from energy development	LN
	Frequency and duration of blackouts		Numer of blackouts and their duration in urban and rural areas	# & min	SB - Benefit from energy development	LN
Energy independence: domestic energy	Total domestic generation and share by type	These indicators reflect the energy independence of Iceland and, as such, its energy security. Measure the amount of domestic energy generation as primary energy and its share in TPES.	Total domestic generation as primary energy by energy type	TWh	SEP - Carbon neutral energy system	NEA
	Proportion of domestic energy sources in TPES		Domestic energy generation as primary energy over TPES	%		NEA

Energy independence: import dependence	Proportion of imported energy sources in TPES	Measures import dependence. A high import ratio indicates exposure to supply shocks, price spikes, and other political risks.	Energy imports as primary energy over TPES	%		WB, NEA
Energy independence: risk of imports	Share of imports coming from politically unstable countries	Measures the share of imported energy coming from politically unstable countries. Impacts the country's energy security.	Energy from politically unstable regions over total imported energy	%		NEA, OECD
	Degree of transportation risk management	Measures the share of imported energy transported through choke points. Impacts the country's energy security.	Energy transported through chokepoints over total imported energy	%		NEA, IEA
Energy transitions	Number of fast-charging spots and other eco-friendly multi-fuel stations	Measures the rate of infrastructure improvements to enable an energy transition.	Count	#	SEC - Change of attitude	EP
	Share of passenger cars by fuel type	These indicators measure the rate of an energy transition and reflect a change of attitude. Furthermore, they show energy use patterns for different types of energy for transportation.	Number of passenger cars by fuel type over total number of passenger cars	%	SEC - Change of attitude	SI
	Energy consumption for transportation by fuel		Energy consumption fuel type over total energy consumption for transportation	%	SEC - Change of attitude	NEA, SI
	Proportion of renewable fuels in total fuel for ships	Measures the rate of an energy transition for ships.	Renewable fuels over total fuels for ships	%		SI, ITA
	Number of planes that use land connected electrical charging	Measures the rate of a possible energy transition for planes.	Count	#		ITA

Note: Indicators calculated yearly

NEA = National Energy Authority, MP = The Master Plan for Nature Protection and Energy Utilization, LN = Landsnet, WB = World Bank, OECD = Organisation for Economic Co-operation and Development, IEA = International Energy Agency, SI = Statistics Iceland, EP = Energy providers, ITA = Icelandic Transport Authority

Table 13
The methodology of indicators for the theme of economically efficient energy system

Theme	Sub-theme	Indicator	Explanation	Metric	Unit	Linkages	Data source
Economically efficient energy system	Diversity in income and industries	Diversity-index for energy consumption by sector	This indicator measures the diversity of energy consumers and, as such, the economic vulnerability of the system.	Modified Shannon-Wiener or HHI diversity index for energy consumption	%	SEC - Reduce energy consumption & energy efficiency	NEA
	Government expenditure / revenue	Government revenue from energy sales	Energy sales are a pillar of the Icelandic economy. This indicator measures whether the energy system is remaining profitable.	Revenue from energy sales over GDP	ISK / GDP	SEC - Energy efficiency	SI, FJS
		Tax revenue of carbon tax and fossil fuels	Economic tools applied by the government. Ideally, if no changes are made to these taxes, the revenue would decrease over time, indicating fewer carbon emissions and less utilization of fossil fuels.	Total revenue from carbon tax over GDP	ISK / GDP	SEP - Minimize emissions ES - Energy transitions SEP - Change of attitude	SI, FJS
		Government expenditure on fossil fuel subsidies	This indicator measures the potential distortion of fossil fuel prices. These subsidies counteract other efforts in reducing fossil fuel consumption and supporting an energy transition.	Total subsidies over GDP	ISK / GDP	ES - Energy transitions SEP - Change of attitude	SI, FJS
		Government investments in energy infrastructure	See in Table 9	Total investments over GDP	ISK / GDP	ES - Strengthen transmission and distribution system	SI, FJS

	development					
Economical and profitable energy system	Investment in the energy sector	Measured by the amount of foreign direct investment net inflows in the energy sector. Indicates how desirable it is to invest in the Icelandic energy system and economy.	FDI in the energy sector over GDP	%	SB - Knowledge creation and technological advancements	WB, IMF
	Energy intensity by sector	Energy consumed per value-added for each sector, e.g., industry, households, and transport. Indicates the profitability of the economic activity, its energy efficiency, and the potential decoupling of energy use from GDP. Can also reflect changes in the fuel mix and technological improvements.	Final energy consumption over value added by sector	kWh / ISK	SEC - Energy efficiency	NEA, SI
	Average levelized cost of electricity	Indicates the economic efficiency of energy generation. Usually, calculated as a technical parameter per energy plant, but here the indicator is averaged across all electricity power plants in the country.	Costs over electricity produced over lifetime averaged across all plants	ISK / years		NEA
	Proportion of energy use covered by long-term contracts	Measures whether Icelandic energy is cost-competitive internationally as long-term contracts are made mainly with foreign industry. It can also be an indicator of economic growth.	Energy use in long-term contracts over TPES	%	SEC - Reduce energy consumption & energy efficiency	NEA, FJS
Affordable energy prices	Share of household income spent on energy	This indicator measures the affordability of energy for households. The affordability of energy to lower-income groups needs to be ensured.	Household expenditure on energy over household income	%	SEC - Reduce energy consumption	SI
	Energy price volatility by type	Volatile energy prices can negatively affect consumers and can indicate a lack of security in the system.	Annual change in energy price per type	% by type	ES - Energy independence	SI

Note: Indicators calculated yearly

NEA = National Energy Authority, SI = Statistics Iceland, FJS = The Financial Management Authority, WB = World Bank, IMF = International Monetary Fund,

Table 14
The methodology of indicators for the theme of sustainable energy production

Theme	Sub-theme	Indicator	Explanation	Metric	Unit	Linkages	Data source
Sustainable energy production	Carbon neutral energy system	Total generation and share by type	Shows the energy supply mix and availability of energy, which reflects both energy security and the sustainability of energy production.	Total energy generation &	TWh & %	ES - Sufficient energy reserves & Diverse energy sources & Energy independence	NEA
		Share of renewables in TPES	A higher share of renewables in TPES leads to fewer emissions of GHGs and air pollutants with the associated negative environmental and health impacts. Furthermore, it increases energy security for the long-run.	Sum of primary energy from renewables over TPES	%		NEA
		Amount of carbon sequestration by energy industry	This indicator measures the carbon offsetting of the energy industry through various methods of carbon sequestration. Such efforts will be necessary to achieve a carbon-neutral energy system.	Tonnes of CO_2 eq. sequestered by the energy industry	t CO_2 eq.		EAI
	Sustainable utilization of resources	Dynamic reserve / production ratio	See above in Table 9	Reserves (current and estimated potential) over production (current and future demand)	Ratio	ES - Sufficient energy reserves	NEA

Minimize impacts on land	Total impact area of power plants	See in Table 7	Total impact area of power plants in Iceland in sq. km over total number of power plants in Iceland	sq. km / plant	NC - Protect the wilderness & Minimize visual pollution	NEA
Minimize emissions	Net emissions from energy production and utilization For: GHG, NOx, CH4, SO2, H2S, and PM2,5 Per capita, over GDP, by sector, or by TPES	Measures the amount of emission of GHG and air pollutants from energy production and utilization. These emissions have a direct impact on climate change and have adverse environmental and health effects. The intensity of emissions can be measured in terms of capita, GDP, by sector, and TPES.	Emissions of [GHG, SO2, H2S, PM2,5 or NOx] over [capita, GDP, TPES, by sector]	t of emissions / [population, ISK, TWh]	SEC - Reduce energy consumption & Energy Efficiency & Cleaner fossil fuels	EAI
	Ambient concentrations of air pollutants in urban areas	Measured for air pollutants such as SO2, H2S, NO2, and PM2,5. These air pollutants can be sourced from energy production and utilization and tend to have higher concentrations in urban areas. These can lead to adverse health impacts.	Concentration of air pollutants per cubic meter	µg per cubic m.	SEC - Cleaner fossil fuels	EAI

Note: Indicators calculated yearly

NEA = National Energy Authority, EAI = Environment Agency of Iceland

Table 15
The methodology of indicators for the theme of sustainable energy consumption

Theme	Sub-theme	Indicator	Explanation	Metric	Unit	Linkages	Data source
Sustainable energy consumption	Reduce energy consumption	Total energy consumption (primary or final) By type, per capita, over GDP, or by sector	Measures the level of energy use, shows energy-use patterns, and energy intensity of society or sectors. Can be measured in terms of primary or final energy and by type, over capita, GDP, or by sector depending on the purpose of the analysis. When measured over GDP, it indicates the relationship of energy use to economic development.	kWh as primary or final energy over [GDP, capita] or by [energy type, sector]	kWh / [capita, ISK, energy type, sector]	EEES - Economic and profitable energy system	NEA, SI
	Energy efficiency	Energy intensity by sector	See in Table 10	Final energy consumption over value added by sector	kWh / ISK	EEES - Affordable energy prices & Economic and profitable energy system SEC - Energy efficiency	NEA, SI
		Ratio of final and primary consumption	Measures the efficiency of energy transformation. Shows the relationship between the energy that enters the system as primary energy and the energy that is available to consumers as final energy.	Final energy consumption over primary energy consumption	%	ES - Strengthen transmission and distribution system	NEA
		Load factor for gross electric capacities	Use-side indicator. Measures the utilization rate or efficiency of electrical energy usage.	Average load over peak load for electricity	%	EEES - Government expenditure / revenue	NEA
		Average age of cars and ships	A use-side indicator reflecting the efficiency of the vehicle or ship fleet. Younger technologies are generally more efficient than older ones.	Sum up age of [cars or ships] over total number of [cars or ships]	Years	ES - Energy transitions	SI
	Cleaner fossil fuels	Emission factor of fossil fuels	Measures the quality of fossil fuels utilized and is a predictor for associated emissions.	Amount of emissions per unit utilized for each fuel	tCO2 eq./Mtoe	SEP - Minimize emissions	EAI

Change of attitude	Share of different forms of transportation chosen	Annual travel habit surveys measure the share of different transportation modes chosen. Can indicate the rate of an energy transition in transportation.	Survey	%	ES - Energy transitions	SSH
	Share of passenger cars by fuel type	See in Table 9	Number of passenger cars by fuel type over total number of passenger cars	%	ES - Energy transitions	SI
	Energy consumption for transportation by fuel	See in Table 9	Energy consumption fuel type over total energy consumption for transportation	%	ES - Energy transitions	NEA, SI

Note: Indicators calculated yearly

NEA = National Energy Authority, SI = Statistics Iceland, EAI = Environment Agency of Iceland, SSH = Samtök sveitarfélaga á höfuðborgarsvæðinu

Appendix B: Delphi survey

Example questions

During the first round of the survey, stakeholders assessed the importance of different sustainability goals and got the opportunity to add topics thought missing from the analysis. An example question from the first round of the survey can be seen below.

Example question from the first round of the Delphi survey:

Theme 1: Nature conservation

Sub-goal 1: Minimize environmental impact and visual pollution of the energy system

Examples of actions mentioned: Evaluate the impact on ecology, geology, etc., more subterranean power cables, minimize impact through design.

- Very important
- Important
- Moderately important
- Insignificant
- Not important

Comments:

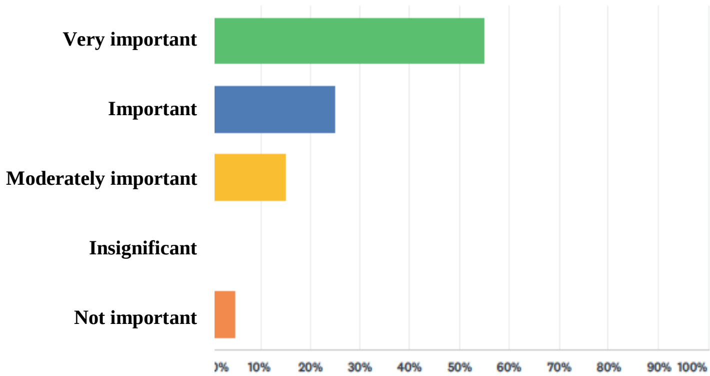
The second round of the survey consisted of updated questions based on the results of the first round, such as the elimination of low scoring topics and the addition of missing ones. In this second round, a simple graph showing the distribution of answers for each question from the first round was included; see the example question below along with a graph in Figure 6. An important feature of the Delphi survey is controlled feedback between rounds, which allows participants to re-estimate their responses with the knowledge of the general opinion of the group (German Association of Energy and Water Industries (BDEW) et al., 2016).

Example of an updated question from the second round of the Delphi survey:

Results of the first round of the survey:

Theme 1: Nature conservation

Sub-goal 1: Minimize environmental impact and visual pollution of the energy system



Updated questions:

Theme 1: Nature conservation

Sub-goal 1a: Minimize the environmental impact of the energy system

Examples of actions mentioned: Evaluate the impact on ecology, geology, etc., minimize environmental impact through design.

- Very important
- Important
- Moderately important
- Insignificant
- Not important

Comments:

Theme 1: Nature conservation

Sub-goal 1b: Minimize visual pollution of the energy system

Examples of actions mentioned: More subterranean power cables, minimize visual impact through design.

- Very important
- Important
- Moderately important
- Insignificant
- Not important

Comments:

Response rates

The response rates of Delphi participants can be seen in Table 16. The first round of the Delphi had a high response rate of 74%. However, the response rate dropped significantly in the second round of the survey to 41%. Potential reason for this drop is stakeholder fatigue or perhaps the timing of the second round of the survey (late July to early August).

Table 16: Response rates of Delphi participants

	Invited	Responded	Response rate
Round 1	27	20	74%
Round 2	27	11	41%

Overarching results

The general results of the two rounds of the Delphi survey can be seen in Table 17. The standard deviation of answers decreased between rounds of the survey indicating a higher level of agreement in the second round of the survey. Tables 18 and 19 show the highest and lowest scoring goals of the two rounds of the Delphi survey.

Table 17: General results of the Delphi survey

		Round 1			Round 2		
		Mean	Max	Min	Mean	Max	Min
Score of importance	Mean	4,09	4,60	3,30	4,09	4,73	2,18
Measure of agreement	Standard deviation	1,00	1,39	0,59	0,83	1,47	0,47

Table 18: Highest scoring goals of the Delphi survey

Theme	Goal	Round 1		Round 2	
		Mean score	St. Dev.	Mean score	St. Dev.
Nature conservation	Minimize the environmental impact of energy development - assess env. impact & minimize impact through design*	-	-	4,73	0,47
Social benefits	Social acceptance, increased public participation & informed debate - public consultation & access to information	4,40	0,75	4,73	0,47

Energy security	Energy transition (especially for transportation on land and sea) - reduce consumption of fossil fuels, infrastructure upgrades, economic incentives & raising awareness	4,60	0,82	4,55	0,93
	Energy independence - less reliance on imported fossil fuels, energy transition, economic incentives & energy transition	4,50	1,05	4,45	1,04
Sustainable energy consumption	Improve air quality and reduce GHG emissions - Less consumption of fossil fuels, support carbon sequestration & quality restrictions on fossil fuels	4,55	0,83	4,73	0,65
	Reduce overall energy consumption and improve energy efficiency - economic incentives for energy efficiency, government leads by example, improved public transportation & bike paths	4,40	0,88	4,73	0,65

* Goal updated between rounds. Therefore, only scores for one of the two rounds.

Table 19: Lowest scoring goals of the Delphi survey

Theme	Goal	Round 1		Round 2	
		Mean score	St. Dev.	Mean score	St. Dev.
Nature conservation	Reclaim nature - wetland restoration, land reclamation & decommission of older power plants	3,6	1,14	3,64	0,92
Energy security	Distributed energy generation – more geographical distribution of power plants & small-scale power plants	3,3	1,17	3,36	1,36
	Ensure that the transmission and distribution system does not stop development - connect with the European power grid*	-	-	2,18	1,33
Economically efficient energy system	Increase diversity in national income – decrease economic risk with more diverse energy consumers, knowledge as export & energy as an export (interconnector)*	3,4	1,23	-	-
	Energy as an export - submarine cable to Europe & domestic industry to produce exports*	-	-	2,82	1,47
Sustainable energy consumption	Social acceptance of energy utilization - More diverse energy consumers, inform the public & reconsider emphasis on heavy industries	3,55	1,39	3,73	1,42

* Goal updated between rounds. Therefore, only scores for one of the two rounds.

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Paper V: Sustainable energy development and the role of geothermal energy in Iceland – Stakeholders’ view

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Sustainable Energy Development and the Role of Geothermal Energy in Iceland -- Stakeholders' View

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ABSTRACT

Sustainable energy development has become a prominent policy objective worldwide. What that entails can differ significantly from one energy system to the next. Without a clear notion of what a sustainable energy future should look like, it is difficult to chart the path towards it. Stakeholder engagement in decision making and policy development is essential as is progressively more recognized, if only to increase public acceptance and capture a more representative picture of the problem in question. An effective stakeholder engagement process can be used to identify what the sustainable energy development of a system would involve. In this research, stakeholders to the Icelandic energy system were engaged for the purpose of determining what a sustainable energy future in Iceland should entail. Key stakeholders of the system were engaged through individual semi-structured interviews, the public's voice was captured through focus groups, and results were verified through a Delphi survey. Based on stakeholder input, it was possible to identify various themes and goals of sustainable energy development in Iceland. As anticipated, geothermal energy was part of that discussion. The environmental and even health benefits of the utilization of geothermal energy for district heating were highlighted by many. Questions were, however, raised on how sustainable geothermal energy really is, how efficiency of utilization could be increased, and the associated environmental impacts decreased. An insight into the role of geothermal energy in Iceland's sustainable energy future and what that future holds in store is crucial to decision-makers in the country, especially since there is no long-term strategy for energy development in place.

1. INTRODUCTION

The role of energy in achieving sustainable development was recognized with the introduction of the UN's Sustainable Development Goal (SDG) 7 on affordable and clean energy, (UN General Assembly 2015). The importance of sustainable energy development has been highlighted by an increasingly energy intensive world with depleting fossil fuels and raised environmental awareness. Therefore, sustainable energy development (SED) is now firmly on the international political agenda and a pressing topic of many governments. In this new SED paradigm, the environmental, economic, and social impacts of energy development are considered; the three pillars of sustainable development (United Nations Development Programme et al., 2000). This includes a recognition of the role energy plays in promoting economic growth and social development. A transition towards renewable energy sources is necessary for SED, both to secure a sustainable supply of energy and to reduce the adverse environmental and health impacts of the current energy system.

SED is a complex and multi-dimensional concept that can vary in meaning based on the context it is applied in and the perspective of the user (Cherp and Jewell 2014). It is important to take account of national circumstances when developing an action plan for SED. Without a clear idea of what a sustainable energy future should entail, it is difficult to determine how it can be reached. Stakeholder engagement informs what SED entails, and facilitates that stakeholders buy into the decision-making process. Decision makers are becoming increasingly aware of the importance of public participation for effective decision making and to increase public acceptance (Irvin and Stansbury 2004). By engaging with stakeholders, it is possible to take account of different viewpoints and, thus, capture a more comprehensive and representative picture of SED and what a sustainable energy future might entail. However, current strategies for public participation vary significantly both in methods and transparency.

In this study, Iceland is presented as a case study and its energy system is analyzed. By engaging with stakeholders, the main challenges and opportunities of SED in the country are identified. The scope of this analysis is limited to assessing how geothermal energy has contributed to SED and how it can further advance it. Currently, there is no long-term energy policy or vision for energy development in Iceland. Work on such a policy is, however, underway. The results of this study, a thorough analysis of stakeholders' goals and objectives for SED in the country, provides valuable insight into what SED in Iceland entails. This insight can serve as a base for an energy policy; an action plan towards SED.

Thus, the aim of this research is to:

- Analyze the past and future role of geothermal energy for sustainable energy development in Iceland according to stakeholders
- Present an effective public participation process to engage stakeholders

The rest of the paper is structured as follows: Section 2 contains a brief overview of what the concept sustainable energy development entails as well as an overview of energy development in Iceland and the utilization of geothermal energy. The third section describes the methodology developed for engaging with stakeholders. The results of stakeholder engagement in Iceland are presented and discussed in the fourth section. Finally, the paper is concluded in section 5 where the potential implications of this analysis are outlined, and next steps are proposed.

2. BACKGROUND

2.1 Sustainable energy development

The purpose of energy systems is to improve human well-being by providing services that both promote economic growth and social development while minimizing environmental and health costs (United Nations Development Programme, United Nations Department of Economic and Social Affairs, and World Energy 2000). Moreover, energy is essential in achieving the desirable social, environmental, and economic goals of sustainable development as confirmed by the introduction of SDG7 (United Nations Development Programme, United Nations Department of Economic and Social Affairs, and World Energy 2000). Broadly speaking, one can say that sustainable energy development (SED) is the application of the concept of sustainable development to energy. SED is sometimes referred to as a new development paradigm where the economic, environmental, and social impacts of energy development are considered, as first introduced in the UNDP's World Energy Assessment report in 2000 (United Nations Development Programme, United Nations Department of Economic and Social Affairs, and World Energy 2000).

One of the most critical challenges currently facing the world is how to provide energy services to all while reducing the associated environmental and health impacts (United Nations Development Programme, United Nations Department of Economic and Social Affairs, and World Energy 2000). A transformation of the current energy system, both in generation and consumption, will be required to address this challenge (International Energy Agency 2008). This transformation calls for a transition to efficient low-carbon and environmentally-sound energy generation with increased utilization of renewable energy sources (International Energy Agency 2008). This is only feasible if modern technologies and renewables are economically viable and the affordability of energy is ensured (United Nations 2002). Sustainable energy consumption will involve increased energy efficiency and awareness of the negative impacts of the current energy system that will lead to a change in current consumption patterns (United Nations 2002). None of this is achievable without the necessary political will and technological advancements to push a transformation of current energy practices (United Nations Development Programme, United Nations Department of Economic and Social Affairs, and World Energy 2000).

It is important that energy development increases international equity by providing modern energy services to all (Oyedepo 2012). A lack of access to energy has been connected with some of the main challenges of sustainable development such as poverty, lack of opportunities for women, and environmental degradation (United Nations Development Programme, United Nations Department of Economic and Social Affairs, and World Energy 2000). Energy services should be equitably affordable and accessible to all while promoting human wellbeing and raising living standards (International Atomic Energy Agency et al., 2005). Furthermore, a secure and reliable supply of energy is necessary for the sustainable development of a society (United Nations Development Programme, United Nations Department of Economic and Social Affairs, and World Energy 2000).

2.2 Energy development in Iceland

Iceland is an isolated island sitting on top of the Mid-Atlantic ridge. It is considered one of the most volcanically active areas in the world with active volcanoes and geysers. The population of Iceland was about 350,000 in 2018 with the majority of people living in the capital region (Statistics Iceland 2018). The rest of the country is mostly sparsely populated which is a challenge for energy distribution. The Icelandic energy system is unique globally due to its high share of renewables in its primary energy use. About 85% of total primary energy supply in Iceland is produced by domestic renewable energy sources, which is the highest share of renewables in any national energy budget (Ministry of Industries and Innovation n.d.). The main renewable sources are geothermal energy and hydropower, respectively, about 62% and 19% of primary energy in 2018 (National Energy Authority of Iceland 2019). Fossil fuels are mainly used for transportation on land, at sea, and in air, and their share had reduced to about 19% in 2018 (National Energy Authority of Iceland 2019). Other energy sources, such as wind generation, are used marginally but could become significant energy sources in the future.

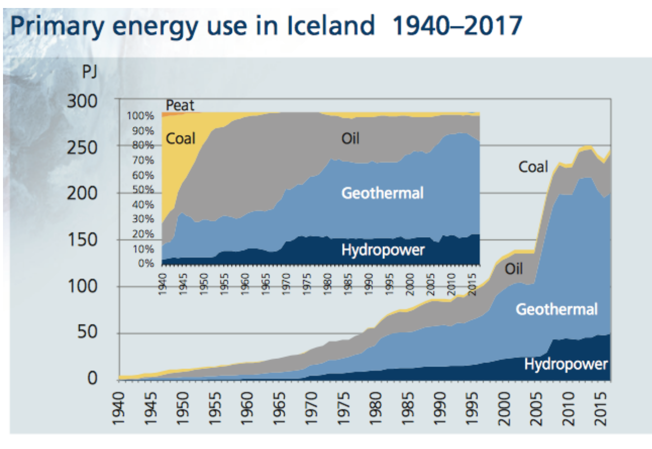

Figure 1: Graphs showing the development of primary energy use in Iceland by energy source. The share of renewables has increased considerably over time to become the highest in any national energy budget (National Energy Authority of Iceland 2018)**.**

Another unique attribute of the Icelandic energy system are the high rates of electricity consumption per capita (Ministry of Industries and Innovation n.d.). In 2017, 19.239 GWh were produced in the country, as seen in Figure 2 (National Energy

Authority, 2017). Almost 100% of electricity production is generated from renewable energy sources; about 73% from hydropower and 27% from geothermal energy. Most of this electricity, or about 77% in 2017, is consumed by energy-intensive industries in the country. General use, which includes residential consumption and other industries, only accounted for about 18% of electricity consumption in 2017. In 1965, Landsvirkjun (National Power Company) first sold electricity for aluminum smelting (National Power Company of Iceland n.d.). Since then a number of hydropower and geothermal plants have been built with the main purpose of supplying electricity to energy-intensive industries, most notably Kárahnjúkar hydropower plant in 2007. This increased electricity production for mostly foreign industrial companies has been highly controversial and resulted in multiple protests by environmentalists, especially against the Kárahnjúkar power plant (National Power Company of Iceland n.d.).

Installed capacity, electricity production and consumption 2015- 2017

Installed capacity in power plants	2017		2016		2015	
	MW	%	MW	%	MW	%
Hydro	1.984	71,7	1.985	72,7	1.986	71,7
Geothermal	708	25,6	663	24,3	665	24,0
Fuel	72	2,6	81	2,9	117	4,2
Wind	3	0,1	3	0,1	3	0,1
Total	**2.767**	**100**	**2.732**	**100**	**2.771**	**100**
Electricity production	**2017**		**2016**		**2015**	
	GWh	%	GWh	%	GWh	%
Hydro	14.059	73,1	13.470	72,6	13.780	73,3
Geothermal	5.170	26,9	5.067	27,3	5.003	26,6
Fuel	2	0,01	2	0,01	4	0,02
Wind	8	0,04	9	0,05	11	0,06
Total	**19.239**	**100**	**18.549**	**100**	**18.798**	**100**
Electricity consumption	**2017**		**2016**		**2015**	
	GWh	%	GWh	%	GWh	%
General use*	3.397	17,7	3.242	17,5	3.434	18,3
Heavy industry*	14.870	77,3	14.334	77,3	14.356	76,4
Losses&use-power plants*	375	2,0	427	2,3	432	2,3
Distribution losses*	223	1,2	185	1,0	207	1,1
Transmission losses*	373	1,9	361	1,9	370	2,0
Total	**19.239**	**100**	**18.549**	**100**	**18.799**	**100**
*Estimated 2017						

Figure 2: Table showing the installed capacity, electricity production and consumption in Iceland from 2015 to 2017 (National Energy Authority of Iceland 2018)**.**

Currently, there is no energy policy in Iceland. This lack of a comprehensive energy policy means there is no long-term vision for energy development in the country. Since the spring of 2018, work has been underway on developing a long-term energy policy for the country to be put before Parliament in the spring of 2020 (Ministry of Industries and Innovation 2018). The aim of this policy is to further sustainable energy development and address the challenges the energy system faces. This involves addressing the question of how to secure a sustainable supply of energy in the country in a responsible manner. A number of potential future challenges for the Icelandic energy system have been identified that the energy policy should address. These include promoting the sustainable utilization of energy resources, supporting an energy transition, and increasing energy equity across the country. It will be necessary to improve infrastructure to meet some of the challenges facing the system. Even though Iceland is a leader in the generation of renewable energy, it is still highly dependent on imported fossil fuels for transportation. In order to meet international obligations for emissions and climate action, an energy transition is essential. It will be important to evaluate how and for what the energy in Iceland is utilized. Considering that power intensive industries consume a large majority of the electricity produced, it will be necessary to take into account how an energy policy could affect these industries and the national budget. The social impacts of energy generation should be recognized to ensure public acceptance. In the preliminary plans for the energy policy, an emphasis is placed on supporting research and innovation to advance an energy transition, identify new energy options, and promote the export of knowledge. Furthermore, the importance of stakeholder engagement and data for policy development and decision making is highlighted (Ministry of Industries and Innovation 2018).

2.2 Utilization of geothermal energy in Iceland

Since the times of Vikings, geothermal energy has been utilized for bathing, washing, and even cooking in Iceland. In the 20th century, the utilization of geothermal energy for space heating and electricity production started and increased steadily (Icelandic Geosurvey n.d.). Currently, geothermal energy is the main energy source for primary energy use, as seen in Figure 1 above (National Energy Authority of Iceland 2019). Geothermal energy is used both directly for space heating and indirectly for electricity production. Recent technological advancement of ground-source heat pumps have enabled the use of geothermal energy outside of the volcanic zone where thermal water or steam is readily available (National Energy Authority of Iceland n.d.).

In 1930, the first boreholes were drilled in the capital, Reykjavík, and used for space heating and a swimming pool. By 1981, 98% of the inhabitants of Reykjavík had geothermal district heating (Icelandic Geosurvey n.d.). Geothermal district heating in the capital significantly reduced the adverse health impacts caused by the burning of fossil fuels for heating that caused black coal clouds to loom over the city (Gunnarsdóttir 2002). This initial success in the capital promoted a huge push for the utilization of geothermal energy through the country. In 2017, almost 90% of houses in Iceland were heated with geothermal energy through district heating, as seen in Figure 3. This transition to geothermal energy for space heating and, later on, electricity production was an important step towards SED in the country. The environmental and health impacts of the formerly fossil fuel-driven energy system were significantly reduced, especially the greenhouse gas emissions of the system. Furthermore, the energy security of the country was improved with increased utilization of domestic energy sources. A clear economic gain has been attributed to this transition, including from reduced carbon tax and health care costs (Gunnarsdóttir 2002).

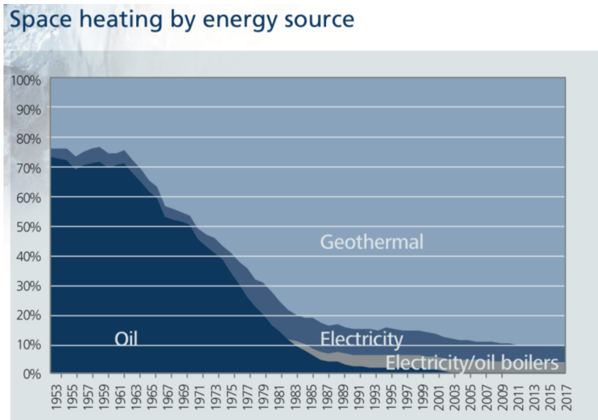

Figure 3: Graph showing space heating by energy source. The share of geothermal energy in space heating has increased substantially over the last few decades (National Energy Authority of Iceland 2018)**.**

Following the oil crisis in 1970, there was an even greater push for an energy transition. In the 1970's, geothermal energy was first utilized for large-scale electricity production using steam turbines and, subsequently, a number of geothermal power plants were opened (National Power Company of Iceland n.d.). In 2017, geothermal energy accounted for about 27% of electricity produced in the country or about 5.000 GWh, as seen in Figure 2 (National Energy Authority of Iceland 2018). The generation of electricity from geothermal energy has grown substantially over the last couple of decades in response to increased demand from energy intensive industries (National Energy Authority, 2019). Most recently, Þeistareykir Geothermal Power Station was opened in two 45 MW steps in 2017 and 2018 which mainly produces electricity for a silicon metal plant situated in the same area (National Power Company of Iceland 2016).

Various challenges to the utilization of the energy source have become apparent. The sustainable utilization of geothermal resources is a concern as experience has shown that excessive production in a geothermal field can only be maintained for a relatively short time without depletion (National Energy Authority of Iceland 2010; Axelsson 2016). Therefore, stepwise development of geothermal power plants is recommended to reduce long-term production costs and promote sustainable utilization (National Energy Authority of Iceland 2010; Axelsson 2016). Numerous different environmental, health, and even social impacts have been associated with the utilization of geothermal energy. These include emissions of greenhouse gases and harmful air pollutants, water contamination, induced seismicity, and resettlement (Shortall et al., 2015). The generation of electricity using geothermal energy has been criticized for lack of efficiency. To increase the efficiency of utilization, geothermal energy should be utilized for combined heat and power generation (Mburu 2009).

3. METHODOLOGY

3.1 Design of stakeholder engagement

The public participation process presented involves five main steps, as seen in Figure 4. The first step involves creating a stakeholder map to identify what stakeholders are involved and should be engaged. For the second step, informed stakeholders of the system are engaged through semi-structured individual interviews. The aim of the third step is to capture public opinion through focus group interviews. Thereafter, interviews are analyzed according to established qualitative methodology to identify emerging themes. The fifth and final step of the process consists of a Delphi survey sent to engaged interviewees to verify identified results. This process and its five steps are further described below.

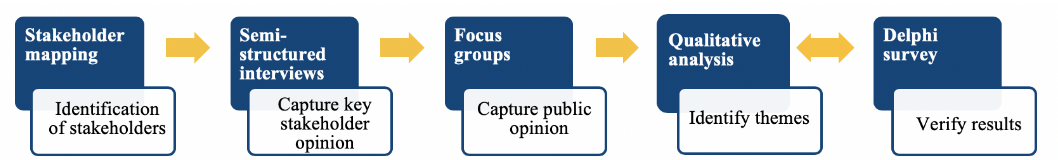

Figure 4: Public participation process consisting of five main steps presented in consecutive order. Diagram compiled by authors.

A vital first step to stakeholder engagement is to identify the stakeholders. It is important to select a diverse group of stakeholders that can give a comprehensive picture of the system in question. A variety of methods can be used to identify all potential stakeholders, such as mind mapping, brainstorming, generic stakeholder lists, value chain and life cycle approaches (Durham et al., 2014). For this analysis, a combination of mind mapping, brainstorming, and value chain approach was applied. Two overarching stakeholder groups were created for this analysis; "value chain" and "value chain influencers & enablers", as seen in Figure 5. The "value chain" is simply the value chain of the Icelandic energy system, from landowners and producers to consumers. The "value chain influencers & enablers" group accounts for those stakeholders that can affect or be affected by the value chain or parts of it but do not directly represent any one part of the chain.

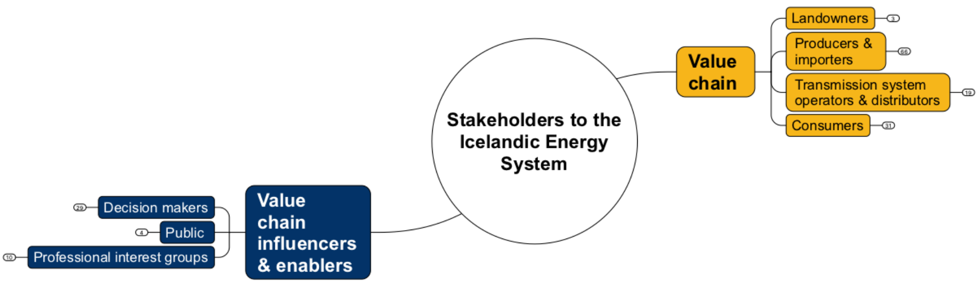

Figure 5: Map of the stakeholders to the Icelandic energy system split into value chain and value chain influencers and enablers. Map only shows the top two layers of categorization; the map expands several layers further to more specific sub-groups. Map generated by authors.

The stakeholder map was used to select a diverse group of interviewees representing the different groups across the map. Informed stakeholders of the system were engaged through semi-structured individual interviews and the public's opinion was captured through focus group meetings. By interviewing more informed stakeholders individually, a greater emphasis is placed on their expert knowledge as compared to the input of stakeholders with perhaps less knowledge of the system. Before stakeholders were engaged, an interview framework was developed consisting of open-ended and non-leading questions (Harvey 2011). The semi-structured nature of the interviews allowed for the flexibility to clarify the interviewee's answers and delve further when deemed necessary and of particular value. The interview framework consisted of questions on the current status of the Icelandic energy system, sustainable energy development, and decision-making in the country. For this paper, the focus is on how stakeholders discussed geothermal energy, specifically, albeit the purpose of the interviews was to assess SED in Iceland in general. For this analysis, 27 stakeholders were engaged through 16 semi-structured interviews and two focus groups meetings from October 2017 to February 2018. Given the interviewees permission, all interviews were recorded and, subsequently, transcribed for a further analysis.

Data from the interviews was systematically analyzed through open-coding in accordance with the methods of grounded theory (Merriam and Tisdell 2016). Following this process, frequently mentioned issues or topics were translated into themes and subthemes that were essentially the goals and objectives of stakeholders for a sustainable energy future in the country. One overarching theme for sustainable energy development in Iceland, a comprehensive long-term energy policy, and six sub-themes were identified that are further described below.

Following a qualitative analysis, a Delphi survey was developed to further verify the identified themes. The Delphi survey technique is a structured stakeholder engagement method consisting of two or more rounds of anonymous surveys. The technique is widely used in various fields with the purpose of obtaining the opinion of diverse stakeholders or experts, generally with the aim of reaching a consensus among the group. For this analysis, the purpose of the Delphi survey was to get interviewees to reaffirm analyzed results and give them the option of adding elements that might not have been mentioned during the interviews. Two rounds of a structured online survey were sent to interviewees and, subsequently, themes were updated as deemed necessary. The results of this analysis were used as a foundation for the selection of sustainability indicators to measure progress towards SED in Iceland.

4. RESULTS AND DISCUSSIONS

4.1 Sustainable energy development in Iceland

A consistent and overarching goal for SED in Iceland according to its stakeholders was a comprehensive long-term energy policy. There under, six different themes were identified that the energy policy should touch on, as seen in Figure 6. These themes are further described in Figure 6.

Nature conservation was a prominent theme in the interviews. Multiple stakeholders emphasized the importance of minimizing the environmental impact of energy development and protecting the wilderness and pristine nature. As tourism has become one of the pillars of the Icelandic economy in recent years, the relationship between energy development and tourism was discussed. A number of stakeholders highlighted that visual pollution of the energy system should be reduced, for instance by increasing the share of subterranean transmission lines.

The second theme was to ensure the social benefits of sustainable energy development. This includes improving social acceptance of energy development by frequently involving and informing stakeholders throughout decision-making. A few interviewees thought that benefits from energy development should be felt in the local community, such as job creation or infrastructure upgrades. Knowledge creation and innovation for technological advancements was identified as part of this sub-goal and were thought essential to SED in Iceland.

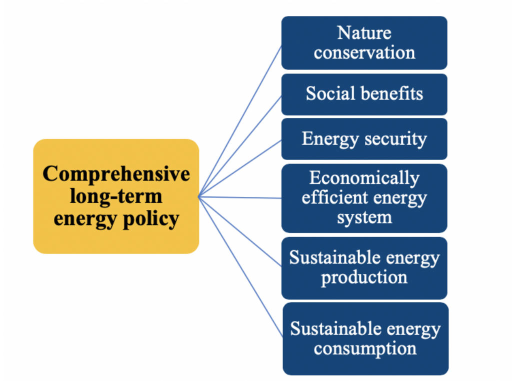

Figure 6: Themes identified from stakeholder interviews; one overarching goal for SED in Iceland and six sub-goals. Diagram generated by authors.

Energy security is integral to sustainable energy development as was recognized by most stakeholders. Some discussed the necessity of a reliable supply of electricity in the entire country enabled, potentially, through increased distributed energy generation and infrastructure upgrades. Many discussed the multiple energy sources in the country and that more diverse energy sources, such as wind generation, contributed to energy security and SED. Finally, energy independence was discussed at length, most prominently, in relation to an energy transition and becoming independent of imported fossil fuels.

Stakeholders discussed that an economically efficient energy system is necessary for SED to be possible. The economic efficiency of energy production and ensuring its profitability was highlighted by a few stakeholders which included expanding the concept of economic value to untouched nature and wilderness. As discussed above, most of the electricity produced in the country is sold to energy-intensive industries which has made energy a significant contributor to the national income. Some stakeholders mentioned that the diversity of customers should be increased since, currently, there is only a handful of large consumers to a great degree in the same sector or subject to the same economic influences. A number of stakeholders argued that the utilization of energy sources could be improved, for instance, by connecting the Icelandic power grid to the European one and selling electricity to continental Europe. Finally, current energy pricing was discussed where some pointed out the lack of equity in energy pricing across the country.

Sustainable energy production was considered essential to SED in Iceland and was discussed to some extent by all stakeholders. This included minimizing the environmental impact of energy production and mandating a more comprehensive environmental impact assessment prior to construction. The sustainable utilization of energy sources was discussed, especially in relation to geothermal energy. The necessity of stricter quality requirements for fossil fuels was mentioned by a couple of stakeholders. A multitude of potential energy options in the country were discussed and the lack of a regulatory framework for new energy options, such as wind, was highlighted by many.

Sustainable energy consumption is necessary for SED in Iceland according to stakeholders. This involves decreasing overall consumption, especially of fossil fuels, and increasing energy efficiency. For this to be possible, a change of attitude and increased awareness of the harmful impacts of the current energy system was thought to be necessary. Interviewees discussed that the government should lead by example, implement economic incentives to promote increased energy efficiency, and improve public transportation. A common topic of discussion was whether energy-intensive industries in Iceland should be continued in the long-term and whether Icelandic energy should be sold to "better" and "cleaner" industries.

These six themes interrelate and overlap to some extent. The overarching goal of a comprehensive long-term energy policy needs to touch on each of these to further sustainable energy development in the country. Through stakeholder engagement, it was possible to identify the sustainability goals of a diverse groups of stakeholders. Stakeholders discussed what a sustainable energy future in Iceland should entail and what actions could take the country there. It was pleasantly surprising that such a comprehensive picture of a sustainable energy future was captured through the interviews. Most stakeholders were knowledgeable of the issue and willing to discuss the various challenges the system faces. As it turns out, stakeholders seemed to be in agreement that changes were necessary to further SED in the country and, to a large extent, had similar thoughts of what SED entails. For instance, a stakeholder representing fossil fuel importers agreed with other stakeholders that an energy transition in transportation was necessary and that his business model just needed to follow along with that, in his opinion, inevitable development.

These results show largely what stakeholders believe SED in Iceland entails which is valuable in the policy development process. The results highlight the lack of a comprehensive long-term energy policy in the country and as presented, the results show what such a policy should involve. Work on an energy policy is already underway in Iceland which even further adds immediacy to the work presented here. An important next step is for the researchers to get in front of the working group on the Icelandic energy policy and present these results.

4.2 Geothermal energy for sustainable energy development in Iceland

Geothermal energy was mentioned often by stakeholders when discussing the Icelandic energy system and its future. It was discussed both in a positive and negative light; as one of the main reasons why Iceland is doing well on energy issues relative to other countries and as one of the challenges the system faces. Stakeholders were aware of the large role geothermal energy plays in the Icelandic energy system, especially through district heating. Five main themes of discussion on geothermal energy for SED were identified from the interviews, as presented in Figure 7. These themes and the role of geothermal energy for SED in Iceland are analyzed further in the following sections. Quotations in the following sections are all translated from Icelandic by the authors.

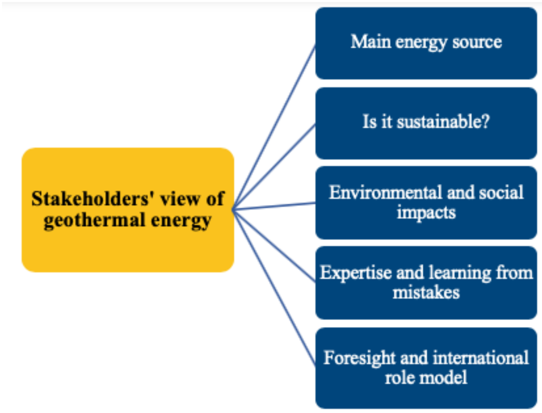

Figure 7: Figure showing the main themes of discussion identified in stakeholders' view of geothermal energy in Iceland. Diagram generated by authors.

4.2.1 Main energy source

When asked to describe the current situation of the Icelandic energy system, interviewees discussed the utilization of geothermal and hydropower energy sources. They mentioned how this combination of energy sources complemented each other well, where geothermal energy provides a stable base load for the system while the generation of hydropower fluctuates more. The direct utilization of geothermal energy for district heating and indirect utilization for electricity production was discussed. One interviewee emphasized the importance of this combination to increase the efficiency of utilization: "We… heat water for district heating and we also produce electricity. That is the best utilization of the heat". As mentioned earlier, stakeholders identified energy efficiency as an important aspect of SED and, therefore, it is important to strive to maximize the efficiency of utilization.

Many interviewees were aware of the fact that geothermal energy is by far the largest energy source in the country when looking at primary energy consumption. The utilization of geothermal energy, especially for district heating, was considered by a few as one of the main reasons Iceland is an international energy leader. Some believed that geothermal's weight in the Icelandic energy mix might even further increase in response to climate change and melting glaciers, as said by one interviewee:

> *... in the next century there will be large changes. Thereby, if one looks at that per se, then one can almost assert that the geothermal system, their weight will increase, and wind will come in. Because wind will continue to be here even if the glaciers disappear.*

Stakeholders considered energy security an important aspect of SED which included increasing the diversity of energy sources. For future development, it will be important to consider the impacts of climate change on the energy sources of the country, particularly hydro, as highlighted in the quote above. The impacts of climate change on geothermal sources are not as clear as those on hydro sources in country, many of which are rooted in the melting glaciers. Therefore, the utilization of geothermal sources could be more reliable for the long-term as it is less climate dependent. Furthermore, the reliability of the resource itself and its utilization was thought to be a contributor to Iceland's current energy security.

Various aspects of geothermal energy were discussed that contribute towards SED. The affordability and accessibility of geothermal district heating was discussed. As put by one interviewee: "It is the only cheap energy in the country and I think it is a basic premise that people, yes, that people live in Iceland is to have, to get this heat". A few stakeholders discussed how geothermal district heating and these low heating prices are not available to all Icelanders, in particular those outside of the volcanic zone. In these cold areas, electricity is used often for heating with cost higher in multiples. One interviewee discussed the following potential solution to this problem:

> *That is one of the big projects where energy efficiency is supported. That is in many areas… heat pumps, for example…. the increased utilization of geothermal energy in cold areas needs to be supported through heat pump projects which, subsequently, supports an energy transition as well.*

Based on this, the increased utilization of heat pumps in cold areas of the country would contribute to SED in a number of ways, such as promoting sustainable energy consumption and increasing equity in energy access and pricing.

4.2.2 Is it sustainable?

One of the main challenges that stakeholders discussed regarding the utilization of geothermal energy was whether it is sustainable. Some stakeholders confused the two terms: sustainable and renewable. A renewable resource is naturally replenished with time and, therefore, renewability is a physical characteristic of the resource. Sustainable energy is energy production that will last for the foreseeable future. If the utilization rate of the resource surpasses its natural recharge rate, it becomes unsustainable. Therefore, the sustainability of an energy resources has to do with its utilization. Geothermal energy is a renewable resource that can be sustainable if managed well and not overutilized. For clarification, the correct terminology is used in the following quotes.

When discussing the sustainability of geothermal energy, one stakeholder went as far to say:

> *[The public and the government] were persuaded to believe that geothermal energy is a [sustainable] energy source. It isn't, at least not on the timescale we use when we are talking about power plants. It is on a much much larger time scale. But on the timescale of construction et cetera, then this is mining. It isn't, not a [sustainable] resource.*

Another stakeholder stated that the sustainability of geothermal depends on "what you define as a sufficiently rapid rate of replenishment". A third one said on a similar note: "geothermal energy isn't exactly easy to deal with… it isn't really the solution that everyone hoped it would be". In this context, a number of stakeholders emphasized the importance of sustainable utilization to ensure its sustainability. Experience has shown that the longevity of production from geothermal resources can be ensured through improved management and sustainable utilization. As put by one interviewee: "we, of course, enjoy having these low electricity and heating prices compared to elsewhere, however, it is no reason to manage the resource poorly". The sustainable utilization of geothermal resources is important for SED (Axelsson 2016). One of the main themes of SED was sustainable energy production which includes utilizing geothermal sources at a rate that does not exceed the natural recharge rate of the field.

4.2.3 Environmental and social impacts

Stakeholders discussed a number of adverse environmental and social impacts associated with the utilization of geothermal energy. One stakeholder said the following:

> *Additionally, [a geothermal source] can pollute a lot and it can be a complete lottery whether it pollutes or not and what chemicals are released into the air depends on where the steam is coming from, what solutes are in this water. So, I believe we discuss geothermal very lightly.*

Similar to this, one stakeholder recalled that, at one point, inhabitants of Reykjavík called for the closure of Hellisheiði geothermal power plant due to hydrogen sulfides pollution that winds blew to the city. These emissions have been associated with adverse health impacts and damage to buildings. The fact that "we don't know the long-term impacts" of geothermal utilization as it has only been used at this scale for a few decades was highlighted by one stakeholder.

One interviewee said about geothermal utilization: "I believe there is a general relative acceptance in the country" but, subsequently, went on to discuss the various environmental impacts it can have. The visual pollution and harmful impacts on geological formation that geothermal utilization can have were mentioned, as said by one stakeholder:

> *It is important to realize the status of geothermal energy and try to better understand what it means. Otherwise, we will just utilize this geothermal energy as it is mining, and we will destroy the immensely beautiful nature that has a lot of attraction for temporary gains. It is completely completely different to observe a geothermal area where there are no man-made structures and the nature is unspoiled.*

This was discussed especially in relation to tourism in the country, a recent pillar of the Icelandic economy. A couple of stakeholders emphasized that retired geothermal sources that were formerly utilized, should be reclaimed to their former state if possible. Emissions from geothermal utilization and, in some cases, induced earthquakes can reduce the quality of life in the local community and impact tourism in the area due to visual pollution. It is important to consider the potential impacts the utilization of geothermal sources can have on local communities, as said by one interviewee: "Must make sure not to trample on the rights of an entire village, people need to think a bit more about the interests of those that live on the margins of [geothermal power plants]".

For geothermal to contribute towards SED, the adverse environmental and social impacts associated with its utilization need to be minimized. One stakeholder even argued for the possibility of zero-emission geothermal utilization and said that this was already technically feasible. One significant step towards this are the internationally acclaimed projects CarbFix and SulFix. In these projects, carbon dioxide and hydrogen sulphide are captured from geothermal utilization and, subsequently, stored as a rock in the subsurface for good (Reykjavik Energy n.d.; Gunnlaugsson 2016). Another possibility mentioned by the stakeholder was to utilize the emissions from geothermal power plants for greenhouses, algae production, and more. Zero-emission geothermal power plants would be an important step towards SED in the country.

4.2.4 Expertise and learning from mistakes

Many stakeholders acknowledged that Iceland is an international leader in the utilization of geothermal energy, both for electricity production and district heating. Nevertheless, the importance of learning from mistakes and being cautious for future development was emphasized, as said by one stakeholder:

> *I believe increased knowledge and consideration in the management of geothermal power plants or geothermal energy; management of geothermal energy and the construction of power plants is a necessary step.*

As discussed above, the renewability of geothermal energy was questioned, the various adverse environmental and social impacts of geothermal utilization were recognized, and current practices of geothermal utilization were compared to mining. One interviewee said: "the tradition in geothermal energy development in Iceland is slow build-up, there are examples that is has not been". The examples discussed were Hellisheiði and Reykjanes power stations that were thought to be "built up way too fast and on too little knowledge". Stakeholders emphasized learning from these mistakes and in the future, there should be stepwise development of geothermal resources. As said by one stakeholder: "We have a resource that has the potential to be sustainable, we should use it with the most possible foresight and knowledge so that it won't be wasted".

For geothermal energy to contribute towards SED, slow and cautious build-up of geothermal power stations is necessary. Stepwise development allows for the exploration of the generating capacity of the geothermal field to ensure the renewability and sustainability of the utilization. Furthermore, a multi-step approach is considered more cost-effective than a single large step strategy (Stefánsson 1992; Axelsson 2016). It is important to minimize the adverse impacts of geothermal utilization throughout the process; from design to management. As put succinctly by one stakeholder, geothermal resources need to be "utilized in a responsible manner".

4.2.5 Foresight and international role model

When discussing the energy transition that took place with geothermal district heating, a number of stakeholders mentioned that a similar kind of foresight and ambition is needed to push SED in Iceland further. A lack of an energy policy and a long-term plan for energy development in the country make this difficult. Stakeholders agreed that a large jump towards SED was taken with geothermal district heating and that another large jump is needed to tackle some of the challenges the system faces currently, such as an energy transition in transportation. One stakeholder put it this way:

> *I feel like there is an incredible lack of ambition in this all. I would like to see plans become much more ambitious and I would like to see a similar kind of attitude towards the electrification of the car fleet as there was when geothermal district heating was adopted.*

A number of stakeholders discussed how Iceland is viewed as an international energy leader with ample amounts of renewables and a clean and pristine country. Subsequently, stakeholders went on to discuss how this image was not necessarily true. As said by one stakeholder:

> *Iceland's image is a bit much of a clean and beautiful country and energy production is a big contributor to this. The fact that we switched to district heating here in the last century and then how our energy is produced, the image from this I believe is very positive in many foreign countries. To some extent, we just need to live up to it.*

More ambitious plans and actions for SED need to be taken for Iceland to live up to this international image which largely is based on its utilization of geothermal resources. Hopefully, the pending energy policy will push the country towards this.

4.3 Advantages and disadvantages of public participation approach

The main benefit of the public participation process presented above is a structured approach to stakeholder engagement that increases comprehensiveness and minimizes the potential for bias. Through this approach, the stakeholders of the system in question are identified and their role and relationships are analyzed. This enables the selection of a diverse group of stakeholders to be engaged. As a result, multiple viewpoints are considered, and a balanced and comprehensive picture of the system is captured. The final step of the process, the Delphi survey, gives stakeholders a chance to review the analysis and verify results which, subsequently, increases their robustness. The aim of this research was to analyze stakeholders' view of SED in Iceland. Through stakeholder engagement, it was possible to capture stakeholders' sustainability goals in this context. The results of such a stakeholder engagement can provide a foundation for policy development and the selection of sustainability indicators. Experience has shown that public participation during policy development promotes a transparent and effective decision-making process and increases the likelihood of public acceptance.

The main downside of the process is that it can be quite labor intensive, time consuming, and, consequently, expensive. As with any qualitative analyses, there is always potential for the researcher's influence and bias. Therefore, the researcher needs to be aware of this throughout the process. The success of the process depends largely on how accessible stakeholders of the system are. As Iceland has a small population with a relatively flat structure, this was not a problem. The researchers were able to interview stakeholders in high-level positions fairly easily as well as the general public which was crucial to the success of this study. This easy access to stakeholders is not a given in all places. Lastly, there is the potential for stakeholder burnout as stakeholders are engaged through interviews as well as several rounds of a Delphi survey. Researchers need to be aware of this and, for instance, always express their gratitude for the interviewees' participation and time.

5. CONCLUSIONS

The importance of sustainable energy development is acknowledged worldwide. SED recognizes the role of energy in promoting sustainable development and highlights the importance of considering the economic, environmental, and social impacts of energy development. What SED involves and actions towards it can differ significantly from one country to the next. Through stakeholder engagement, it is possible to identify what SED in the country entails and what challenges the energy system faces. For this study, a public participation process was developed to analyze SED in Iceland. The aim of this five-step process was to capture a comprehensive and balanced picture of a sustainable energy future in Iceland by engaging a diverse group of stakeholders. Even though the focus was on the Icelandic system, the goal is that the methodology developed, and knowledge gained from this study will be transferable to other countries and energy systems.

The focus of this paper was on the past and future role of geothermal energy for SED in Iceland. Stakeholders recognized that the utilization of geothermal energy for both electricity production and, especially, district heating were instrumental steps towards SED in the country. An energy transition in district heating from fossil fuels to geothermal energy brought about environmental, social, and health benefits. The same ambition and foresight as shown during this energy transition is thought to be necessary to push SED even further. According to stakeholders of the Icelandic energy system, the main challenge for SED in the country is the lack of a long-term and broad plan of action for SED manifested in an energy policy. The results of this analysis can be used as a foundation for the development of such a policy which, currently, is underway.

Six main themes of a comprehensive and long-term energy policy in Iceland were identified from stakeholder engagement: nature conservation, social benefits, sustainable energy production, sustainable energy consumption, energy security, and economically efficient energy system. Geothermal energy was discussed often by stakeholders, both in a positive and negative light. A number of negative environmental and social impacts of geothermal utilization were identified by stakeholders. Furthermore, questions were raised on whether geothermal resources can be considered sustainable. For geothermal energy to contribute to SED in the future, it needs to be utilized sustainably and at a rate that does not exceed the natural recharge rate of the field. If Iceland is to keep its status as an international leader in the utilization of geothermal resources, lessons need to be learned from former mistakes and practices developed further. This includes cautious multi-step development of geothermal power stations to ensure their sustainability, minimizing the associated harmful impacts, and ensuring that social benefits are felt in the local community. Energy security in the country was contributed to geothermal energy; a reliable, domestic, and cheap energy source. Although, the equity in its distribution was questioned as district heating is not as readily available in cold areas of the country. The pending energy policy should attempt to address the numerous challenges to geothermal utilization presented here, thereby, ensuring a future role for geothermal energy in Iceland.

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