



Decarbonising Road Freight Transport in Iceland: A Feasibility Assessment Under Harsh Climate Conditions in Remote Regions

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Department of Engineering

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Ph.D. Dissertation



Decarbonising Road Freight Transport in Iceland: A Feasibility Assessment Under Harsh Climate Conditions in Remote Regions

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Dissertation submitted to the Department of Engineering, School of Technology at Reykjavík University in partial fulfilment of the requirements for the degree of **Doctor of Philosophy (Ph.D.)**

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Decarbonising Road Freight Transport in Iceland: A Feasibility Assessment Under Harsh Climate Conditions in Remote Regions

Albert Alonso-Villar

Abstract

Background:

The decarbonisation of road freight transport is a multifaceted challenge, which involves technical, economic, social, and infrastructural considerations. Heavy-Duty Vehicles (HDVs), responsible for 40% of the emission in the transport sector, operate across diverse and demanding applications and are heavily reliant on fossil diesel, making their decarbonisation complex. While existing literature has largely focused on addressing a specific aspect of the HDV transition, such as greenhouse gas emissions (GHG) analysis, technical assessments of a limited range of powertrains and configurations, or isolated evaluations of infrastructure requirements, these studies often overlook the well-to-wheel nature of the decarbonisation challenge. In Iceland, the complexity of this challenge is further expanded by the harsh climate conditions, sparse population, and ageing infrastructure. While Iceland's abundant renewable energy presents an opportunity to transition away from fossil fuels in the freight sector, the transition demands a comprehensive understanding of the technical feasibility and infrastructure requirements.

Aim:

This thesis begins with a comprehensive evaluation of alternative fuel powertrains to identify the most favourable solution to decarbonise road freight transport in Iceland. Based on this initial assessment, the thesis focuses on Battery-Electric Trucks (BETs) as the most promising solution to achieve the decarbonisation goals, conducting a detailed assessment of the feasibility and implications of HDV electrification in Iceland. This research addresses the unique challenges posed by Iceland's Arctic-like climate and remoteness, seeking to bridge the existing gaps by integrating multiple dimensions of the transition using real-life data, including detailed vehicle energy performance assessments under adverse conditions, optimal charging network design, and impact of charging loads on the power grid. Overall, the main goal of this thesis is to answer the question "Are BETs a feasible option to decarbonise the road freight transport sector in Iceland?"

Method:

To achieve our goal, this thesis first evaluates the technical, environmental, and economic feasibility of multiple powertrain options in Iceland, including BET, hydrogen fuel cell (FCV), and other alternative fuels. This analysis is carried out using AFLEET and GREET databases to assess the HDV life cycle emissions and total cost of ownership (TCO), as well as considering factors like energy security and local fuel production capacity. Subsequent studies focus specifically on battery-electric powertrains, assessing their performance using detailed vehicle energy consumption models (FASTSim) to account for adverse climate and freight conditions. Additionally, a novel methodology for planning fast-charging infrastructure is proposed, which incorporates a non-linear charging optimisation framework to determine the magnitude of charging loads from

battery-electric trucks and locate power demand points from fast-charging stations along Iceland's main freight routes. Finally, PyPSA is used to conduct power flow simulations to evaluate the effects of charging loads from battery-electric trucks on the national grid and identify potential bottlenecks in the infrastructure. This integrative methodology provides a comprehensive understanding of the technical feasibility, infrastructure requirements, and systemic impacts of freight transport electrification.

Results:

The findings indicate that battery-electric trucks offer significant environmental and economic advantages, despite the limitations of current battery technology. Hydrogen and compressed natural gas are promising alternatives for regional trucks but are constrained by high life cycle costs and insufficient feedstock availability. The battery-electric truck performance analysis reveals a range reduction of 41–47% under challenging conditions, emphasising the necessity of on-route charging for full fleet electrification. The proposed charging infrastructure planning methodology highlights that larger batteries and higher charging rates can minimise routing delays, while power flow simulations indicate that the additional charging loads can cause localised grid bottlenecks, particularly in remote regions like the Westfjords.

Conclusion:

Overall, the outcomes of this thesis emphasise the feasibility of electrifying road freight transport in Iceland, although strategic planning will be required to mitigate grid constraints, especially in the Westfjords and other vulnerable areas. By integrating technical, economic, and environmental assessments, this thesis provides a holistic framework for guiding road freight electrification in Iceland and similar regions. The findings contribute to advancing sustainable freight transport while offering a scalable approach for other similar challenging contexts globally.

Decarbonising Heavy-Duty Road Freight Transport in Iceland: Feasibility and impact assessment of the charging load on the transmission and distribution system

Albert Alonso-Villar

Útdráttur

Bakgrunnur:

Aflkolun víðgötuflutninga er marglaga áskorun sem felur í sér tæknileg, efnahagsleg, félagsleg og innviðaðfræðileg atriði. Þungar vöruflutningabifreiðar (HDV), sem bera ábyrgð á 40% losunar innan samgöngugeirans, starfa í margvíslegum og krefjandi verkefnum og eru að mestu háðar jarðeldsneyti, sem gerir aflkolun þeirra flókna. Þó svo að fyrirliggjandi ráðstafanir hafi að mestu fjallað um ákveðna þætti HDV umbreytingar, s.s. gróðurhúsalofttegunda (GHG) greiningu, tæknilegar útfærslur drifkerfa og innviðaðþarfa, hafa þessar ráðstafanir oft horft framhja hringekju aflkolunar. Á Íslandi er þessi áskorun enn flóknari vegna harðra veðurskilyrða, dreifðrar byggðar og aldraðra innviða. Þó svo að mikil endurnýjanleg orka landsins sé tækifæri til að hverfa frá jarðefnaeldsneyti, þarf umskiptin nákvæma þyptingu tæknilegrar hagkvæmni og innviðaðþarfa.

Markmið:

Rannsóknin hefst á víðtækri greiningu á valkostum fyrir eldsneytiskerfi til að bera kennsl á hagkvæmstu lausnina fyrir aflkolun víðgötuflutninga á Íslandi. Á grundvelli þessarar frumgreiningar beinist ritmiðin að rafknúnum flutningabifreiðum (BET) sem mest lofa til að ná áfangasigri í aflkolunarmarkmiðum, með ítarlegri greiningu á raunverulegri möguleika og afleiðingum rafvæðingar þungaflutninga á Íslandi. Rannsóknin tekst á við einstakar áskoranir vegna kalda veðursins og fjarlægða, með því að sameina margar hliðar umskiptanna með raunverulegum gögnum, þ.m.t. ítarlegri orkunotkun bifreiða undir erfiðum skilyrðum, hámarkshæfri hleðslunetagerð og áhrifum hleðsluálags á raforkukerfið. Í heildina er markmið ritgerðarinnar að svara spurningunni: "Eru rafmagnsvörubílar raunhæfur kostur fyrir aflkolun víðgötuflutninga á Íslandi?"

Aðferðafræði:

Til að ná markmiðum okkar metur þessi ritgerð fyrst tæknilega, umhverfislega og efnahagslega hagkvæmni mismunandi drifkerfiskosta á Íslandi, þar á meðal rafmagnsvörubíla (BET), vetniseldsneytisfrumur (FCV) og aðrar valkostir við hefðbundið eldsneyti. Þessi greining er framkvæmd með AFLEET og GREET gagnagrunnum til að meta losun í líftíma þungaflutningabifreiða (HDV) og heildareignarkostnað (TCO), auk þess sem tekið er tillit til þátta eins og orkuöryggis og innlendra eldsneytisframleiðslugetu. Nánari rannsóknir beinast sérstaklega að rafknúnum drifkerfum, þar sem frammistaða þeirra er metin með ítarlegum orkunotkunarlíkönum ökutækja (FASTSim) til að taka mið af erfiðum veðurskilyrðum og flutningskröfum. Að auki er sett fram nýstárleg aðferðafræði við skipulagningu hraðhleðsluinnviða, sem felur í sér ólínulegt hleðslu bestunarlíkan til að ákvarða stærð hleðsluálaga frá

rafmagnsvörubílum og finna staðsetningar álagspunkta fyrir hraðhleðslustöðvar meðfram helstu flutningsleiðum á Íslandi. Að lokum er PyPSA notað til að framkvæma orkuflæðislíkanagreiningu til að meta áhrif hleðsluálaga frá rafmagnsvörubílum á landsnetið og greina mögulega flöskuhálsa í innviðum. Þessi samþætta aðferðafræði veitir heildstæða innsýn í tæknilega hagkvæmni, innviðakröfur og kerfisleg áhrif rafvæðingar vörubungaflutninga.

Niðurstöður:

Niðurstöðurnar benda til þess að rafmagnsvörubílar bjóði upp á verulegan umhverfislegan og efnahagslegan ávinning, þrátt fyrir takmarkanir á núverandi rafhlöðutækni. Vetni og þjappað jarðgas eru lofandi valkostir fyrir svæðisbundna flutninga en eru takmarkaðir af háum lífhringakostnaði og ófullnægjandi aðgengi að hráefnum. Frammistöðugreining rafmagnsvörubíla sýnir 41–47% drægisrýrnun við krefjandi aðstæður, sem undirstrikar nauðsyn hleðslu á leiðinni til að ná fullri rafvæðingu flotans. Tillaga að skipulagi hleðsluinnviða sýnir að stærri rafhlöður og hærri hleðsluhraði geta dregið úr tafar á leiðum, en orkuflæðislíkan gefur til kynna að aukin hleðsluálög geti valdið staðbundnum flöskuhálsum í raforkukerfinu, sérstaklega á afskekktum svæðum eins og á Vestfjörðum.

Niðurlag:

Niðurstöður þyta á fram raunhæfi rafvæðingar, en skipulagning er nauðsynleg til að draga úr áhrifum á netið, einkum á Vestfjörðum og öðrum viðkvæmum svæðum. Með því að samþætta tæknilega, efnahagslega og umhverfislega greiningu veitir þessi ritgerð heildrænt ramma fyrir leiðsögn við rafvæðingu víðgötuflutninga á Íslandi og svipuðum svæðum. Niðurstöðurnar stuðla að framþróun sjálfbærra vöruflutninga á sama tíma og þær bjóða upp á stigstærð nálgun fyrir önnur svipuð krefjandi samhengi á heimsvísu.

Per la yaya Vicenta, la iaia Maria Rosa, el yayo Antonio, i l'avi Màrius

The undersigned hereby certify that they recommend to the School of Technology at Reykjavík University for the acceptance of this Dissertation entitled **Decarbonising Road Freight Transport in Iceland: A Feasibility Assessment Under Harsh Climate Conditions in Remote Regions** submitted by **Albert Alonso-Villar** in partial fulfilment of the requirements for the degree of **Doctor of Philosophy (Ph.D.) in Applied Sciences**.

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Albert Alonso-Villar
Doctor of Philosophy

Acknowledgments

I have deeply enjoyed this PhD, and I want to thank all the people who made it possible.

I want to thank Jón Steinar, for giving me the chance to come to Iceland and sparking my interest in research. This PhD definitely started during that time in Austurbrú, maybe even during one of the *réttir*.

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This PhD has allowed me to have a job which I loved, meet amazing people, and live in this beautiful country. I'm forever grateful.

Preface

This Ph.D. thesis is an original work by the author, Albert Alonso-Villar. This doctoral work has been conducted at the School of Science and Engineering at Reykjavik University, Iceland with Hlynur Stefnánsson, Brynhildur Davíðsdóttir, Eyjólfur I. Ásgeirsson, and Ragnar Kristjánsson as supervisors.

Table of Contents

Abstract	i
Útdráttur	iii
Acknowledgments	x
Preface	xi
Table of Contents	xii
List of publications	xvi
Declaration of Contribution	xviii
1. Introduction	1
1.1 Background.....	2
1.1.1 Technical feasibility assessments in alternative fuel heavy-duty vehicles .	2
1.1.2 Battery-electric truck performance under adverse conditions.....	3
1.1.3 Fast-charging infrastructure design models	3
1.1.4 Power grid impact assessments and BET charging loads	4
1.1.5 Regional challenges in Iceland.....	4
1.2 Research Goals and Research Questions	5
1.2.1 Goal 1: To identify the most feasible alternative fuel powertrain to decarbonise heavy-duty vehicles in Iceland, in terms of GHG and air pollutant emissions, TCO, technical feasibility, and impact on energy security	6
1.2.2. Goal 2: To evaluate the impact of adverse climate and operational conditions on the feasibility of electrifying short and regional haul freight transport in Iceland	6
1.2.3. Goal 3: To determine the charging infrastructure requirements to support long-haul freight electrification in Iceland	7
1.2.4. Goal 4: To evaluate the effect of fast-charging loads from BETs on the transmission and distribution systems, focusing on identifying the potential grid reinforcements required to support BET operations along Iceland’s primary freight routes.....	8
1.3 Research Methodology	8
1.4 Summary of Included Papers and their Contribution to the Thesis.....	9
1.4.1 Paper I: Technical, economic, and environmental feasibility of alternative fuel heavy-duty vehicles in Iceland	9
1.4.2 Paper II: Electrification potential for heavy-duty vehicles in harsh climate conditions: A case study based technical feasibility assessment.....	11
1.4.3 Paper III: Optimising and Planning Fast-Charging Infrastructure for Long-Haul Electric Trucks	12
1.4.4 Paper IV: Impact assessment of battery-electric HDVs charging loads on the transmission and distribution system in Iceland and mitigation strategies.....	13

2. Paper 1	15
1. Introduction.....	16
2. Methods	19
2.1. Selection of representative heavy duty vehicle categories for Iceland.....	19
2.2. Alternative fuel powertrains included in the scope	20
2.3. Life cycle analysis (LCA).....	21
2.4. Total cost of ownership (TCO).....	21
2.5. AFLEET tool and GREET.....	21
2.6. HDV technical demands in Iceland	26
2.7. Domestic renewable fuel production	27
2.8. System boundaries	28
3. Results and discussion	28
3.1. Technical feasibility of alternative fuel HDV powertrains.....	28
3.2. Meeting the HDV energy demand with domestically produced fuels.....	30
3.3. GHG and air pollutants emissions	31
3.4. Total cost of ownership and externality costs.....	36
3.5. Identifying the most attractive alternative fuel pathway	37
4. Main limitations.....	39
5. Conclusions.....	39
6. References.....	40
3. Paper 2	48
1. Introduction.....	49
2. Methods	52
2.1 Data collection, processing, and case study design	52
2.1.1. Description of case study and road freight activity in Iceland.....	52
2.1.2. Selection of representative trips and drive cycle generation.....	55
2.1.3. Electric HDV design parameters.....	57
2.2 Vehicle energy consumption model	58
2.2.1. Battery-electric HDV model calibration	59
2.2.2. Influence of climate conditions on the vehicle energy consumption model.....	60
2.3. Charging model	62
2.4. Electric range sensitivity analysis and scenario design	64
2.5. Electrification feasibility assessment of case study fleet.....	66
3. Results and discussion	66
3.1 Impact of ambient and drive cycle conditions on the driving range.....	66
3.1.1. Impact of different driving cycles on vehicle’s energy consumption	66
3.1.2. Impact of ambient temperature and wind.....	67
3.1.3. Impact of payloads and use of tail-lift.....	67
3.1.4. Combined impacts of use and environmental conditions on the driving range	68
3.2. Fast-charging performance: Impact of BTMS, ambient temperature and charging power	68
3.3 Electrification potential of the case study fleet.....	71
3.4. Implications from electrifying the case study fleet.....	72
3.5. Summary of results and policy suggestions.....	73
4. Conclusions.....	74
5. References.....	74

4. Paper 3	80
1. Introduction.....	81
2. Methods	85
2.1. Estimating BET energy consumption and charging requirements	85
2.1.1. Real driving data collection and analysed routes	85
2.1.2. BET design parameters and climate conditions assumptions	87
2.1.3. Vehicle energy consumption model and charging assumptions	88
2.2. Determining optimal charging locations and charging durations.....	89
2.2.1. Charging network design assumptions.....	89
2.2.2. Charging optimisation model	90
2.3. Scaling the charging stations with queueing theory	93
3. Results.....	94
3.1. BET energy performance assessment	94
3.2. On-route charging optimisation	95
3.3. Sizing the charging stations	98
4. Discussion.....	100
4.1. Actual impact of charging sessions on the routing time.....	100
4.2. Overview of FCS network proposed configurations	101
4.2.1. Locations and distance between FCS.....	101
4.2.2. Number of charging points per station and charging loads.....	101
4.3. Limitations of the study and further research	102
4. Conclusion	103
5. References.....	104
5. Paper 4	108
1. Introduction.....	110
2. Methods and data	112
2.1. Vehicle performance assessment	112
2.1.1. Driving data and analysed routes	112
2.1.2. Battery-electric truck design parameters.....	113
2.1.3. Vehicle energy consumption model.....	114
2.2. Charging optimisation model	115
2.3. Power grid assessment	117
2.3.1. The Icelandic transmission grid	117
2.3.2. Power flow analysis with Python for Power Systems Analysis.....	118
2.3.3. BET charging requirements and power grid impact assessment.....	121
3. Results.....	122
3.1. BET performance and charging loads	122
3.2. Power grid assessment	125
3.2.1. Reference scenario	125
3.2.2. 2030 scenario.....	127
3.2.3. 2030 BET scenario	129
3.2.4. Summary of results.....	132
4. Discussion.....	132
4.1. Impacts of the combined 2030 and BET loads on the current power grid and operational challenges.....	132
4.2. Potential mitigation strategies	133
4.3. Limitations	133
5. Conclusion	134
6. References.....	135
6. Discussion	139

5.1 Overall feasibility of BET to decarbonise freight transport in Iceland	140
5.2 Main contributions of the thesis and practical implications	143
5.3 Limitations	145
7. Conclusion and Future Work.....	146
8. Bibliography.....	148
9. Appendix.....	151
9.1 Charging optimisation model	151
9.2 PyPSA model.....	153

List of publications

Appended publications

This thesis is based on the following publications:

[Paper I] Alonso-Villar, A., Davíðsdóttir, B., Stefánsson, H., Ásgeirsson, E. I., & Kristjánsson, R. (2022). Technical, economic, and environmental feasibility of alternative fuel heavy-duty vehicles in Iceland. *Journal of Cleaner Production*, 369, 133249.

[Paper II] Alonso-Villar, A., Davíðsdóttir, B., Stefánsson, H., Ásgeirsson, E. I., & Kristjánsson, R. (2023). Electrification potential for heavy-duty vehicles in harsh climate conditions: A case study based technical feasibility assessment. *Journal of Cleaner Production*, 417, 137997.

[Paper III] Alonso-Villar, A., Davíðsdóttir, B., Stefánsson, H., Ásgeirsson, E. I., & Kristjánsson, R. (2024). Optimising and Planning Fast-Charging Infrastructure for Long-Haul Electric Trucks. Under review at the Journal eTransportation (2nd review)

[Paper IV] Alonso-Villar, A., Davíðsdóttir, B., Stefánsson, H., Ásgeirsson, E. I., & Kristjánsson, R. (2025). Impact assessment of battery-electric HDVs charging loads on the transmission and distribution system in Iceland and mitigation strategies. Will be submitted to the Journal of Energy.

Other publications

The following publications overlap with the content of this thesis and, therefore, have not been included.

[a] Alonso-Villar, A., Davíðsdóttir, B., Stefánsson, H., Ásgeirsson, E. I., & Kristjánsson, R. (2023). Technical and economic assessment of battery electric and hydrogen fuel cell heavy-duty vehicles for long-haul freight applications in Iceland. In *Heavy-duty vehicle electrification: Technical, economic, and environmental assessment* (pp. 11–32). CRC Press.

Declaration of Contribution

The work for each paper was distributed among the authors as follows:

- Paper I **Albert Alonso-Villar:** Conceptualisation, Methodology, Investigation, Writing–original draft, Data curation. **Brynhildur Davíðsdóttir:** Conceptualisation, Writing–review & editing, Supervision, Funding acquisition. **Hlynur Stefánsson:** Conceptualisation, Methodology, Validation, Writing–review & editing, Supervision, Funding acquisition. **Eyjólfur Ingi Ásgeirsson:** Conceptualisation, Methodology, Validation, Writing – review & editing, Supervision, Funding acquisition. **Ragnar Kristjánsson:** Writing–review & editing, Supervision, Funding acquisition.
- Paper II **Albert Alonso-Villar:** Conceptualisation, Methodology, Investigation, Writing–original draft, Data curation. **Brynhildur Davíðsdóttir:** Conceptualisation, Writing – review & editing, Supervision, Funding acquisition. **Hlynur Stefánsson:** Conceptualisation, Methodology, Validation, Writing – review & editing, Supervision, Funding acquisition. **Eyjólfur Ingi Ásgeirsson:** Conceptualisation, Methodology, Validation, Writing – review & editing, Supervision, Funding acquisition. **Ragnar Kristjánsson:** Writing – review & editing, Supervision, Funding acquisition.
- Paper III **Albert Alonso-Villar:** Conceptualisation, Methodology, Investigation, Writing–original draft, Data curation. **Brynhildur Davíðsdóttir:** Conceptualisation, Writing – review & editing, Supervision, Funding acquisition. **Hlynur Stefánsson:** Conceptualisation, Methodology, Validation, Writing – review & editing, Supervision, Funding acquisition. **Eyjólfur Ingi Ásgeirsson:** Conceptualisation, Methodology, Validation, Writing – review & editing, Supervision, Funding acquisition. **Ragnar Kristjánsson:** Writing – review & editing, Supervision, Funding acquisition.
- Paper IV **Albert Alonso-Villar:** Conceptualisation, Methodology, Investigation, Writing–original draft, Data curation. **Brynhildur Davíðsdóttir:** Conceptualisation, Writing – review & editing, Supervision, Funding acquisition. **Hlynur Stefánsson:** Conceptualisation, Methodology, Validation, Writing – review & editing, Supervision, Funding acquisition. **Eyjólfur Ingi Ásgeirsson:** Conceptualisation, Methodology, Validation, Writing – review & editing, Supervision, Funding acquisition. **Ragnar Kristjánsson:** Writing – review & editing, Methodology, Supervision, Funding acquisition

1. Introduction

The decarbonisation of road freight transport is a multifaceted challenge, which involves technical, economic, social, and infrastructural considerations. Heavy-duty vehicles (HDVs), responsible for 40% of the emission in the transport sector, operate across diverse and demanding applications and are heavily reliant on fossil diesel, making their decarbonisation complex (IEA, 2017). While existing literature has largely focused on addressing a specific aspect of the HDV transition, such as greenhouse gas emissions (GHG) or total cost of ownership (TCO) analysis (Lajevardi et al., 2019), technical assessments of a limited range of powertrains and configurations (Forrest et al., 2020), or isolated evaluations infrastructure requirements (Mojlish et al., 2025), these studies often overlook the well-to-wheel nature of the decarbonisation challenge.

In Iceland, the complexity of this challenge is further expanded by the harsh climate conditions, sparse population, and ageing infrastructure (Apiyo, 2019). While Iceland's abundant renewable energy presents an opportunity to transition away from fossil fuels in the freight sector, the transition demands a comprehensive understanding of the technical feasibility and infrastructure requirements for its specific context.

Heavy-duty alternative fuel powertrains, and specially battery-electric trucks (BETs), are seen as a promising solution for decarbonising the road freight transport sector, due to their potential to achieve GHG emission reductions, energy security improvements, and reductions in operational costs (Alonso-Villar et al., 2022). However, while electric vehicles have made considerable progress in the light-duty vehicle (LDV) segment, their adoption in the HDV sector remains limited. Factors such as high capital costs, performance uncertainties under challenging conditions, limited driving range, and infrastructure gaps have slowed the transition in this sector, especially for long-haul applications (Wappelhorst and Rodríguez, 2021).

Overcoming these barriers is particularly challenging in Arctic regions like Iceland, where harsh climate conditions and difficult geography add further complexity to the deployment of BETs (Alonso-Villar et al., 2023). These factors increase the energy consumption of electric trucks, reducing their effective range (Basma et al., 2021) and making the development of an adequate fast-charging infrastructure a key consideration for the successful BET adoption.

This thesis addresses the urgent need to decarbonise the heavy-duty transport sector by assessing the technical, environmental, and economic feasibility of alternative fuel powertrains to identify the most favourable solution for the Icelandic context. Subsequently, the research focuses on the potential of BETs to meet freight transport demands in Iceland, exploring the impact of harsh climate conditions on the electrification potential of HDVs and the infrastructure requirements for the deployment of electric freight vehicles in remote and rural areas.

This thesis aims to investigate the overall feasibility of transitioning towards a decarbonised freight transport fleet in Iceland. This aim can be broken down into the following goals:

- G1: To identify the most feasible alternative fuel powertrain to decarbonise heavy-duty vehicles in Iceland, in terms of GHG and air pollutant emissions, TCO, technical feasibility, and impact on energy security
- G2: To evaluate the impact of adverse climate and operational conditions on the electrification feasibility of short and regional haul freight transport in Iceland
- G3: To determine the charging infrastructure requirements to support long-haul freight electrification in Iceland
- G4: To evaluate the impact of fast-charging loads from BETs on the Icelandic power grid

By combining life cycle analyses, technical assessments, and infrastructure planning models, this thesis provides a unique comprehensive framework to support the transition to decarbonising freight transport. The outcomes of this research offer valuable insights for policymakers and industry stakeholders, contributing directly to Iceland's climate action goals and the broader global effort to reduce emissions from the transport sector.

1.1 Background

This section provides an overview of the research background underlying the PhD project. The following review summarises the state of research on alternative fuel HDVs, with a focus on BETs, charging infrastructure, and the impacts on power grids, highlighting key gaps in the literature addressed by this thesis.

1.1.1 Technical feasibility assessments in alternative fuel heavy-duty vehicles

Although improvements in powertrain efficiency and routing schedules can lead to emission reductions in current fossil diesel trucks, the literature generally acknowledges that alternative fuels are better suited to achieve significant emission reductions in HDVs (Stančin et al., 2020).

The literature extensively examines the potential benefits for various alternative fuel HDV powertrains, including zero-emission vehicles (ZEV) such as battery-electric vehicles (BEVs), and hydrogen fuel cell vehicles (FCVs), and biofuels such as compressed natural gas (CNG), biodiesel, and other biomass feedstock-based fuels (Stančin et al., 2020). The research mostly focuses on environmental and economic analysis, in terms of GHG emissions and TCO, respectively.

The literature review revealed that the outcomes from the environmental and economic assessments are strongly dependant on the regional context. Factors such as the electricity carbon-intensity, the power grid generation mix, energy prices, the local feedstocks available, as well as the HDV applications addressed, are proved to deeply influence the results of the assessments (Lajevardi et al., 2019). Since these factors vary regionally, so do the outcomes of each analysis, which emphasises the need for context-specific assessments.

Zero-emission powertrains have drawn a lot of attention in the literature. Studies such as Lajevardi et al. (2019) and Sen et al. (2017) find that BEVs offer the highest GHG emission reduction potential when powered by low-carbon electricity, reducing emissions by 30–70% compared to diesel, depending on drive cycles and grid carbon intensity. FCVs also achieve significant reductions (60–99%) when using hydrogen produced via renewable energy but are constrained by low efficiency and high costs. Alternative fuels like LNG and biodiesel are also viewed as valid solutions in some contexts due to their technological and commercial readiness. Overall, LNG can provide moderate GHG reductions of up to 13%, but life-cycle emissions are often only marginally lower than diesel, as shown by Rial and Pérez (2021).

Economic assessments highlight that alternative fuels face significant cost challenges, depending on the context. Lajevardi et al. (2019) and Lopez et al. (2020) find that BEVs have higher TCO compared to diesel due to battery costs and infrastructure requirements. Contrarily, studies such as Sen et al. (2017) suggest that operational savings from fuel and maintenance can offset these costs over a vehicle's lifecycle, particularly in regions with access to cheap renewable electricity. FCVs, while promising for long-haul applications, currently have an unattractive TCO compared to both BEVs and diesel, as found by Çabukoglu et al. (2019).

Aside from GHG emissions and TCO, there are other key aspects to the HDV decarbonisation which are often overlooked in the literature. These include the impact on local energy security (IEA, 2021), the overall operational feasibility of meeting regional demands (Forrest et al., 2020), and air pollutant emissions (Michalek et al., 2011). Further research is needed in alternative fuel assessments to include such fields and offer a complete perspective on the feasibility of transitioning towards road freight transport decarbonisation. This thesis addresses such gaps by conducting a context-specific technical, environmental, and economic assessment of a broad set of alternative fuels using Iceland as the case study.

1.1.2 Battery-electric truck performance under adverse conditions

The technical feasibility of BET is still an emerging field, as indicated by Forrest et al. (2020). The literature in electric HDV feasibility identifies key barriers for broad widespread, including limited range (Melander et al., 2022), high energy consumption under payload conditions (Khani and Emami, 2022), slow charging times (Qasim and Csiszar, 2021), and infrastructure availability (Imre et al., 2021).

Studies such as Çabukoglu et al. (2018), highlight that larger battery capacities and the availability of fast-charging infrastructure improve the feasibility of BET deployment for regional haul applications. However, for long-haul freight, the lack of adequate range and recharging options remains a significant barrier. Forrest et al. (2020) also demonstrated that HDV electrification potential increased with higher vehicle ranges and on-route charging availability. Overall, the research indicates that freight operations and truck configurations settings are strongly linked to HDV electrification feasibility. However, the literature often overlooks the potential variation in BET performance under adverse climate conditions, which can also impact BET range (Basma et al., 2021). The influence of adverse climate conditions such as low temperatures and strong winds, added to the already challenging demands of freight transport, are of great relevancy for HDV electrification, especially in regions with harsh climates.

Therefore, further research is needed on BET performance under adverse climate and freight conditions. To close this research gap, this thesis investigates the performance of several HDV configurations under different climate and freight scenarios and evaluates the electrification potential of a freight fleet in Iceland.

1.1.3 Fast-charging infrastructure design models

Existing literature can be divided into two primary approaches when it comes to planning on-route charging networks: demand-oriented and coverage-oriented.

Demand-oriented frameworks prioritise the placement of charging stations based on projected usage patterns, focusing on maximising the efficiency and utility of charging infrastructure. These models often rely on freight activity data, vehicle energy consumption profiles, and routing patterns to identify high-demand charging locations. Studies such as Çabukoglu et al. (2018) used energy consumption data for national truck fleets in Switzerland to identify key charging locations along major freight corridors. The primary benefit of the demand-oriented approach is its ability to optimise the charging network and minimise infrastructure investment costs. These models are particularly effective in urban and regional contexts, where freight traffic is more predictable, and infrastructure investments can be concentrated in high-traffic areas.

Coverage-oriented frameworks, on the other hand, aim to ensure that charging infrastructure is available across a wide geographic area. Hall & Lutsey, (2019) applied coverage-oriented models to identify the minimum number of stations required to provide full route coverage for long-haul freight in Los Angeles area. This approach prioritises accessibility and range assurance for BETs, although it does not provide optimal solutions (Kchaou-

Boujelben et al., 2021). However, these models often require higher initial investments and may result in underutilised infrastructure in low-demand areas.

However, the literature reviewed revealed a lack of comprehensive approaches tailored to remote areas with adverse climate conditions, such as Arctic-like regions. Such factors critically affect BET performance as shown by Alonso-Villar et. al (2023). This thesis aims at addressing this gap in research by developing an integrated methodology including BET performance under adverse conditions with fast-charging infrastructure design.

1.1.4 Power grid impact assessments and BET charging loads

The integration of fast-charging BETs into power grids presents significant challenges, especially in regions with limited grid capacity. Existing research primarily focuses on the impact of passenger electric vehicles loads on the grid (Haraldsson, 2020), while the integration of BET fast-charging loads on the power grid remain and emerging field.

Mojlish et al. (2025) examined the feasibility of installing ultra-fast charging stations for passenger BEVs in Wollongong, Australia, highlighting challenges linked to peak demand, transformer and line overloads, system losses, and voltage fluctuations. Mowry & Mallapragada (2021) analysed the effects of highway fast-charging stations in Texas, focusing on grid operational costs and technical constraints such as component limits and line upgrades. In the Icelandic context, Apiyo (2019) and Haraldsson (2020) studied the impact of transitioning to a BEV fleet using MATPOWER, a power system simulation tool, to simulate different load scenarios. Their findings indicated that increased BEV penetration would lead to higher peak loads, voltage drops, and line overloading, necessitating infrastructure upgrades and additional power generation.

Contrarily to passenger vehicles, freight BETs are characterised by low flexibility schedules, as truck drivers prioritise fast-charging to minimise the stopped time, which poses additional challenges to grid operations (Burnham et al., 2017). With the anticipated expansion of high-power fast-charging infrastructure to meet the growing BET demand, the impact on the power grid is expected to become even more pronounced (Mowry & Mallapragada, 2021).

This thesis aims at evaluating the impact of long-haul freight electrification on the power grid in Iceland, expanding the understanding of the technical feasibility of BET integration.

1.1.5 Regional challenges in Iceland

Iceland's unique geographic, climatic, and political context presents both opportunities and challenges for the decarbonisation of HDVs. On one hand, Iceland's abundant renewable energy resources, mostly coming from hydropower and geothermal energy, set a strong foundation for transitioning to low-carbon freight transportation. On the other hand, the combination of harsh Arctic-like weather, sparse population density, and an ageing infrastructure power grid network poses significant challenges to implement solutions to achieve the decarbonisation goals (Apiyo, 2019).

In 2020, Iceland committed to ambitious climate action goals, including achieving carbon neutrality by 2040 and a 55% reduction in GHG emissions covered by the Effort Sharing Regulations (ESR) by 2030 compared to 2005 levels, as outlined in the Climate Action Plan (Ministry of the Environment, Energy and Climate 2020). While the government has announced measures to phase out fossil fuels in the transport sector, there is a lack of specific strategies targeting the decarbonisation of HDVs. The Climate Action Plan includes provisions for renewable fuel production and mentions the establishment of a task force for heavy-duty transport, but concrete plans for implementing alternative fuel powertrains, addressing infrastructure gaps, or overcoming operational challenges are not included. A revision of the plan was presented in June 2024, which introduced additional measures such as a ban on new

registrations of fossil fuel freight vehicles by 2035 (Ministry of the Environment, Energy and Climate, 2024a). However, further efforts are needed to develop more specific actions that ensure the successful implementation of alternative fuel HDVs.

In 2024, Iceland’s Ministry of the Environment, Energy and Climate published a roadmap for hydrogen and e-fuels development, which outlines strategies for the decarbonisation of the transport and maritime sectors using hydrogen and e-fuels. This report addresses the integration of hydrogen HDV powertrains in the segments where BETs use is less viable (Ministry of the Environment, Energy and Climate, 2024b). To the best of the author’s knowledge, a detailed roadmap for BETs or other alternative fuel HDV has not been developed.

In terms of power grid integration, existing research has used Iceland as a case study to model the impacts of EV charging loads on transmission and distribution systems (Apiyo, 2019; Haraldsson, 2020). However, these studies have focused predominantly on passenger electric vehicles and have not considered the unique challenges posed by HDVs, such as high-power fast-charging demands and inflexible charging schedules.

This thesis addresses these gaps by providing the first detailed investigation of BET performance variations under Iceland’s climatic and operational conditions, as well as a holistic assessment of alternative fuel powertrains and the planning of a fast-charging network for HDVs. The contributions from this thesis can be used to inform the transition towards HDV decarbonisation in Iceland, addressing its unique regional challenges and providing outcomes aligned with the country’s broader climate goals.

1.2 Research Goals and Research Questions

The research carried out throughout this PhD can be categorised in four stages, with each stage addressing one aspect of the quest for decarbonisation of the HDV transport sector in Iceland. The thesis includes four journal papers, which addressed 6 research questions and 4 goals. The research questions are directly addressed in the discussion section of this thesis. Figure 1 illustrates the thesis outline.

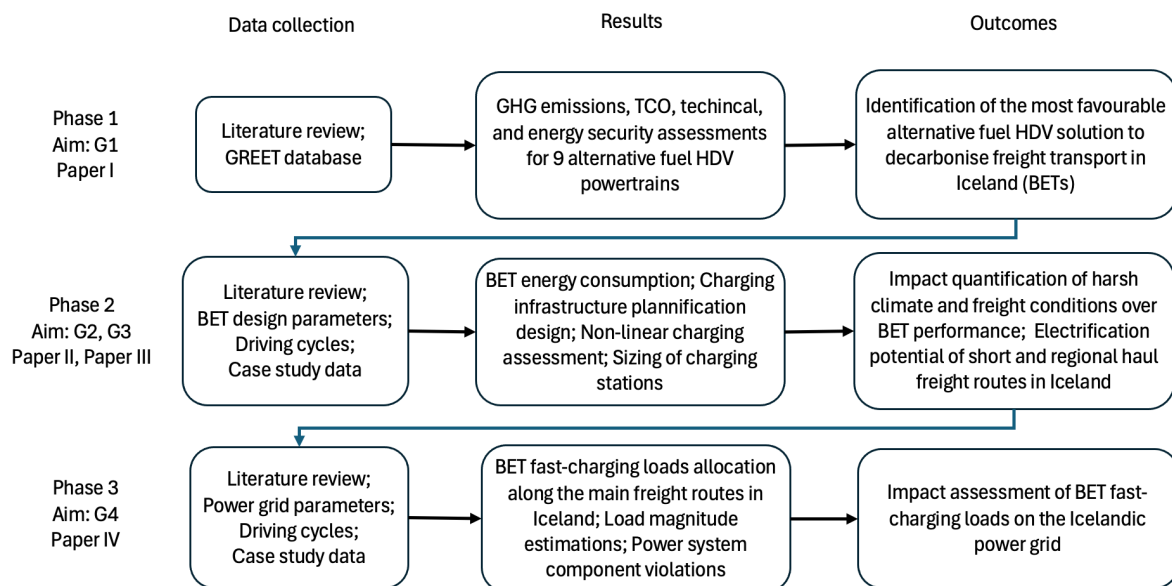


Figure 1. Thesis outline

1.2.1 Goal 1: To identify the most feasible alternative fuel powertrain to decarbonise heavy-duty vehicles in Iceland, in terms of GHG and air pollutant emissions, TCO, technical feasibility, and impact on energy security

The PhD research started by investigating different potential alternative fuels that could be used to replace fossil diesel in the HDV transport sector in Iceland. The literature review carried out revealed that alternative fuel HDV studies usually focus solely on GHG emissions and TCO assessments (Lajevardi et al., 2019), while other relevant aspects such as air pollutant emissions, the drivetrain's feasibility to meet the freight transport demands, or their impact on energy security were not commonly addressed. Therefore, in Phase 1 we carried out an environmental, economic, technical, and energy security assessment for a set of relevant alternative fuel candidates with the aim of identifying the most suitable solution for Iceland. The alternative fuel powertrains considered in the study included battery-electric (BEV), fuel-cell hydrogen (FCV), diesel hybrid electric (HEV), biodiesel (B100, B20), renewable diesel (RD100, RD20), compressed natural gas (CNG), and liquified natural gas (LNG). The main research question of the paper was:

- RQ1: Given the technical demands of HDV in Iceland, what alternative fuel powertrain represents the most feasible solution to transition away from fossil fuels in terms of GHG and air pollutant emissions and total cost of ownership?

To answer the research question, this paper carried out a broad feasibility analysis of the powertrains' capacity to meet Iceland's freight demands, a feedstock inventory assessment, a life cycle GHG and air pollutant emissions for different powertrains and, lastly, a TCO (Total Cost of Ownership) assessment for the selected powertrains. The results were then compared to identify the most attractive powertrain regarding operational feasibility, environmental and economic terms. The results suggested that BETs achieve the highest GHG emission reduction while presenting competitive TCO, although the limited range of current battery technology implied certain technical feasibility limitations. Therefore, these outcomes were used to develop the second paper, which focused solely on freight HDV battery-electrification feasibility.

1.2.2. Goal 2: To evaluate the impact of adverse climate and operational conditions on the feasibility of electrifying short and regional haul freight transport in Iceland

While Phase 1 indicated that BETs were the best option to decarbonise road freight transport in Iceland, it was still necessary to further investigate the technical viability of using battery-electric powertrains considering the Arctic-like adverse conditions found in Iceland and challenging freight demands. The literature review carried out for second paper revealed that the available studies did not fully cover the expected performance variations in adverse contexts such as variable weather or heavy payloads, which can greatly impact vehicle range. Therefore, further exploration is required to quantify the impact on the electric range from variable weather conditions, heavy payloads, and auxiliary equipment. Understanding such impacts could reduce the BET performance uncertainties from fleet operators and ultimately accelerate the transition toward HDV electrification.

Based on the identified gaps in the literature, this study used the freight activity of a company operating in Iceland as a case study to address the following research questions:

- RQ2: To what extent do climate and freight conditions impact the electrification potential of heavy-duty vehicles?
- RQ3: Considering unfavourable climate conditions, to what extent can the case study freight activity be carried out with battery-electric trucks?

To answer the first research question, the presented study aimed to quantify the impact of climate (low temperatures, headwind) and freight (payload, use of tail-lift and route characteristics) variables on BETs range. A vehicle energy consumption model is used to simulate the performance of different electric truck designs over pre-recorded freight routes. The charging performance under different ambient and battery conditions is also addressed using non-linear charging rates. The results obtained by answering the first research question were used to assess the electrification potential of the case study freight fleet, considering the harsh Icelandic climate conditions and different on-route charging scenarios. The developed methodology in Paper II served as a foundation for the subsequent study in Paper III, which would address long-haul routes and include charging infrastructure planning considerations in more detail.

1.2.3. Goal 3: To determine the charging infrastructure requirements to support long-haul freight electrification in Iceland

As the outcomes from Paper II were limited to short and regional haul freight transport, the scope of Paper III was extended to include long-haul routes and examine the charging infrastructure requirements to support long-haul electrification in Iceland. In this study we developed a comprehensive methodology to design fast-charging networks for BETs, including the number of required fast-charging stations (FCS), their optimal locations, and the number of charging points required per location. The methodology also incorporates the detailed vehicle energy consumption model used in Paper II to determine the vehicle charging requirements, considering adverse climate conditions (e.g. cold temperatures, headwind) and high freight demands (e.g. maximum payloads, mountain pass routes).

The proposed methodology is used to design a charging network to support the Reykjavík-Westfjords freight routes, using different battery and charger capacity assumptions. The following research questions were used to achieve G3:

- RQ4: What are the charging network requirements to support a 100% battery-electric heavy-duty vehicle fleet in the Reykjavík-Westfjords route?
- RQ5: How can fast-charging infrastructure for battery-electric trucks be optimally designed to support long-haul freight operations in remote and rural regions with harsh climate conditions?

To answer the research questions, we first pre-selected potential charging locations along the analysed routes based on existing infrastructure such as gas stations, restaurants, and towns. Then, we simulated BET performance in adverse conditions (low temperature and headwind) to ensure that the charging network is optimised considering worse case scenarios, with a special attention into the BET's performance between the pre-selected charging locations. The BET performance results are then used in an optimisation model to determine the ideal charging spots, charging durations, and average service rate. Lastly, the number of charging plugs required at each identified location is estimated using a queueing model based on arrival rate assumptions.

1.2.4. Goal 4: To evaluate the effect of fast-charging loads from BETs on the transmission and distribution systems, focusing on identifying the potential grid reinforcements required to support BET operations along Iceland’s primary freight routes

While the outcomes from Paper III addressed the design and planning of fast-charging infrastructure for BETs, they did not account for the implications of these charging loads on Iceland’s power grid. This gap was addressed in Paper IV, which focused on evaluating the impact of fast-charging BET loads on the transmission and distribution systems, with a particular emphasis on identifying the grid reinforcements required to ensure reliable BET operations along Iceland’s primary freight routes.

The literature review carried out for this study revealed that research on integrating electric vehicle charging loads has predominantly focused on passenger vehicles, with limited exploration of the unique challenges posed by BETs. The high-power requirements and inflexible charging schedules associated with BET operations can create localized stress on power grids, especially in remote regions with limited grid capacity. Therefore, this study aimed to address the following research question:

- RQ6: What are the impacts of fast-charging BET loads on the Icelandic power grid?

To address these questions, the study used the vehicle energy consumption model introduced in Paper II and the charging optimisation model developed in Paper III to determine the BET charging requirements over the main freight routes in Iceland and to allocate the charging infrastructure and power demands, respectively. Lastly, in Paper IV we conducted power flow simulations using Python for Power System Analysis (PyPSA) to evaluate the effects of these loads on Iceland’s transmission and distribution systems. These simulations identified critical grid stress points, including overloaded lines, voltage instabilities, and areas requiring capacity upgrades.

1.3 Research Methodology

This section outlines the methodologies employed throughout the thesis, describing the tools and models used in each stage of the research and emphasizing their adaptation to the Icelandic context.

The thesis begins with life cycle analysis (LCA) tools to evaluate the environmental, economic, and technical feasibility of various alternative fuel HDV powertrains. In paper I, AFLEET and GREET models (Argonne National Laboratory, 2020) were used extensively to assess the Well-to-Wheel GHG emissions, TCO, and air pollutant emissions for alternative fuels, including biodiesel, renewable diesel, hydrogen, and compressed/liquefied natural gas. To reflect Iceland’s specific energy mix and conditions, the data was tailored to include factors like low-carbon electricity production dominated by geothermal and hydropower. A thorough literature review on alternative fuels provided baseline parameters for fuel efficiency, life cycle emissions, and feedstock availability. This review identified research gaps, such as the limited assessment of energy security impacts and the feasibility of local fuel production, which were addressed by incorporating Iceland-specific feedstock data into the models.

In paper II, the FASTSim (Future Automotive Systems Technology Simulator) tool (Brooker et al., 2015) was used to evaluate the energy consumption of BETs under varying conditions. Another literature review was carried out to adjust the BET parameters to reflect Arctic-like conditions, including low temperatures, headwinds, mountainous terrain, and

payload variations. Data collection for this stage involved real-life freight activity patterns and HDV configurations from Ölgerðin, an Icelandic company and fleet operator. EPA HDV test drive cycles datasets on regional freight routes were used to model BET performance accurately and assess the energy consumption and range impacts under adverse conditions.

Building on the methodology developed in Paper II, Paper III introduced a charging optimisation model based on Gurobipy (Gurobi Optimization, 2023) to design fast-charging station (FCS) networks for long-haul BET routes. This model integrated the BET energy consumption outputs from FASTSim to identify optimal charging station locations, charging durations, and charging capacities. The optimisation framework prioritized minimizing operational delays while accounting for constraints such as battery degradation and vehicle charging times.

Paper III also incorporated queuing theory into the charging network design methodology to estimate the number of charging points required at each station. By simulating vehicle arrival rates and service times, the model ensured efficient station sizing while avoiding bottlenecks during peak usage. This integrated approach provided a detailed blueprint for charging infrastructure development tailored to Iceland's geographic and climatic challenges.

Finally, Paper IV used the methodological foundations from the previous papers to assess the impact of charging loads from BETs on Iceland's power grid using PyPSA (Python for Power System Analysis) (Brown et al., 2018), an open-source power system simulation tool. This analysis evaluated the additional demand from FCS networks on transmission and distribution systems, identifying potential grid bottlenecks and capacity constraints. The simulations incorporated spatially distributed charging load data, derived from the optimisation model developed in Paper III, and accounted for Iceland's renewable-dominated grid. An extensive data collection was carried out to incorporate real-life component data from lines, transformers, generators, switched shunts, and loads. These data was kindly provided by key power grid stakeholders in Iceland, such as Landsnet, Rarík, Orkuveita Vestfjarda, and Landsvirkjún.

1.4 Summary of Included Papers and their Contribution to the Thesis

1.4.1 Paper I: Technical, economic, and environmental feasibility of alternative fuel heavy-duty vehicles in Iceland

The first step of this thesis was to evaluate the feasibility of alternative fuel powertrains for HDVs in Iceland and identify the best candidate/s to transition away from fossil fuels in the freight sector. The literature reviewed carried out revealed that most studies on alternative fuel powertrains focus on GHG and TCO assessments, while overlooking other relevant aspects such as air pollutant emissions, technical feasibility, and impact on energy security. In Paper I, we address these gaps by developing a comprehensive assessment framework that evaluates alternative fuel powertrains across environmental, economic, and technical dimensions.

Problem

The HDV sector in Iceland is largely dependent on fossil fuels, contributing significantly to GHG emissions. Like many countries, the Icelandic government announced measures to phase out fossil fuels from the road freight transport sector by 2050, but specific measures were not specified in the action plan (Ministry of the Environment, Energy and

Climate, 2020). Alternative fuels are seen as a potential solution to cut down emissions while complying with the technical demands of heavy-duty transport (Stančín et al., 2020; Forrest et al., 2020), but there is limited research on their applicability to HDVs. Additionally, existing literature primarily examines greenhouse gas emissions and total cost of ownership (Lajevardi et al., 2019), and often neglects relevant factors such as energy security, technical feasibility, vehicle performance under adverse climate conditions.

Without clear solutions or specific policies to transition away from fossil fuels in HDVs, it is necessary to assess the environmental, technical, and economic viability of alternative fuel powertrains for HDVs in Iceland to identify the most favourable solution to meet the transition goals. This paper aims to address this gap by evaluating which alternative fuel powertrain offers the most feasible solution to decarbonise Iceland's HDV sector, considering GHG and air pollutant emissions, TCO, energy security, and technical feasibility.

Methodology

This study developed a comprehensive framework to evaluate the feasibility of alternative fuel HDV powertrains in Iceland. The first step involved conducting a systematic literature review to identify relevant alternative fuel powertrain options to include in the analysis and explore research gaps in existing alternative fuel feasibility assessments. The selected powertrains included battery-electric (BEV), hydrogen fuel cell (FCV), diesel hybrid electric (HEV), biodiesel (B100, B20), renewable diesel (RD100, RD20), compressed natural gas (CNG), and liquefied natural gas (LNG). The literature review also revealed that most studies tend to focus on GHG emissions and TCO assessments, often overlooking critical aspects such as air pollutant emissions, feedstock availability, and the technical feasibility of powertrains to meet demanding freight requirements.

Each powertrain was evaluated in terms of their life cycle CO₂ and air pollutant emissions, TCO, impacts on energy security, and technical feasibility. The environmental assessments were carried out using life-cycle analysis tools, including Argonne National Laboratory's GREET database and AFLEET tool to quantify the GHG and air pollutant emissions for each powertrain from a Well-to-Wheel (WtW) perspective. AFLEET tool was also used to calculate the TCO, incorporating purchase, operational, and maintenance costs over a 15-years period. The technical feasibility assessment focused on the ability of each powertrain to meet Iceland's freight demands, considering general payload capacities, operational ranges, and infrastructure compatibility. Finally, an inventory analysis was carried out to evaluate the sustainability and availability of biofuel and renewable fuel feedstocks within Iceland.

Lastly, the results from the environmental, economic, and technical assessments were compared across all powertrain options to identify the most favourable solution for the Icelandic context.

Contribution

Paper I directly contributes to fulfilling G1 by identifying BETs as the most feasible solution for decarbonising HDVs in Iceland. The outcomes of this paper suggest that BETs offer the most favourable environmental and economic results, including highest reduction in GHG emissions and competitive TCO. Additionally, the paper emphasises that BETs contribute to increasing energy security in Iceland due to the abundant electricity resources in the country.

The outcomes of Paper I also highlight critical limitations of BET implementation, such as range constraints and infrastructure requirements, which establish the foundation for subsequent studies on battery-electric HDV feasibility in Iceland. These findings serve as a starting point for Paper II, III, and IV.

1.4.2 Paper II: Electrification potential for heavy-duty vehicles in harsh climate conditions: A case study based technical feasibility assessment

While Paper I identified BETs as the most feasible solution for decarbonising the HDV sector, it also highlighted key limitations for their deployment such as range constraints and infrastructure challenges. Paper II builds on these findings by investigating how Iceland's Arctic-like conditions, including low temperatures and high winds, affect BET performance and freight transport electrification potential.

Problem

The electrification of HDVs is essential for reducing fossil fuel dependency and GHG emissions, but its feasibility in regions with adverse climates and demanding freight conditions remains unclear (Melander et al., 2022; Qasim and Csiszar, 2021). Nevertheless, existing literature on HDV electrification does not fully cover the performance variations of BETs in adverse contexts such as extreme weather and heavy payloads, which can reduce range significantly. The uncertainty around factors like driving range and charging infrastructure requirements under these conditions slows down the adoption of electric HDVs, especially in regions with harsh conditions like Iceland. This paper uses the freight activity of a company operating in Iceland as case study to quantify the impact of adverse climate and freight conditions on BET performance, and to assess the extent to which freight activity can be carried out using BETs.

Methodology

In Paper II, we aimed to evaluate the technical feasibility of HDV electrification in Iceland under harsh climatic and freight conditions. To achieve this, a case study approach was employed using real-world freight activity data from Ölgerðin's delivery fleet, an Icelandic beverage company which operates in the Reykjavík capital area. The analysis started with collecting and processing the freight data from Ölgerðin's fleet, which included HDV configurations, recorded drive cycles with speed and altitude time-series, route categories, payloads, and tail-lift usage. The battery-electric vehicles selected for the analysis were based on Ölgerðin's current fleet, which include sprinter vans, boxed trucks, semi-trailers, and trailer trucks. As for the routes, these were divided into downtown, suburbs, and out-of-town (i.e., regional) routes.

This study used FASTSim (Brooker et al., 2015) to estimate the vehicle energy consumption over the analysed routes, adjusting the model to reflect the adverse climate (e.g., low temperature, headwind) and freight (e.g., heavy payloads, tail-lift usage) conditions present in Iceland. The impact of low temperatures and battery thermal management systems (BTMS) on charging performance was also evaluated to determine the charging requirements and impact on charging time.

Finally, this study assessed the electrification potential of Ölgerðin's routes by combining the results of the vehicle energy consumption model with route-specific characteristics. Therefore, the electrification potential was evaluated for each vehicle and each route category, identifying the respective charging requirements.

Contribution

Paper II contributes to the thesis by addressing critical uncertainties in BET performance under harsh climatic and freight conditions, directly supporting G2. The study

demonstrates that while adverse conditions can reduce vehicle range by up to 47%, short-haul routes can still be electrified with minimal modifications. Regional-haul routes, however, require strategic planning of on-route charging infrastructure to ensure operational reliability.

The methodology developed in Paper II forms the basis for subsequent studies, particularly Paper III, which focuses on charging infrastructure planning, and Paper IV, which examines grid impacts of BET adoption. By quantifying the impacts of harsh conditions and developing a framework for assessing electrification feasibility, Paper II bridges the gap between theoretical assessments and real-world implementation.

1.4.3 Paper III: Optimising and Planning Fast-Charging Infrastructure for Long-Haul Electric Trucks

Paper III continues the work developed in Paper II to evaluate the decarbonisation potential of long-haul road freight applications using BETs. Paper III also delves into the required fast-charging infrastructure required to support the integration of BETs in long-haul routes, considering Iceland's harsh-climate and remote conditions and using the routes to the Westfjords as case study.

Problem

The transition towards long-haul freight transport electrification is, partially, held back by the lack of suitable fast-charging infrastructure (Imre et al., 2021), particularly in remote regions with low traffic flow and harsh weather conditions, like Iceland's Westfjords. Existing fast-charging networks are mostly designed for passenger vehicles and urban areas, rendering them inadequate for the specific needs of BETs in long-haul operations (Danese et al., 2021). Moreover, the high costs and low utilisation rates of charging stations in rural regions further complicate infrastructure development. This paper aims to develop an optimised fast-charging network tailored for BETs operating in remote regions with challenging climates, focusing on identifying ideal charging station locations and configurations to support long-haul freight in Iceland.

Methodology

In this study, we developed a comprehensive methodology for planning fast-charging infrastructure for long-haul BETs in remote regions with adverse climate conditions, using the Reykjavik-Westfjords freight routes in Iceland as the case-study. The analysis began with the estimation of BET energy consumption and charging requirements under adverse conditions using the methods developed in Paper II. Two BETs were selected for the analysis, with two battery capacity configurations (360 kWh and 540 kWh) and two charging power levels (350 kW and 500 kW).

The results of the vehicle energy consumption model were then used to determine the optimal locations and durations of charging stops. A demand-oriented approach was adopted, using existing infrastructure such as gas stations and rest stops as potential locations for fast-charging stations. A non-linear charging optimisation framework using Gurobi was applied to minimise total travel time while ensuring the vehicles always maintained a minimum 10% state-of-charge (SOC). This optimisation process aimed to meet operational demands while reducing range anxiety.

Finally, this study assessed the scalability of the proposed charging infrastructure by applying queueing theory to determine the optimal number of charging plugs per station, using the service rate calculated with the optimisation model and traffic flow to estimate truck arrival rates and distribution along the routes. The impact of varying battery capacities and charging rates was also evaluated in terms of infrastructure implications and derived charging loads.

Contribution

Paper III directly addresses G3 by providing a detailed methodology for designing a fast-charging network capable of supporting long-haul freight electrification in Iceland. The study identifies the number and locations of required charging stations, the derived charging loads, and the number of charging plugs necessary to minimise delays. By focusing on the Reykjavík-Westfjords route, Paper III offers insights into infrastructure planning for remote and rural regions with harsh climatic conditions. These findings, as well as the developed methodology, set the required foundations for investigating the impact of BET charging loads in Paper IV.

1.4.4 Paper IV: Impact assessment of battery-electric HDVs charging loads on the transmission and distribution system in Iceland and mitigation strategies

Lastly, Paper IV uses the methodologies developed in the previous papers to propose a robust fast-charging network to support the main freight routes in Iceland and calculate the derived fast-charging loads. This study develops a model of the Icelandic power grid to evaluate the impact of the calculated loads on the national power flow and identify potential system bottlenecks.

Problem

The scale of BET charging demands and the power grid's ability to accommodate them are critical factors in assessing the technical feasibility of freight electrification (Burnham et al., 2017). A higher penetration of BETs will significantly increase electricity consumption, which could lead to system instability (Apiyo, 2019). During peak demand periods, fast-charging stations with several BET may require power levels comparable to typical urban and industrial loads (Burnham et al., 2017). Additionally, long-haul freight operations are characterised by rigid schedules, with drivers prioritising fast-charging sessions to reduce routing time, creating further operational challenges for the grid (Burnham et al., 2017). As BET adoption grows, the demand for high-power fast-charging infrastructure is expected to expand accordingly, adding more stress on the grid (Mowry & Mallapragada, 2021).

Therefore, comprehensive assessments of grid capacity and reliability under rising load conditions are essential to determine the feasibility of integrating BET charging demands into transmission and distribution networks.

Paper IV aims to evaluate the impact of BET fast-charging loads on Iceland's transmission and distribution system and identify potential grid reinforcements required to support BET operations along the country's primary freight routes. These insights are crucial to supporting the large-scale deployment of BETs, facilitating the decarbonisation of long-haul transport, and achieving emissions reduction targets.

Methodology

Building on the foundations of the previous papers, Paper IV used the methods from Paper III to design a reliable and optimised charging network using detailed BET performance under adverse climate and freight conditions to support the main freight routes in Iceland. The charging requirements for BETs were then determined using the charging optimisation model from Paper III, allocating the charging stops and calculating the resulting power demand at each charging location.

Then, in Paper IV, we introduced a PyPSA model of the Icelandic power grid which was developed using accurate data provided by the key power grid stakeholders in Iceland.

The developed PyPSA model was used to assess the impact of BET charging loads on the Icelandic power grid, using the charging loads determined through the charging optimisation model. Three scenarios were considered: a reference case representing current grid operations, a 2030 scenario reflecting expected general electricity demand growth, and a 2030 BET scenario incorporating the additional charging loads from BETs. The power flow analysis focused on evaluating voltage stability, line loading, and potential component constraints under increasing power consumption levels and BET integration.

Contribution

Paper IV contributes directly to G4 by assessing the potential implications of integrating BET charging loads on the Icelandic power grid. The results emphasise that the increase in general power consumption may contribute to voltage instability across the national grid, a challenge that becomes more pronounced with the addition of BET charging loads. Paper IV indicates that the Westfjords may be the region which requires the most upgrades or adjustments to accommodate the rise in power demand, especially BET loads, as the region shows critical voltage violations in the 2030 BET scenario due to the limited grid capacity.

2. Paper 1

Technical, economic, and environmental feasibility of alternative fuel heavy-duty vehicles in Iceland

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Abstract

The literature available on alternative fuel heavy-duty trucks often focuses on greenhouse gas emissions and total cost of ownership assessments, drawing an insightful but incomplete picture of the best solutions for each context. Using Iceland as case study, this paper attempts to provide a broader perspective by including energy security, technical feasibility and air pollutant emissions in the assessment. AFLEET and GREET are used to calculate the life cycle emissions and the total cost of ownership of 10 heavy-duty powertrains using representative vehicle categories in Iceland: regional and delivery trucks. The technical feasibility of battery-electric and hydrogen trucks is addressed in terms of battery/tank required capacity for representative fuel efficiency values, while the resources available in Iceland are used to determine the local fuel production capacity and the potential impact of each alternative fuel pathway on energy security. The results suggest that battery-electric trucks present the highest environmental and economic benefits, although the limited range of current battery technology implies a high penetration only in delivery trucks. Hydrogen and compressed natural gas pathways present attractive results for regional trucks, although their implementation is limited due to high life cycle costs and insufficient feedstock capacity. Renewable diesel stands out as a potential solution to fill the gap for regional trucks as it presents overall satisfactory results throughout all dimensions addressed. The results suggest that a 100% alternative fuel heavy-duty fleet energy demand could be met using local resources in Iceland.

Keywords: Heavy-duty vehicle; Alternative fuel; Total cost of ownership; Life cycle assessment; Energy security

Acronyms: GHG, Greenhouse Gas; HDV, Heavy Duty Vehicle; LDV, Light Duty Vehicle; TCO, Total Cost of Ownership; WTW, Well-to-Wheel; WTP, Well-to-Pump; PTW, Pump-to-Wheel; BEV, Battery Electric Vehicle; FCV, Fuel Cell Electric Vehicle (hydrogen); HEV, Hybrid Electric Vehicle; B20, Biodiesel 20% blend; B100, Biodiesel, pure fuel; RD20, Renewable Diesel 20% blend; RD100, Renewable Diesel, pure fuel; LNG, Liquefied Natural Gas; CNG, Compressed Natural Gas; VOC, Volatile Organic Compounds; VMT, Vehicle Miles Travelled.

1. Introduction

The transport sector is responsible for approximately 22% of the total global energy related CO₂ emissions, with road freight transport accounting for around 40% of the total emissions within this sector (IEA, 2017). Road freight transport is a crucial sector to address to achieve a sustainable transition away from fossil fuels, which environmental impact has been under the spotlight in the last years. Consequently, regulators have pushed for stricter greenhouse gas (GHG) emission limits for freight vehicles (European Commission, 2019) and many countries worldwide have established goals aiming at the decarbonisation of this sector (Kluschke et al., 2019). Road freight vehicles are as diverse as the purposes they fulfil and vary in size, weight and engine power among other factors. For the purpose of this study, these will be defined as heavy duty vehicles (HDVs), encompassing all commercial vehicles with a gross vehicle weight (GWT) of 3.5 tons or more and designed for the transportation of goods. Passenger vehicles and other vehicles which weigh less than 3.5 tons will be referred as light duty vehicles (LDVs) (IEA, 2017).

The Nordic countries formed by Denmark, Finland, Norway, Iceland and Sweden have developed ambitious policies aiming to reduce their GHG emissions and improve energy security (Regjeringen, 2019). As a result of their efforts, the region has achieved a deep decarbonisation of the electricity and heating sectors yet the transport sector remains a challenge as all five countries rely on carbon intensive means of transport. Transport currently represents 40% of Nordic CO₂ emissions and reducing emissions depends on transitioning away from fossil fuels (Sovacool, 2017).

Similarly to its Nordic peers, Iceland's renewable energy penetration in the transport sector is negligible and relies heavily on fossil fuel imports (Orkustofnun, 2020a). In 2019, transport accounted for half of the GHG emissions from the energy sector, with road vehicles representing over 95% of the total emissions from the transport sector. HDVs were responsible for 21% of the on-road GHG emissions (Umhverfisstofnun, 2019) although only representing 5% of the total road vehicle fleet (Samgöngustofa, 2022).

The Icelandic government announced measures to phase out all fossil fuels throughout the energy sector, including the road transport sector by 2050, to achieve carbon neutrality by 2040 and to reduce GHG emissions by 55% by 2030 compared to 2005. The actions to realise these goals were provided in the 2020 Climate Action Plan (Ministry for the Environment, 2020a). Unlike in most other sectors, specific measures for heavy transport were not specified in the action plan apart from the formation of a task force aiming at accelerating sustainable energy transition in heavy duty road transport and some thoughts on domestic production of renewable fuels (Ministry for the Environment, 2020b). This is problematic because there is no clear solution to decarbonize the highly diesel dependent road freight sector in Iceland. As shown in Fig. 1, there are certain technologies emerging in the LDV fleet which can potentially reduce GHG emissions, such as battery electric or hybrid powertrains, whereas there is no sign of alternative fuel powertrain penetration in the HDV fleet and the number of diesel trucks keeps increasing (Umhverfisstofnun, 2019).

Although improving powertrain efficiency and optimisation of freight routes can reduce emissions, these are insufficient to achieve deep GHG emission reduction (European Commission, 2019). Alternative fuels have gained significant attention due to their potential to cut down emissions (Stančin et al., 2020) and transition from fossil fuels while complying with the technical demands of heavy transport (Forrest et al., 2020).

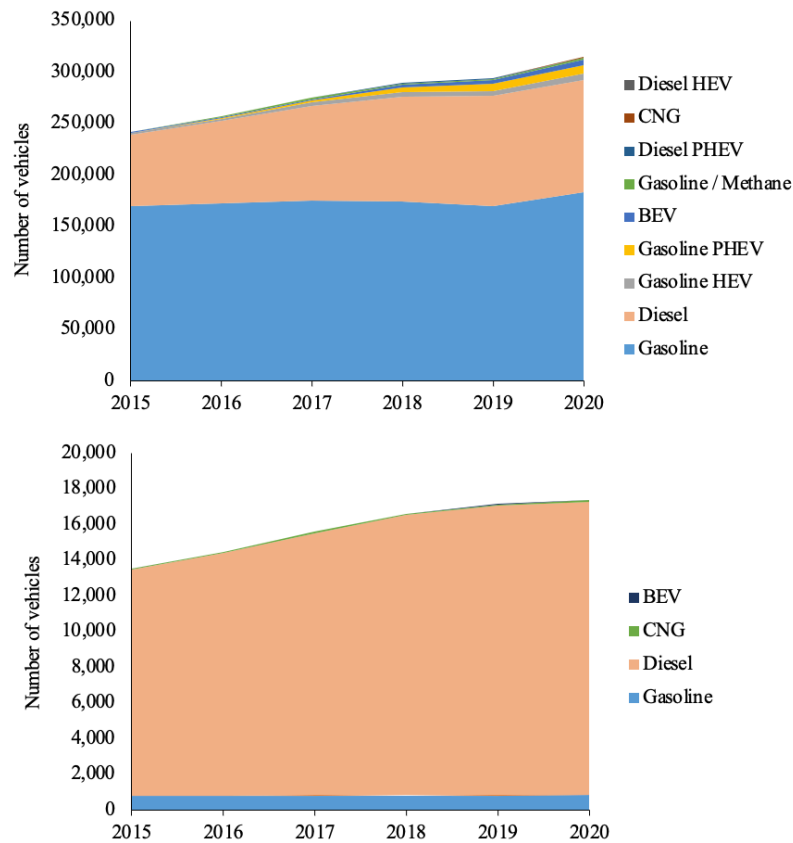


Figure 1. Icelandic LDV (above) and HDV (below) fleet by energy source (Statistics Iceland, 2020)

Alternative fuels can be defined as fuels derived from sources other than petroleum, contrary to conventional fossil-based fuels such as gasoline and diesel. There are several alternative fuel HDV powertrain technologies commercially available like biodiesel (U.S. Department of Energy, 2021a), compressed natural gas (CNG) and liquified natural gas (LNG), as well as hybrid powertrains (Fulton and Miller, 2015). Battery electric and hydrogen fuel cell powertrains also reached commercial stage recently (Lajevardi et al., 2019). The use of alternative fuels in LDV has been extensively addressed in the literature, including context specific studies in Iceland such as in Shafiei et al. (2014) and Shafiei et al. (2015). That is not the case for HDVs, where more effort is required to assess and to compare the performance of alternative fuels in HDVs in terms of emissions, energy efficiency and costs (Lopez et al., 2020).

In the reviewed literature, electric HDV powertrains often presented the lowest GHG emissions although the overall emission reduction potential varied depending on the carbon intensity of the electric grid, subsystem efficiencies and driving cycles considered. Lajevardi et al. (2019) concluded that electric powertrains achieved the highest GHG emission reduction, with catenary electric and battery electric emitting about 60–99% and 30–70% less GHG compared to baseline diesel depending on the drive cycle and carbon intensity of the electricity used. Sen et al. (2017) suggested that battery electric vehicles (BEV) accounted for 70% less GHG emissions than baseline diesel. As in Lajevardi et al. (2019), the study highlighted that the reduction potential varies significantly depending on the origin of the electricity. Additionally, Sen et al. (2017) estimated the air pollutant emissions for each powertrain and found that BEV accounted for the lowest air pollutant emissions throughout its life cycle. Contrary to the previous results, Zhang et al. (2022) found that hybrid powertrains present greater GHG emission reduction potential compared to electric and fuel cell trucks.

Authors also investigated the total cost of ownership (TCO) of different alternative fuel powertrains. In this regard, the literature review held no consensus. Lajevardi et al. (2019) and Lopez et al. (2020) found that only hybrid powertrains accounted for better TCO results

compared to diesel due to significant fuel savings. Lajevardi et al. (2019) results showed that plug-in hybrid diesel powertrains accounted for better TCO than conventional diesel for both short and long-haul trips, while BEVs accounted for 22–66% higher costs than conventional diesel due to the cost of the battery pack and fast charging stations. Lopez et al. (2020) got similar results with hybrid electric urban buses, achieving lower TCO than diesel. Contrary to the previous studies, Sen et al. (2017) found that BEVs life cycle costs were 27% lower than baseline diesel, followed by hybrid powertrains and biodiesel which all presented cost reduction to diesel. Fuel costs were the main contributor to the TCO for all powertrains, followed by maintenance costs. The costs of battery manufacturing and battery replacement increased significantly the TCO of electric powertrains. Jaller et al. (2020) concluded that financial incentives were required for BEVs to achieve lower TCO to diesel.

FCVs are seen as a promising technology for freight applications due to their zero tailpipe emissions and higher range compared to BEV (Çabukoglu et al., 2019). Zhao et al. (2013), Lee et al. (2018) and Lajevardi et al. (2019) found that hydrogen fuel cell powertrains achieved significant reductions in life cycle GHG emission, although the reduction potential is strongly influenced by the hydrogen production pathway and the use of electricity mix. Çabukoglu et al. (2019) concluded that emission mitigation would be harder with FCVs compared to BEVs given the lower efficiency of the powertrain and fuel production. Significant efforts should be carried out to reduce the TCO of FCV powertrains as its lifetime costs are currently unattractive compared to diesel and even to BEV (Lajevardi et al., 2019).

LNG powertrains have also gained attention in powering freight vehicles due to their capacity to reduce emissions, fuel energy density and commercial readiness. Rial and Pérez (2021) found that LNG drivetrains presented lower emissions for all pollutant categories than diesel, with minor improvements regarding life cycle GHG emissions. Langshaw et al. (2020) found that LNG drivetrains could account for about 13% life cycle GHG emission reduction compared to diesel if LNG reached parity with diesel in terms of energy efficiency. Gustafsson and Svensson (2021) also explored the potential environmental benefits of liquid biomethane (LBM) and LNG. Contrary to Rial and Pérez (2021), the study found that LNG fails to reduce life cycle emissions in HDVs and could even represent a 10% increase in GHG emissions to conventional diesel. However, the results showed that LBM had a greater well-to-wheel emission reduction potential to both conventional diesel and LNG, accounting for reductions of around 45–70% and 50–75% with LBM from manure and food waste respectively. In terms of cost, Rial and Pérez (2021) results indicated a higher TCO for LNG compared to diesel while Langshaw et al. (2020) concluded that access to public refuelling LNG stations enabled a 7% reduction in TCO to baseline diesel.

Çabukoglu et al. (2018), Çabukoglu et al. (2019) and Forrest et al. (2020) focused on investigating the technical feasibility of battery electric and hydrogen fuel cell powertrains to meet freight transport demands. Forrest et al. (2020) investigated different deployment scenarios for both BEV and FCV technologies, considering different battery capacities and range, refuelling opportunities and charging rates, while Çabukoglu et al. carried out a similar investigation for the national Swiss truck fleet for both BEV (2018) and FCV (2019) powertrains. Both Forrest et al. (2020) and Çabukoglu et al. (2018) stated that BEV feasibility increased with bigger battery capacities and the availability of fast charging infrastructure, although Çabukoglu et al. (2018) concluded that the development of a battery swapping infrastructure would be required to meet the daily routes. Both studies concluded that FCV achieved a higher diffusion compared to BEV in most cases, with range or refuelling times not being a limiting factor for its deployment.

The literature available on alternative fuel HDVs often focuses on GHG emissions and TCO assessments, which arguably are the most relevant aspects for fleet operators and policy makers when comparing alternative fuel powertrains. Other aspects such as air pollutant emissions or the drivetrain's feasibility to meet the freight transport demands are not commonly addressed, although these are of great relevance to determine the most adequate

alternative fuel solution (Michalek et al., 2011). Energy security has also become a significant pillar of the energy transition, as current events evidenced the negative impacts that reliance on foreign energy sources have over affordable energy and security of supply (IEA, 2021a). Therefore, local resources should also be considered when discussing the transition towards alternative fuels in a specific region or country. The consideration of these five pillars (GHG, TCO, air pollutants, technical feasibility and energy security) is crucial to determine the most adequate solution for each case study, as it provides a more accurate picture of reality other than focusing only on GHG emissions.

The present study attempts to fill the gap in alternative fuel powertrain assessment by including all five pillars in the comparison, using Iceland as the case study. The main research question of the paper is; given the technical demands of HDV in Iceland, what alternative fuel powertrain represents the most feasible solution to transition away from fossil fuels in terms of GHG and air pollutant emissions and total cost of ownership? To answer the research question, this paper carried out a broad feasibility analysis of the drivetrain's capacity to meet Iceland's freight demands, a feedstock inventory assessment, a life cycle GHG and air pollutant emissions for different powertrains and, lastly, a TCO assessment for the selected powertrains. The results are then compared to identify the most attractive powertrain regarding operational feasibility, environmental and economic terms. The outcomes of this study contribute directly to Iceland's Climate Action Plan goals of 'A.8 Energy transition in heavy transport' and 'C.4 Domestic renewable fuels' (Ministry for the Environment, 2020b).

To the best of the authors knowledge, this is the first paper to address the transition towards renewable energy in the HDV sector in Iceland and the first comprehensive analysis to investigate environmental, economic, technical and energy security aspects regarding the transition away from fossil fuels in HDV in the same study. This original structure has been inspired by the methodological approach of Rial and Pérez (2021), Jaller et al. (2021) and López et al. (2020). This case study can contribute to the decarbonisation of the heavy-duty sector by providing insights regarding the sustainable transition in HDV in Iceland and the original analysis framework for future studies.

2. Methods

2.1. Selection of representative heavy duty vehicle categories for Iceland

This section introduces the HDV categories that will be featured in the analysis. The focus of the study relies on the HDVs used to transport goods, which represent around 80% of the freight activity in Iceland (Statistics Iceland, unpublished data). Road freight driving data from Icelandic HDV fleet operators was collected to determine the vehicle characteristics representative of the Icelandic context. Table 1 presents the HDV categories considered in this study based on the collected data, which are divided into delivery trucks, accounting for the trips carried out with a 3.5–12 ton truck within the Reykjavík capital area, and regional trucks going from Reykjavík to the main economic points around the country. The vehicle lifetime considered for both is 15 years.

Table 1. Summary of the vehicle information considered in the scope of this study (Eimskip, 2020, personal communication)

Vehicle category	Type of trip (haul)	Representative model	Number of annual trips	Annual mileage (km) ^a	Distance per trip (km)	Energy consumption (MPDGE) ^b
Combination regional haul truck (12<ton)	Reykjavik – Akureyri / East Coast	Volvo FH16	200	100,000	500	4.8
Delivery van (3.5-12 ton)	Reykjavik area	Opel Movano	4.000	30,000	8	8.3

^a Annual mileage estimates from Eimskip used in the technical, TCO and emission analysis. The average values from the whole HDV fleet from Samgöngustofa (2022) are used in the energy security analysis: 24,500 km and 14,000 km for regional and delivery trucks respectively.

^b Miles Per Diesel Gallon Equivalent.

2.2. Alternative fuel powertrains included in the scope

The powertrains assessed in this study are conventional diesel, battery electric (BEV), hydrogen fuel cell (FCV) from electrolysis, diesel hybrid electric (HEV), biodiesel (B100, B20), renewable diesel (RD100, RD20), compressed natural gas (CNG) and liquified natural gas (LNG). Biodiesel and renewable diesel are not the same fuel as they present several differences in their use and production processes. RD100 is suitable for its direct use in diesel engines and it is mostly produced via biochemical and thermochemical pathways, while B100 needs some adaptation for its use in diesel engines and it is produced via transesterification (U.S. Department of Energy, 2021a).

The selection of the powertrains included in the scope was based on their relevance in the literature (Lajevardi et al., 2019), data availability to perform the calculations (Argonne National Laboratory, 2020) and commercial readiness (Forrest et al., 2020). The resources available in Iceland as well as the low-carbon electricity production played an important role at defining the fuel production pathways for hydrogen, B100, RD100, CNG and LNG. Synthetic fuels were not included in the scope due to their current low life cycle efficiencies and lack of relevance in the literature, although the authors acknowledge that synthetic fuels are a promising prospect for the future decarbonisation of HDVs (Transport and Environment, 2020).

Eimskip’s regional and delivery trucks reported fuel economy was used as the baseline to estimate the fuel efficiency of the rest of the considered powertrains, using alternative fuel ratios from Argonne National Laboratory (2020). The outcomes from Henning et al. (2019) were used to further adjust the fuel economy of BEV, FCV and HEV to account for the loss in performance linked to the cold and windy conditions in Iceland. The vehicle specifications for BEV and FCV are described in Table 2 and Table 3, respectively (Kleiner and Friedrich, 2017). The fuel economy values for each powertrain are presented in Table 5.

Table 2. Vehicle specifications for 40-ton BEV and FCV regional trucks

Vehicle component	Battery size (kWh)	Weight of the battery size (kg)	Output power (kW)	Fuel cell stack (kW _{el})	Fuel cell tank (kg)
BEV	700	3,825	335	-	-
FCV	5	30	335	100	90

Table 3. Vehicle specifications for 12-ton BEV and FCV regional trucks

Vehicle component	Battery size (kWh)	Weight of the battery size (kg)	Output power (kW)	Fuel cell stack (kW _{el})	Fuel cell tank (kg)
BEV	150	800	170	-	-
FCV	3	15	170	40	10

2.3. Life cycle analysis (LCA)

LCA is used in this study to assess the environmental impacts of the different alternative fuel pathways. LCA represents a well-established methodology to explore the impacts on the environment produced by a specific product, process or service throughout all the stages of its life cycle. This analysis is necessary to fairly compare alternatives, as upstream activities could represent significant energy and material consumption which consequently might produce large amounts of GHG emissions in addition to the downstream activities (Duchin and Hertwich, 2003). The life cycle assessment of fuels used for transportation can also be referred as well to wheel (WTW) analysis, which includes the environmental impacts associated with all the stages of the fuel lifespan. WTW analysis can be divided in two main stages: well to pump (WTP), which is composed by the activities associated with the fuel production process; and pump to wheel (PTW), which accounts for the vehicle operation activities (Argonne National Laboratory, 2020). The vehicle cycle processes are also considered, including the extraction of raw materials, manufacturing and vehicle disposal. A detailed definition of the system boundaries considered in the LCA is carried out in Section 2.8.

2.4. Total cost of ownership (TCO)

TCO is an important indicator for fleet operators (Jaller and Pahwa, 2020) which consists of the aggregation of several economic performance metrics that contribute to the overall costs of owning a vehicle over a determined period (Jaller et al., 2021). Several factors contribute to the TCO analysis of a specific HDV powertrain including purchase cost, fuel consumption, maintenance and repair costs, insurance, financing and the years of utilization of the vehicle, among other costs (Argonne National Laboratory, 2020). This study will use TCO to assess the use of different alternative fuel powertrain technologies in economic terms.

2.5. AFLEET tool and GREET

AFLEET (Alternative Fuel Life-Cycle Environmental and Economic Transportation) tool has been used in this study to estimate the life cycle petroleum consumption, GHG emissions, air pollutant emissions and cost of ownership of the selected powertrain technologies (Argonne National Laboratory, 2020).

AFLEET uses data from the Greenhouse gases, Regulated Emissions and Energy use in Technologies (GREET) model, an analytical tool that simulates the energy use and emissions of different vehicle and fuel combinations throughout their whole life cycle. GREET, also developed by Argonne's Laboratory, is used in this study to estimate the WTW emissions at a process level, considering process-specific energy efficiencies, different shares of fuel types, combustion technologies and emission factors for combustion technologies. We use GREET to calculate the emissions associated with the fuel production process, electricity generation, fertilizer use, vehicle material recovery and production, vehicle component fabrication, vehicle assembly and final disposal (Argonne National Laboratory, 2020). The

vehicle operation emission factors are based on EPA's Motor Vehicle Emission Simulator (MOVES) database, which includes data for tailpipe, tire and brake wear emissions for different HDV categories (EPA, 2015). The electricity generation mix has been adjusted to reflex the Icelandic low carbon energy system using 2020 values, which account for 68% of the total electricity produced from hydropower, 29% from geothermal, 0.04% from wind and 0.02% from residual oil (Orkustofnun, 2020c). The emission factors are summarised in Table 4. GREET biofuel production parameters for biodiesel, renewable diesel, CNG and LNG have also been adjusted to represent the Icelandic context.

Table 4. Emission factors from electricity production sources (g/kWh)

Substance	Hydropower ¹	Geothermal ¹	Oil generator ²
CO ₂	1.50	29.50	785
NO _x			4.65
PM _{2.5}			0.01
PM ₁₀			0.01
VOC			0.01
SO _x		3.50 ³	0.10
CO			0.03
CH ₄		0.05	

¹Orkustofnun (2020d)

²Argonne (2020)

³It is assumed that all H₂S emissions from geothermal power get converted to SO_x

Equation (1) summarises the methodology of GREET to calculate the WTW emissions for each powertrain pathway (Cai et al., 2017),

$$\begin{aligned}
 WTW_{CF_s} = & \left(\sum_p \sum_i \sum_j \left[\left(\frac{1}{\eta_p} - 1 \right) * PF_{p,i} * CT_{p,i,j} * EF_{CF_s,i,j} \right] \right. \\
 & \left. + \sum_p \sum_i \left[Upstream_{CF_s,i} * \left(\frac{1}{\eta_p} - 1 \right) * PF_{p,i} \right] \right) \\
 & * \frac{GGE}{MPGGE} + VO_{T,CF_s} + VO_{TBW,CF_s}
 \end{aligned} \quad (1)$$

where p , i , j and s refer to process, share of process fuel, share of combustion technology and air pollutant emission factor, respectively; WTW_{CF_s} is the well-to-wheel emissions of the respective air pollutant or GHG (g/km); η_p is the energy efficiency of process p of the fuel supply chain; $PF_{p,i}$ is share of process fuel i in process p ; $CT_{p,i,j}$ is the share of combustion for technology j of process fuel i in the process p ; $EF_{CF_s,i,j}$ refers to the air pollutant s emission factor of using process fuel i and combustion technology j (g/mmBTU); $Upstream_{CF_s,i}$ is the air pollutant s fuel cycle emissions from process fuel production i (g/mmBtu); GGE is the LHV energy content in a gasoline gallon equivalent (Btu/gal); FE is the vehicle fuel economy (km/GGE); and VO_{TBW,CF_s} refer to the vehicle operation air pollutant emissions, including tire and brake wear (g/km).

Equation (2) shows how the TCO for each powertrain is calculated over a 15-year period (adjusted from Zhang et al., 2022),

$$TCO = C_b + \sum_{t=1}^{15} \frac{(C_e * P_f * L_e) + C_o}{(1+r)^t} \quad (2)$$

where C_b represent the purchase cost of vehicles (USD); C_e is the vehicle's fuel economy (L/km); P_f refers to the fuel price (USD/L); L_e is the annual driving mileage per vehicle (km); C_o is other related costs such as maintenance (USD); r is the discount factor; and t is the life cycle of the vehicle (years).

Equation (2) has been applied through AFLEET's TCO module to assess the net present value of operation and fixed costs (Argonne National Laboratory, 2020) for the selected HDV powertrains over 15 years of planned ownership. The costs considered in the analysis include the initial investment to purchase the vehicles, loan financing, insurance, fuel consumption, component replacements and applicable taxes. The same conditions to finance the acquisition of the vehicles is considered for all vehicles to ensure a fair comparison; 5 years loan with an interest rate of 6.2% (Trading Economics – Iceland; visited in October 2021) and considering an initial payment of 20% (Rial and Pérez, 2021). The discount factor used in the analysis is 7% (Shafiei et al., 2014), which is applied to financing, fuel, diesel exhaust fluid, maintenance and repair, insurance, and license and registration costs, while the inflation rate considered is 2.5% (Statista – Iceland; visited in October 2021). Diesel exhaust fluid is used in diesel and biodiesel powertrains to reduce the amount of air pollutants, which cost is assumed to be 4.3 USD/L (N1, 2022). A summary of relevant data used in the TCO analysis is presented in Table 6.

The assumptions regarding battery and fuel cell stack replacement in terms of linked costs, air pollutant and GHG emissions are presented in Table 5. It is assumed that lithium-ion (Li-Ion) batteries are used in BEV and HEV (Sen et al., 2017) and polymer electrolyte membrane (PEM) fuel cells are used in FCV (U.S. Department of Energy, 2021b). According to Sen et al. (2017), the lifetime of a BEV regional truck battery is 4 years while for a HEV is 3 years. Given that battery technology is improving fast (Nykqvist and Olsson, 2021), this study assumed a 5-year battery lifetime for BEV and HEV regional trucks which implies two replacements throughout the vehicle's life. The same number of replacements is assumed for regional FCV fuel cell stack, which reported lifetime is about 25,000 h of operation (James et al., 2018). Batteries in delivery trucks are considered to last as long as the vehicle, so no replacement is considered (Argonne National Laboratory, 2020). The same is considered for fuel stacks in delivery trucks due to their lower vehicle operational use compared to regional trucks.

Table 5. Adjusted battery and fuel cell stack replacement cost (USD) and emission factors (tons)

Component	Capacity	Cost (USD) ¹	GHGs (t) ²	CO (t)	NO _x (t)	PM ₁₀ (t)	PM _{2.5} (t)	SO _x (t)	VOC (t)
Battery (BEV)	700 kWh	90,000	12.670	0.009	0.022	0.010	0.006	0.104	0.004
Fuel cell stack	100 kW _{el}	7,600	2.490	0.002	0.004	0.002	0.001	0.020	0.001

¹ Assumed costs of 132 USD/kWh for Li-Ion battery (Bloomberg, 2021) and 76 USD/kW for PEM fuel cell (US Department of Energy, 2021b). HEV battery size is 5 kWh (Kleiner and Friederich, 2017).

² The GHG and air pollutant emissions linked to the fuel cell stack replacement have been estimated using the ratio between GHG emitted to produce a battery pack and a fuel cell stack from Simon et al. (2021).

Current legislation exempts vehicles used for transportation of goods weighing 5 tons or more from excise tax, while commercial vehicles of 5 tons or less are subjected to a 13% excise tax (Skatturinn, 2021). Due to the composition of the HDV fleet, where less than 30% of the vehicles weigh less than 5 tons (Statistics Iceland, unpublished data), no excise tax has been adopted in the model. Existing economic incentives have been accounted for BEV and FCV in terms of loan financing (Arion Banki, 2021) and a 12,000 USD VAT exemption per vehicle. A discount of 3,600 USD has also been applied to HEV (Skatturinn, 2021).

The externalities cost of the different fuel and vehicle pathways has also been included in the analysis to better assess the impacts of shifting from conventional diesel to alternative fuel HDVs (Argonne National Laboratory, 2020). The pollutants included in the scope are representative of the main effects on human health and the environment defined by the European Environment Agency: global warming (CO, CO₂), acidification (NO_x, SO_x), shortening of life expectancy (NO_x, particulate matter) and precursor to particulate matter and ozone (VOC) (Koolen and Rothenberg, 2018).

Table 7 presents a summary of the externality costs considered in this study for petroleum use, GHG, and air pollutant emissions, which have been adjusted to reflect the Icelandic context. The estimated costs for petroleum use are based on the risk factors regarding oil supply disruptions, oil price increments and current policies aiming at enhancing oil security (Michalek et al., 2011). The value used for CO₂ emissions is the average carbon tax applied to diesel fuels in Iceland (Ministry of Finance and Economic Affairs, 2018). The marginal cost of health damages corresponding to SO_x, VOC, NO_x and PM_{2.5} emissions are estimated using the AP2 model on AFLEET, distinguishing air pollutant emissions from mobile sources and from electricity production (Jaramillo and Muller, 2016). Two population density scenarios have been considered taking the national average density (3 hab/km²) and the Reykjavík capital area density (219 hab/km²).

Equation (3) presents a general description of AFLEET's methodology to calculate the costs linked to petroleum use, GHG social costs and harmful air pollutant emissions,

$$Ext.costs_j = \sum_{t=1}^{15} C_f * P_{j,k} * Np_{j,k} + Hf_i * E_{i,j} * Nh_{i,j} * VKT + Sf_i * E_{i,j} * Ns_{i,j} * VKT \quad (3)$$

where i, j and k refer to air pollutant, powertrain and fuel type, respectively; C_f is the oil consumption valuation factor in 2020 (2020 USD/barrel); $P_{j,k}$ refers to the annual well-to-wheels petroleum use for powertrain j and fuel type k (barrels/year); $Np_{j,k}$ is the net present value factor for petroleum consumption for 15 years; Hf_i is the marginal health cost factor for pollutant I (USD/g); $E_{i,j}$ refers to vehicle emissions (g/km); $Nh_{i,j}$ is the net present value factor for health costs for 15 years; Sf_i is the marginal GHG social cost factor for pollutant I (USD/g); $Ns_{i,j}$ is the net present value factor for GHG social costs for 15 years; and VKT refers to the vehicle kilometres travelled per year. Equation (3) has been applied through AFLEET's externality costs module.

Table 6. Essential model input data

Vehicle category	Fuel Type	Fuel cost (USD/L) ¹	Fuel Economy (MPDGE) ²	Purchase price after taxes & benefits (USD/vehicle) ³	Maintenance and Repair (USD/km) ⁵
Delivery truck	Diesel	1.82	8.30	87,200	0.12
	BEV	0.06 (USD/kWh)	23.40	186,000 – 210,000	0.08
	FCV	14.20 (USD/kg)	15.70	113,500 ⁴	0.08
	HEV	1.82	8.70	105,900	0.09
	B20	1.52	8.25	87,200	0.12
	B100	2.13	8.25	87,200	0.12
	RD20	1.58	8.25	87,200	0.12
	RD100	2.24	8.25	87,200	0.12
	CNG	4.12 (USD/GGE)	7.05	138,000	0.13
	LNG	4.93	7.05	125,000	0.13
Regional truck	Diesel	1.82	4.80	162,000	0.11
	BEV	0.06 (USD/kWh)	9.15	235,000 – 587,000	0.09
	FCV	14.20 (USD/kg)	5.65	437,500	0.09
	HEV	1.82	4.25	180,700	0.10
	B20	1.52	4.80	162,000	0.11
	B100	2.13	4.80	162,000	0.11
	RD20	1.58	4.80	162,000	0.11
	RD100	2.24	4.80	162,000	0.11
	CNG	4.12 (USD/GGE)	4.35	212,000	0.12
	LNG	4.93	4.35	199,400	0.12

¹ Average prices for the last 6 years. Diesel, hydrogen and methane prices were obtained from Skeljungur; electricity costs from European Commission (2022). Adjusted values for B20, B100, RD20, RD100 and LNG (Argonne, 2020). A yearly price escalation rate is applied on diesel and biodiesel (3.6%); electricity (2%); and hydrogen, CNG and LNG (1.8%)

² Adjusted fuel economy values using Eimskip as baseline and alternative fuel ratios from Argonne (2020).

³ Purchase price for all vehicles includes VAT over AFLEET default costs. The financial benefits for BEV, FCV and HEV are also included (Skatturinn, 2021)

⁴ Estimated purchase cost assuming the same cost difference ratio between regional BEV and FCV

⁵ Default values from Argonne (2020)

Table 7. Externalities costs considered in the study for petroleum use, GHG and air pollutant emissions. A deterioration rate of 2.2%/year is applied to all values presented to account for operation emissions increasing as the vehicle ages.

Substance	Petroleum Use (USD per barrel) ¹	Social cost (USD/ton)	Health cost – Mobile sources (USD/ton) ⁴		Health cost – Power generation (USD/ton) ⁴	
			Low density	High density	Low density	High density
Petroleum use	17					
CO ₂		40 ²				
CO		16 ³				
NO _x			6,500	6,440	6,140	9,690
PM _{2.5}			30,050	179,250	10,660	77,970
PM ₁₀			3,450	14,520	1,220	6,320
VOC			1,430	20,420	1,090	7,985
SO _x			16,910	103,460	15,520	54,560

¹ Argonne (2020)

² Ministry of Finance and Economic Affairs (2018)

³ Waldhoff et al. (2011)

⁴ Jaramillo and Muller (2016)

2.6. HDV technical demands in Iceland

BEV and FCV are seen as promising technologies that could drastically reduce emissions in the transport sector (Forrest et al., 2020). Although it has been proved that fossil fuel LDVs can be replaced with battery electric and hydrogen fuel cell powertrains without significant changes in driving patterns, their use in HDVs remains uncertain due to the limited ranges and technical capabilities of current battery and fuel cell technology (Forrest et al., 2020). In addition, the implementation of battery and fuel cell HDV drivetrains in Iceland proves even more complex given the lack of charging/refuelling infrastructure (EAFO, 2021) and the harsh climatic conditions. BEV and FCV powertrains are subject to significant performance losses in cold environments, affecting fuel economy and overall range (Henning et al., 2019). Table 8 presents a range of BEV and FCV fuel efficiencies from Forrest et al. (2020) along with the fuel efficiencies calculated by this report. For delivery trucks, the fuel efficiency in Iceland seems acceptable as it falls within the reported values for BEV and FCV. The values for regional trucks are significantly worse, with BEV presenting about 41–53% lower fuel efficiency than reported values.

The fuel efficiencies in Table 8 are used to quantify the difference in performance in terms of the battery and fuel tank size required to meet a certain range in Iceland. The results are compared to the reported battery and fuel cell tank capacities by Kleiner and Friedrich (2017) and Moultak et al. (2017), which are used as the reference. The maximum battery capacities for delivery and regional BEV considered are 300 kWh and 700 kWh, while the maximum tank size for delivery and regional FCV are 25 kg and 90 kg. If the estimated capacities are higher than the reference values, these will be considered unrealistic given the state of current technology (Forrest et al., 2020).

Table 8. BEV and FCV fuel efficiency from Forrest et al. (2020) and own calculations

Vehicle category	BEV reported efficiency (kWh/km)	BEV fuel efficiency (kWh/km)	FCV reported efficiency (km/kg)	FCV fuel efficiency (km/kg)
Delivery truck	0.62—1.2	1.05	17.70—24.14	21.78
Regional truck	1.22—1.53	2.61	7.71—17.70	7.81

Data from Table 1 is used to broadly characterize the technical demands of HDVs in Iceland, including annual distance, number of trips per year and average distance per trip. The present study attempts to use the technical demands in Table 1 and the vehicle performance considerations from Table 8 to address the feasibility of heavy-duty BEV and FCV powertrains in Iceland.

2.7. Domestic renewable fuel production

Although Iceland's renewable energy resources are widely used to power the electricity and heating sectors, domestic energy penetration in the transport sector is negligible. The great dependency on foreign oil in the transport sector can negatively affect security of supply and affordable energy prices in Iceland. To address this issue, the Climate Change Action Plan 2020 has established targets to increase domestic renewable fuel production from rapeseed oil and waste to enhance energy security. Nevertheless, the targets are not detailed and a comprehensive study in domestic fuel production is lacking (Ministry for the Environment, 2018).

The present work attempts to contribute to the development of such a study by calculating the fuel production capacity from feedstocks available in Iceland using literature feedstock estimates: rapeseed oil for B100 and RD100 (Bernodsson, 2018), landfill gas for CNG and LNG (Sorpa, 2020; Mannvit, 2010) and electricity for BEV and FCV (Orkustofnun, 2020b). In addition, this study investigates to what extent could domestic fuel be used to supply the HDV fleet in Iceland. As one of the major contributors to the transport sector's oil demand, tackling HDV dependency on foreign diesel could carry significant benefits to Iceland's energy security as fuel imports would decrease (Ministry of Industries and Innovation, 2020).

There are other factors directly affecting energy security of supply in Iceland apart from fuel imports, such as the dependency on critical minerals (IEA, 2021c). The authors acknowledge the limitations of this exercise and point out that the outcomes from this section are incomplete as the dependency on other commodities should be considered. In this analysis the authors have assumed that reducing fuel imports increases energy security.

The HDV fuel consumption is calculated using the following Equation (4),

$$\text{Fuel consumption}_{ic} = \frac{VKT_c}{FE_{ic}} * n_c * f \quad (4)$$

where i and c refer to powertrain type and to vehicle category (delivery truck or regional truck), respectively; VKT refers to the annual vehicle kilometres travelled (km/vehicle) reported by Statistics Iceland for the respective vehicle category; FE_i is the fuel economy for powertrain i (MPGGE), taken from Table 6; n is the estimated total number of vehicles for each category (2,500 regional trucks and 13,400 delivery trucks (Statistics Iceland, 2020)); and f is the conversion factor from GGE to MJ (120.24 MJ in a GGE). The capacity to meet the HDV fuel demand for each fuel pathway using Icelandic feedstock is estimated using the following Equation (5),

$$\text{Capacity to meet HDV fuel demand}_i = \frac{FP_i * \eta_i}{FD_i} * 100 \quad (5)$$

where i refers to the respective fuel pathway; η_i is the Well-to-Tank production efficiency for fuel pathway i ; FP refers to the estimated fuel production capacity (GWh); and FD is the total HDV fleet fuel demand from summing the fuel consumption for each vehicle category using equation (4) (GWh).

2.8. System boundaries

The system boundaries of this study are determined in this section. Fig. 2 illustrates the different stages considered in the analysis, including WTP, PTW, fuel cycle and vehicle cycle. The activities considered for each stage are explained in Section 2.3.

It is considered that all vehicle operation emissions occur in Iceland, while vehicle production emissions occur beyond the national borders. Upstream emissions of BEV, FCV, CNG and LNG are produced within Iceland borders, while fossil diesel's upstream emissions happen overseas. As for the biodiesel pathways, the upstream emissions are mixed; emissions linked to the production and import of fertilisers happen overseas, while the emissions from rapeseed cultivation and transport occur in Iceland.

Energy inputs and emissions from power plant infrastructure construction and refuelling stations are not included in the scope of the analysis. Emission allocation for the biofuel pathways has been avoided whenever possible following the ISO 14040 and 14044 recommendations (Heijungs and Guinée, 2007).

3. Results and discussion

3.1. Technical feasibility of alternative fuel HDV powertrains

The assumptions introduced in Section 2.6 and the contributions of Forrest et al. (2020) are used to evaluate the operational feasibility of BEV and FCV powertrains in Iceland. The fuel efficiency values presented in Table 6 are used to calculate the required battery capacity for BEV and the required fuel tank size for FCV to meet 100, 300 and 500 km of range. The outcomes are presented in Table 9 for both vehicle categories.

For delivery trucks, the results indicate that the required battery capacity to meet 100 km and 300 km falls within the reported values in the literature (1–300 kWh). Considering that delivery trucks in Iceland average 8 km per trip, these could do up to 13 trips per day without recharging with a battery capacity of 105 kWh.

The results suggest that the impact of the Icelandic conditions in electric regional trucks is significant. Table 9 shows that an electric regional truck would require a battery capacity of 1.307 kWh to meet 500 km of range, which exceeds the maximum realistic capacities (1–700 kWh). Given that regional trucks average 500 km per trip, the use of BEV for regional applications is not realistic without a recharging infrastructure in place.

The results presented in Table 9 suggest that the implementation of FCV could comply with most of the HDV freight activity in Iceland. Regional trucks could meet the required 500 km range milestone with a tank of 64 kg of hydrogen, which is reachable with current technology.

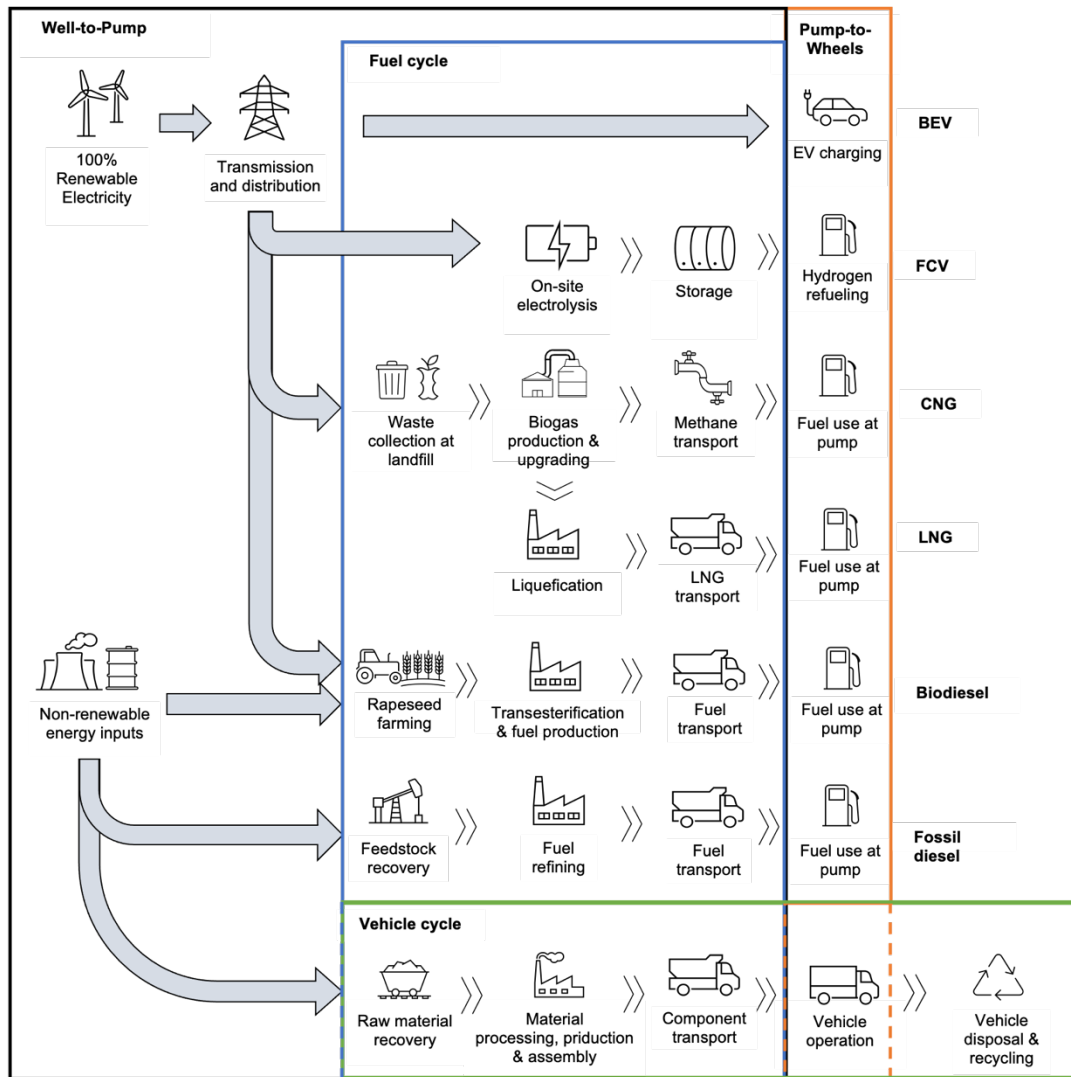


Figure 2. System boundaries description. The dotted outward line represents the limits of the system considered (Argonne, 2020; Rial et al., 2021).

Taking into consideration the values reported by Forrest et al. (2020) and the technical demands identified for HDV in Iceland, it could be suggested that there is a great potential for BEV deployment in Iceland for short haul trips. Nevertheless, a charging infrastructure should be implemented to increase the penetration of BEV in regional haul applications. FCV could potentially meet the technical demands of all vehicle categories due to the satisfactory performance of fuel cell technology in Iceland without an extensive refuelling infrastructure on road.

Apart from meeting the operational demands, another significant technical barrier for BEV and FCV deployment in Iceland would be the power grid capacity. The current transmission and distribution system does not have much capacity left to handle the increased load from charging and electrolysis, which could potentially lead to overloading of transmission lines (Haraldsson, 2020). It is crucial to improve the understanding of the potential future electricity demand from HDV and assess the charging station loads impact on the electric power grid in Iceland.

Table 9. Required battery capacity and fuel tank size to meet 100, 300 and 500 km range for different fuel efficiencies considering Icelandic conditions

Range (km)	BEV, battery size (kWh)		FCV, fuel tank (kg)	
	Delivery trucks	Regional trucks	Delivery trucks	Regional trucks
100	105	261	5	13
300	315	784	14	38
500	525	1,307	23	64

3.2. Meeting the HDV energy demand with domestically produced fuels

In this section, the impact on energy security of each pathway is evaluated in terms of the percentage of the fleet's fuel demand met with local fuels. The assumptions introduced in Section 2.7 are used to estimate the fuel demand of the entire Icelandic HDV fleet. Respectively, the fuel demand is calculated assuming a 100% transition towards BEV, FCV, B100, RD100, CNG and LNG using equation (5). For each alternative fuel HDV pathway, this study calculated the % of the fuel demand that could be met with local fuel production estimates from the literature using equation 6.

The results of this section are relevant to evaluate the impact of local alternative fuel production on energy security in Iceland, as using local feedstock for fuel production could potentially reduce the need for fossil fuel imports, decreasing dependency on foreign countries and enhancing sustainable development (Cergibozan, 2022).

The results are presented in Table 10. According to the calculations carried out by this study, the total energy demand required for a 100% electric HDV fleet would add up to 370 GWh. To put this figure in perspective, the total electricity generation for general use (excluding heavy industry) in 2020 was 4,340 GWh (Orkustofnun, 2020e). The electricity requirements for a 100% heavy duty BEV fleet would add up to 8% of the total electricity production, which could suggest that the Icelandic energy system would be able to meet the extra power demand from electric HDV considering the future development of wind power capacity (Landsvirkjun, 2021). The energy demand for a 100% hydrogen fuel cell HDV would account for 800 GWh, which represents 18% of the total electricity produced in Iceland in 2020. BEV appears more attractive than FCV in terms of required capacity given the higher efficiency of the battery electric pathway, which matches the results from Forrest et al. (2020).

The biodiesel and renewable diesel fuel demand for the entire HDV fleet would account for 852 GWh. These results indicate that Icelandic rapeseed biodiesel and renewable diesel could meet 100% of the total diesel demand from the HDV sector.

Using the available arable land for rapeseed cultivation could collide with wetland restoration projects, a measure considered in the Icelandic Climate Action Plan to mitigate GHG emissions from drained wetlands (Ministry for the Environment, 2020a). Although both measures aim at reducing emissions, it is significant to point out that there exists a potential tradeoff between them as these cannot be carried out on the same place. In addition, the impact of such a production scale in terms of people migration to the countryside and required infrastructure should be considered in future research.

The total methane fuel production would fall significantly short to meet the fuel demand for the CNG and LNG pathways, representing roughly 2% of the total fuel demand. These results suggest that methane fuel from landfill is only capable of playing a minor role in supplying fuel to the HDV fleet.

Table 10. Estimated feedstock production capacity, total fuel demand and impact on energy security. The fuel demand is calculated using the average annual distances for the HDV fleet from Statistics Iceland: 24,500 km for regional trucks and 14,000 km for delivery trucks.

Vehicle technology	BEV	FCV	Biodiesel	Renewable diesel	CNG	LNG
Feedstock required	Electricity	Electricity	Rapeseed	Rapeseed	Landfill gas	Landfill gas
Fuel demand (GWh)	370	800	852	852	1,060	1,090
Production capacity (GWh)	4,340	4,340	980	860	20	20
Fuel demand met with production capacity (%)	>100%	>100%	~100%	~100%	2%	2%

3.3. GHG and air pollutants emissions

This section presents the outcomes of the WTW GHG and air pollutants emission analysis for each powertrain and vehicle category. The results are broken down into different stages of the life cycle, as to portrait where the emissions are being produced and to potentially identify hotspots throughout the life cycle of each fuel and vehicle combination. The stages are vehicle production (including all processes involved in the vehicle cycle as shown in Fig. 2, except for vehicle operation), upstream processes (fuel production processes), and vehicle operation (including maintenance and disposal). Moreover, this exercise allows the study to differentiate emissions being produced in Iceland and abroad.

The CO_{2eq} emission results are presented in Fig. 3, with BEV standing out as the best option for both regional and delivery trucks, matching the results from Lajevardi et al. (2019) and Sen et al. (2017), followed closely by FCV. Most of the emissions produced by the BEV and FCV pathways occur abroad, with vehicle production overweighting upstream emissions in all cases except for regional haul FCV.

The results for both regional and delivery trucks show that the B20, RD20, B100 and RD100 pathways present similar results to fossil diesel, accounting for around 1–4% life cycle emission reductions compared to diesel. Vehicle operation emissions from B100 and RD100 could be considered as carbon neutral given that the released emissions during the vehicle combustion, mostly CO₂, are offset by the carbon sequestration achieved during rapeseed cultivation (Bernodusson, 2018). If such premise is considered, B100 and RD100 can achieve up to 80% of GHG emission reduction compared to fossil diesel for both vehicle categories.

HEV presents the highest emissions of all powertrains considered in the regional truck category, contrary to the results of Rial and Pérez (2021) which accounted for minor improvements in GHG emissions compared to diesel. This fact could be explained by the poor fuel economy considered due to the negative impact that the cold conditions in Iceland have over HEV powertrains, which can lead up to 15% higher fuel consumption (U.S. Department of Energy, 2020). HEV presents better results in delivery trucks, accounting for 4% emission reduction to diesel (Rial and Pérez, 2021).

CNG presents a 20% and 16% reduction in emissions compared to diesel in regional and delivery trucks, respectively. These results are contrary to Sen et al. (2017) and Tong et al. (2015), who concluded that CNG lead to higher life cycle emissions than diesel. This divergence can be explained by the difference in the natural gas feedstocks considered in the studies, fossil natural gas and landfill gas (Gustafsson and Svensson, 2021). The environmental benefits of using landfill gas based CNG are aligned with Lajevardi et al. (2019). LNG presents similar reductions in GHG emissions, although slightly higher to CNG in both vehicle categories. LNG's emission reduction matches with the literature considering biomethane feedstocks (Gustafsson and Svensson, 2021).

Overall, vehicle operation stands out as the main source of life cycle GHG emissions for all the internal combustion powertrains, leaving the relative contribution of vehicle production and upstream emissions as secondary factors (Rial and Pérez, 2021).

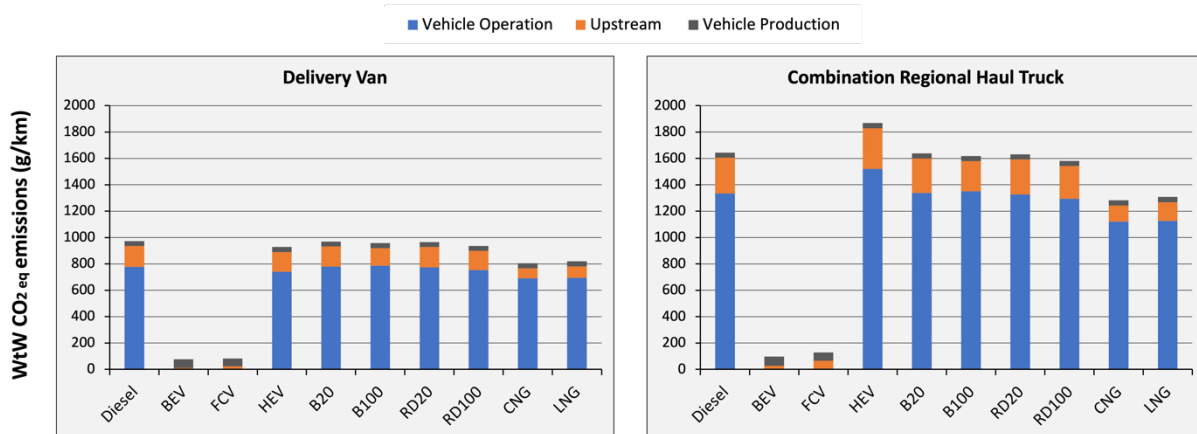


Figure 3. Well to Wheel CO_{2eq} emissions from delivery (left) and regional truck (right).

Upstream emissions for B20, B100, RD20 and RD100 are significantly influenced by the assumptions taken regarding the rapeseed cultivation process, as for the fuel consumption of the agricultural machinery and fertilizer use. Similarly, CNG and LNG upstream emissions are also strongly linked to the methane leakage considered in the analysis (1%).

Table 11 shows the total upstream GHG emissions for the biodiesel and renewable diesel pathways using different allocation methods, which compensate emissions using negative carbon credits. For instance, the energy allocation method accounts for the emissions avoided by replacing the energy content of fossil products for biofuel products in the system (Argonne National Laboratory, 2020). The application of allocation methods in LCA is a rather controversial field due to the complexity of bioenergy systems and the numerous valuable linked byproducts (Pereira et al., 2019). As no-allocation was not available in GREET, energy-based allocation was the method used when calculating the upstream emissions of B20, B100, RD20 and RD100. The authors considered appropriate to include the impact these methods have on a reference substance of the analysis, GHG, as to allow the consideration of the effects of each method. No allocation was applied to CNG and LNG pathways, following the directives of ISO 14044 and ISO 14040 (Heijungs and Guinée, 2007).

Table 11. Summary of upstream GHG emissions on different allocation methods (tons)

Type of allocation method	B20	B100	RD20	RD100
Energy	368	322	374	349
Market Value	377	364	384	402
Mass	347	213	347	215

The air pollutant emissions linked to delivery and regional trucks are presented in Figure 4 and Figure 5 respectively. As it can be observed, CNG and LNG powertrains account for significantly larger CO emissions compared to the other powertrains, which coincides with the results of Sen et al. (2017). Most CO emissions occur in the vehicle operation stage, except for the BEV and FCV pathways where vehicle production represents the largest source of emissions. HEV presents a considerable reduction in CO emissions to diesel, which also aligns with Sen et al. (2017). Biodiesel and renewable diesel results account for similar results to diesel in all phases. BEV and FCV present the best results in this regard due to not producing exhaust emissions, although the vehicle production accounts for slightly larger CO emissions

to the other powertrains.

Diesel powertrains account for the largest emissions of NO_x which are mostly produced in the vehicle operation stage in combustion engine vehicles (Koolen and Rothenberg, 2018). BEV, FCV, CNG and LNG present significantly better results, accounting for 90% reduction in NO_x emissions to fossil diesel in both vehicle categories. These results are aligned with Zhang et al. (2022) for BEV and FCV and with Rial and Pérez (2021) for CNG and LNG.

The results for both vehicle categories also show that BEV and FCV emit 12 and 25 times more life cycle SO_x than their internal combustion counterparts, which matches with Liu et al. (2021). This is linked to the current electricity generation mix Iceland (Orkustofnun, 2020c) and the large electricity demand required for battery charging and hydrogen production. Due to the higher electricity demand for hydrogen production, FCV accounts for approximately twice the SO_x emissions to BEV's pathway, although the emissions from the vehicle production stage are larger for BEV. Contrary to Sen et al. (2017), fossil diesel presents the lowest SO_x emissions overall for both vehicle categories, although this result may be influenced again by the electricity mix considered in this study.

The results show significantly larger VOC emissions for the biodiesel and renewable diesel pathways, with upstream emissions as the major contributor throughout the life cycle of these fuels. This is because of the great impact mineral fertilizer consumption and agriculture machinery have on the upstream VOC emissions, especially noticeable in the B100 and RD100 pathways (Fridrihsone et al., 2020). Similar to Rial and Pérez (2021), the vehicle production stage is responsible for a significant VOC emissions share in all pathways and vehicle categories.

The results show that all life cycle stages of internal combustion powertrains account for a significant share of PM_{2.5} emissions, which aligns with Rial and Pérez (2021). Biodiesel and renewable diesel pathways account for higher PM_{2.5} emissions in both vehicle categories, which could be linked to the higher mineral fertilizer used for rapeseed cultivation (Fridrihsone et al., 2020). FCV accounts for the lowest PM_{2.5} emissions for both vehicle categories, which matches Zhang et al. (2022). BEV accounts for the highest vehicle production particulate matter emissions for both vehicle categories, given the broad mineral mining and processing requirements to manufacture the batteries (IEA, 2021b). It is significant to highlight that PM₁₀ emissions from BEV exceed fossil diesel all stages combined emissions for delivery trucks, as shown in Fig. 4. The alignment of this study's BEV particulate matter emissions results in comparison and the literature is mixed. According to Liu et al. (2021), BEV accounts for higher PM₁₀ emissions to diesel for both vehicle categories, while the present study found that BEV presents better results in regional trucks. This difference could be attributed to different assumptions in the electricity generation mix. BEV's vehicle operation PM_{2.5} and PM₁₀ upstream emissions in regional trucks may be linked to the tire and break ware (Liu et al., 2021).

Fig. 6 and Fig. 7 break down the externality costs for each vehicle category, powertrain, and fuel combination over 15 years for two types of population density scenarios: low density (national average, 3 people per km²) and high density (Reykjavík capital area, 473 people per km²). HEV pathway accounts for the highest externality costs for both vehicle categories in the low-density scenario, while BEV accounts for the lowest externality costs. In the high-density scenario, LNG and FCV present the highest externality costs for delivery and regional trucks respectively. In the high-density scenario, both BEV and FCV present worse results than conventional diesel due to the impact of SO_x emissions. The outcomes of this exercise serve to contextualise the impact of air pollutants, which can be significantly different depending on where these are produced.

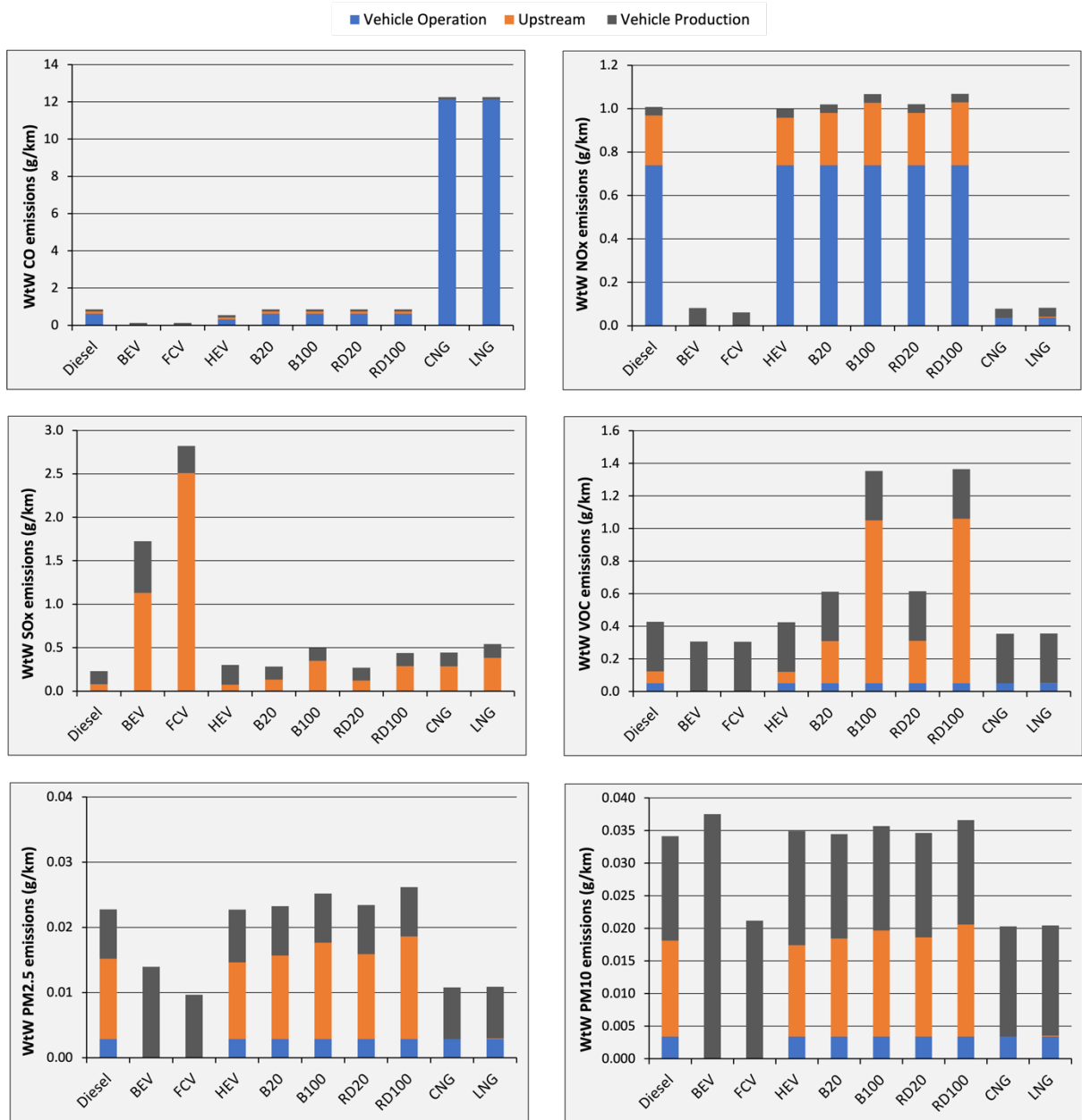


Figure 4. Well to Wheel CO, NO_x, SO_x, VOC, PM_{2.5} and PM₁₀ emissions from Delivery Trucks

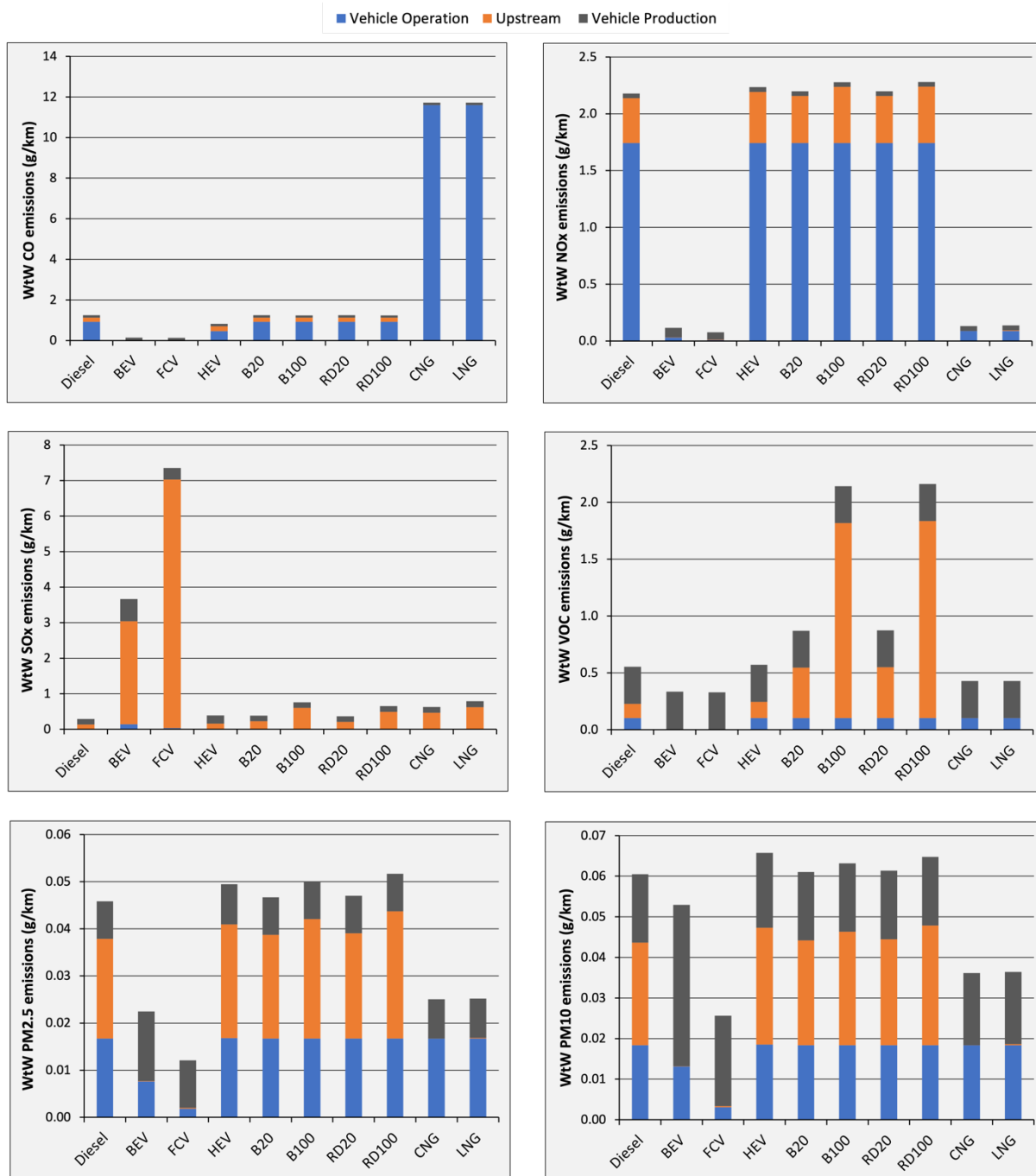


Figure 5. Well to Wheel CO, NO_x, SO_x, VOC, PM_{2.5} and PM₁₀ emissions from Regional Trucks

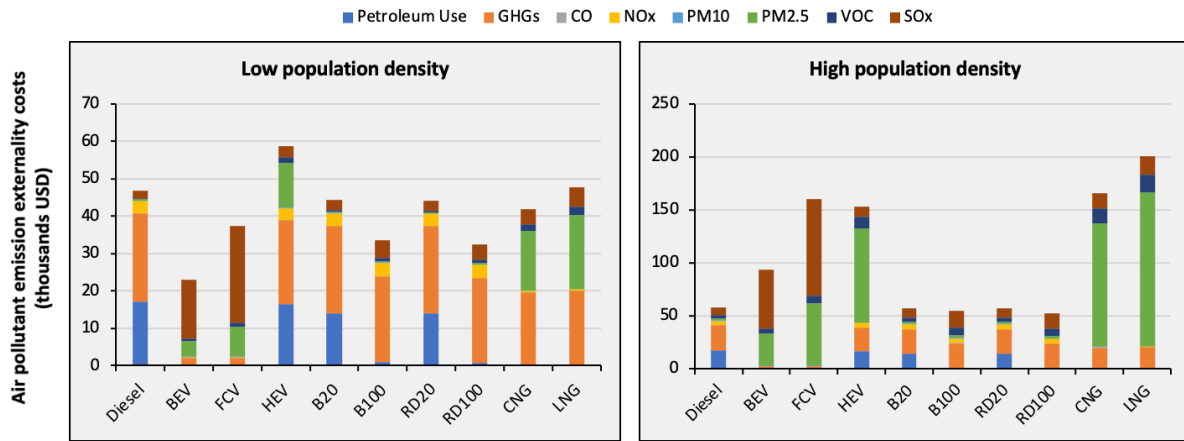


Figure 6. Air pollutant emission externality costs for delivery trucks.

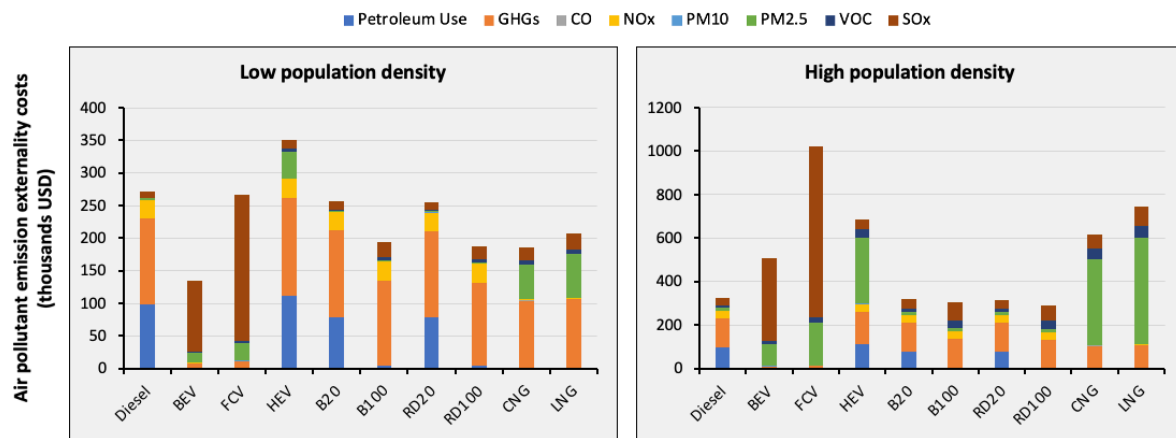


Figure 7. Air pollutant emission externality costs for regional trucks.

3.4. Total cost of ownership and externality costs

This section presents the outcomes of the TCO analysis based on the assumptions presented in Section 2.5. Fig. 8 summarises the empirical results of the TCO analysis for both regional and delivery trucks. The total cost of each pathway is further broken down by the contribution of each cost factor considered in the analysis, including financing; capital costs; fuel costs; diesel exhaust fluid; maintenance and repair; insurance; license and registration and battery replacement costs. Fig. 8 also includes the externality costs presented in Figs. 6 and 7 overlapped over the TCO results, as both cost variables are relevant to assess the attractiveness of each vehicle and fuel combination. The results of this section are deeply influenced by the assumption taken in Table 2 regarding fuel economy, capital costs and fuel costs. Therefore, the results may only apply to the Icelandic context and other regions with cold environments.

The results in Fig. 8 suggest that BEV and B20/RD20 account for the lowest TCO for delivery trucks and regional trucks respectively. BEV lifetime costs are about 20% lower to diesel for both vehicle categories, which aligns with Sen et al. (2017). The initial investment is the greatest cost factor for BEV, accounting for over half the TCO in both vehicle categories. Battery replacement increases 17% regional BEV's TCO. The results align with Sen et al. (2017) but do not match with Lajevardi et al. (2019) and Lopez et al. (2020) who claim that hybrid powertrains present economic benefits to BEV. In addition, the results of this study contrast with Sen et al. (2017), Lajevardi et al. (2019), Lopez et al. (2020) and Jaller et al. (2021) who claimed that hybrid powertrains presented better TCO than conventional diesel.

The divergence in the results of this study and the literature may be explained by the low fuel efficiency considered for the battery powered drivetrains, which is described in Section 2.6. The effect of the cold conditions in Iceland over the fuel economy was especially significant for HEV regional trucks, which lead to a higher fuel consumption than conventional diesel and consequently to higher vehicle operation costs.

FCV shows the worst TCO results for regional trucks due to the high cost of hydrogen fuel, which aligns with Lajevardi et al. (2019) and Zhang et al. (2022). Nevertheless, the results for FCV improve significantly in delivery trucks, going from a 43% difference regarding diesel in regional trucks to only a 12% difference in TCO. Therefore, FCV appears more attractive in terms of TCO than B100, RD100 and LNG. Overall, fuel expenditure represents the highest cost for all pathways and vehicle categories, with the exemption of BEV. The relative contribution of fuel costs to the TCO is significantly larger in regional trucks due to their lower fuel efficiency and higher mileage.

These outcomes suggest that developing incentives to reduce fuel cost at pump would be very effective to promote FCV and LNG, while vehicle purchase cost subsidies would have the greatest effect on reducing BEV's TCO.

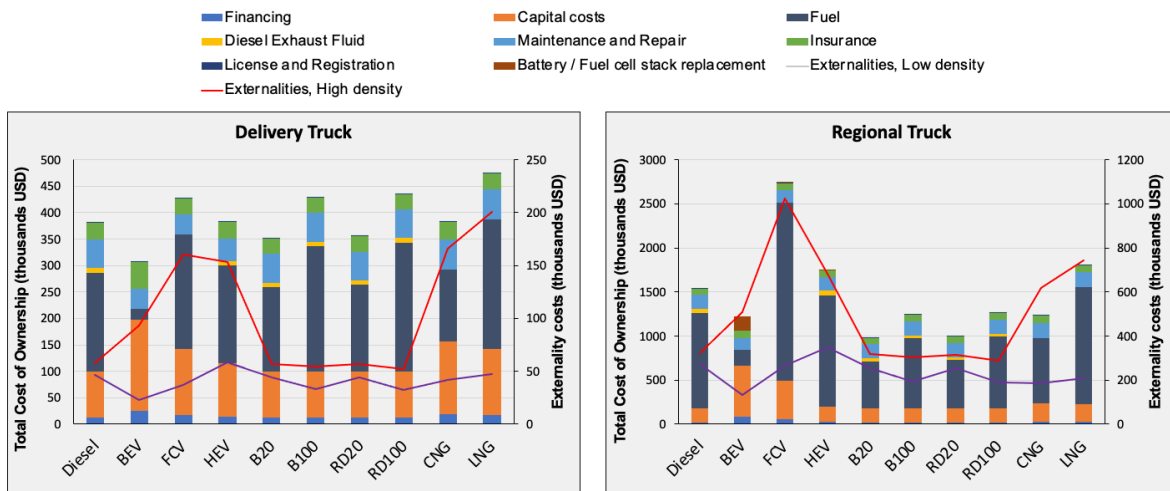


Figure 8. Total cost of ownership of delivery truck (left) and regional truck (right) against respective externality costs

3.5. Identifying the most attractive alternative fuel pathway

This section takes the outcomes presented in Sections 3.1, 3.2, 3.3 and 3.4 and contextualises them in terms of the Icelandic case study to determine the attractiveness of each powertrain. BEV stands out as the most attractive pathway for both vehicle categories in terms of overall GHG and air pollutant emissions (Sen et al., 2017). The BEV pathway also presents highly competitive TCO results for both vocations, and the electricity generation requirements are within reach. According to the findings of this study, BEV should be prioritized over the other alternative fuels in the transition away from fossil fuels in HDVs as long as operational demands are covered.

As discussed in Section 3.1, BEV limitations imply the need for additional solutions to fully achieve a 100% transition away from fossil diesel. For delivery trucks, the results suggest that FCV is the most attractive pathway whenever BEV cannot be implemented as it enables a great reduction in GHG emissions and accounts for a somehow competitive TCO (12% higher than conventional diesel's). FCV also represents an attractive solution for regional trucks, as these overcome the operational limitations of BEV and reduce GHG emissions. Nevertheless, FCV's TCO results denotes a major limitation for wide market diffusion. In such scenario, RD100 stands out as one of the best options for regional haul trucks

as it overcomes the operational limitations of BEV, presents a competitive TCO and its local production could meet 100% of the fuel demand. Moreover, RD100 has a great GHG emission reduction potential if the vehicle operation emissions are assumed to be carbon neutral, although this assumption is not accounted in Fig. 8.

Considering the feedstock limitations and BEV capacity to meet most of short haul vocation demands along with FCV, the use of CNG and RD100 should be confined to regional haul vocations. Taking the estimated energy demand from regional haul HDV, RD100 could meet up 100% of regional haul fuel demand, while CNG and LNG would roughly meet 2%. These estimations suggest that the whole Icelandic HDV fleet could be operated on 100% renewable and domestically produced fuels, prioritizing BEV for short haul vocation and renewable diesel for regional haul in terms of a cost-effective implementation.

To provide a comprehensive summary of the results of this study, the performance of the different fuel/vehicle combinations included in the scope for both vehicle categories has been scaled from worst to best in terms of GHG emissions and TCO as shown in Fig. 9. The results which fall within the first quartile of each respective scale (top 25%) are highlighted in green and the results on the last quartile (worst 25%) are highlighted in red. In addition, the technical demands and energy security aspects are also scaled from worst (red) to best (green) based on the results presented in Section 3.3 and Section 3.4. The powertrains highlighted in green indicate that the potential to meet the technical demands of the HDV or meeting the fuel demand with domestic resources is feasible with current technology, while red indicates non feasibility and yellow suggests that the feasibility is limited and subjected to improvements in the current (i.e., availability of refuelling stations, installed power capacity, grid upgrades) or the technology itself.

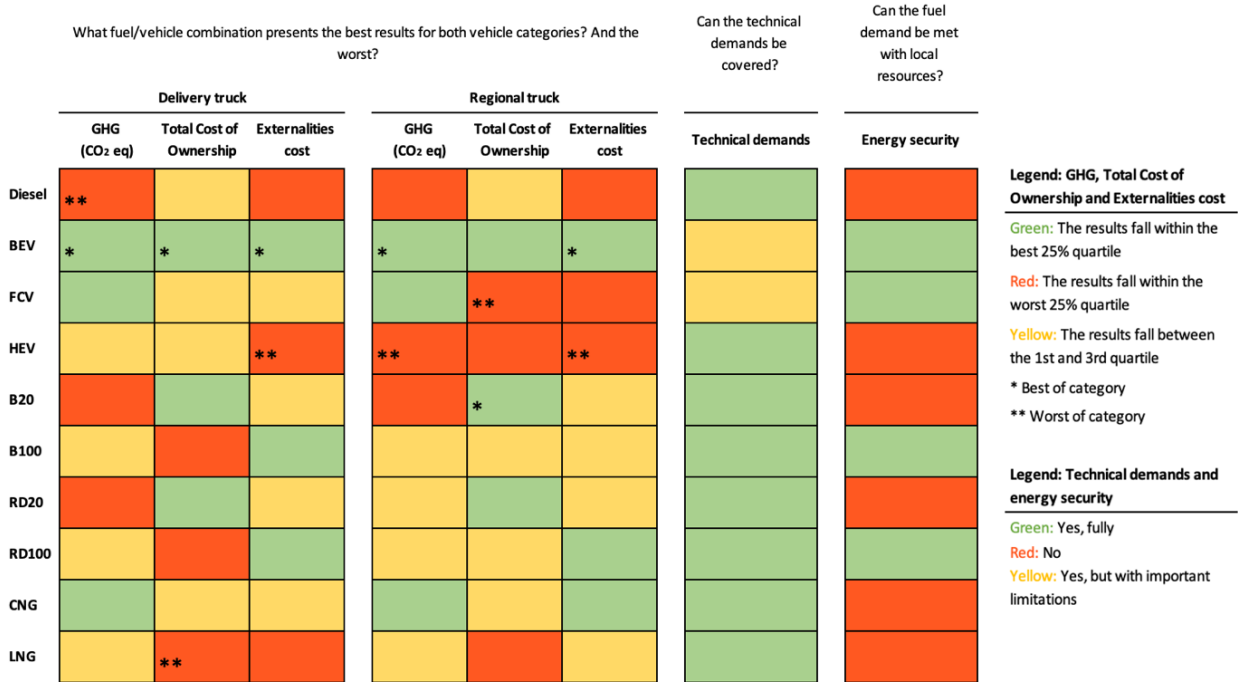


Figure 9. Graphic summary of the main results for both vehicle categories

4. Main limitations

The availability of Icelandic context specific data to carry out the LCA was the main limitation encountered during this study. Therefore, default data from AFLEET and GREET databases was adjusted to reflect the Icelandic reality when possible. Future improvements in powertrain technology were not included in the analysis, which could play a relevant role in their potential implementation. Future work is required to account for these aspects and obtain a better picture of the potential transition towards alternative fuel HDV in Iceland.

5. Conclusions

This study investigates the performance of different alternative fuel HDV in terms of life cycle TCO, GHG and air pollutants emissions, energy security and operational feasibility. The outcomes of the analysis are then compared to identify the most attractive vehicle and fuel combinations. The outcomes of this study contribute specifically to Iceland's Climate Action Plan goals of 'A.8 Energy transition in heavy transport' and 'C.4 Domestic renewable fuels' and to Iceland's sustainable energy transition in general. The main results of this study are:

- BEV should be prioritized in delivery trucks and complemented with FCV to meet 100% of the operational demands. This would imply approximately 5% of additional power over 2020 electricity generation levels to produce the necessary electricity.
- For regional haul trucks, BEV also presents competitive results in environmental, economic and energy security terms, although BEV's shortcomings to meet the demanding operational dimensions of regional haul trucks with the current available infrastructure in Iceland and battery technology implies the necessity for other solutions.
- As FCV's TCO results for regional trucks are currently uncompetitive, RD100 stands out as the most attractive fuel to transition away from fossil fuels as it presents a lower TCO to diesel and could meet the technical demands of HDV with locally produced renewable diesel from Icelandic rapeseed, although it presents minor overall GHG reductions unless carbon neutrality of vehicle operation emissions is considered.
- The hydrogen pathway should not be completely discarded as it shows significantly better results to RD100 in terms of GHG emissions, while having the potential to overcome BEV's operational shortcomings. Therefore, the evolution of the hydrogen fuel cost in Iceland should be followed closely as it represents the main barrier for a feasible diffusion of fuel cell regional trucks.

The framework used to carry out this study covers important questions intrinsic to the energy transition in the transport sector regarding the powertrains addressed; 'What's the best option for our context?' (Environmental and economic assessment), 'Can it be done?' (Technical feasibility) and, lastly, 'Would it increase energy self-sufficiency?' (Energy security). This framework can be used in other contexts with different assumptions.

Additional unsolved questions arise from this study. Future research should carry out an in-depth analysis on:

- Determining the daily distance driven by HDV in Iceland and energy demand.
- Evaluating the upgrades required in the power grid infrastructure to enable BEV and FCV deployment as well as the linked costs.

CRedit authorship contribution statement

Albert Alonso-Villar: Conceptualisation, Methodology, Investigation, Writing – original draft, Data curation. **Brynhildur Davíðsdóttir:** Conceptualisation, Writing – review & editing, Supervision, Funding acquisition. **Hlynur Stefánsson:** Conceptualisation, Methodology, Validation, Writing – review & editing, Supervision, Funding acquisition. **Eyjólfur Ingi Ásgeirsson:** Conceptualisation, Methodology, Validation, Writing – review & editing, Supervision, Funding acquisition. **Ragnar Kristjánsson:** Writing – review & editing, Supervision, Funding acquisition.

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.

Data availability

All data will be made available on request except confidential data provided by Eimskip and Statistics Iceland

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3. Paper 2

Electrification potential for heavy-duty vehicles in harsh climate conditions: a case study based technical feasibility assessment

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Abstract

Battery-electric heavy-duty vehicles are considered a potential solution to reduce emissions in freight transport and increase energy security. However, battery-electric trucks are not a one-fits-all solution due to current battery technology limitations and vast diversity in freight operations and vehicle categories. Although the literature available in electric truck feasibility provides an insightful overview of their potential, it does not fully cover the performance variations under adverse climate and technical conditions.

This paper attempts to fill the gap in the literature by quantifying the impact of low temperatures, headwind, variable payload, and tail-lift use over different freight vehicles from a case study fleet in Iceland. NREL's FASTSim is the vehicle energy consumption model used for the analysis. The study also addresses on-route fast-charging, considering realistic non-linear charging rates and performance in low temperatures.

The results showed that the range of the analysed vehicles can experience a decrease of 41-47% under unfavourable conditions, compared to the estimated range under ideal conditions. Short-haul routes could be electrified even under the most challenging conditions, while regional routes might require some planification adjustments to reach 100% route electrification in tough conditions. On-route charging would be necessary to achieve full fleet electrification. In tough conditions, sprinter vans met 49% (85% with charging) of the analysed routes, while trucks met 83% (90% with charging).

The outcomes of this research support several UN Sustainable Development Goals (3, 7, 8, 11, 12, 13) and could be used to develop specific measures within the Icelandic 2020 Climate Action Plan. The methodology used is feasibly replicable for teams who wish to perform a similar analysis in different contexts.

Keywords: Heavy-duty vehicle; Climate conditions; Battery-electric vehicle; Technical feasibility; Freight transport

1. Introduction

There is an urgent need to transition away from fossil fuels in the transport sector to avoid catastrophic climate change (Wappelhorst and Rodriguez, 2021), reduce the dependency on imported oil and move towards energy self-sufficiency (IEA, 2021). The electrification of the transport sector, which involves transitioning towards zero-emission powertrains such as battery-electric or hydrogen fuel cell, is considered a potential solution to reduce emissions and fossil fuel dependency (Transport and Environment, 2022). Governments worldwide are developing policies to speed up the transition towards electric mobility, including a ban on new registrations of fossil fuel passenger vehicles and vans by 2035 along with stricter emission standards in Europe (European Commission, 2022). These policies have translated into a significant increase in the uptake of passenger electric vehicles worldwide. In 2021, battery-electric cars accounted for 18% of the new registrations in Europe, which represented an increase of 7% in just one year (European Environment Agency, 2021). While the electrification of passenger vehicles seems to be underway, the same cannot be said about the heavy-duty vehicle (HDV) sector (Wappelhorst and Rodriguez, 2021). In the EU, only 0.4% of new medium and heavy-duty truck registrations in 2020 were electrified powertrains such as battery-electric and hydrogen fuel cell. In the US, the share of such registrations was roughly 0.03% in the same year (Wappelhorst and Rodriguez, 2021). So far, only a few governments have set targets to phase out internal combustion engine truck sales, including the US by 2040 (Minjares, 2022), Austria by 2035 and Cape Verde by 2050. Most of these targets are yet to be supported by policies (Wappelhorst and Rodriguez, 2021).

Whereas battery-electric, hydrogen fuel-cell and other e-fuel trucks are promising technologies which could contribute to the decarbonisation of freight transport, this study focuses solely on battery-electric trucks due to its higher emission reduction potential (Lajevardi et al. 2019) and Well-to-Wheel efficiency (Transport and Environment, 2020).

Although battery-electric HDVs are already cheaper to operate compared to their diesel counterparts in certain contexts (Alonso-Villar et al., 2022), low uptake is primarily explained by high capital costs (Transport and Environment, 2022) and uncertainties around the technical capacities of electric HDVs regarding driving range (Melander et al., 2022), payload capabilities (Khani and Emami, 2022), potential additional time losses due to recharging (Qasim and Csiszar, 2021), and infrastructure availability (Imre et al., 2021), among other barriers. Therefore, policies are required to ensure rapid adoption of electric trucks (Transport and Environment, 2022), especially when considering the long service life of these vehicles (Rout et al., 2022). The wide variations of sectorial and national freight operations affect the viability of electric trucks (Liimatainen et al., 2019), so it is important to understand the technological potential of electric HDVs and the charging infrastructure requirements necessary to design effective policies and investments to achieve the targets (Forrest et al., 2020). Electric truck feasibility assessments are a key tool to inform policy and investment development, as well as to provide a better understanding of the capabilities of electric powertrains.

Research in electric HDV feasibility assessment is still an emerging field (Forrest et al., 2020). The literature in this field includes diverse approaches, depending on the scope (national or regional fleet vs a specific set of vehicles), vehicle configurations, freight operation, freight activity data (statistics, surveys, or truck trip telemetry), charging infrastructure availability, and battery sizes. Table 1 summarises the most relevant literature reviewed by this study, briefly stating the main considerations carried out by each study.

Table 1. Summary of most relevant literature and comparison to this study

Research	Scope and driving data used	Energy consumption model	Vehicle configuration/s addressed	Charging model	Consideration of adverse conditions in vehicle performance
Forrest et al. (2020)	Freight transport in California (national statistics and surveys)	No - Average fuel efficiency assumptions	Class 2B-8 trucks	Linear rate	No
Liimatainen et al. (2019)	Freight transport in Switzerland and Finland (national statistics and surveys)	No - Average fuel efficiency assumptions	Rigid, articulated and semi-trailers	None	No
Çabukoglu et al. (2018)	Freight transport in Switzerland (national statistics and surveys)	Own methodology	Rigid and articulated trucks	Battery swapping	No
Fiori et al. (2018)	Freight transport in urban areas (Own recordings from case study fleet)	Own methodology	Delivery vans	No	No
Basma et al. (2021)	Regional and long-haul freight transport (VECTO drive cycles)	Simcenter Amesin	Semi-trailer	None	Extreme temperatures and variable payload
Tanvir et al. (2020)	Drayage (Tour generation algorithm)	Own methodology	Class 8, port drayage semi-trailer	Linear rate	No
This study	Urban, suburban and regional haul freight transport (Own recordings from case study fleet)	FASTSim	Delivery van Boxed truck Trailer Semi-trailer	Non-linear charging rates	Extreme temperature, headwind, variable payload, intense tail-lift use

Forrest et al. (2020) investigated the technical feasibility of battery-electric trucks in terms of range, charging power, and charging infrastructure availability. This study used a representative subset of the medium and heavy-duty vehicle fleet in California to evaluate the extent of travel demand that could be met using battery-electric trucks. Forrest et al. (2020) demonstrated that electrification potential increased with higher vehicle ranges and on-route charging availability. Liimatainen et al. (2019) also estimated the electrification potential of Finnish and Swiss truck fleets using freight survey data under different battery technology and charging scenarios. The results showed that 71% of the Swiss freight demand could be covered by electric trucks, while the electrification potential of the Finnish fleet was lower due to the use of long and heavy truck-trailer combinations. Çabukoglu et al. (2018) also investigated the technical feasibility of electrifying the Swiss truck fleet, identifying the requirements to enable maximum electric truck deployment. The results showed that certain conditions must be met to achieve widespread use, including increasing the permissible weight of electric trucks, adequate on-route charging, and high-capacity charger at the home-base. In addition,

Çabukoglu et al. (2018) concluded that allowing battery swaps would achieve higher electrification potential compared to charging. Other studies used their own recorded driving data and vehicle energy consumption models to calculate the fuel economy of a specific vehicle sets. Fiori et al. (2018) developed a vehicle energy consumption model to estimate the fuel economy of electric delivery vans operating in central Rome, validating the results with real vehicle telemetry. Tanvir et al. (2020) investigated the electrification potential of Class 8 HDVs in drayage operations, concluding that 85% of the drayage tours analysed were electrifiable, assuming home base charging between tours. Basma et al. (2021) analysed the technology potential for battery-electric semi-trailers using the vehicle simulation tool VECTO (European Commission, 2018). This study determined that, with projected improvements in battery technology, a 700-kWh battery would be sufficient to cover most freight applications met with semi-trailers.

Overall, research in this field indicates that HDV electrification feasibility is strongly linked to the freight operation (transport of goods, drayage) and type of truck (semi-trailer). Nevertheless, the available literature does not fully cover the expected performance variations in adverse contexts such as variable weather or heavy payloads, which can greatly impact range. To the best of the authors knowledge, only Basma et al. (2021) investigated the impact of payload and extreme temperature conditions (35°C and -7°C) on the performance of semi-trailers in regional and long-haul cycles. The results showed that extreme temperatures reduced the electric range no more than 9% if efficient heat pumps were used for cabin heating, while heavy payloads could decrease the range between 6-13%. Nevertheless, the impact of strong headwind conditions was not considered. The impact of auxiliary equipment use (i.e., tail-lifts) is also usually overlooked, which load is met with the tractive battery and can therefore impact the vehicle's range (Alke, 2019). All these factors increase the vehicle's energy consumption and should be considered simultaneously, especially in regions with harsh climates. Therefore, the performance of electric HDVs requires further exploration to quantify the impact on the electric range from variable weather conditions, heavy payloads, and auxiliary equipment. Understanding such impacts could reduce the scepticism of fleet operators and ultimately accelerate the transition toward HDV electrification.

Based on the identified gaps in the literature, this study uses the freight activity of a company operating in Iceland as a case study to address the following research questions:

- 1. To what extent do climate and freight conditions impact the electrification potential of heavy-duty vehicles?**
- 2. Considering unfavourable climate conditions, to what extent can the case study freight activity be carried out with battery-electric trucks?**

To answer the first research question, the presented study aims to quantify the impact of climate (low temperatures, headwind) and freight (payload, use of tail-lift and route characteristics) variables on the range of battery-electric HDVs. A vehicle energy consumption model is used to simulate the performance of different electric truck designs over pre-recorded freight routes. The charging performance under different ambient and battery conditions is also addressed using non-linear charging rates. The results obtained by answering the first research question are used to assess the electrification potential of the case study delivery fleet, considering the tough Icelandic climate conditions and different on-route charging scenarios.

To the best of the authors knowledge, this is the first study to carry out such an assessment. The outcomes of this study are a detailed methodology to quantify battery-electric HDV performance in variable conditions and non-linear fast-charging performance, which goes beyond the oversimplified performance estimates provided by HDV manufacturers. Moreover, the relevance of the addressed variables in feasibility assessments is also determined, with a special focus on those variables that are not usually addressed in the

literature such as headwind and tail-lift use. This novel methodological approach, which level of detail enables other researchers to replicate the study in other contexts, can reduce the uncertainty around electrification of HDVs and accelerate the transition towards freight decarbonisation and energy security.

2. Methods

This section presents the methodology used to answer the research questions introduced in the previous chapter. Figure 1 outlines the methodological approach, illustrating the overall flow of the methods chapter.

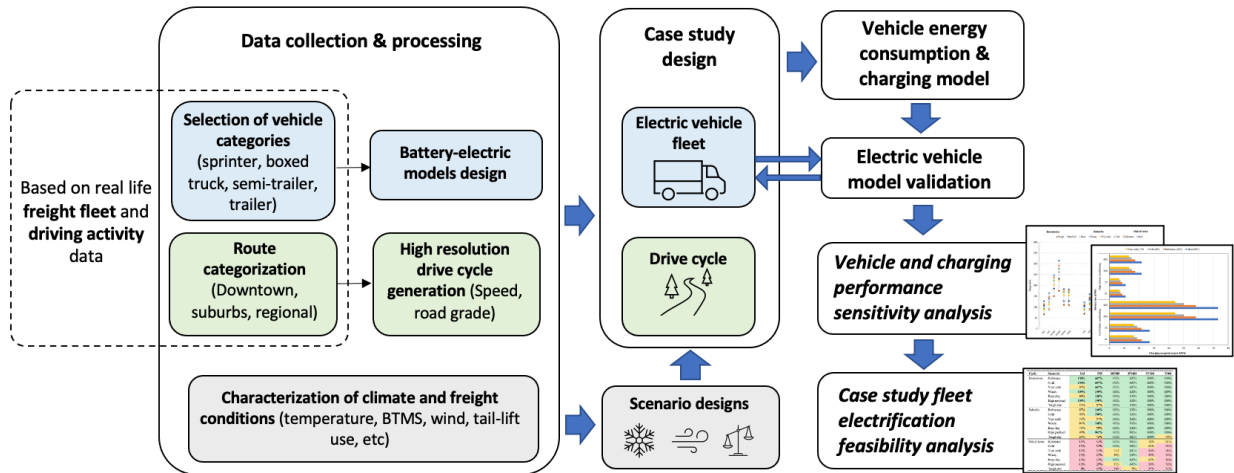




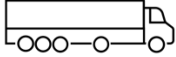

Figure 1. Outline of the methodological approach

2.1 Data collection, processing, and case study design

2.1.1. Description of case study and road freight activity in Iceland

This study uses real-world driving data from delivery vehicles operated by Ölgerðin, a brewery and beverage company based in Reykjavík, to estimate the energy consumption of electric freight vehicles in Iceland. Ölgerðin's current fleet is currently composed of conventional diesel boxed trucks, semi-trailers, trailers, and sprinters, which transport goods to several destinations in the Reykjavík metropolitan area and other major economic areas in the south-west of Iceland. This region accounts for a large share of the Icelandic population and has a significant freight activity currently being carried out by polluting diesel trucks. Table 2 summarises the main details of the Ölgerðin's fleet.

Table 2. Description of the case study fleet

Vehicle type	Representative model	Class	Drivetrain	Power (kW)	GVW ^a (ton)
Sprinter van		Light duty	4x2	84	5
Boxed truck		Medium duty	6x2	250	15
Semi-trailer		Heavy duty	6x2	390	27
Trailer		Heavy duty	6x2/4	390	40

^a Gross Vehicle Weight

All vehicles are equipped with an on-board telemetry system that captures the vehicle's coordinates and speed. Data from 395 trips were retrieved from the telemetry system, which were categorized by area of operation: Downtown, Suburbs and Out-of-Town.

Downtown routes consist of drive cycles within Reykjavík city centre, which encompass residential streets where low speeds and frequent stop-and-go driving are common. The drive cycles included in the Suburbs category have similar features, although the use of arterial roads from the city centre to the suburban areas is more frequent, and average higher speeds over residential streets due to the lack of traffic lights. Finally, the routes in the Out-of-Town category consist of regional-haul trips from Reykjavík to other municipalities. The common use of expressways in this category usually implies longer distances and higher speeds. Figure 2 shows the distribution of relevant drive cycle statistics across the fleet sample such as speed, distance, driving time and number of stops.

Table 3 puts Ölgerðin's driving data into context by comparing it to the average estimates for the Icelandic national freight fleet. Road freight transport was responsible for around 30% of the total emission from the road transport (Umhverfisstofnun, 2022) although freight vehicles represent about 10% of the road fleet (Samgöngustofa, 2022). Ölgerðin's fleet accounts for longer daily and annual driving distances, especially for the truck categories, which suggests that Ölgerðin's operations are considerably more demanding than the average freight activity in Iceland. Therefore, it is assumed that the results of this research could be extrapolated to most of the national road freight fleet except for the long-haul route

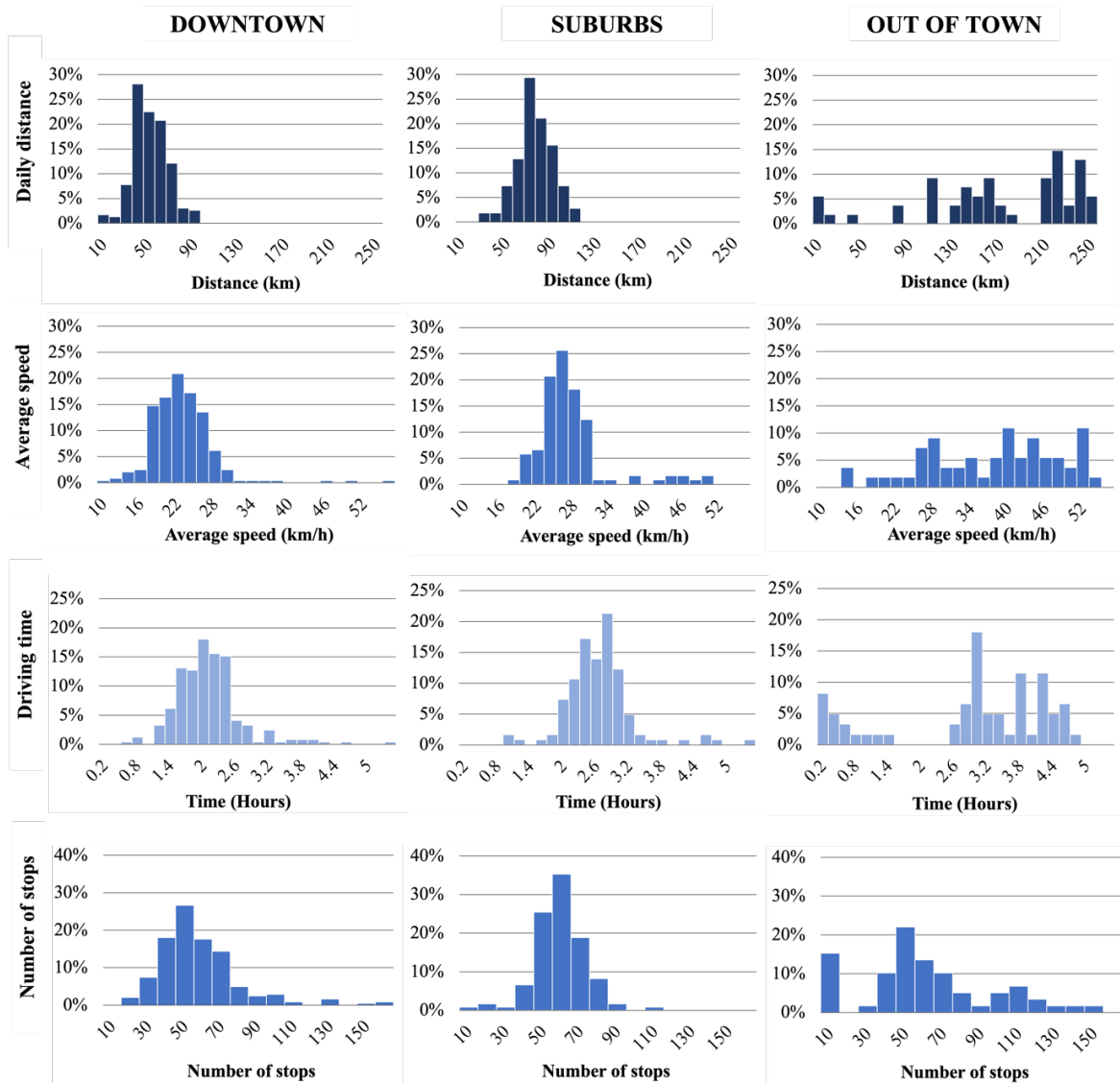


Figure 2. Distribution for daily distance covered, trip average speed, trip driving time, and number of stops. The number of stops shows each time the vehicle's speed is zero, including traffic lights.

Table 3. Average daily and annual driving for the national freight fleet and Ölgerðin's fleet

Vehicle category	National fleet ^a			Ölgerðin's fleet ^b	
	Number of vehicles	Average driving per day (km)	Average driving per year (km)	Average driving per day (km)	Average driving per year (km)
Delivery vehicles	30,309 (69%)	35.94	13,118	54.11	12,985
Trucks ≤ 12 ton	6,222 (14%)	38.26	13,966	72.56	17,415
Trucks > 12 ton	7,200 (16%)	67.19	24,525	155.64	37,355

^a Samgöngustofa (2022). The % in the Number of vehicles column shows the percentage of each category over the entire fleet.

^b Estimated values based on Ölgerðin's activity. The average estimates for delivery vehicles, trucks ≤ 12 ton and trucks > 12 ton are based on downtown, suburb, and out-of-town routes, respectively.

2.1.2. Selection of representative trips and drive cycle generation

Out of all the driving data collected, the most challenging case for each drive cycle category was selected for further analysis. The total daily distance was the variable used to filter the trips under the assumption that the longest routes would represent a tougher test for battery-electric powertrains over shorter routes. High resolution time series for speed, latitude and longitude were prepared for each of the selected driving cycles. Additional data processing was required to adjust the frequency irregularities found in the raw data extractions caused by the loss of GPS signal and the telemetry system's varying settings. To guarantee consistency throughout all the drive cycles analysed, the time series were resampled down to a uniform one-second resolution and the missing values were linearly interpolated. Latitude and longitude time series were used to retrieve the elevation at each time stamp using GPS Visualizer online database (GPS Visualizer, 2022), which was later used to calculate the road grade variation using Equation (1), where:

$$Road\ grade(\%) = \frac{Rise}{Run} * 100 \quad (1)$$

Rise is the difference between two consecutive altitude points, and *Run* is the distance between two consecutive coordinate locations. The driving cycles considered in this study are presented in Figure 3.

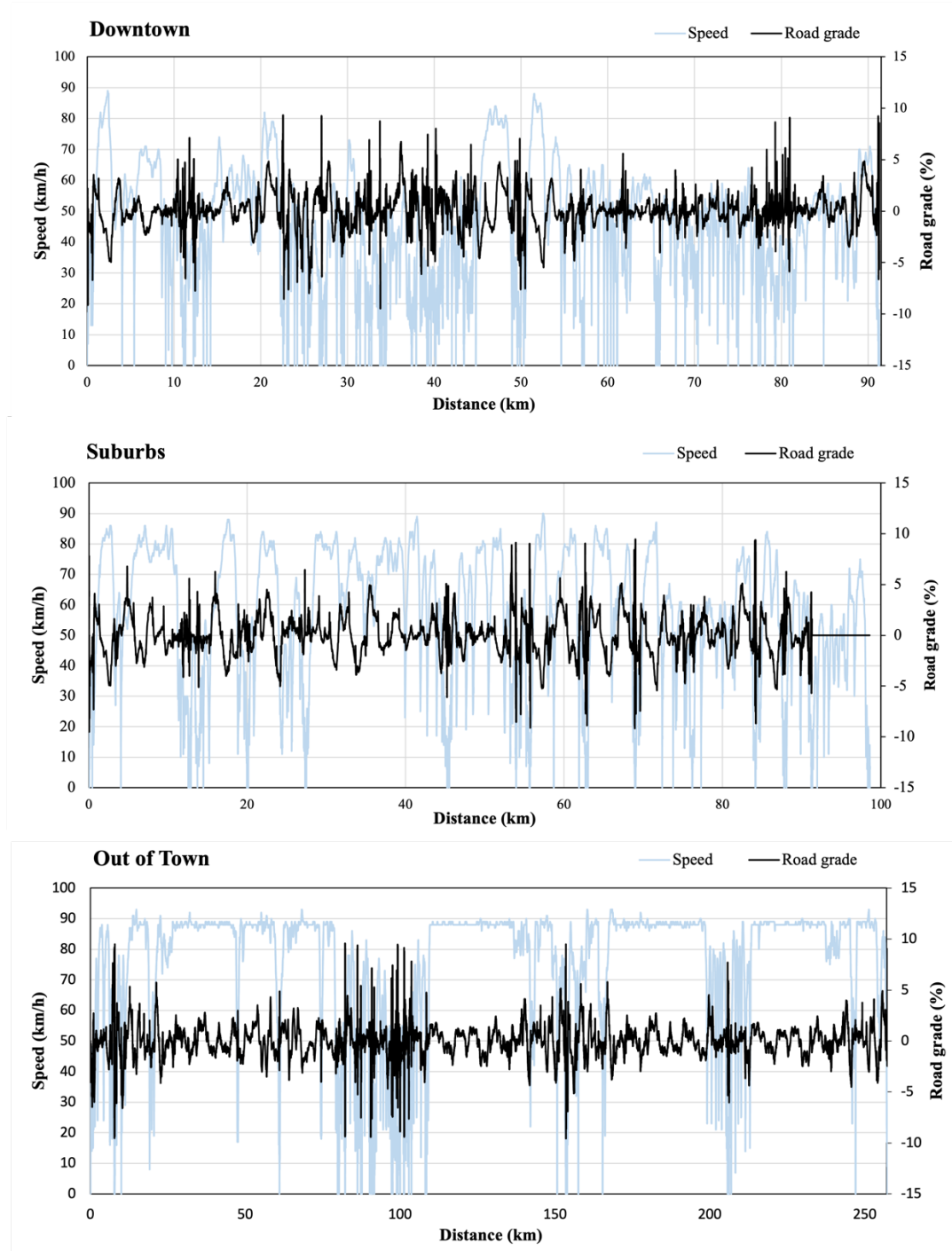


Figure 3. Speed and road grade for the drive cycles considered in the study

2.1.3. Electric HDV design parameters

The vehicle categories selected for study are based on Ölgerðin's fleet, with the aim of setting up battery-electric models similar to the ones that are currently being used.

Therefore, technical data from commercial battery-electric HDVs have been used to generate battery-electric versions of the vehicle categories shown in Table 2: (1) sprinter van, (2) boxed truck, (3) semi-trailer, and (4) trailer. The specifications of Mercedes-Benz commercial BEV portfolio were used to inform the design of the generated electric trucks. This decision was made based on the market-share relevancy of Mercedes-Benz in the heavy, medium, and light duty commercial vehicle segments (Mulholland, 2022) and due to data availability and consistency. Therefore, the sprinter vans are based on Mercedes-Benz's eSprinter models (Mercedes-Benz, 2022a) while the boxed truck, semi-trailer and trailer models are based in different configurations of the eActros (Mercedes-Benz, 2022b). The assumed electric vehicle design parameters are presented in Table 4.

Table 4. Parameters used for battery-electric truck design based on Mercedes-Benz models (Mercedes-Benz, 2022a; Mercedes-Benz 2022b)

Category	Parameter	Sprinter 35 (S41)	Sprinter 47 (S55)	Boxed truck 300 (BT300)	Boxed truck 400 (BT400)	Semi-trailer (ST300)	Trailer (T300)
Vehicle	Drag coefficient	0.32 ^a	0.32 ^a	0.5 ^b	0.5 ^b	0.521 ^c	0.7 ^b
	Frontal area (m ²) ^d	6.30	6.30	9.43	9.43	9.43	9.43
	Centre of gravity ^e	0.53	0.53	0.53	0.53	0.53	0.53
	Weight fraction on drive axle ^f	0.42	0.42	0.59	0.59	0.59	0.59
	Wheelbase (m)	3.92	3.92	4.60	4.60	4.60	4.60
Powertrain	Efficiency ^g	0.95	0.95	0.95	0.95	0.95	0.95
	Charging power (kW)	80	80	160	160	160	160
	Power (kw)	85	85	400	400	400	400
	Battery size (kWh)	41	55	300	400	300	300
	Usable battery size (kWh)	35	47	291	388	291	291
Wheels ^h	Energy density (Wh/kg) ^g	130	130	130	130	130	130
	Wheel inertia (kg/m ²) ^g	0.82	0.82	0.815	0.815	0.815	0.815
	Number of wheels	4	4	6	6	10	12
	Radius (m)	0.356	0.356	0.522	0.522	0.522	0.522
	Coefficient of friction	0.008	0.008	0.005	0.005	0.005	0.005
Weight	Permissible gross weight (kg)	3,500	3,500	27,000	27,000	40,000	40,000
	Payload capacity (kg)	1.038	0.884	17,600	16,600	29,600	30,000
	Payload considered in the analysis (kg)	0.500 (48%)	0.500 (57%)	9,000 (51%)	9,000 (54%)	15,000 (51%)	15,000 (50%)
	Total truck weight considered (kg)	3,000	3,100	18,400	19,400	25,400	25,000

^a Mercedes-Benz Canada (2010)

^b Volvo Trucks (2022)

^c Hariram et al. (2019)

^d Based on the diesel model of eActros. Sprinter models based on eSprinter.

^e Default values for Class 8 truck (Brooker et al., 2015).

^fBased on axle load reported by Mercedes-Benz (2022)^b

^gBrooker et al. (2015)

^hOwn estimates assuming a 20°C ambient temperature

All models are assumed to be equipped with a tail-lift to load and unload goods. When in operation, the average power demand from the tail-lift is assumed to be 4.8 kW for all vehicles, based on estimations from Palfinger.

2.2 Vehicle energy consumption model

This study used FASTSim (Future Automotive Systems Technology Simulator) tool (Brooker et al., 2015) to estimate the vehicle energy consumption (kWh/km) of electric powertrains under variable conditions.

FASTSim is an open-source tool developed by NREL that enables for detailed vehicle performance analysis while requiring relatively simple vehicle design data inputs, including powertrain components such as the battery, motor, wheel, energy management, auxiliary loads and component efficiency and limits (Brooker et al., 2015). FASTSim uses a backward approach to calculate the energy demand based on a given drive cycle, weather variables and other factors such as road grade and rolling resistance coefficients. The model simulates drag, acceleration, ascent, rolling resistance, vehicle component's efficiency and power limits, and regenerative braking at a one-second resolution basis (Brooker et al., 2015).

The following equations summarise FASTSim's methodology to calculate the vehicle energy consumption. First, Equation (2) is used to calculate the battery power output (Ehsani et al., 2004):

$$P_{out} = \frac{v(t)}{\eta_t \eta_m} \left(m_v g (f_r + \theta) + \frac{1}{2} \rho_{air} C_d A_f v(t)^2 + m_v \frac{dv}{dt} \right) + P_{aux} \quad (2)$$

where $v(t)$ is the vehicle speed (m/s); η_t is the transmission efficiency; η_m is the electric motor efficiency; m_v is the vehicle mass (kg); g is the gravitational acceleration (9.81 m/s²); f_r is the rolling resistance coefficient; θ is the road grade; C_d is the aerodynamic drag coefficient of the vehicle; ρ_{air} is the air mass density at a given temperature; A_f is the front area of the vehicle; and P_{aux} is the power derived from auxiliary loads (ie. cabin heating).

Eq.1 illustrates that the vehicle power demand is only related to the driving cycle properties (vehicle speed, acceleration, and road grade), assuming a constant mass (Yeow et al., 2022). Electricity is also recovered through the vehicle's regenerative system, which uses the electric motor generator-mode to partially capture some of the mechanical power dissipated in braking events, instead of letting the kinetic energy be wasted as heat (Rivelino et al., 2018). The regenerative braking power can be expressed as Equation (3) (Xiao et al., 2016):

$$P_{regen} = \frac{\alpha v(t)}{\eta_t \eta_m} \left(m_v g (f_r + \theta) + \frac{1}{2} \rho_{air} C_d A_f v(t)^2 + m_v \frac{dv}{dt} \right) + P_{aux} \quad (3)$$

where α is the regenerative braking factor, linked to the percentage of total braking energy applied by the electric motor. Equation (4) defines the net energy consumption of an electric powertrain (Ehsani et al., 2004):

$$E_{net} = \int_0^t P_{out} dt + \int_0^t P_{regen} dt \quad (4)$$

The net energy consumption can be used to calculate the battery state-of-charge (SOC) at any time instance of the drive cycle, using Equation (5) (Tanvir et al., 2020):

$$SOC_{(i)}(t) = SOC_{(i-1)}(t) - \frac{E_{net}(t)}{E_{bat}} \quad (5)$$

Where $SOC_{(i)}(t)$ is the battery state-of-charge at a given time instance; $E_{net}(t)$ is the net energy consumption; E_{bat} is the battery energy capacity (kWh). Lastly, the state-of-charge at the end of the driving cycle can be calculated as a function of the SOC at the beginning of the same, using Equation (6) (Fiori et al., 2018; Ehsani et al., 2004):

$$SOC_{Final}(t) = SOC_0(t) - \sum_{i=1}^N SOC_i(t) \quad (6)$$

2.2.1. Battery-electric HDV model calibration

To test the accuracy of the design assumptions, the range of the generated battery-electric vehicles was estimated using standardized driving cycles and compared to the vehicle’s official range estimate. The validation test was carried out under the same conditions as the official tests, including 20°C ambient temperature, partially laden vehicle, and a pre-conditionate battery pack. The payload assumptions were 50% of the total vehicle’s capacity and no significant auxiliary loads were assumed.

The eSprinter official range was estimated using the Worldwide Harmonized Light Test Procedure (WLTP) drive cycle (Mercedes-Benz, 2022a), while the official ranges of the eActros configurations were determined in a private test doing short-radius distribution (Mercedes-Benz, 2022b). Given that the drive cycles used in the eActros official tests are not publicly available, the validation test for these models was carried out using two standardized HDV drive cycles: Heavy-Heavy Duty Diesel Truck (HHDDT) and City Suburban Heavy Vehicle Cycle (CSHVC). Both HHDDT and CSHVC are frequently used to calculate fuel consumption and emissions of HDVs in real-life conditions (Wang, 2015), and are assumed to be representative of short-radius distribution. The drive cycles are illustrated in Figure 4.

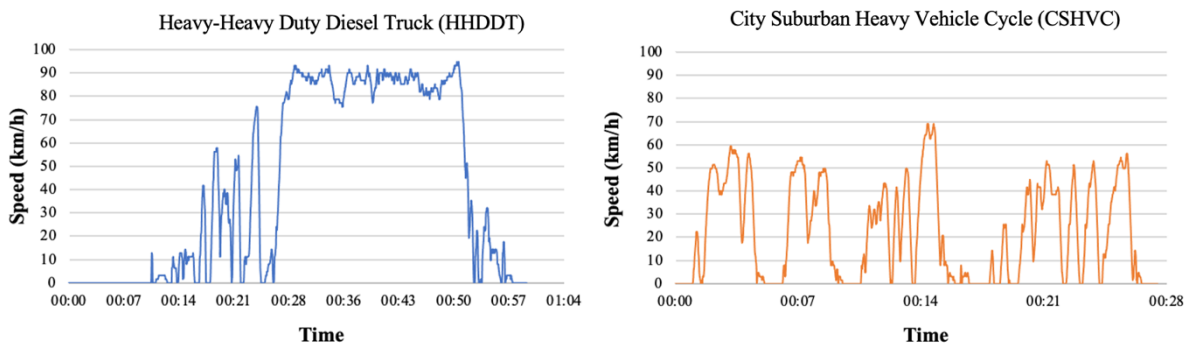


Figure 4. Drive cycles used in the validation test.

As shown in Table 5, the validation test results indicate that the vehicle energy consumption model predicted similar ranges to the ones announced by the manufacturer, with differences of 2-11% between the calculated and the reported range. Based on the difference in calculated/reported range (%) results shown in Table 5, the design parameters presented in Table 4 are assumed to be representative enough to carry out the electrification feasibility assessment.

Table 5. Calibration test results. The calculated range is compared to the official range announced by the manufacturer.

Parameter	S41	S55	BT300	BT400	ST300	T300
Calculated range (km)	105	140	311-318	409-414	229-254	225-232
Reported official range (km) ^a	102	137	300	400	220	220 ^c
Difference in calculated/reported range (%) ^b	3%	2%	3%	2%	11%	4%

^a Mercedes-Benz (2022a); Mercedes-Benz (2022b)

^b The average difference between the calculated and reported range for CSHVC and HHDDT are included in the difference in range (%) values for BT300, BT400, ST300, and T300.

^c The reported range for the trailer is assumed to be the same as ST300 instead of the official estimation by Mercedes-Benz. That is because the official T300 range was calculated without a trailer (Mercedes-Benz, 2022b)

2.2.2. Influence of climate conditions on the vehicle energy consumption model

Climate conditions can considerably increase vehicle energy consumption and reduce driving range. Battery-electric HDVs are particularly sensitive to adverse weather conditions (Basma et al., 2021) due to their limited range compared to conventional diesel trucks and limited charging infrastructure (Forrest et al., 2020). This section introduces the climate variables addressed in this study, linked to the equations illustrated in Section 2.2.

The effects of low temperatures on electric HDVs addressed in this study include the thermal needs for the battery pack (Basma et al., 2021), the cabin heating energy demand (Doyle and Muneer, 2019), tire rolling resistance (Ejmont et al., 2018), and air density and drag (Hariram et al., 2019).

The thermal management of battery electric HDVs can have a measurable impact in energy consumption and consequently in the vehicle's driving range. This additional energy demand is mostly linked to the Battery Thermal Management System (BTMS) and the cabin heating loads (Basma et al., 2021). Battery-electric vehicles are equipped with a BTMS device whose main function is to ensure that the temperature of the battery cells is within the optimum design range, allowing the battery to operate safely and efficiently (CIC, 2021).

The BTMS can account for a considerable power demand to meet the battery thermal needs, which may exceed 5 kW during extreme temperature conditions (Basma et al., 2020). The BTMS load is also linked to the size of the battery, meaning that bigger battery packs will require higher loads to reach the same optimum operating conditions over a smaller battery pack (Basma et al., 2021).

Since electric vehicles cannot rely on the waste heat from a combustion engine to warm the cabin, the traction battery must provide power to heat the cabin (Doyle and Muneer, 2019). The cabin heating power demand is linked to the difference between the desired indoor cabin temperature (T_i) and the outdoor ambient temperature (T_o). The greater the difference between T_i and T_o , the more power is required to reach T_i (Doyle and Muneer, 2019). Therefore, the energy consumption from cabin heating increases during cold days. The desired T_i considered in this study is 20°C.

The average BTMS and cabin heating power demand from Basma et al. (2021) are used to quantify the impact on the vehicle's energy consumption, which is illustrated in Figure 5.

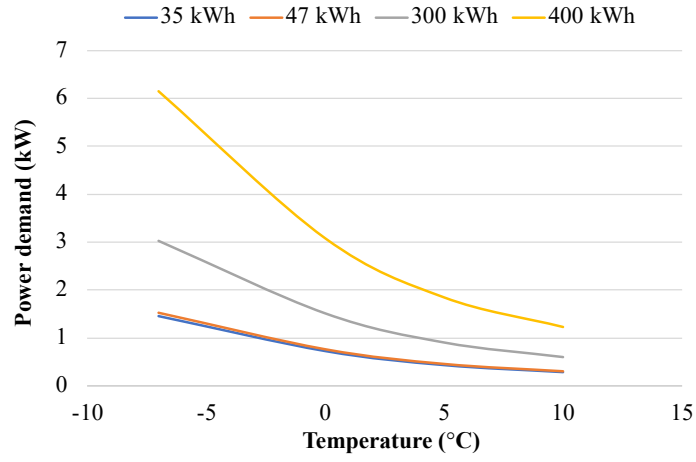


Figure 5. Average power demand from BTMS and cabin heating for different battery sizes. The values for 35 kWh and 47 kWh battery sizes are own estimates based on Basma et al. (2021). Note: 35 kWh and 47 kWh overlap.

Low temperatures also increase the tire rolling friction coefficient, which has an impact on the vehicle's energy consumption. To account for such effects, the tire rolling coefficient values from Ejsmont et al. (2018) are considered in this study. Specifically, this study used the values for tires T1084 and T1077 on a ISOr20 surface road for the truck and sprinter models, respectively. Figure 5 illustrates the variation of the rolling resistance coefficient for both tires as a function of temperature traveling at 80 km/h. Figure 6 values have been estimated based on the measurements of Ejsmont et al. (2018) and are considered in the analysis.

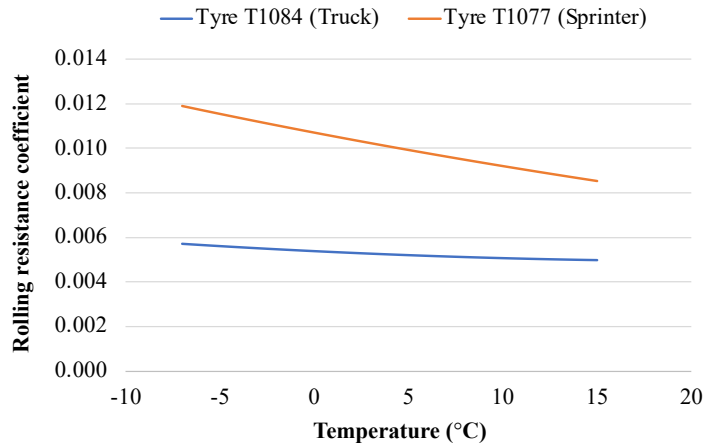


Figure 6. Relation between rolling friction coefficient and temperature. Values estimated based on Ejsmont et al. (2018)

The impact of headwinds is also considered in the electric vehicle feasibility assessment. This study adopted a simplified model to calculate the relative aerodynamic drag increment due to headwind driving conditions. Equation (8) is used to calculate the aerodynamic drag force for all vehicle models considered in the scope,

$$F_{aero} = \frac{1}{2} \rho C_d A (v - W)^2 \quad (8)$$

where F_{aero} is the aerodynamic drag force (N); ρ is air density (kg/m^3); C_d and A are the drag coefficient and the vehicle's frontal area (m^2) from Table 4, respectively; v is the vehicle speed (m/s); and W is the wind speed (m/s). The term $(v - W)$ represents the relative

airspeed, where W is positive for tailwinds and negative for headwinds; F_{aero} is calculated assuming a vehicle speed of 80 km/h and no wind.

To account for headwind conditions, this study re-calculates the vehicle drag coefficient using Equation (9), considering the increase in F_{aero} calculated using Equation 8 under different W values. The variation in air density due to ambient temperature can also be adjusted to represent headwind in low temperatures. This step is necessary to represent headwind in FASTSim.

$$C_d = \frac{2 * F_{aero}}{\rho * A_f * (v - W)^2} \tag{9}$$

Figure 7 illustrates the variation in drag coefficient over different headwind speeds for the sprinter, boxed truck, semi-trailer, and trailer models traveling at 80 km/h at 10°C.

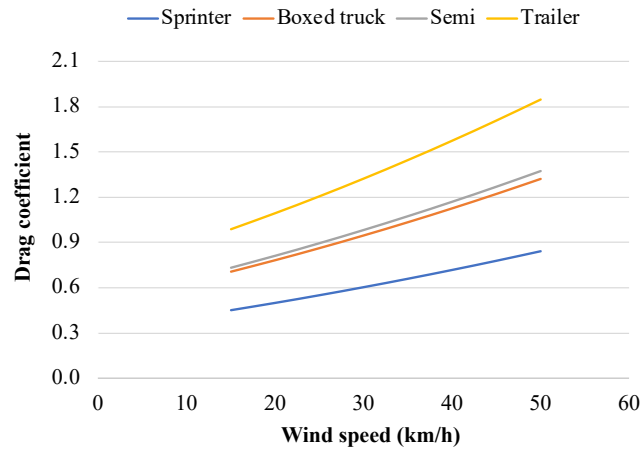


Figure 7. Drag coefficient variation over headwind speeds (Own estimates)

2.3. Charging model

This study adopted a simplified empirical charging model to evaluate the impact of on-route fast-charging over the range of battery-electric HDV. The charging sessions were simulated using a pre-recorded fast-charging curve from a Rivian R1T (Out of Spec Studios, 2022), shown in Figure 8, which illustrates the relationship between the power accepted at port and the battery SOC. The non-linear behaviour of the battery SOC over the charging session is usually linked to the vehicle’s Battery Management System (BMS), which continuously adjusts the charging rate to prevent overcharging and damaging the battery (Motoaki et al., 2018). The BMS is strongly influenced by the vehicle’s SOC and ambient temperature, among other factors (Motoaki et al., 2018). By using this top-down approach, the charging sessions can be simulated considering a realistic non-linear variable charging rate, accounting for the vehicle’s SOC and ambient temperature.

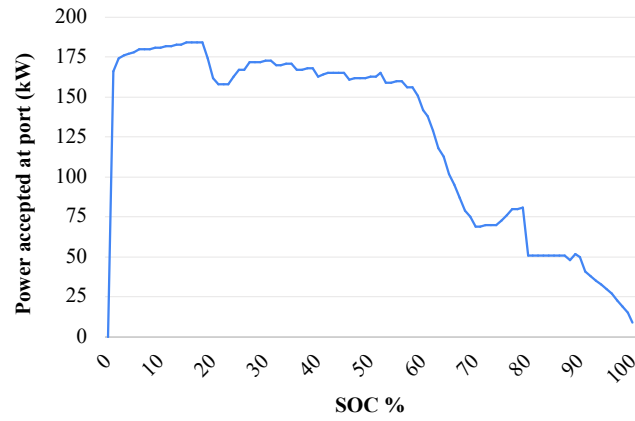


Figure 8. Power accepted at port and SOC (Out of Spec Studios, 2022)

Similarly to Zhang et al. (2012) and Arias et al (2017), this study adopted a 2-piece charging profile linearization based on the Rivian R1T recording. Therefore, the charging curve shown in Figure 8 is divided into two sections to account for different battery conditioning stages, which are shown in Figure 8. The ‘Low BMS’ curve represents a charging stage with minimal battery conditioning, allowing for maximum charging power during most of the session, while the ‘High BMS’ curve accounts for significant limitations in power accepted due to high battery conditioning. It is assumed that the first curve may be applied when the battery SOC ranges within 0-70%, as long as the battery temperature is optimal. The second curve is assumed to be applicable to batteries outside the optimal temperature range or with a SOC over 70%.

The charging profiles considered in this study are illustrated in Figure 9. The duration of the charging sessions is adjusted to 30 minutes, as it is assumed that fleet operators would avoid long on-route charging periods due to tight route schedules and the higher costs of fast-charging compared to charging at the depot. The different charging power capacities considered in the model are shown in Table 4.

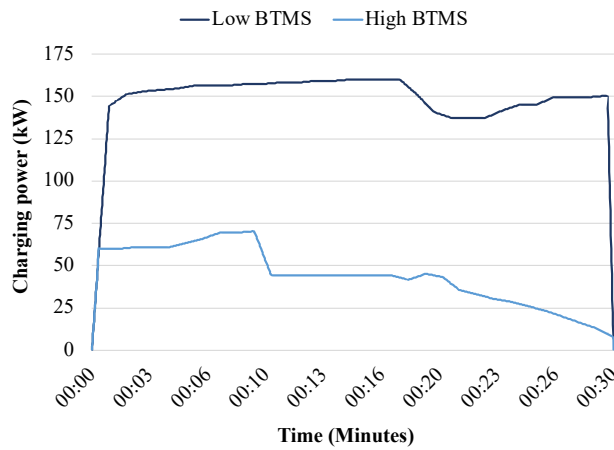


Figure 9. Charging curves for a 160-kW charger at 25°C considering different battery SOC. The duration of each curve is 30 minutes. Based on Rivian R1T recorded session (Out of Spec Studios, 2022).

The effects of ambient conditions are also considered in the charging model. Cold temperatures are shown to have a negative impact on Li-Ion battery charging speeds, which translates into longer charging sessions. The findings of Motoaki et al. (2018) and Gorbunova and Anisimov (2018) are used to estimate the charger performance loss derived from low temperatures.

Figure 10 illustrates the relationship between temperature and loss in charger performance compared to ideal conditions (i.e., 25°C). Figure 9 has been used to inform the assumptions regarding loss in delivered charging power due to low temperatures in the charging model, which are applied to the original charger capacity. For instance, a 20% charger capacity loss is estimated at a temperature of 10°C. This means that, for a 160-kW charger, the maximum capacity available at 10°C would be 127 kW.

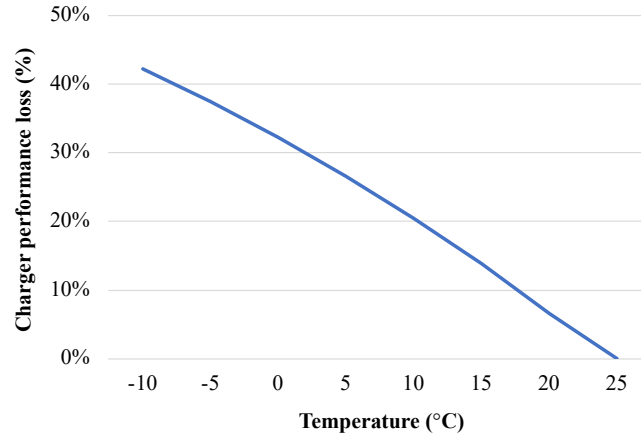


Figure 10. Relationship between ambient temperature and charger performance loss, based on Motoaki et. al. (2018)

The increase in SOC by charging can be described with Equation (10) (Hamed, 2016);

$$SOC_i(t) = SOC_{(i-1)}(t) + \int_0^t \frac{I_i}{C_{bat}} dt \quad (10)$$

where $SOC_{(i)}(t)$ is the battery state-of-charge at a given time instance; I_i represents the variable charging rate (kW); and C_{bat} is the battery capacity (kWh).

2.4. Electric range sensitivity analysis and scenario design

The range of the analysed vehicles is determined using the vehicle's usable battery capacity (kWh) values from Table 4 and the vehicle's energy consumption (kWh/km) over a specific route, which is calculated using the vehicle energy consumption model introduced in Section 2.2.

As explained in Section 2.2.2., energy consumption is strongly linked to ambient conditions such as temperature or wind. Moreover, payload and the number of tail-lift uses are other variables associated with freight operations that may alter the vehicle's energy. Therefore, a sensitivity analysis is carried out to evaluate the impact of these ambient and freight variables on the vehicle's energy consumption. The variables analysed are temperature, headwind, payload, and number of programmed tail-lift uses. A set of scenarios has been designed to study each variable individually, including:

- (1) Reference: This scenario represents a regular day of operation based on Ölgerdın's average values for tail-lift uses. It is assumed that the vehicle starts at 100% payload capacity and finishes at 0%. The temperature assumed is 10°C. The other scenarios are built on top of the reference scenario.
- (2) Ideal: The temperature considered is 20°C, representing the same environmental conditions from the Mercedes-Benz range tests.
- (3) Cold: The temperature is set to 0°C, and other variables are adjusted accordingly.

- (4) Very Cold: The temperature is set to -7°C , and other variables are adjusted accordingly.
- (5) Windy: Headwind at 40 km/h is assumed during 50% of the route.
- (6) Payload: The reference payload is increased up to $\sim 90\%$ of the vehicle capacity for all the routes.
- (7) Busy day: The number of tail-lift uses is multiplied by 4.
- (8) Tough day: This worst-case scenario combines Very cold, Windy, Payload and Busy day.

Solar irradiation has been proved to affect cabin temperature and consequently influence energy consumption from cabin heating and cooling systems (Hemmati, S. et al., 2021). However, the impact of solar irradiation over cabin heating loads in this study is assumed to be negligible due to Iceland's relatively limited insolation and high cloud coverage (Veðurstofa Íslands, 2023).

These scenarios are presented in Table 6 in more detail. The parameters of each scenario are based on the considerations from Section 2.2.2, and the scenarios are applied for each vehicle and drive cycle from Section 2.1. The impact of on-route charging in the vehicle's range is also estimated using the assumptions from Section 2.3.

Table 6. A detailed description of the scenarios used in the analysis.

Parameter	Reference	Ideal	Cold	Very cold	Windy	Payload	Busy day	Tough day
Wind speed (km/h) ^a	-	-	-	-	40	-	-	40
Headwind (%) ^b	-	-	-	-	50%	-	-	50%
Temperature ($^{\circ}\text{C}$)	10	20	0	-7	10	10	10	-7
Air density (kg/m ³)	1.22	1.20	1.28	1.31	1.23	1.22	1.22	1.31
Num. tail-lift uses ^c	40	40	40	40	40	40	160	160
Aux. loads (kW): 41 kWh ^d	0.294	-	0.735	1.465	0.294	0.294	0.294	1.465
Aux. loads (kW): 55 kWh	0.305	-	0.764	1.522	0.305	0.305	0.305	1.522
Aux. loads (kW): 300 kWh	0.608	-	1.520	3.030	0.608	0.608	0.608	3.030
Aux. loads (kW): 400 kWh	1.234	-	3.084	6.148	1.234	1.234	1.234	6.148
Road resistance (sprinters)	0.009	0.008	0.009	0.011	0.009	0.009	0.009	0.011
Road resistance (trucks)	0.005	0.005	0.005	0.006	0.005	0.005	0.005	0.006
Charging power loss (%) ^e	-20%	0%	-31%	-39%	-20%	-20%	-20%	-39%
Increase in payload (%)	-	-	-	-	-	40%	-	40%

^a Average wind speed in Reykjavík is around 26 km/h during winter and can get over 40 km/h (Weather Spark, 2023). The maximum wind speed has been assumed in this study to represent worst case scenario.

^b % of the route with headwind

^c Each programmed tail-lift use is assumed to take 60 seconds at an average load of 4.8 kW

^d Auxiliary loads include the energy consumption linked to BTMS and cabin heating

^e Estimates based on Section 2.3

2.5. Electrification feasibility assessment of case study fleet

An HDV electrification feasibility assessment refers to the technical potential of electric trucks to meet freight demands (Forrest et al., 2020). In this study, the electrification potential of Ölgerðin's fleet is evaluated for each drive cycle, vehicle, and scenario, including the availability of on-route charging. Therefore, the range estimates calculated using Section 3.1. are compared to the total daily distance covered per each trip during the entire study period, under the scenarios presented in Section 2.1. A route is assumed to be electrifiable if the estimated range of the analysed vehicle is higher than the total daily distance covered for all trips and scenarios. If the electric range is lower, the estimated range is recalculated by accounting for the extended range achieved by including a 30-minute on-route fast-charging session. Figure 11 outlines the methodology used to evaluate the electrification potential.

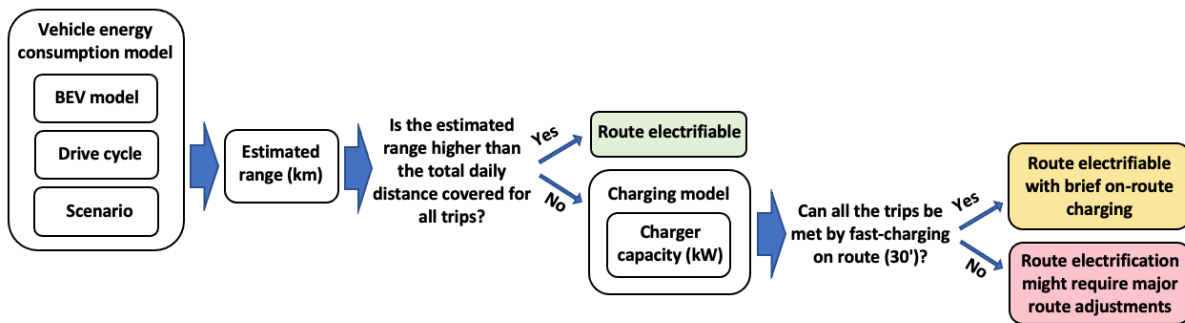


Figure 11. Flowchart illustrating the electrification feasibility analysis.

3. Results and discussion

3.1 Impact of ambient and drive cycle conditions on the driving range

This section presents the sensitivity analysis results, which are presented in the following impact categories: driving cycles, temperature and headwind, payload and tail-lift, and combined impact. A brief summary of the results is presented at the end of this section. The energy consumption of the analysed electric HDVs has been estimated considering the scenarios described in Section 2.4. Table 7 shows the variation in vehicle energy consumption under the different scenarios and routes analysed, while Figure 12 shows the variation in vehicle range.

3.1.1. Impact of different driving cycles on vehicle's energy consumption

As shown in Figure 12, both sprinters achieve their maximum range under downtown driving conditions, while trucks present their lowest range during downtown driving conditions and achieve the maximum range on out-of-town routes. Trucks account for higher energy consumption during stop-and-go driving compared to sprinter vans, mostly due to their significantly higher total weight which represents a severe toll in this type of conditions. As shown in Table 7, the maximum fuel efficiency for trucks is achieved in out-of-town cycles.

For all vehicles and drive cycles, the highest range is achieved under ideal conditions while the lowest range is achieved in the tough scenario. Nevertheless, the maximum range variation, or the difference between the highest and lowest range achieved, varies depending on the drive cycle. For the sprinters, the highest range variation is seen in downtown driving (53-55%), followed closely by suburbs (49-50%). The different truck categories experience the widest variation in range in downtown and suburb driving (41-48%). Out of town driving accounts for the lowest expected range variation for all vehicles (34-38%).

Table 7. Energy consumption (kWh/km) per vehicle and route.

Cycle	S41	S55	BT300	BT400	ST300	T300
Downtown	0.30-0.52	0.31-0.52	1.19-1.88	1.29-2.17	1.58-2.59	1.60-2.62
Suburbs	0.32-0.50	0.33-0.52	1.14-1.85	1.23-2.15	1.47-2.43	1.51-2.48
Out of town	0.31-0.46	0.33-0.48	1.06-1.55	1.11-1.69	1.27-1.90	1.35-1.99

3.1.2. Impact of ambient temperature and wind

The results showed that the range reduction grows exponentially as the temperature decreases, which is especially noticeable in BT400. In the arguably warm reference scenario (10°C), the sprinters already show a considerable drop in the range of 10-22% compared to ideal conditions across all drive cycles, while the truck categories experience a minor decrease in range of 3-10%. Cold conditions (0°C) increased the impact for all vehicles, following a similar pattern to the reference scenario. Once again, the sprinters accounted for the biggest range reduction compared to ideal conditions at 16-30%, followed by boxed trucks (7-20%) and semi-trailer and trailer trucks (5-11%). The results for very cold conditions (-7°C) showed a steeper decrease in range, with the sprinters averaging a 35% range loss across all drive cycles. BT300 and BT400 results were quite different, averaging 18% and 26% respectively. Both ST300 and T300 presented a similar average range loss at 15% compared to ideal conditions. The results are similar to Basma et al. (2021), who estimated a 3% loss in range for 300 kWh semi-trailers in long-haul drive cycles. The present study estimated a 8% loss in driving range for the same vehicle category in Out-of-town routes. The variation in the results of both studies may be explained by the different assumptions taken, specially involving the driving cycle analysed and the temperature scenario comparisons.

The impact of headwind on range is arguably constant for sprinter vans, accounting for a 5-10% drop in all drive cycles. For trucks, the impact of headwind is slightly higher in out-of-town routes compared to downtown and suburbs. BT300 and BT400 experience a 6-9% drop in range in downtown and suburbs conditions, while the drop can increase up to 15-16% in out of town. The expected range loss for ST300 and T300 is slightly lower, accounting for drops of 4-6% in downtown, 6-8% in suburbs and 12-14% in out of town. Headwind is the only variable which impact was stronger in out-of-town routes other than in downtown and suburb routes.

3.1.3. Impact of payloads and use of tail-lift

The impact of heavy payloads was significantly noticeable for all vehicles, especially in downtown and suburban driving conditions. Sprinter vans averaged 3-5% lower ranges compared to reference conditions, while the trucks averaged drops of 18-28% in the same drive cycles. For out-of-town routes, the range losses were 3% for the sprinters and 13-19% for the trucks. The results for semi-trailers were similar to Basma et al. (2021) estimates for the same vehicle category in long-haul routes, which predicted a 13% loss in driving range for heavy loaded trucks. Overall, the heavy payload scenario was significantly less harsh for the sprinters, mainly due to the limited cargo space.

Similarly to the heavy payload scenario, the impact of tail-lift use is more significant in downtown and suburbs for all vehicles. For these drive cycles, the intense tail-lift use accounted for a 18-20% drop in range for the sprinters. In out-of-town conditions, the range loss gets down to 8-14%. Tail-lift use influence is lower in the big trucks, averaging a 4-7% in downtown and suburb driving and 2-4% in out of town.

3.1.4. Combined impacts of use and environmental conditions on the driving range

Combining all the adverse scenarios (very cold, headwind, heavy payload, and busy) yielded the highest reduction in range for all vehicles compared to ideal conditions. Overall, sprinter vans suffered more in downtown conditions while trucks presented higher energy consumption during suburb driving. The average range loss under tough conditions in downtown routes was 54% for both sprinters, losing around half of the estimated range under ideal conditions. The sprinters present slightly better results for suburbs and out of town routes, although the range loss still range from 49-50% and 39-42% respectively. The results for trucks show a similar pattern to the sprinters, with tough conditions claiming 41-47% of the vehicle’s range in downtown routes, 42-48% in suburbs, and 34-38% in out of town.

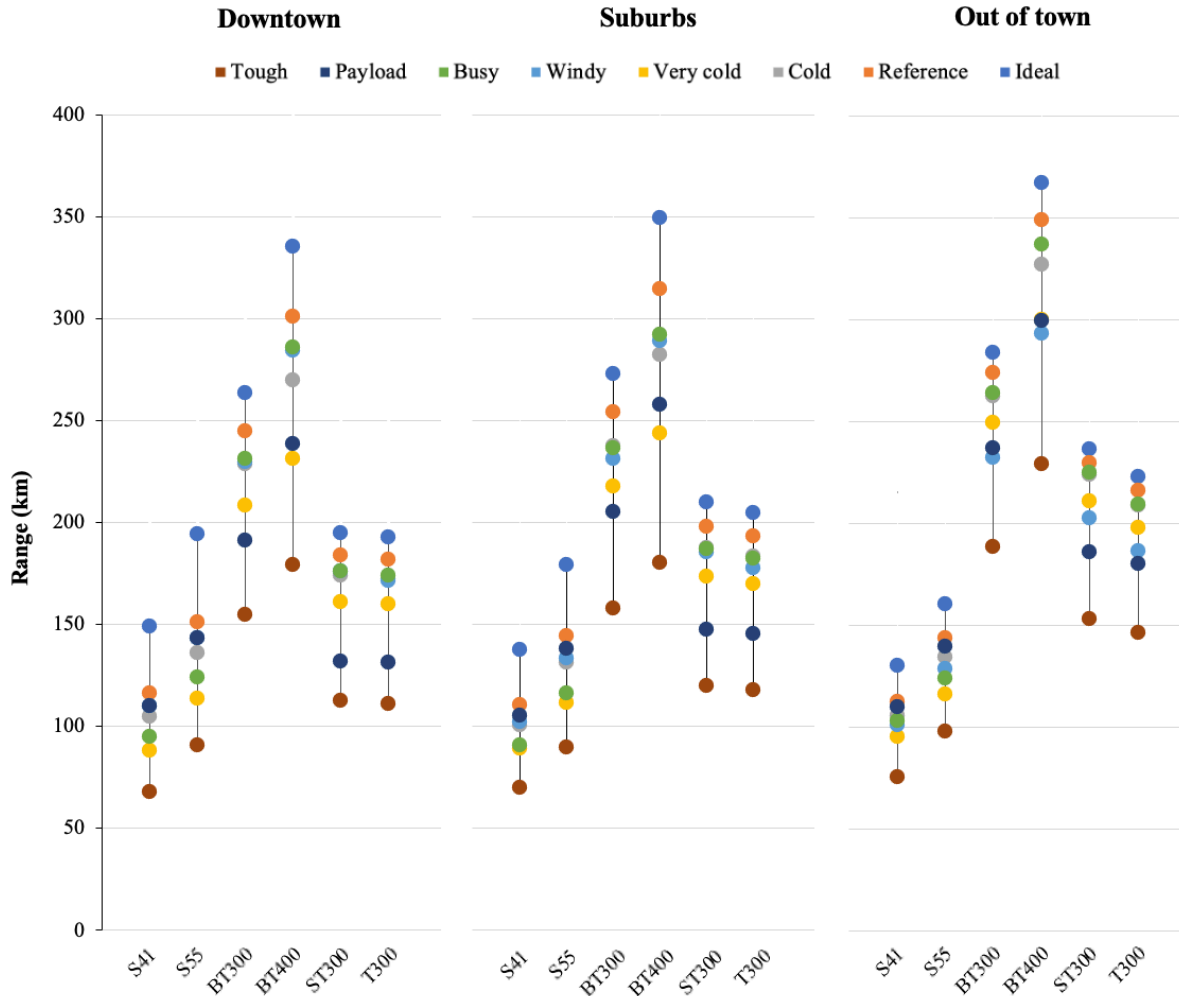


Figure 12. Range variation for each vehicle under the different scenarios analysed and drive cycle conditions. S41 (Sprinter van 41 kWh), S55 (Sprinter van, 55 kWh), BT300 (Boxed truck, 300 kWh), BT400 (Boxed truck, 400 kWh), ST300 (Semi-trailer, 300 kWh), T300 (Trailer, 300 kWh).

3.2. Fast-charging performance: Impact of BTMS, ambient temperature and charging power

The fast-charging performance of the analysed vehicles has been estimated considering the assumptions described in Section 2.5. The performance evaluation is carried out in terms of added kWh over a 30-minute fast-charging period, considering charger capacities of 80 kW and 160 kW.

Figure 13 illustrates the added kWh for each battery size under four temperature

scenarios (very cold, cold, reference, and ideal) and two battery conditioning scenarios (low and high), represented in Figure 8. According to the results shown in Figure 13, a 30-minute charging session at 80 kW in ideal conditions can add up to 27 kWh to the battery pack, which represents 77% and 58% of added SOC to a 41 kWh and 55 kWh battery pack, respectively. Under the same conditions, charging at 160 kW can add up to 73 kWh, which represents 25% and 19% of added SOC in a 300 kWh and 400 kWh battery pack. These values are aligned with the announced charging time by the Mercedes-Benz, which claims that its 41-kWh sprinter can charge from 10-80% in 20 minutes (Mercedes-Benz, 2022a) and the 300 kWh battery pack can go from 0-50% charge under 1 hour (Mercedes-Benz, 2022b).

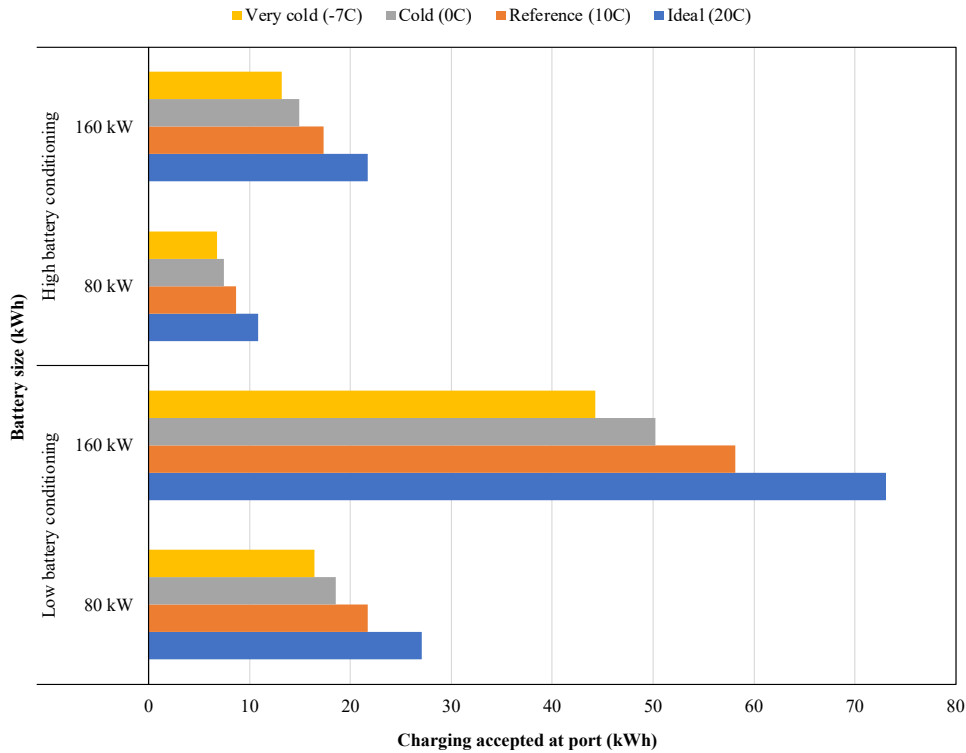


Figure 13. Charging accepted by the vehicle (kWh) over 30-minute fast-charging sessions for different temperature and battery conditioning scenarios. The charger capacity is 80 kW for 41 kWh and 55 kWh batteries and 160 kW for kWh and 400 kWh. To account for realistic charging, the rate from Figure 8 is used for the 80-kW charger at low battery conditioning.

Aside from the battery conditioning and temperature considerations, the charger capacity represents another critical variable when evaluating the potential of fast-charging to enable route electrification. Moreover, it is probable that 160 kW chargers, or even 80 kW, are not available everywhere (European Commission, 2023). This section represents a brief insight to the implications of using other charger capacities over the added charge. Table 8 shows an example of charging in ideal conditions, including charger capacities of 160 kW, 80 kW, 40 kW and 20 kW and the already known battery sizes.

Table 8 indicates how much SOC could be added for the 300 kWh and 400 kWh trucks if the charging session was carried out using 80, 40 and 20 kW capacity chargers. Not surprisingly, the added charge would drop around 50% in an 80-kW charger compared to a 160 kW charger, following a similar trend for the other chargers as the capacity gets cut in half. It would take one hour of charging with at 80 kW to add up as much charge as with the 160-kW charger, while it would take 4 hours at 40 kW and around 8 hours at 20 kW.

Assuming maximum charging speeds, S41 and S55 would be able to charge up to 55% and 29% with a 40-kW charger, and 26% and 14% with a 20 kW charger.

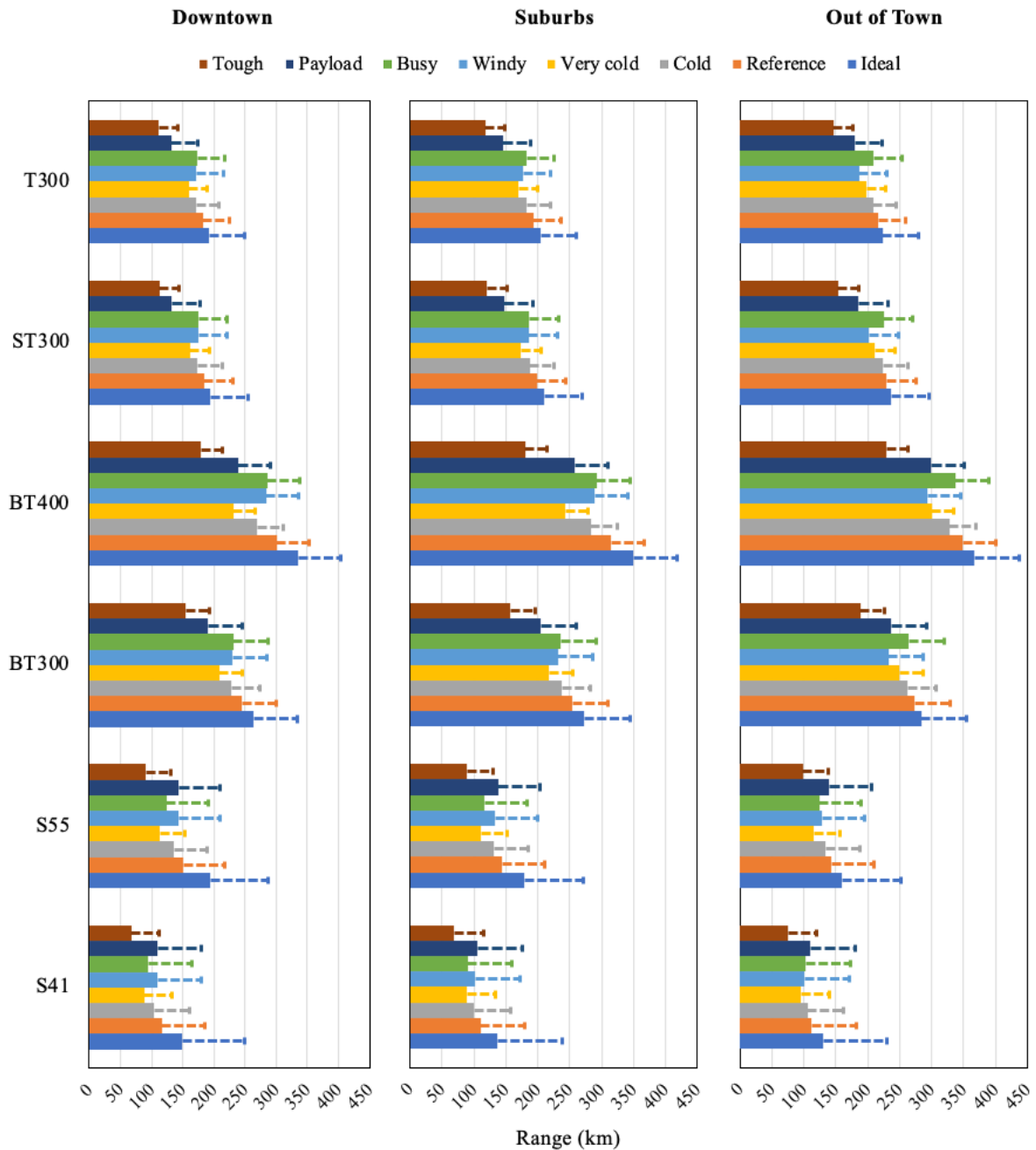


Figure 14. Electric range per each vehicle, scenario, and drive cycle. The dotted line represents the range extension achieved by charging under each scenario.

Table 8. Added battery SOC (%) for different battery and charging power capacity at 20°C during 30-minute charging period.

Battery capacities (kWh)	160 kW	80 kW	40 kW	20 kW
41	-	77%	52%	26%
55	-	58%	29%	14%
300	25%	13%	6%	3%
400	19%	9%	4%	2%

3.3 Electrification potential of the case study fleet

The electrification potential of Ölgerðin's fleet is evaluated using the methodology introduced in Section 2.5. Table 9 summarises the results of this analysis, showing the % of trips met and the overall electrification potential per each vehicle, drive cycle, scenario, and on-route charging availability. Green cells indicate that the studied vehicle would be capable of covering all trips under the analysed route category and scenario without requiring on-route charging. The results highlighted in yellow indicate that the analysed vehicle would require a brief (30-minute) fast-charging session to meet all trips within the studied route, while the cells highlighted in red indicate that the vehicle would require longer charging sessions. The results presented in Table 9 suggest that both sprinter vans are likely to rely on on-route fast-charging to meet all downtown and suburb trips, although a 30-minute charging session would be sufficient to meet all routes. Therefore, it can be assumed that no major route adjustments would be needed to electrify these routes with sprinter vans. Nevertheless, both sprinters seem to be unfit to meet out-of-town routes, not even in the most favourable conditions, requiring several charging sessions to meet all routes.

The results shown in Table 9 suggest that BT300, BT400, ST300 would be capable of meeting all downtown and suburb routes without requiring on-route charging, while ST300 would be likely to fast-charge only during unfavourable conditions. Therefore, it can be deduced that no significant changes would be required to meet the freight activity with these electric trucks. Lastly, BT400 stands out as the most suited vehicle to cover out-of-town routes, only requiring on-route charging in tough conditions. BT300, ST300 and T300 would rely heavily on on-route charging to meet these longer routes, probably having to adjust their route plans to fit longer charging sessions or several programmed stops under tough conditions.

Batteries are expected to lose capacity over its service life, degrading up to 30% at end-of-life (Nykvist and Olsson, 2021). Considering such degradation, the analysed vehicles would still be able to meet all downtown and suburban routes if these could charge around 30 minutes on-route. Nevertheless, battery degradation would increase the vehicle's dependency on on-route charging availability. Current improvements in battery remaining useful life predictions are expected to reduce uncertainties around long-term battery health and safety performance (Wang et al. 2023).

Table 9. Electrification potential per drive cycle, vehicle, and scenario. The % shows the number of trips electrifiable out of the total. Green: Route electrifiable without requiring on-route charging; Yellow: Route electrifiable including a brief (30-minute) fast-charging session, not major routing plan adjustments required; Red: Major route adjustments are required to fit longer/several on-route charging sessions to enable route electrification.

Cycle	Scenario	S41	S55	BT300	BT400	ST300	T300
Downtown	Reference	100%	100%	100%	100%	100%	100%
	Cold	100%	100%	100%	100%	100%	100%
	Very cold	97%	100%	100%	100%	100%	100%
	Windy	100%	100%	100%	100%	100%	100%
	Busy day	99%	100%	100%	100%	100%	100%
	High payload	100%	100%	100%	100%	100%	100%
	Tough day	77%	98%	100%	100%	100%	100%
Suburbs	Reference	97%	100%	100%	100%	100%	100%
	Cold	92%	100%	100%	100%	100%	100%
	Very cold	73%	97%	100%	100%	100%	100%
	Windy	94%	100%	100%	100%	100%	100%
	Busy day	75%	98%	100%	100%	100%	100%
	High payload	95%	100%	100%	100%	100%	100%
	Tough day	24%	75%	100%	100%	100%	99%
Out of town	Reference	15%	28%	100%	100%	78%	61%
	Cold	13%	22%	100%	100%	69%	54%
	Very cold	13%	17%	94%	100%	56%	54%
	Windy	13%	22%	80%	100%	54%	54%
	Busy day	13%	22%	100%	100%	74%	54%
	High payload	15%	24%	81%	100%	54%	52%
	Tough day	9%	13%	54%	78%	37%	31%

3.4. Implications from electrifying the case study fleet

In our previous work in Alonso-Villar et al. (2022), we carried out a detailed life cycle emission and TCO (Total Cost of Ownership) assessment for different alternative fuel HDV powertrains in Iceland over a 15-year period. The results showed that battery-electric powertrains presented the lowest GHG emissions of all powertrains considered, while also accounting for lower air pollutant emissions to diesel HDVs, except for SO_x and PM₁₀. Alonso-Villar et al. (2022) also proved that the TCO of battery-electric HDVs was lower to diesel HDVs, even though the capital cost of electric trucks were over twice as much as conventional diesel trucks.

This section provides a brief insight of the environmental and economic implications of transitioning toward electric freight vehicles from a fleet operator's perspective, using Ölgerðin as the case study. Table 10 shows the annual fuel expenses and associated emissions from the vehicle operation stage for both diesel and electric pathways.

The reduction achieved in both fuel expenses and emissions is significant, especially for the larger trucks. According to the results shown in Table 10, replacing one of the heavy-duty trucks (i.e., semi-trailer) for an electric model could save Ölgerðin up to 45,000 USD per year in fuel expenses, assuming that the truck is charged using low-cost electricity at depot. Using an electric semi-trailer would also avoid around 56 tons of CO₂ emissions annually. According to the results in Table 10, replacing conventional diesel commercial vehicles for electric models would reduce 90% the annual fuel expenses and 98% of their tail-pipe emissions.

The highly decarbonized national power grid along with the low cost of electricity contribute greatly to achieve these results, which may only apply to the Icelandic context.

Table 10. Annual energy consumption, fuel expenses and CO₂ emissions linked to diesel and battery-electric powertrains. All values are shown per vehicle.

Powertrain	Diesel			Battery-electric		
	Diesel consumption (L)	Fuel expenses (USD) ^b	CO ₂ emissions (kg) ^c	Electricity consumption (kWh)	Charging expenses (USD) ^d	CO ₂ emissions (kg) ^e
Vehicle ^a						
Delivery van	1,091	2,519	2,871	4,840	319	47
Truck < 12 ton	5,724	13,216	15,064	24,142	1593	237
Truck > 12 ton	21,627	49,936	56,919	64,171	4235	629

^a Estimates carried out using the annual driving values from Ölgerðin in Table 3.

^b The fuel expenses are calculated using fuel economy values from Eimskip. Delivery van: 0.08 L/km; Truck < 12 ton: 0.56 L/km; Truck > 12 ton: 0.65 L/km. The diesel cost assumed is 2.3 USD/L (Global Petrol Prices, 2023a)

^c Tailpipe emissions from diesel vehicles, assuming 2.7 kg of CO₂ emitted per L of diesel (Comcar, 2023).

^d The fuel expenses are calculated using average energy consumption (kWh/km) for all scenarios and routes. Delivery van: 0.41 kWh/km; Truck < 12 ton: 1.54 kWh/km; Truck > 12: 1.91 kWh/km. The electricity cost assumed is 0.066 USD/kWh (Global Petrol Prices, 2023b).

^e Emissions from electricity production, assuming the carbon intensity of the Icelandic electricity mix in 2021: 9.3 g CO₂/kWh (Orkustofnun, 2020).

3.5. Summary of results and policy suggestions

The main results from the previous sections are summarised as follows:

- As expected, unfavourable ambient and freight conditions increase the energy consumption of electric HDVs, representing a significant reduction in range. The extent of the impact is strongly linked to the type of vehicle and drive cycle analysed. This illustrates the importance of considering climate and freight factors when assessing truck electrification potential instead of relying on reported ranges from manufacturers.
- The impact of headwind and tail-lift use, factors which are usually overlooked in the electrification assessments, proved to have a significant impact in range. Headwind's impact was especially significant in out-of-town routes, while tail-lift use is more significant in small battery size vehicles compared to big trucks.
- Fast-charging in low temperatures would represent a significant reduction in added charge, although not as much as charging during high battery conditioning. Both variables should be considered in route planning to maximize fast-charging sessions.
- The proposed battery-electric vehicle fleet would be capable of meeting 100% of Ölgerðin's downtown and suburb routes, while it is likely that some route planification adjustments would be required to fit the necessary fast-charging sessions to electrify out-of-town routes. Sprinter vans proved to be unsuited to cover out-of-town routes. Overall, on-route charging would be necessary to achieve full electrification.
- The positive results of the challenging Ölgerðin case study strongly indicate a potential for electrification of HDV fleets in urban settings, despite harsh climate conditions.

Overall, these results indicate that the electrification of road freight activity in urban settings could be an optimal starting point to reduce HDV emissions in Iceland. Nevertheless, the implementation of battery-electric HDVs needs to be carefully studied and prepared with regards of vehicle configuration, freight requirements, environmental conditions, and available charging infrastructure. Moreover, the significant energy consumption from auxiliary loads emphasises the need for optimisation strategies to reduce the impact on the driving range, such

as correlating vehicle dynamics and auxiliary loads (i.e., shifting the application of auxiliary loads to regenerative braking periods) (Berzi et al., 2020). Future improvements in the precision of SOC prediction systems, like the Kalman filter, will also play an important role in managing the vehicle performance in adverse conditions (Li et al., 2021). The outcomes of this research suggest that policies should be developed to promote a widespread electrification for HDVs operating in downtown and suburb routes, including suitable charging stations both at depot and on-route.

4. Conclusions

This study evaluated the performance of different battery-electric HDV configurations using real driving data from a delivery fleet operating in southwest Iceland. The following research questions were addressed: (1) To what extent do climate and freight conditions impact the electrification potential of heavy-duty vehicles?; and (2) Considering unfavourable climate conditions, to what extent can the case study freight activity be carried out with battery-electric trucks?

The results showed that the performance of the analysed vehicles is strongly correlated with drive cycle, climate, and freight conditions. Overall, the variables addressed have a considerable impact on the range of the analysed vehicles and should be considered in HDV electrification assessments. The results also showed that fast-charging performance is significantly influenced by low temperatures and battery conditioning, factors which need to be considered when planning on-route charging sessions. Delivery vans would meet 73% of the routes under reference scenario conditions and 49% under tough day conditions. If on-route charging was available (30-minute session), the routes met would increase to 85% and 74% respectively. For the same conditions, trucks would meet 95% and 83% of the routes respectively, and up to 100% and 90% with on-route charging availability. Policies should be developed to facilitate the widespread use of urban freight electrification, as the emission reduction potential is significant.

This is the first study to quantify the impact of low temperatures, variable payloads, headwind, and tail-lift use over the driving range of different configurations of heavy-duty vehicles. These results could potentially inform policy development and reduce uncertainties regarding electric HDV technical capabilities, ultimately providing a favourable framework for electric truck deployment and increasing engagement from fleet operators. Moreover, the detailed methodology presented can be used to replicate this study using different contexts.

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4. Paper 3

Optimising Fast-Charging Infrastructure for Long-Haul Electric Trucks in Remote Regions under Adverse Climate Conditions

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Abstract

This study proposes a novel methodology for planning fast-charging infrastructure for long-haul battery-electric trucks (BETs) in low-traffic flow regions. The research addresses the challenge of early-stage charging infrastructure development and optimally locating fast-charging stations (FCS) in remote areas, with a focus on optimisation, impact on routing time, and reliability. The proposed methodology uses a vehicle energy consumption, a non-linear charging optimisation framework, and a queueing model to design an efficient fast-charging station network in Iceland's Reykjavík-Westfjords freight routes under harsh climate and freight conditions. The results suggest that larger batteries and higher charging rates significantly reduce additional routing times, with minimal extra time required for 540 kWh trucks using 500 kW chargers, averaging 25 minutes. In contrast, trucks with smaller 360 kWh batteries and 350 kW charging rates require longer additional routing times, with an average of 83 minutes. These findings highlight the impact of battery capacity and charging rate on route electrification feasibility, allowing for potential alignment with freight schedules. This study provides insights for policymakers and fleet operators to guide infrastructure development and prioritise investments, contributing to the broader goal of freight transport electrification. Future research should investigate the potential impact of the derived charging loads on the power grid.

Keywords: Charging network; Heavy-duty vehicles; Battery-electric trucks; Optimisation; Queueing theory; Long-haul

1. Introduction

The transport sector is responsible for 20% of the global GHG emissions, a third of which comes from road freight transport alone (European Commission, 2024a). Road freight transport is usually carried out using heavy-duty vehicles (HDVs), such as tractor or trailer trucks, which in recent years have been in the spotlight of regulators aiming to reduce CO₂ emissions and increase energy security in the freight sector (Ge & Friedrich, 2020). A clear example of such trend is the European Commission's regulation on emission standards for HDVs, which was revised in 2023 to include more ambitious goals to reduce CO₂ emissions in HDVs (European Commission, 2024a). In addition, several European governments have already made commitments to phase out new registrations of fossil fuel HDVs by 2040 (Council of the European Union, 2024), in favour of zero-emission vehicles (ZEVs) such as battery-electric trucks (BETs).

BETs are considered a potential solution to decarbonise the road freight transport sector due to their low Well-to-Wheel CO₂ emissions (Lajevardi et al., 2019), reduction of fossil fuel dependency (Alonso-Villar et al., 2022), and competitive Total Cost of Ownership (TCO) (Sen et al., 2017) (Forrest et al., 2020). BETs have also proved to be capable of carrying out urban and short-haul freight applications while charging only at the home-base, even in adverse climate and freight conditions (Alonso-Villar et al., 2023). An increasing number of BET models are becoming available in the market, including trucks capable of long-haul applications with ranges over 400 km (Scania, 2024), although the BET market share barely represents 1.2% of new HDV registrations worldwide (IEA, 2023).

Contrary to short-haul applications, the feasibility of electrifying long-haul routes is strongly linked to the availability of on-route fast-charging stations (FCS) (Hurtado-Beltran et al., 2021). Long-haul trucking is characterised by long distance trips, usually including multiday travel, without returning to the home base daily. These characteristics make recharging along the route a key requirement to enable the utilisation of BETs for long-haul applications (Shoman et al., 2023). Existing FCS infrastructure is mostly designed to meet the charging demands of passenger vehicles, which are significantly different to the charging requirements of BETs covering long-haul routes, rendering them unsuitable (Danese et al., 2021). Therefore, the development of FCS infrastructure suitable for BETs is a necessary step to enable the widespread adoption of electric HDVs and to accelerate the decarbonisation of freight transport (Jochem et al., 2019).

Efforts are being made in this regard, such as the EU Alternative Fuel Infrastructure Regulation, which sets targets on public charging infrastructure along the main freight transport corridors in Europe, or the TEN-T network. These targets require the member states to build a charging station exclusive for HDVs every 60 km along the main corridors and every 100 km in the rest of the road network by 2030 (European Parliament, 2023). It could be argued that this approach for FCS development is feasible in freight corridors with a great charging demand and truck traffic flow, such as the TEN-T network. In other contexts, like rural or remote regions, such an approach may be too expensive and ultimately result in unprofitable infrastructure (Jochem, et al., 2019). Such regions may benefit from a tailored approach to develop FCS infrastructure capable of meeting BET freight transport demands (Fu et al., 2024).

Several studies have developed methodologies for charging network planning to estimate the necessary infrastructure for a given BET flow, covering a wide range of case studies and levels of sophistication. Some of these studies limit their research to estimating the number of charging stations required (Hall & Lutsey, 2019), while others use detailed optimisation models to determine the specific location of the charging stations (Zhang et al., 2019).

Additionally, some studies incorporate queueing models to estimate the number of charging points needed per station (Speth et al., 2022), while others assess the impact of the charging loads on the power grid (Shoman et al., 2023) and overall profitability (Jochem et al., 2019).

Table 1 summarises the literature review carried out in this study, briefly indicating the scope and considerations of the most relevant reviewed studies in charging network planning.

Table 1. Summary of relevant literature and comparison to this study

Research	Scope	Approach	Energy consumption model	Charging optimisation	Charging station location	Charging station sizing
Speth et al. (2022)	Long-haul, national	Demand	No - Average kWh/km assumptions	No - Fixed average charging time	Yes - Mean distance of 100 km	Yes - Queueing model
Whitehead et al. (2021)	Short haul, regional	Hybrid Demand/Coverage	No - Average range assumptions	No - Fixed average charging time	Yes - Exact location out of pre-selected set	None
Jochem et al. (2019)	Passenger vehicles	Hybrid Demand/Coverage	No - Assumed range of 150 km	No - Fixed average charging time	Yes - Exact location	Yes - Queueing model
Hall & Lutsey (2019)	Drayage/ long-haul, regional	NA	No - Average kWh/km assumptions	No	None	None
Shoman et al. (2023)	Long-haul, national	Demand	No - Average kWh/km assumptions	No - Fixed average 30 minute charging time	Yes - Aggregated in 25x25km area	Yes - Queueing model
Li et al. (2023)	Freight fleet, case study	Demand	No - Average kWh/km assumptions	Yes – Yalmip, Gurobi	No – Single centralised station	Yes – Yalmip, Gurobi
This study*	Long haul, regional	Demand	Yes - FASTSim	Yes – Gurobi, non-linear charging	Yes - Exact location	Yes - Queueing model

*This study is the only one to consider adverse climate conditions in the assessment

The scope of analysis varies greatly across the literature. Some studies use entire national BET fleets (Speth et al., 2022) while others focus solely on a specific BET application or region (Whitehead et al., 2021). In terms of data, some studies use a bottom-up approach, using truck fleet activity datasets and analysing each vehicle individually and aggregating the results (Çabukoglu et al., 2018), while others take a top-down approach, using general assumptions for the entire fleet (Shoman et al., 2023).

In terms of locating charging stations, the available literature mainly consists of two approaches: demand-oriented and coverage-oriented (Kchaou-Boujelben, 2021; Speth et al. 2022). Roughly, the demand-oriented approach finds the minimum number of stations required to meet a certain charging demand, estimated based on traffic flows, vehicle range, and mandatory rest periods. This approach tends to favour charging station locations near urban areas, where high traffic flows and stops are more significant, and optimises the number of charging stations in the network. On the other hand, the coverage-oriented approach uses a fixed minimum distance between charging stations (e.g. 100 km), independently of traffic flow

or vehicle charging requirements, but does not provide optimal solutions (Kchaou-Boujelben et al., 2021).

Most studies use a coverage-oriented approach to design charging networks due to the lower data and computational requirements (Shoman et al., 2023). However, this approach might lead to an underutilisation of some charging stations and carry an elevated cost, especially in regions where traffic flow is not that high (Jochem et al., 2019).

Some examples of recent research using coverage-oriented approach include Shoman et al. (2023), who use a trip chain model to evaluate the charging requirements for BETs in long-haul operations in Europe. The study uses traffic flow data, mandatory rest periods, and fixed vehicle energy consumption values to estimate the power demand and number of chargers required in aggregated areas of 25km x 25km along the analysed routes. The results do not include the exact locations of the charging stations. Hall & Lutsey (2019) quantified the infrastructure needs and associated costs for different applications and adoption levels of BETs in the Los Angeles area, including inter-city long-haul operations. The exact FCS locations were not addressed. Hall & Lutsey (2019) results showed that initial FCS infrastructure deployment needs to be carefully planned out for specific BET applications and routes, since the early introduction of BETs (100 vehicles or less) would imply high infrastructure expenditures with low utilisation rates. Speth et al. (2022) apply a coverage-oriented approach to design a BET fast-charging network in Germany, using traffic count data and on-site queueing models to determine the approximate FCS locations and number of plugs per station. The results showed that, for a BET penetration of 15% and 50% public charging, FCS placed every 50 km would require 2-8 plugs per station, while FCS placed every 100 km would require 2-13 plugs.

In contrast, demand-oriented approach requires more sophisticated optimisation models and detailed truck trip datasets to determine the required infrastructure. This approach results in a high utilisation of charging points, although it might enhance range-anxiety if the FCS are set far apart (Shoman et al., 2023). Jochem et al., (2019) uses a demand-driven optimisation model to estimate the minimum number of FCS along the highway network required to meet passenger vehicle trips for a set of European countries, as well as evaluate the FCS profitability. Jochem et al. (2019) conclude that FCS workloads and profitability vary significantly depending on their location, highlighting the relevance of careful selection of FCS locations.

Whitehead et al. (2021) uses short-haul truck trip data to design an optimal public charging network that could support urban BET operations in Southeast Queensland. The results showed that a relatively modest charging network (up to 10 FCS) would be sufficient to cover all charging needs for trucks operating in the analysed area, since most of the charging would be done at depots, although the results did not specify the number of plugs per station. Whitehead et al. (2021) also emphasised the need for access to high-resolution truck trip data to accurately plan regional charging networks.

Li et al. (2023) focuses on a case study fleet in China including light, medium, and heavy-duty vehicles to plan a single centralised charging station. The study proposes a methodology to estimate the charging demand, size of charging stations, and charging schedules using an optimisation model. Li et al. (2023) also addressed the costs linked to potential upgrades in the power grid under different charging strategies.

Although the existing literature covers an extensive range of models and case studies with varying levels of detail, there is a lack of comprehensive FCS network planning methodologies that consider the unique characteristics of remote areas with adverse climate conditions and uneven terrains, which can significantly impact the BET performance (Alonso-Villar et al., 2023). Therefore, the authors believe there is a need for a tailored model that addresses such challenging conditions. This methodology could be of interest to policymakers and fleet operators alike, as the model outcomes could offer insights to guide infrastructure planning and prioritise investments which support freight transport decarbonisation. To

address this gap, this study aims to develop and test a holistic methodology for designing an optimal fast-charging network for remote areas and specific BET applications, considering adverse climate and geographical conditions. This methodology incorporates three main elements: a detailed vehicle energy consumption model; an optimisation model used to determine the ideal FCS locations and charging durations; and a queueing model.

The proposed methodology is tested using Iceland as the case study, which presents an interesting scenario due to its harsh climate conditions, great reliance on road heavy-duty vehicles for freight transport (Iceland has no freight rail system), and lack of charging infrastructure suitable for HDVs. Specifically, the analysis focuses on freight routes from Reykjavik to the Westfjords. The Westfjords present one of the most challenging cases for BETs in Iceland, due to the limited infrastructure (there are only a few gas stations along the main roads), scattered population, limited power grid capacity, and road conditions (with numerous mountain passes). This study uses the proposed methodology to plan an optimal fast-charging infrastructure to support a 100% battery-electric heavy-duty vehicle fleet on the Reykjavik-Westfjords route. First, we pre-selected the potential charging locations along the analysed routes based on existing infrastructure such as gas stations, restaurants, and towns. Then, we simulated BET performance in adverse conditions (low temperature and headwind) to ensure that the charging network is optimised considering worst case scenarios, with a special attention to the BET's performance between the pre-selected charging locations. The BET performance results are then used in an optimisation model to determine the ideal charging spots, charging durations, and average service rate. Lastly, the number of charging plugs required at each identified location is estimated using a queueing model based on arrival rate assumptions. The potential additional time required to cover the routes to fit charging sessions is also estimated.

To the best of the authors' knowledge, this study is the first to use a holistic FCS planning method that includes vehicle energy consumption, charging optimisation, exact FCS locations, and queueing models while considering adverse climate conditions, non-linear charging sessions, and trip segmentation analysis. Our study is unique as it addresses initial charging infrastructure planning for long-haul BETs in remote and mountainous regions, using detailed driving cycle data and trip-segmentation methods to determine the exact optimal charging locations for the analysed trucks, while considering worst-case scenario climate and freight conditions. This analysis also determines the total charging time required to meet a certain route, which can be used to evaluate the potential additional time BETs would take to carry out freight routes. The outcomes of this study can provide useful insights for policy makers and fleet operators into charging network planning and overall freight electrification feasibility, as it addresses relevant aspects such as infrastructure optimal design and routing times. The proposed framework of this study is summarised in Figure 1.

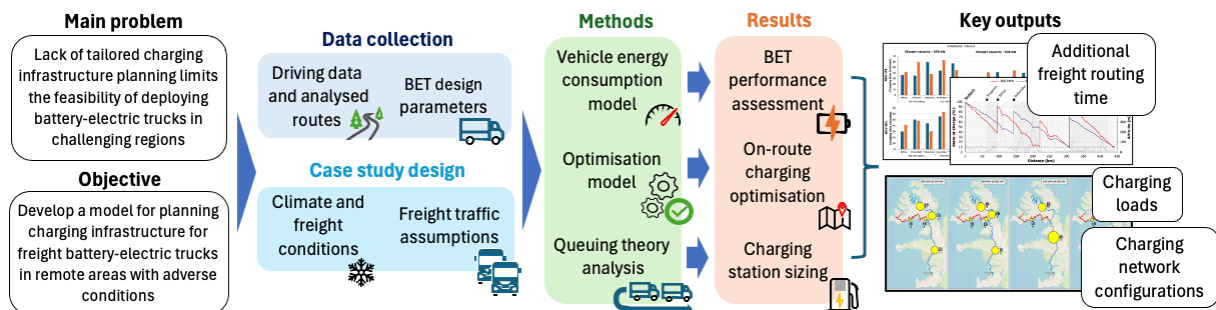


Figure 1. Flowchart describing the proposed framework for charging infrastructure planning and main problem addressed in this study

2. Methods

The methodology used in this analysis to design a charging network for the Reykjavík-Westfjords route can be divided in three main steps, as illustrated in Figure 2. First, the BETs energy consumption and charging demands are determined using a vehicle energy consumption model. This model uses real driving data, BET models design parameters, and climate conditions to estimate the charging requirements needed to meet the route’s power and time demands. The results of this first step are used to optimally locate charging infrastructure along the route and estimate the service rate (BETs served per plug) for each station. Finally, in the last step the calculated service rate is used to determine the size of the station in terms of number of charging points required using queueing theory. The assumptions and methods used across the three main steps are presented in the following sub-sections.

This study uses two battery capacities (360 kWh and 540 kWh) and two charging rates (350 kW and 500 kW) as a built-in sensitivity analysis to assess how these variations impact the optimal design of a charging network. This approach also provides insights into the effects of reduced battery capacity due to ageing, implicitly considering the impacts of range reduction due to battery ageing.

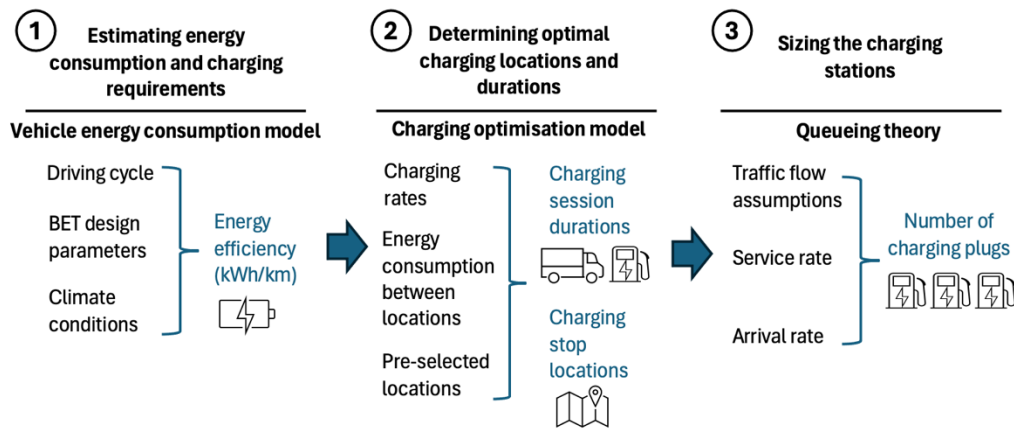


Figure 2. The flowchart illustrates the main steps of the proposed methodology to design an optimal charging network.

2.1. Estimating BET energy consumption and charging requirements

This section introduces the data collection process, the analysed routes, BET design assumptions, and the vehicle energy consumption model used in step one of the methodology illustrated in Figure 2.

2.1.1. Real driving data collection and analysed routes

The driving data was collected using the iOS GPS Tracker app during test drives in a passenger vehicle. The data collected was used to generate one-second resolution time series for vehicle speed, coordinates, and altitude, which are used in the vehicle energy consumption model. Additional data processing was required to remove irregularities in the time series frequency due to loss of GPS signal. To correct this issue, the time series were resampled down to a uniform one-second resolution to guarantee consistency throughout the drive cycles, and the missing values were linearly interpolated.

This study analyses both outbound and return trips to both destinations since the distribution of topographical events (e.g. mountain passes) varies depending on the route

direction, which effects BET energy consumption and charging requirements. Figure 3 shows the speed and road grade for the outbound and return routes from Reykjavík (i.e., RVK) to Ísafjörður (i.e., IFJ) in the north Westfjords, while Figure 4 shows the same information for the route from Reykjavík to Bíldudalur (i.e., BIL) in the south Westfjords. All routes share a considerable section of the drive cycle since these start or finish in Reykjavík and only differ in the Westfjords area. The routes take around 6 hours to complete. Figure 5 shows a map of Iceland with the analysed routes.

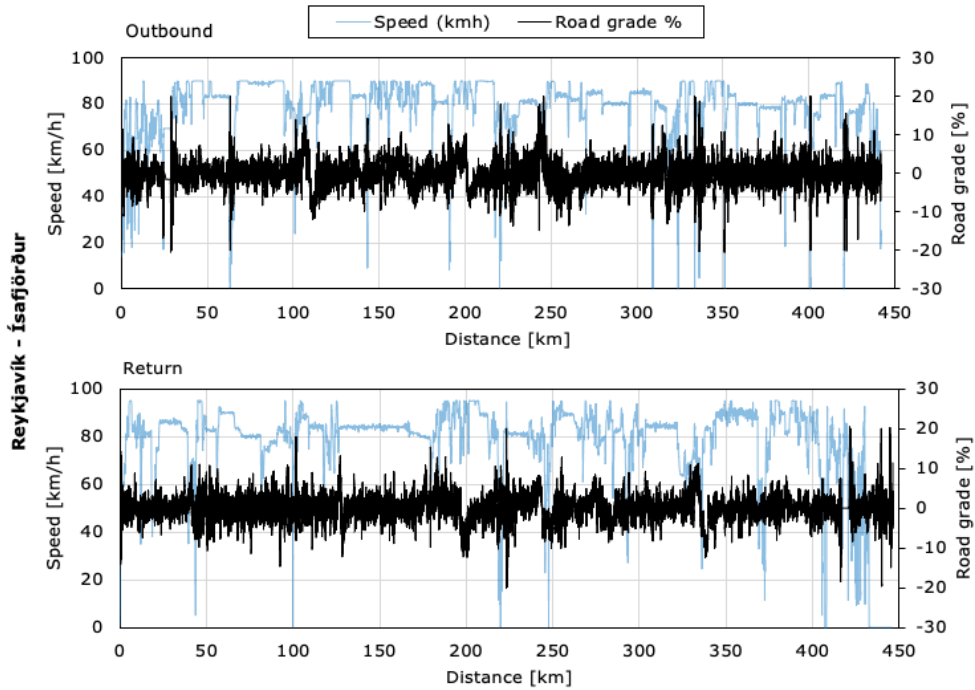


Figure 3. Speed and road grade data for Reykjavík-Ísafjörður outbound and return trips. Trip durations are 6 hours and 1 minute (outbound) and 5 hours 46 minutes (return)

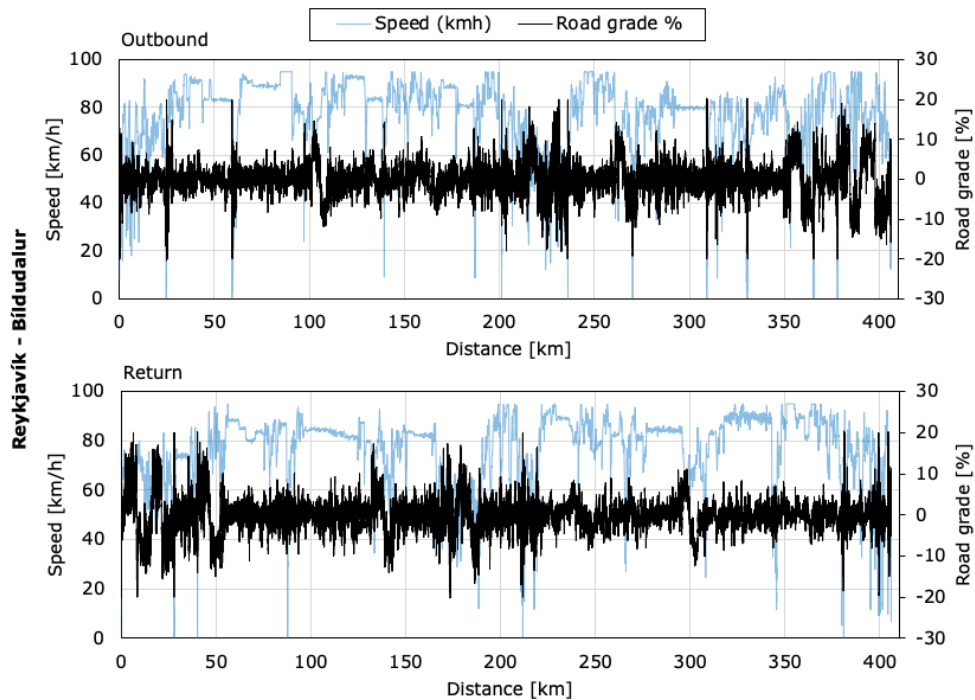


Figure 4. Speed and road grade data for Reykjavík-Bíldudalur outbound and return trips. Trip durations are 5 hours 43 minutes (outbound) and 5 hours 39 minutes (return).

2.1.2. BET design parameters and climate conditions assumptions

The selected BET is a tractor truck (i.e. semi-trailer), as this truck configuration is widely used for long-haul road freight applications. The BET design parameters are based on Volvo’s FH Electric model (Volvo Trucks, 2024), although several parameters are adjusted to account for the cold conditions in Iceland. Two battery pack size configurations are considered based on Volvo’s battery pack options, a low-entry version with 350 kWh (i.e., BET@350) and a maximum-spec version with 540 kWh (i.e., BET@540). The climate conditions considered in this analysis are representative of Iceland (Weather Sparks, 2023), including low temperatures (-7 °C) and strong headwinds (40 km/h during 50% of the route). These have an impact on the auxiliary loads linked to the Battery Thermal Management System (BTMS) (Basma et al., 2021), the wheels coefficient of friction (Ejsmont et al., 2018), and the aerodynamic drag force (Volvo Trucks, 2022). Table 2 presents the BET design parameters considered in this study, adjusted to the assumed climate conditions (Alonso-Villar et al., 2023).

Table 2. BET design parameters used based on Volvo FH Electric model (Volvo Trucks, 2024a; Volvo Trucks, 2024b)

Category	Parameter	Tractor truck
Vehicle	Drag coefficient ^a	0.5
	Frontal area (m ²)	8.5
	Centre of gravity	0.54
	Weight fraction on drive axle	0.59
	Wheelbase (m)	3.90
Powertrain ^b	Efficiency ^c	0.95
	Charging power (kW) ^d	350/500
	Power (kW)	490
	Battery capacity (kWh)	360/540
	Auxiliary loads BTMS (kW) ^e	3.03 / 5.77
	Usable battery capacity (%) ^f	95
	Energy density (Wh/kg) ^c	130
Wheels	Wheel inertia (kg/m ²) ^g	0.815
	Number of wheels	10
	Radius (m)	0.522
	Coefficient of friction ^h	0.006
Weight	Permissible gross weight (kg)	44,000

^a Volvo Trucks (2022). Air density is assumed to be 1.31 km/m³ at -7 °C

^b Volvo Trucks (2024b)

^c Brooker et al. (2015)

^d ChargedEVs (2024). The analysis considers 500 kW charging capacity, despite Volvo FH Electric’s current maximum is 350 kW

^e Basma et al. (2021)

^f Mercedes-Benz Trucks (2024)

^g Own estimates assuming -7 °C ambient temperature

^h Own estimates based on Ejsmont et al., (2018). This study assumes a fixed average friction value over the entire route, adjusted to reflect low-temperature conditions, as detailed in Alonso-Villar et al. (2023)

2.1.3. Vehicle energy consumption model and charging assumptions

This study uses FASTSim (Future Automotive Systems Technology Simulator) vehicle consumption model to estimate the BET performance. FASTSim, developed by NREL (Brooker et al., 2015), serves as a comprehensive modelling and simulation platform designed for analysing the performance and energy consumption of various vehicle types, including conventional, hybrid, and electric vehicles. FASTSim integrates a range of adjustable vehicle parameters, such as vehicle dynamics and powertrain characteristics, to accurately predict fuel consumption under different driving conditions. The following equations summarise FASTSim's methodology to calculate the vehicle energy consumption. Equation (1) is used to calculate the battery power output (Ehsani et al., 2004):

$$P_{out} = \frac{v(t)}{\eta_t \eta_m} \left(m_v g (f_r + \theta) + \frac{1}{2} \rho_{air} C_d A_f v(t)^2 + m_v \frac{dv}{dt} \right) + P_{aux} \quad (1)$$

where $v(t)$ is the vehicle speed (m/s); η_t is the transmission efficiency; η_m represents the electric motor efficiency; m_v is the vehicle mass (kg); g is the gravitational acceleration (9.81 m/s²); f_r gives the rolling resistance coefficient; θ is the road grade; C_d is the aerodynamic drag coefficient of the vehicle; ρ_{air} represents the air mass density at a given temperature; A_f is the vehicle's frontal area; and P_{aux} is the power linked to auxiliary loads. Electricity is also recovered through the vehicle's regenerative system (Rivelino et al., 2018), which can be expressed as Equation (2) (Xiao et al., 2016):

$$P_{regen} = \frac{\alpha v(t)}{\eta_t \eta_m} \left(m_v g (f_r + \theta) + \frac{1}{2} \rho_{air} C_d A_f v(t)^2 + m_v \frac{dv}{dt} \right) + P_{aux} \quad (2)$$

where α represents the regenerative braking factor. Equation (3) gives the net energy consumption of an electric powertrain (Ehsani et al., 2004):

$$E_{net} = \int_0^t P_{out} dt + \int_0^t P_{regen} dt \quad (3)$$

The net energy consumption is used to calculate the battery state-of-charge (SOC) at any time instance of the drive cycle, using Equation (4) (Tanvir et al., 2020):

$$SOC(t) = SOC(t-1) - \frac{E_{net}(t)}{E_{bat}} \quad (4)$$

Where $SOC(t)$ is the battery SOC at a given time instance; $E_{net}(t)$ is the net energy consumption; and E_{bat} is the battery energy capacity (kWh).

The model was calibrated using EPA's HDDT and HWFET driving cycles (EPA, 2024), and the specifications from the official Volvo FH Electric 540 kWh range test (Volvo, 2022b). The calibration process details can be found in our previous work Alonso-Villar et. al. (2023).

2.2. Determining optimal charging locations and charging durations

This section presents the methodology and assumptions used to determine the optimal positioning of charging stations used in step two of the methodology illustrated in Figure 2.

2.2.1. Charging network design assumptions

As mentioned in the introduction, this study uses a demand-oriented approach due to the remoteness and low traffic flow of the studied area, especially in the Westfjords region. The goal of carrying out a demand-oriented analysis is to determine the minimum number of on-route fast-charging stations required to meet the freight demands, aiming to reduce costs and increase infrastructure utilisation rate (Hall & Lutsey, 2019). However, this approach can lead to drivers experiencing range anxiety if charging events are set to be far apart. In addition, it is rather frequent that truck drivers get stuck in the snow during the winter months due to difficult driving conditions in Iceland, leaving the driver to wait a considerable amount of time to be rescued with cabin heating playing a key role in the drivers' comfort. To reduce range anxiety and guarantee the comfort of the drivers in terms of ensuring that the battery always has enough power left to support cabin heating, this study implements the two following measures: First, the BET energy consumption is calculated assuming a combination of worst-case scenario climate and freight conditions, including low temperatures, strong headwind, and full payload across the entire route. Second, a safety net of 10% SOC is implemented throughout the analysis, implying that BETs are not allowed to have less than 10% SOC at any point of the route. All in all, these measures ensure that BETs will be capable of meeting the route even in the most adverse conditions, while reducing range anxiety and guaranteeing the driver's comfort.

The geographical distribution of the potential charging station locations is based on the current existing infrastructure shown in Figure 5, consisting of gas stations and towns. This approach takes on the assumption that placing charging stations in locations with already existing infrastructure (e.g, grid connections) would be desirable to avoid additional construction costs. Moreover, the identified locations along the route are assumed to be used for current freight drivers to take their rest times and refuel, which implies that drivers could stick to their usual rest/refuel locations. Therefore, this study identifies every point of interest shown in Figure 5 as a potential charging location, independently of other factors relevant to charging infrastructure such as capacity of distribution lines, transformers, and others, which will be addressed in further studies. This study assumes that there will be slow-chargers available on the origin-destination points, which will charge the BETs up to 100% SOC overnight. The slow-chargers are not included in the scope, since the analysis focuses on the required FCS on-route.

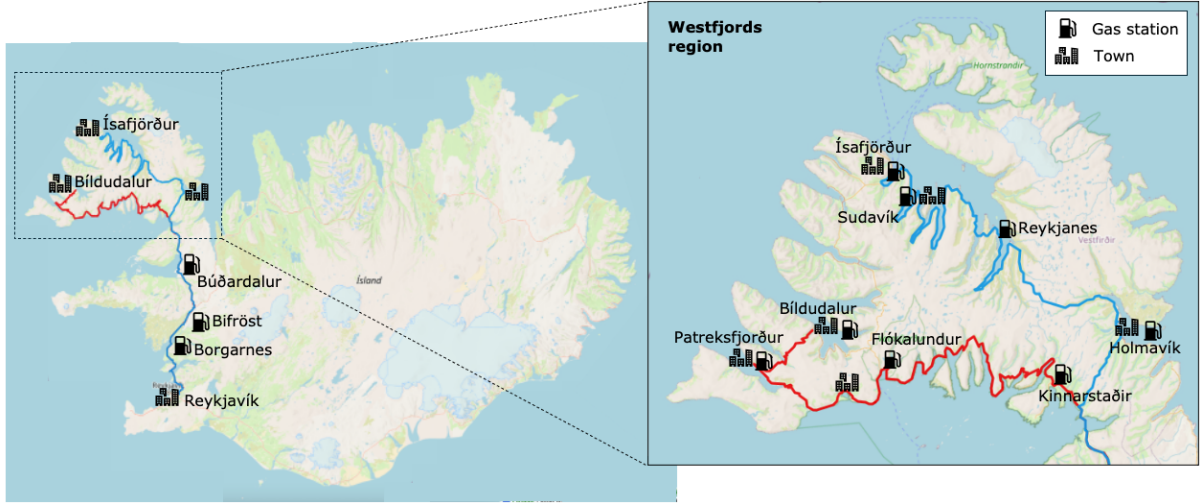


Figure 5. Analysed routes and relevant infrastructure. The red line indicates the section of the route to and from Bíldudalur (South way), while the blue line indicates the route to and from Ísafjörður (North way)

2.2.2. Charging optimisation model

This study proposes an optimisation model to determine the number of stops, the exact location, and the duration of charging sessions. The results are also used to determine the service rate of the chargers, in terms of how many trucks can be served per hour per individual charger.

The model assumes a piecewise linear approximation of the non-linear charging curve, similar to the one shown in Figure 6 which sections represent the average charging rate during different SOC periods. This study uses Gurobi as the optimisation software (Gurobi Optimization, 2023). The parameters presented in Figure 6 are described in the following paragraphs.

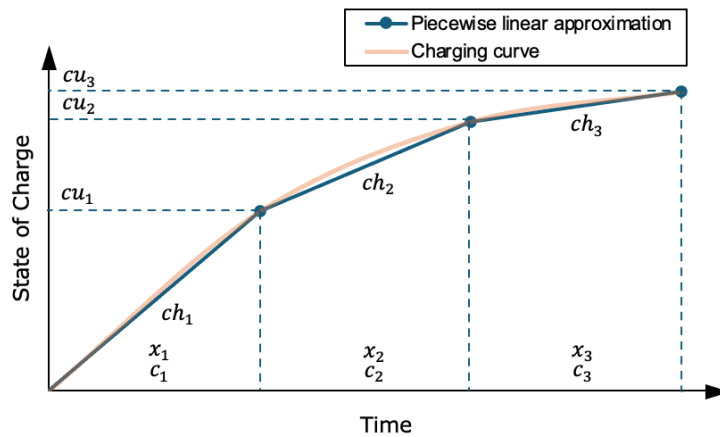


Figure 6. Piecewise linear approximation for the non-linear charging curve. Here the non-linear curve is approximated with three linear sections.

The objective function used in the optimisation model aims at minimising the time the BET spends stopped, and hence the overall on-route duration, which is represented by Equation (5).

$$MIN Z = \sum_{i \in I} \sum_{j \in J} (f * Y_i + X_{ij}) \quad (5)$$

where $MIN Z$ represents the aim of the objective function to minimise the total time spent charging; i represents the charging location from the considered set I ; j is the number of breakpoints/segments from set J used for the piecewise linear approximation; f is the fixed time needed to start and finish each charging stop (minutes); Y_i is a binary variable used to determine whether charging occurs at location i . When $Y_i = 1$, the BET charges, otherwise, it does not; and $X_{i,j}$ is a continuous variable which represents the charging time (minutes) at charging location i in segment j of the linearly approximated charging curve.

The optimisation model includes several constraints linked to the charging process, battery management, driving range and overall operational feasibility, which make sure the results are feasible and effective in optimising the charging stops. Equation (6) defines the constraint used to activate the binary variable Y_i if the model decides to charge at location i .

$$X_{i,j} \leq Y_i * M \quad \forall i \in I, j \in J \quad (6)$$

where $X_{i,j}$ represents the charging time at location i within segment j ; and M indicates the maximum allowed time for a charging stop (set at 240 minutes).

Equation (7) represents the minimum allowed state of charge constraint;

$$SOC_i \geq minc \quad \forall i \in I \quad (7)$$

where SOC_i indicates the state of charge when arriving at charging location i ; and $minc$ represents the minimum allowed SOC (kWh), which is here set to 10% of battery capacity. This constraint ensures that SOC_i is always greater than or equal to $minc$ at all locations i .

The SOC for the initial location and the subsequent locations are calculated using Equations (8) and (9). For the first charging location $i = 1$, SOC_1 is calculated based on the initial state-of-charge, SOC_0 , minus the energy consumed by driving to the first location, use_1 .

$$SOC_1 = SOC_0 - use_1 \quad (8)$$

The SOC for the subsequent locations, $i > 1$, is calculated using Equation (9);

$$SOC_i = SOC_{i-1} + \sum_j (ch_{i-1,j} * X_{i-1,j}) - use_i \quad \forall i > 1 \quad (9)$$

where SOC_{i-1} indicates the state of charge in the previous location (kWh); $ch_{i,j}$ is the number of kW added to the battery per minute of charging at location i within segment j of the piecewise approximation curve (i.e. the slope of the section); and use_i represents the reduction in SOC when driving from $i - 1$ to i , or the energy consumption (kWh). For subsequent locations $i > 1$, the SOC_i is updated based on the previous SOC, the charge added in the previous location, and the energy consumption at the current location.

This study takes two charging sections, 0-90% and 90-100%, assuming BETs can accept maximum charging power up to 90% SOC and then slowing down to accept half power after that.

The maximum charging within each segment of the piecewise approximation is defined by equations 10-12. Equation (10) ensures that only one charging segment is active at each location i ;

$$\sum_j C_{i,j} = 1 \quad \forall i \quad (10)$$

where $C_{i,j}$ is a binary variable equal to 1 if the initial SOC is within segment j when arriving at location i , or else it will be equal to 0. Equation (11) ensures that the charge added at each location within each segment does not exceed the maximum charging rate;

$$ch_{i,j} \cdot X_{i,j} \leq charg_{i,j} \cdot \sum_{k=1}^j C_{i,k} \quad \forall i, j \quad (11)$$

where $charg_{i,j}$ is the maximum allowable charging rate at location i within segment j . Equation (12) further ensures that the charging process respects the maximum allowable SOC for each segment;

$$SOC_i + ch_{i,j} \cdot X_{i,j} \leq cu_{i,j} + (1 - C_{i,j}) * M \quad \forall i, j \quad (12)$$

where $cu_{i,j}$ describes the maximum SOC of segment j at location i ; and M serves as an upper bound to deactivate the constraint if the state of charge is not within the segment j when arriving at location i . The added charge at each location within each segment cannot exceed the maximum charging rate multiplied by the activated segments.

Equations 13 and 14 represent the upper and lower bound constraints for the SOC based on the activated segments. Equation (13) ensures that SOC_i does not exceed the energy accumulated from the activated segments, while Equation (14) ensures that SOC_i is greater than or equal to the energy accumulated from the activated segments up to the previous segment.

$$SOC_i \leq \sum_j C_{i,j} * cu_{i,j} \quad \forall i \quad (13)$$

$$SOC_i \geq \sum_j C_{i,j} * cu_{i,j-1} \quad \forall i, j > 1 \quad (14)$$

Lastly, Equation (15) represents the constraint to calculate the total charging variable for each location;

$$XT_i = \sum_j X_{ij} * ch_{i,j} \quad \forall i \quad (15)$$

where T_i describes the total charge added at each location, which is the sum of charging time X_{ij} multiplied by the charging rate $ch_{i,j}$ for all segments j .

These constraints ensure that the charging process respects the defined limitations for battery capacity, charging rates, and energy consumption, while minimising the total charging time. No constraints for minimum number of breaks or resting times were added since the range of the vehicles already ensured compliance in that regard.

The charging duration results from the optimisation model are used to calculate the service rate of the individual chargers, or the number of BETs that can be served per hour per charging plug, based on the estimated charging demands for each location i .

An example of the optimisation model code can be found in the appendix.

2.3. Scaling the charging stations with queueing theory

This study uses queueing theory to determine the optimal number of charging plugs for each station, based on the approach by Shooman et al. (2023). Queueing theory is a mathematical model which determines the required number of counters in a system to meet a specific customer average waiting time for a certain service rate and arrival rate (Septh et al., 2022). A queueing system is characterised by the arrival rate of customers, the service times, the service discipline, service capacity, and the waiting room, among other factors (Adan and Resing, 2015). In terms of a BET charging station, the arrival rate is described by the temporary distribution of the arrival of BETs (the customers) to the charging station. The service time is defined by the time customers spend at the charging station (charging + waiting), which is determined by the number of counters (plugs) and the average number of BETs queueing up. The service discipline refers to the service guidelines followed when customers arrive, such as first come first served, priority groups, or random order. Lastly, the service capacity and waiting room refer to the limitations with regards to the number of servers (plugs) or customers (BETs) in the system (Adan and Resing, 2015).

In this study, the arrival rate, or the number of BETs that come to a charging station per hour, is calculated combining the outcomes from the optimisation model, which determines the number of stops and the location where these take place, with the daily average traffic flow values from the Icelandic Road and Coastal Administration (Vegagerðin, 2024). Based on the administration estimates, this study assumes that the proportion of heavy-duty vehicles is 10% on the Ring Road and 20% on other highways and rural areas. As traffic increases, the proportion of heavy-duty vehicles decreases. This study assumes that 100% of HDV traffic on the analysed routes consists of battery-electric trucks. The service rate per charger, or the number of BETs that a charger can serve per hour, is also determined using the charging duration results from the optimisation model.

Queueing theory has already been used in the literature to scale charging stations for BETs (Speth et al., 2022). This study uses a multiple-channel queueing model with Poisson arrivals and exponential service times (Anderson et al., 2014). A multiple-channel system includes two or more different service channels (plugs) which have the same service capacity. In this approach, BETs arriving to the charging station wait in a single queue and then move to the first available plug to charge. Figure 7 illustrates the multiple-channel queueing system.

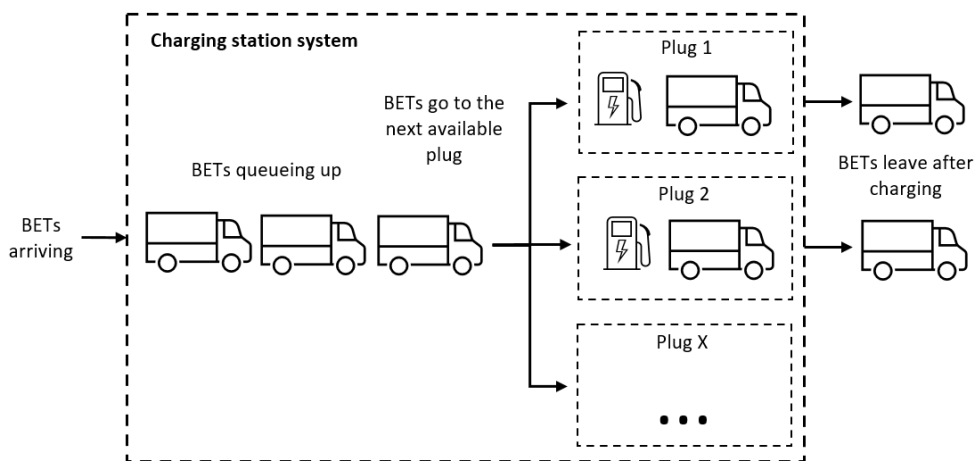


Figure 7. Multiple-channel queueing system (Anderson et al., 2014)

This study uses the Kendall notation for queueing models (Adan and Resing, 2015), where γ is the mean arrival rate of BETs at the charging station, μ is the mean service rate for each charger, and k is the number of chargers available at the station. The calculations are

carried out using the following equations. Equation (16) gives the probability that no trucks are in the charging station:

$$P_o = \frac{1}{\sum_{n=0}^{k-1} \frac{(\gamma/\mu)^n}{n!} + \frac{(\gamma/\mu)^k}{k!} \left(\frac{k\mu}{k\mu - \gamma}\right)} \quad (16)$$

Equation (17) gives the number of BETs in the waiting line:

$$L_q = \frac{(\gamma/\mu)^k \gamma \mu}{(k-1)! (k\mu - \gamma)^2} P_o \quad (17)$$

Equation (18) gives the average time BETs spend at the waiting line:

$$W_q = \frac{L_q}{\gamma} \quad (18)$$

And Equation (19) gives the average time BETs spend in the charging station, waiting in line and charging:

$$W = W_q + \frac{1}{\gamma} \quad (19)$$

The previous equations serve as a simplified approximation of the behaviour of BETs at charging stations, and these are applicable under the following assumptions (Anderson et al., 2014):

- BETs arriving to the charging station follow a Poisson probability distribution.
- The mean service rate is equal for each charging plug. However, this changes depending on the capacity of the charger and the BET battery capacity.
- BETs arriving wait in a single queue and move to the first available charging plug to charge.

3. Results

3.1. BET energy performance assessment

This section introduces the results from the vehicle energy consumption model introduced in Section 2.1.3, belonging to the first step of the overall methodology presented in Figure 2. Table 3 presents a summary of the energy performance results for both 360-kWh and 540-kWh vehicle models, including total energy consumption, recovered regenerative braking energy, fuel economy, and estimated range for each route. The results show that the modelled BETs consume around 1,276-1,295 kWh to cover the analysed routes, with energy consumption varying slightly from the outbound and return journeys for every route due to small variations in the recorded drive cycles.

The results also suggest a similar fuel economy for both truck models, averaging 2.23-2.35 kWh/km, which translates into an estimated average range of roughly 156-162 km for the 360-kWh model and 231-238 km for the 540 kWh during the adverse winter conditions. These results confirm the need to charge on-route, as the trucks need to cover over 400km to meet each route.

A detailed assessment, including a sensitivity analysis of how adverse climate and freight conditions impact BET performance, can be found in Alonso-Villar et al. (2023).

Table 3. Average results for BET energy performance throughout the analysed routes, including outbound and return.

Vehicle	Route	Total energy consumption (kWh)	Total regenerated energy (kWh)	Fuel economy (kWh/km)	Estimated range (km)
360 kWh	RVK-IFJ	1,276	284	2.23	162
	RVK-BIL	1,285	349	2.31	156
540 kWh	RVK-IFJ	1,287	280	2.27	238
	RVK-BIL	1,295	343	2.35	231

The energy consumed to cover each of the route segments is shown in Figure 8. The energy demands vary considerably across the route segments, as the charging opportunities that delimit the segments are unevenly distributed. This results in segments which account for more than twice the energy requirements compared to other segments, significantly impacting charging planification. The most demanding segments are Hólmavík-Reykjanes, Reykjanes-Sudavík, and Kinnarstaðir-Flókalundur, which are all situated in the Westfjords peninsula.

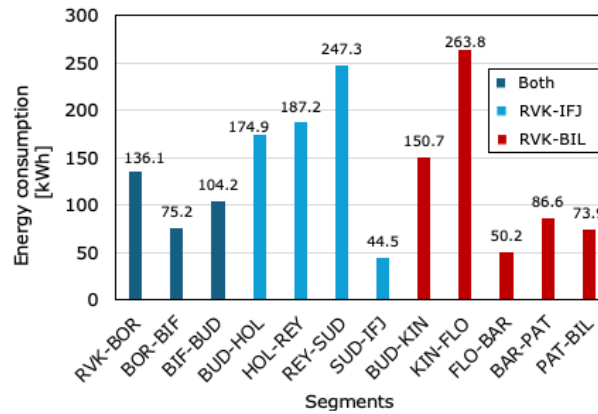


Figure 8. Approximate distribution of energy consumption for the analysed routes

3.2. On-route charging optimisation

The performance results from the previous section were used in the optimisation model to determine the optimal charging sessions throughout the analysed routes. The results presented in this chapter include the number of stops required to meet the route, the location where the stops take place, the ideal charging duration for each stop, and the energy added to the battery.

Figure 9 illustrates the SOC for both truck models traveling the RVK-IFJ route, both outbound and return trips, along with the altitude variation and the SOC allowed. Figure 9 shows that the 360-kWh BET would require three charging sessions to cover the route, including stops at Bifröst, Hólmavík, and Reykjanes, while the 540-kWh model would be capable of covering the route stopping only twice in Búðardalur and Reykjanes. The results from the optimisation model also show that the ideal charging locations are the same for outbound and return trips for both vehicles.

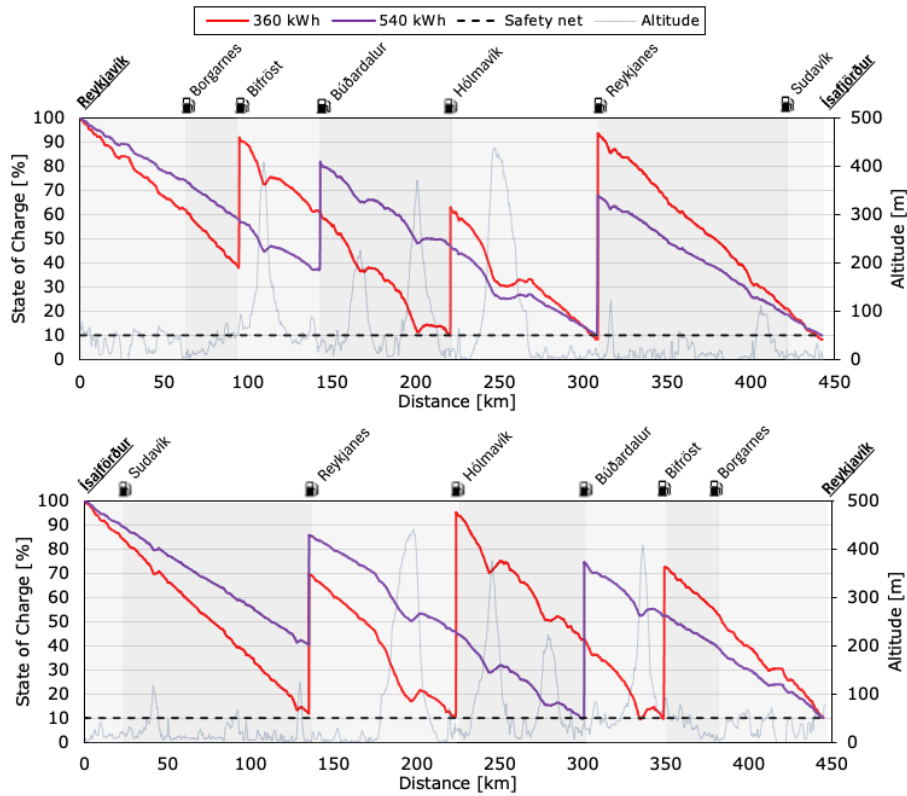


Figure 9. SOC over the Reykjavík to Ísafjörður route, outbound (above) and return (below) trips

Although the charging stops are the same for both outbound and return trips, the required charge added at each location varies significantly. The optimal added charge results are shown in Table 4, which indicate that the overall charging demands for the small and big battery trucks can range from around 184.3-291.83 kWh and 229.15-331.29 kWh, respectively. Reykjanes accounts for the highest charging demand for both vehicles.

Table 4. Charge added per each location and truck model, Reykjavík-Ísafjörður route

Vehicle	Location	Charge added (kWh), outbound	Charge added (kWh), return
360 kWh	Bifröst	184.3	213.86
	Hólmavík	181.17	291.19
	Reykjanes	291.83	198.79
540 kWh	Búðardalur	229.15	331.29
	Reykjanes	296.85	234.57

The SOC for the RVK-BIL route is shown in Figure 10. Similarly to the RVK-IFJ route, the optimal charging stops are carried out in the same locations for both outbound and return trips for both truck models. The 360-kWh truck stops at Bifröst, Kinnarstaðir, and Flókalundur, while the 540-kWh model stops at Búðardalur and Flókalundur.

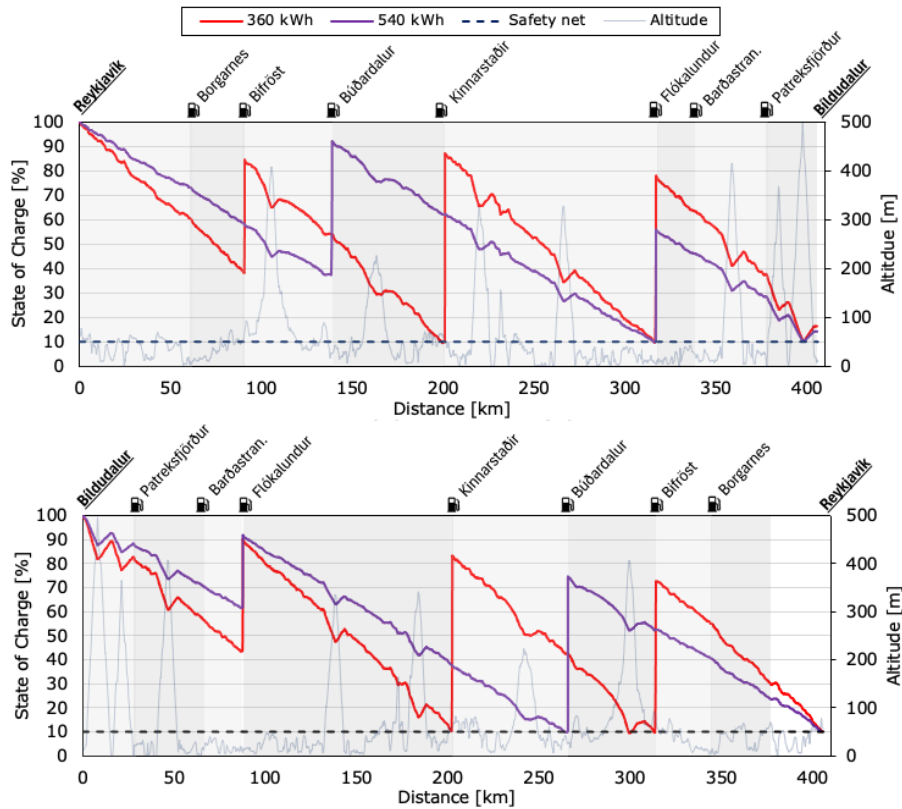


Figure 10. SOC for the Reykjavík to Bíldudalur route, outbound (above) and return (below) trips

Table 5 shows the charge added at each stop for both vehicles, with Kinnarstaðir accounting for the highest charging demand for the 360-kWh truck with 263.77 kWh, while Búðardalur stands out as the stop with the highest charge added for the 540-kWh truck with 331.52 kWh.

Table 5. Charge added per each location and truck model, Reykjavík Bíldudalur route

Vehicle	Location	Charge added (kWh), outbound	Charge added (kWh), return
360 kWh	Bifröst	158.45	214.26
	Kinnarstaðir	263.77	250.85
	Flókalundur	232.64	158.59
540 kWh	Búðardalur	280.54	331.52
	Flókalundur	235.83	153.89

Figure 11 presents the optimal time duration for each charging session, truck model, and route. Since charging times are affected by the power capacity of the chargers, the results are shown for both charging capacities considered in the study, 350 kW and 500 kW. The optimisation model results show that charging sessions take around 30 to 63 minutes when charging at 350 kW, while charging durations decrease to 21 to 44 minutes at 500 kW.

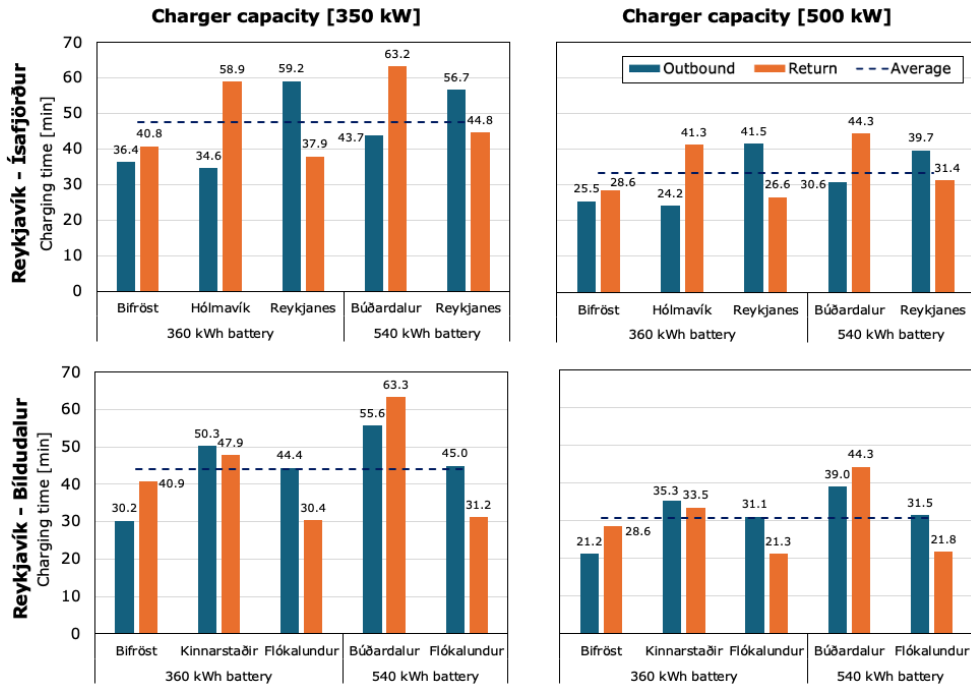


Figure 11. Charging time at each stop and trip (outbound and return) for both 360 kWh and 540 kWh trucks, RVK-IFJ (above) and RVK-BIL (below)

Table 6 shows the total charging time required to meet the routes for both truck models and charger capacities. As an example of the results, the charging time needed for the smaller battery vehicles using the slower charger is 60 minutes (85%) longer than the charging time needed for the vehicle with the larger battery using the faster chargers.

Table 6. Total time spent charging per route, battery capacity, and charger capacity (minutes)

Route	360 kWh @ 350kW	360 kWh @ 500kW	540 kWh @ 350 kW	540 kWh @ 500 kW
RVK-IFJ	130.2	91.2	100.2	70.2
IFJ-RVK	137.4	96.6	108.0	75.6
RVK-BIL	125.0	87.5	100.6	70.5
BIL-RVK	119.4	83.4	94.2	66.0

3.3. Sizing the charging stations

The results from the previous sections are used in this chapter to determine the optimal size of the charging stations in terms of number of plugs, which is the final step of the three-step methodology presented in Figure 2. The service rate for each charging station is determined using the average charging times calculated in Section 3.2, while the arrival rate is estimated based on truck traffic flow assumptions from Section 2.3. The arrival rate is determined assuming a 6-hour peak demand window. Table 7 shows the assumptions for arrival and service rate used in this section. Since the BET's battery capacity and charging rates influence the arrival and service rate, these have been adjusted accordingly.

Table 7. Arrival and service rate used per location, battery capacity, and charger capacity

Location	Traffic (trucks/ day)	Arrival rate (trucks/hour)		Service rate (trucks/hour)			
		360 kWh	540 kWh	360 kWh @350 kW	360 kWh @500 kW	540 kWh @350 kW	540 kWh @500 kW
Bifröst	90	15	-	1.62	2.31	-	-
Búðardalur	90	-	15	-	-	1.06	1.52
Hólmavík	70	11.67	-	1.28	1.83	-	-
Reykjanes	70	11.67	11.6 7	1.24	1.76	1.18	1.69
Kinnarstaðir	20	3.33	-	1.22	1.74	-	-
Flókalundur	20	3.33	3.33	1.70	2.43	1.67	2.38

The queueing theory method introduced in Section 2.3 is used to determine the optimal number of charging plugs needed per station to meet the arrival rate described in Table 7, assuming a fixed average service rate per each station. The waiting time is limited to 10 minutes maximum. Table 8 summarises the results for the queueing model, indicating the number of plugs required per location, the added total capacity, the capacity factor or frequency of use, the average number of trucks waiting in line, and the average time spent in line. The results are shown for both truck models and charging capacities considered.

Table 8. Charging station sizing results per location, battery capacity, and charger capacity

Vehicle	Charger capacity	Location	Number of plugs	Station capacity (MW)	Plug capacity factor	Average number of trucks in line	Average time spent in line (minutes)
360 kWh	350 kW	Bifröst	11	3.85	0.99	2.44	9.77
		Hólmavík	12	4.2	0.99	0.82	4.22
		Reykjanes	12	4.2	0.99	1.16	6.01
		Kinnarstaðir	5	1.75	0.94	0.19	3.49
		Flókalundur	4	1.4	0.87	0.14	2.62
	500 kW	Bifröst	8	4	0.99	1.91	7.63
		Hólmavík	8	4	0.99	1.61	8.26
		Reykjanes	9	4.5	0.99	0.78	3.99
		Kinnarstaðir	4	2	0.86	0.13	2.33
		Flókalundur	3	1.5	0.78	0.15	2.66
540 kWh	350 kW	Búðardalur	17	5.95	0.99	1.32	5.31
		Reykjanes	12	4.2	0.99	1.8	9.26
		Flókalundur	4	1.4	0.83	0.16	2.89
	500 kW	Búðardalur	12	6	0.99	1.85	7.43
		Reykjanes	9	4.5	0.99	1.1	5.70
		Flókalundur	3	1.5	0.78	0.16	0.16

Assuming an entire 360 kWh BET fleet, the busiest charging stations in terms of traffic flow are Bifröst, Hólmavík, and Reykjanes, needing 11-12 350 kW charging plugs per station. Considering that each charger has a maximum of 350 kW capacity output, the charging stations would add up to a total capacity of 3.85-4.2 MW. These stations also account for the highest capacity factor or utilisation rate, with at least one truck charging nearly continuously during peak hours. Bifröst would be the busiest charging station, with an average of 2.44 trucks waiting in line and an average waiting time of 9.77 minutes. Flókalundur and Kinnarstaðir would require 4 and 5 plugs respectively to meet the arrival rate under a 10-minute waiting line restriction. Flókalundur would be the least busy station, with an average of 0.14 trucks in line and an average waiting time of 2.62 minutes.

Increasing the capacity of the chargers to 500 kW would reduce the required number of plugs for all stations, although these would not necessarily reduce the average time spent waiting in line. Also, the capacity factor of the charging plugs would decrease due to a lower utilisation rate. Switching to 500 kW chargers would increase the overall stations installed capacity, consequently increasing the overall load derived from peak charging periods. The fewer stops from the 540-kWh BET translate into a significantly concentrated demand in Búðardalur, specially with the 350 kW charger network, adding up to 17 charging plugs in a single station. For the same location, the number of plugs required would decrease to 12 if 500 kW chargers were used. The scenario with 540 kWh BETs and 500 kW chargers also translate into the highest capacity installed for charging stations.

4. Discussion

4.1. Actual impact of charging sessions on the routing time

The results from Section 3.2 indicate that the analysed BETs would need to stop several times to meet the addressed routes, independently of the charging capacity considered. This necessity could potentially translate into an increase in total route time, which could vary from 66 to 130 minutes depending on the battery capacity and the charging rate available. However, truck drivers must comply with mandatory rest regulations, in which charging sessions can be fitted in. In Iceland such regulations consist of a 45-minute break for every 4 hours of driving (European Commission, 2024b), which provide an opportunity to integrate charging sessions and potentially reduce the impact on overall route times. Table 9 shows how the required charging times for each route and battery capacity/charging rate scenario would fit considering the mandatory 45-minute break.

Table 9. Additional route time required (charging time minus 45-minute mandatory rest) by battery capacity considered (kWh) and fixed charging capacity (kW).

Route	Additional route time (minutes)			
	360@350	360@500	540@350	540@500
RVK-IFJ	85.1	46.1	55.4	25.3
IFJ-RVK	92.7	51.4	63.0	30.7
RVK-BIL	80.0	42.5	55.6	25.5
BIL-RVK	74.1	38.5	49.4	21.2
Average additional routing time	83.0	44.6	55.9	25.7

Overall, the results indicate that BETs would require additional time to complete the routes in adverse climate and freight conditions, and that the total additional time is strongly linked to the charging rates and the BET battery capacity considered. Not surprisingly, the best results are achieved by 540@500 with an average total added time of 25 minutes, which makes it the most attractive for fleet operators in terms of route time. On the other hand, the 360@350 scenario seems unlikely to be accepted by fleet operators as these would need to add more than one hour to their routing times (Qasim et al., 2021).

These insights can be used by fleet operators to optimise their operations and decide which battery capacity would better fit their activity, based on the charging rates available and mandatory rest periods, as well as their willingness to accept some additional time due to charging sessions.

4.2. Overview of FCS network proposed configurations

The results from the analysis indicate that the FCS optimal location varies depending on the battery capacity assumed in the analysis, independently of the charging rate assumed. The different charging network configurations proposed are shown in Figure 12.

4.2.1. Locations and distance between FCS

For BET@360, the optimal FCS locations for the Reykavík-Westfjords route are five (Bifröst, Hólmavík, Reykjanes, Kinnarstaðir, and Flókalundur), while BET@540 would need only three FCS (Búðardalur, Reykjanes, and Flókalundur). For the BET@360 FCS configuration, the stations are placed closer together averaging 109 km between FCS, with a maximum distance of 136 km between Ísafjörður and Reykjanes. The average distance between FCSs for the BET@540 FCS configuration is 156 km, with the largest distance between FCS being significantly higher, at around 172 km between Búðardalur and Flókalundur. Although the locations proposed have been optimised to minimise the time the truck spends stopped, based on the battery capacity (and range) of the analysed BETs under demanding conditions, the large distances between stations could pose some challenges in the occurrence of unexpected events which impact the performance of BETs. Slower emergency chargers could be placed between FCS which are farther apart to ensure trucks could still charge in case of sudden drop in BET performance or malfunction.

4.2.2. Number of charging points per station and charging loads

The number of charging points per each station was determined based on the service and arrival rate assumptions from Table 7. The analysis considered peak usage to minimise waiting times. The derived charging load was calculated based on the charger capacity and the number of charging points per location.

As shown in Figure 12, the results from the optimisation model tend to minimise the number of stops and accumulate charging points at a few selected locations, since that is the fastest way to cover the route and minimise waiting times.

The distribution of the charging load is strongly linked to the battery capacity of the trucks. Figure 12 shows that the largest loads occur in the 540 kWh BET scenarios, where peak demands could reach up to 6 MW in Búðardalur, while BET@360 scenarios reach a maximum of 4.2 MW in Reykjanes and Hólmavík. In all scenarios, the north route in the Westfjords peninsula accounts for significantly larger loads compared to the south route, which is mainly due to the larger traffic flow assumptions in the route to Ísafjörður, as well as the estimated charging requirements.

For the same charging capacity, FCSs optimised for BET@540 tend to have more charging points compared to BET@360, as BET@540 requires less FCS and the number of charging points per station increases to reduce the risk of bottlenecks. Therefore, using BETs with bigger battery capacity in an optimised FCS network could lead to busier charging stations.

These results can be useful for locating charging loads and evaluating the infrastructure needs in terms of charging points and potential power grid upgrades.

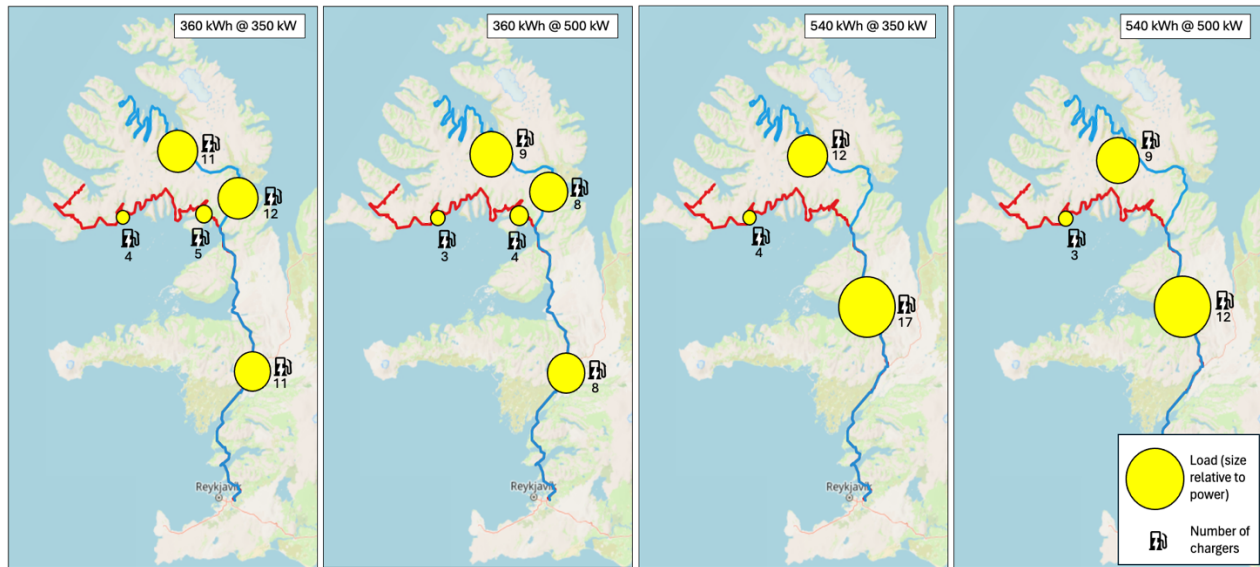


Figure 12. Number of chargers/derived peak load for different FCS configurations based on vehicle battery capacity and charger capacity

4.3. Limitations of the study and further research

Our study provides a comprehensive and detailed methodology to design an optimal FCS network, however it presents several implementation challenges and limitations which require further analysis in future research.

One of the main limitations is the extensive data requirements needed to run the vehicle energy consumption model, which include high resolution time series from freight trucks driving activity. Acquiring such data can be difficult since fleet operators might be reluctant to share it due to its sensitive nature (Whitehead et al., 2022). Additionally, accurate traffic flow data is also necessary to determine the optimal number of charging points required per station. The extensive data requirements might also lead to challenges in scaling up the scope of the analysis. The detailed nature of the proposed methodology is especially designed to provide highly accurate results for specific freight routes, making it particularly valuable for planning charging infrastructure in the early stages of freight electrification. Nevertheless, extending the scope to cover the entire national freight activity would require a significant increase in data input and computational resources.

The number of charging points per station is optimised based on BETs travelling the Reykjavik-Westfjords route, which represents one of the many freight routes in the area. The proposed charging stations might also be used by other BETs carrying out different freight routes, which could potentially lead to congestion issues. Once again, this study highlights the importance of freight travel patterns data availability to accurately estimate BETs charging demands and arrival rates to design an optimal charging network. Further research should be carried out aiming to include more freight routes into the analysis to better optimise the network.

Another potential limitation of our study relies on the fact that our methodology optimised the charging network based on adverse climate and freight conditions (e.g. cold temperatures, headwind, high payloads) to ensure the BETs would be able to cover the route even in worst case scenario conditions. In addition, peak demand periods are also used to scale the number of required charging points per FCS. Although this approach is useful in reducing range anxiety and waiting times, its conservativeness might lead to higher costs and underutilisation of infrastructure for milder scenarios.

Our study used only a few battery capacities (i.e. 360 and 540 kWh) and charging rates (i.e. 350 and 500 kW) in the simulations, which does not cover all available battery

technologies. This simplified approach aims at making the analysis more comprehensive and focused on near-term applications. However, future research should consider the prospects in battery and charging technology, including larger capacity batteries, faster charging rates, and factors like battery degradation.

Another critical aspect which was not included in the scope of this study is the implications of BET charging loads on the power grid (Shoman et al., 2023). The introduction of FCS, especially during peak demand periods, could impose a substantial strain on the existing transmission and distribution lines, as well as transformers and substations, potentially requiring upgrades (Hall & Lutsey, 2019). Moreover, our approach tends to concentrate the charging loads in only a few places, leading to potential power grid congestions. Further research should be carried out to assess the potential infrastructure upgrades and linked costs, as well as to carry out a cost-benefit analysis of different approaches in charging network planning.

Overall, the proposed methodology offers a robust framework for charging network optimisation which can provide detailed insights for policymakers and fleet operators. Addressing the mentioned limitations and further research topics could enhance its scalability to other contexts and improve the accuracy of the outcomes.

4. Conclusion

This study proposes a comprehensive methodology to design charging networks for battery-electric trucks, including the number of required stations, their optimal locations, and the number of charging points required per location. The methodology also incorporates a detailed vehicle energy consumption model to determine the vehicle charging requirements, considering adverse climate conditions (e.g. cold temperatures, headwind) and challenging freight demands (e.g. maximum payloads, mountain pass routes). This study offers a robust framework to design optimal charging networks in the early stages of freight electrification, especially tailored for low-traffic regions.

The proposed methodology is used to design a charging network to support the Reykjavík-Westfjords freight routes, using different battery capacity and charger capacity assumptions. Our findings indicate that battery capacity assumptions significantly influence the optimal design of a charging network, particularly in terms of station locations and the average distance between stations, while both battery capacity and charging rate assumptions impact charging loads and the number of chargers required per station. Overall, the results indicate that larger battery capacities and higher charging rates can significantly reduce additional route times, with 540 kWh battery trucks and 500 kW chargers requiring an average of only 24 minutes in the analysed routes. Although the tolerance for additional routing time may vary between fleet operators, such results highlight the potential for route electrification in ways that could be aligned with freight schedules. Furthermore, power grid upgrades would likely be necessary to accommodate peak charging demands, which can reach 6 MW of additional load on the transmission and distribution network. Further research should focus on the impacts of the charging loads on the power grid, potential upgrades, and the associated costs.

Policymakers can use the outcomes of this study to guide infrastructure development, set regulatory targets, and prioritise investments towards freight transport decarbonisation. This study can also benefit fleet operators by providing guidance into route planning optimisation and routing time, as well as tackling uncertainties around BET performance under adverse conditions.

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5. Paper 4

Impact assessment of battery-electric HDVs charging loads on the transmission and distribution system in Iceland and mitigation strategies

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Abstract

This study investigates the impact of battery-electric truck deployment on Iceland's national power grid, with a focus on long-haul freight transport under Arctic conditions. The research proposes a novel approach combining detailed vehicle energy consumption models, a charging optimisation framework, and a comprehensive non-linear power flow analysis to assess the technical feasibility of electrifying long-haul freight routes in Iceland.

Driving data were collected using GPS trackers during real-world test drives and used to calibrate a vehicle energy consumption model (FASTSim). The model outputs informed a charging optimisation framework to determine the location and power capacity of charging stations along Iceland's main freight corridors. These charging loads were then integrated into a non-linear power flow analysis (PyPSA) of the national grid under current (2023) and projected (2030) demand scenarios.

The findings indicate that BET charging demand is highly uneven, significantly reshaping regional load profiles with loads rising up to 16.5% in the South and 10.8% in the North compared to the 2030 scenario. The Westfjords also show 8.5% increase despite its smaller relative size.

The results suggest that the increased electricity demand from electric truck charging stations and the forecasted power consumption in 2030 could lead to voltage violations and line overloading in the current grid setup. While BET deployment does not create new line overloads beyond those already expected in the 2030 baseline, it increases flows on several lines and exacerbates existing vulnerabilities. The Westfjords are identified as the most constrained area, with critical voltage violations linked to limited grid capacity.

The findings emphasise that electrifying long-haul freight transport in Iceland is technically feasible but will require targeted planning and mitigation measures such as voltage support or on-site storage or renewable energy generation. This research provides valuable insights into the technical feasibility of electrifying long-haul freight in Arctic regions and contributes to the global understanding of sustainable transport electrification in isolated and renewable-energy-dominated power systems.

Keywords: Battery-electric trucks; Power flow analysis; Charging loads; Long-haul; Power grid

1. Introduction

The transport sector is one of the largest contributors to energy-related greenhouse gas (GHG) emissions, accounting for 22% of worldwide emissions (European Commission, 2024). Road freight vehicles alone are responsible for 40% of the direct emissions from the transport sector (IEA, 2017). Typically, road freight transport uses heavy-duty vehicles (HDVs), such as tractor or trailer trucks, which rely on fossil diesel. In recent years, these vehicles have become a focal point for regulators seeking to reduce CO₂ emissions and enhance energy security in the freight sector (Ge & Friedrich, 2020).

Battery-electric trucks (BETs) are considered a potential solution to decarbonise road freight transport due to their low Well-to-Wheel CO₂ emissions (Lajevardi et al., 2019), reduced dependence on fossil fuels (Alonso-Villar et al., 2022), and competitive Total Cost of Ownership (TCO) (Sen et al., 2017; Forrest et al., 2020). While BETs have proved a viable option for short-haul applications even in adverse conditions (Alonso-Villar et al., 2023), the electrification feasibility of long-haul routes is more challenging as it is highly dependent on on-route fast-charging stations (FCS) (Hurtado-Beltran et al., 2021). Contrary to short-haul applications, long-haul trucking is characterised by covering longer distances (over 400 km) without the chance to return to charge at the home base, which implies that BETs will rely on public charging stations along the routes (Jochem et al., 2019).

The magnitude of the BETs charging loads and the capacity of the power grid to cope with them remains a key consideration in determining the technical feasibility of freight electrification. Increased BET penetration will drive higher electricity consumption, altering power flow, grid losses, and voltage stability (Apiyo, 2019). Fast-charging stations capable of supporting several simultaneous events may draw power levels exceeding 1 MW, which power demands can match or surpass those of urban and industrial loads (Burnham et al., 2017). Moreover, freight BETs are characterised by low flexibility schedules, as long-haul drivers prioritise minimal stopped times and rapid charging, which poses additional challenges to grid operations (Burnham et al., 2017). As BET adoption increases, the scale of high-power fast-charging facilities is expected to grow correspondingly, further intensifying the impact on the grid (Mowry & Mallapragada, 2021).

In this context, comprehensive assessments of grid capacity and reliability under increased loads become essential to evaluate the feasibility of accommodating the charging loads onto transmission and distribution systems, which insights are crucial to ensuring the widespread deployment of BETs, advancing long-haul decarbonisation, and achieving emission reduction targets (Mowry & Mallapragada, 2021).

While the integration of battery-electric vehicles (BEVs) into the power grid has been widely studied in the context of passenger BEVs, research on BET charging remain an emerging field. Existing BEV research highlights multiple technical challenges associated with fast-charging stations, including voltage fluctuations, and component overloading. For instance, Mowry and Mallapragada (2021) examined highway fast-charging in Texas, showing how spatially concentrated and inflexible charging demands can strain system operations, while Mojlish et al. (2025) reviewed the grid impacts of ultra-fast charging in Australia, identifying issues such as power quality degradation, transformer overload, and system instability. These findings underscore that large-scale deployment of high-power charging stations poses significant risks to grid reliability and efficiency.

While passenger BEV studies provide useful insights, their findings cannot be directly extended to BETs, which present distinct charging characteristics due to higher energy demand and long-haul duty cycles. Research focusing specifically on BETs has primarily focused on estimating charging demand and planning infrastructure deployment. Shoman et al. (2023), for instance, modelled BET charging requirements along major European freight routes, while Alonso-Villar et al., (2024) developed a charging optimisation model for freight transport in Iceland. Both studies offered insights on the scale and distribution of charging infrastructure

needs but did not analyse the impacts on the power grid.

At the system level, only a handful of studies have explored the broader impacts of large-scale EV adoption. Montoya and Fernando (2020) emphasised the importance of demand response models and data-driven approaches to better capture the stochastic nature of charging behaviour in grid studies. Similarly, case studies in Iceland have shown the potential severity of EV integration. Apiyo (2019) found that BEV charging loads could significantly increase peak demand and cause voltage drops and line overloading, while Haraldsson (2020) simulated similar scenarios using MATPOWER (Zimmerman et al., 2011), highlighting the need for both infrastructure upgrades and additional generation capacity. Although informative, these analyses remain region-specific and largely centred on passenger vehicles rather than heavy-duty freight.

Overall, the existing literature establishes that fast charging poses a substantial challenge to grid operations, but the specific case of BETs has not yet been systematically addressed, and no study has quantified the magnitude of BET fast charging loads at the national level or assessed their impact on peak demand across transmission and distribution systems. This gap underscores the need for comprehensive assessments that combine spatially and temporally resolved BET charging patterns with detailed grid modelling, providing insights that are essential for enabling long-haul decarbonisation and achieving emission reduction targets.

Arctic countries such as Iceland provide a particularly relevant context for such assessments. Freight electrification in Iceland faces unique challenges due to the harsh climate conditions and difficult roads, which affect vehicle performance and increase charging demand. Furthermore, Iceland's scattered population implies the need to travel to remote places with limited grid support and frequently ageing infrastructure (Apiyo, 2019). BET deployment poses significant uncertainties regarding the impact of charging loads on the national power grid, and limited knowledge exists on the ability of the grid to manage these loads, which might limit the widespread use of BET in the freight transport sector. In addition, the limited flexibility of on-route charging for freight BET poses further constraints on the grid, as tight routing schedules limit the potential for charging load shifting. This study uses Iceland as a case study to investigate the technical challenges faced by the power grid during the early stage of BET deployment while accounting for the forecasted increase in national electricity consumption in 2030 (Orkustofnun, 2024). To do so, this study uses FASTSim to determine BETs energy consumption and charging requirements over the analysed routes (Brooker et al., 2015) and the charging optimisation model proposed by Alonso-Villar et al. (2024) to allocate the charging infrastructure and power demands. Lastly, the power flow assessment of the impacts of the charging loads on the Icelandic grid is carried out using PyPSA (Python for Power System Analysis) (Brown et al., 2018). As far as the authors can tell, this is the first real-life data-driven study to combine a vehicle energy consumption model, a charging optimisation model, and a highly detailed national grid power flow analysis. Figure 1 illustrates the framework of this study. Add PFA justification here.

To sum up, the main objectives of this study are to identify the optimal locations to place a robust and reliable charging network for BETs serving the freight main routes in Iceland, determine their on-route charging requirements and derived peak-demand loads, and evaluate the impact of these loads on power flow over the national grid, while explicitly considering the limited flexibility of freight charging demands. Furthermore, the power flow analysis is carried out under conditions close to peak system demand, providing insights into system performance under stressed operating conditions. This paper underscores the critical role of detailed grid assessments in evaluating the feasibility of integrating BETs and advancing the decarbonisation of freight transport, particularly in congested grid systems.

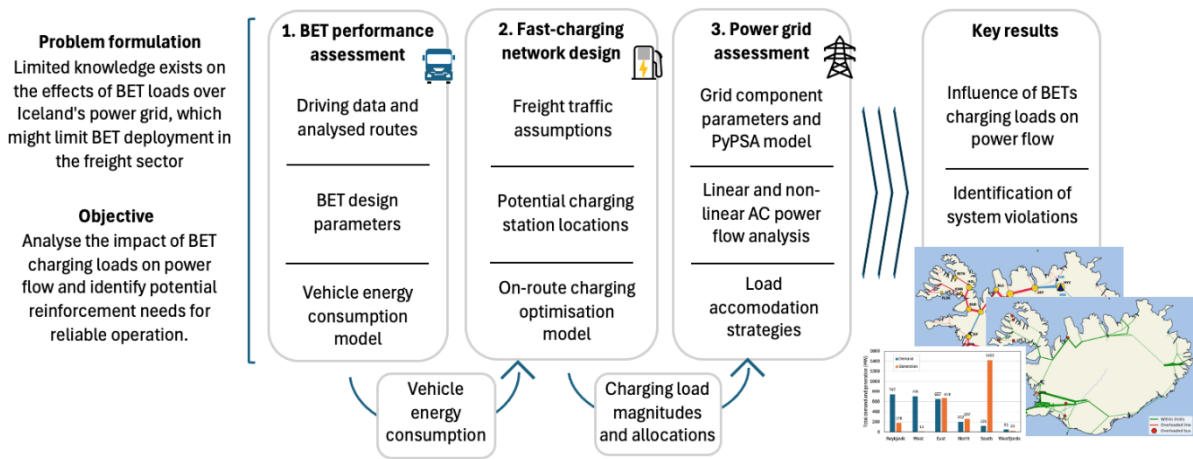


Figure 1. Problem formulation, objective, and flowchart of the structure of this study.

2. Methods and data

This section introduces the methodology used to estimate the energy consumption of the analysed BET, to allocate and determine the magnitude of on-route charging loads, and to perform a power flow analysis of the Icelandic electric system to explore the ability of the grid to cope with the additional charging loads.

2.1. Vehicle performance assessment

2.1.1. Driving data and analysed routes

Driving data for this study was collected during test drives in a passenger vehicle using the iOS GPS Tracker application. The dataset consists of time series with a temporal resolution of one second, containing vehicle speed, geographical coordinates (latitude and longitude), and altitude. These variables were used as inputs to the vehicle energy consumption model. The data covers representative driving conditions on Icelandic roads relevant for the study. To address irregularities caused by GPS signal loss, the data was resampled to a uniform one-second resolution, and missing values were linearly interpolated.

The study examines outbound and return trips to assess how variations in topographical features along different route directions impact BET energy consumption and charging needs. The routes analysed include the ring road, which is the primary highway to travel around the country and connects most parts of the population, and the routes to the Westfjords region, which connects important fishing industry sites to the main highway network. Figure 2 illustrates the analysed routes along with the proposed locations for FCS. These locations were initially selected based on the availability of existing infrastructure, such as gas stations and rest areas. This pre-selection of potential FCS locations will be used as input for the charging optimisation model introduced in Section 2.2, which determines the optimal charging stops for BETs along the analysed routes.

This analysis focuses exclusively on the on-route fast charging sessions and does not include slow charging performed at destinations or fleet depots in the assessment. The BETs are assumed to start with 100% state-of-charge (SOC).

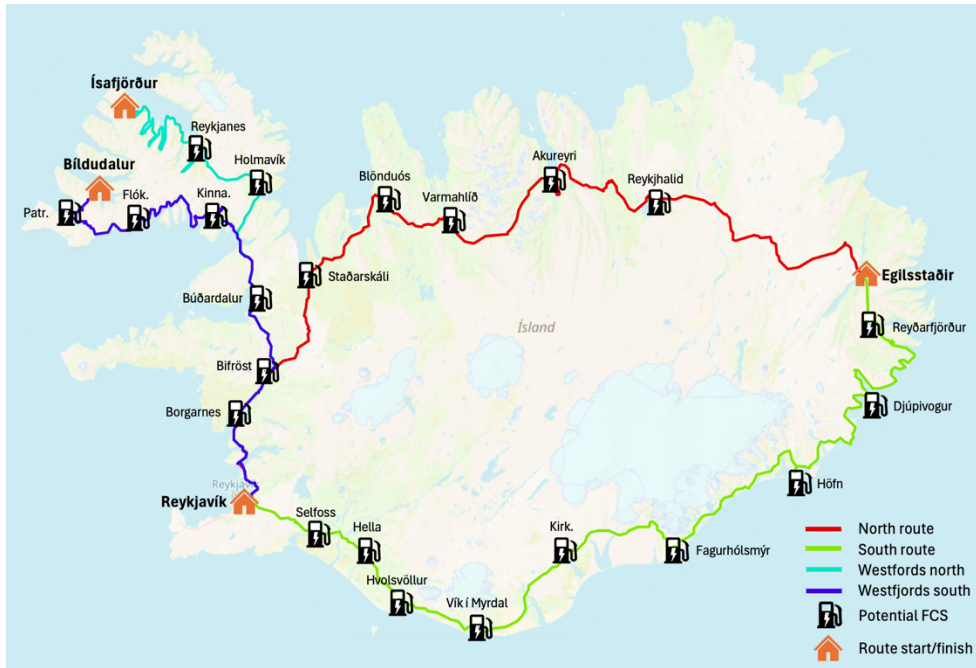


Figure 2. Analysed routes and candidate locations for charging stations

2.1.2. Battery-electric truck design parameters

The analysis uses a battery-electric tractor truck based on the eActros 600 (Mercedes, 2024), a configuration commonly used for long-haul freight transport. The analysis incorporates typical adverse climate conditions in Iceland, including low temperatures ($-7\text{ }^{\circ}\text{C}$) and strong headwinds which influence the battery thermal management system (BTMS) (Basma et al., 2021), wheel friction (Ejsmont et al., 2018), and aerodynamic drag (Volvo Trucks, 2022). Adjusted BET design parameters based on these climate conditions are presented in Table 1 (Alonso-Villar et. al, 2023).

Table 1. BET design parameters used based on eActros 600 model (Mercedes, 2024)

Category	Parameter	Value for eActros 600
Vehicle	Drag coefficient ^a	0.5
	Frontal area (m ²)	8.5
	Centre of gravity	0.54
	Weight fraction on drive axle	0.59
	Wheelbase (m)	3.90
Powertrain	Efficiency ^b	0.95
	Charging power (kW)	500/1000
	Power (kW)	600
	Battery capacity (kWh)	600
	Auxiliary loads BTMS (kW) ^c	6
	Usable battery capacity (%)	95
Wheels	Energy density (Wh/kg) ^b	130
	Wheel inertia (kg/m ²) ^d	0.815
	Number of wheels	10
	Radius (m)	0.522
Weight	Coefficient of friction ^e	0.006
	Permissible gross weight (kg)	44,000

^a Volvo Trucks (2022). Air density is assumed to be 1.31 km/m^3 at $-7\text{ }^{\circ}\text{C}$

^b Brooker et al. (2015)

^c Basma et al. (2021). Auxiliary power demand for both cabin heating and battery thermal management at $-7\text{ }^{\circ}\text{C}$.

^d Own estimates assuming -7 °C ambient temperature

^e Own estimates based on Ejsmont et al., (2018). This study assumes a fixed average friction value over the entire route, adjusted to reflect low-temperature conditions, as detailed in Alonso-Villar et al. (2023)

2.1.3. Vehicle energy consumption model

This study uses FASTSim (Future Automotive Systems Technology Simulator) to estimate the energy consumption and performance of battery-electric trucks (BETs). Developed by NREL (Brooker et al., 2015), FASTSim is a versatile platform for analysing the performance of conventional, hybrid, and electric vehicles. It incorporates vehicle dynamics and powertrain parameters to predict energy consumption under various driving conditions. The key equations summarising FASTSim's methodology are outlined in the following. The battery power output is calculated using Equation (1) (Ehsani et al., 2004):

$$P_{out} = \frac{v(t)}{\eta_t \eta_m} \left(m_v g (f_r + \theta) + \frac{1}{2} \rho_{air} C_d A_f v(t)^2 + m_v \frac{dv}{dt} \right) + P_{aux} \quad (1)$$

where $v(t)$ is the vehicle speed (m/s); η_t and η_m is the transmission and electric motor efficiency; m_v is the vehicle mass (kg); g is the gravitational acceleration (9.81 m/s²); f_r is the rolling resistance coefficient; θ is the road grade; C_d is the aerodynamic drag coefficient of the vehicle; ρ_{air} is the air mass density at a given temperature; A_f is the vehicle's frontal area; and P_{aux} represents the power linked to auxiliary loads. Regenerative braking recovers electricity (Rivelino et al., 2018) as expressed by Equation (2) (Xiao et al., 2016):

$$P_{regen} = \frac{\alpha v(t)}{\eta_t \eta_m} \left(m_v g (f_r + \theta) + \frac{1}{2} \rho_{air} C_d A_f v(t)^2 + m_v \frac{dv}{dt} \right) + P_{aux} \quad (2)$$

where α is the regenerative braking factor. The net energy consumption of the electric powertrain is calculated using Equation (3) (Ehsani et al., 2004):

$$E_{net} = \int_0^t P_{out} dt + \int_0^t P_{regen} dt \quad (3)$$

The battery SOC is updated over time using Equation (4) (Tanvir et al., 2020):

$$SOC(t) = SOC(t-1) - \frac{E_{net}(t)}{E_{bat}} \quad (4)$$

where $SOC(t)$ is the SOC at a given time, $E_{net}(t)$ is the net energy consumption, and E_{bat} is the battery capacity (kWh).

The model was calibrated using EPA's HDDT, HWFET (EPA, 2024), and NREL's Long-haul (Brooker et al., 2015) driving cycles and the conditions from the eActros 600 range test (Mercedes, 2024). Table 2 summarises the calibration results. Details of the calibration process are available in Alonso-Villar et al. (2023) and in the annex.

Table 2. eActros 600 calibration model results

Parameter	HHDDT	HWFET	Long-haul
Drive cycle distance (km)	41.3	16.5	804
Energy consumption (kWh/km)	1.35	1.13	1.23
Estimated range (km)	445	531	487
Difference to official range (500 km)	-11%	6%	-3%

2.2. Charging optimisation model

This study uses the optimisation model introduced by Alonso-Villar et al. (2024) to determine the number of stops, charging locations, and charging session durations for BETs travelling the routes shown in Figure 2. Gurobi Optimization (2023) is used to solve the model. The charging process is modelled using a piecewise linear approximation of the non-linear charging curve, where different segments represent average charging rates across specific SOC ranges. The objective function minimises the total charging time, as described in Equation (5):

$$MIN Z = \sum_{i \in I} \sum_{j \in J} (f * Y_i + X_{ij}) \quad (5)$$

where $MIN Z$ is the total charging time, i represents charging locations, j represents SOC segments, f is the fixed time for initiating and completing a charging stop, Y_i is a binary variable indicating whether charging occurs at location i , and $X_{i,j}$ is the charging time at location i in segment j . The objective function is based on the assumption that fleet operators seek to minimise on-route charging, as its more expensive than depot charging and extends overall trip duration, disrupting tight routing schedules.

The optimisation model ensures the feasibility of charging operations by activating a binary variable Y_i whenever a charging stop occurs at location i . This relationship is enforced by the constraint represented in Equation (6):

$$X_{i,j} \leq Y_i * M \quad \forall i \in I, j \in J \quad (6)$$

where $X_{i,j}$ represents the charging time at the location i for the segment j and M is the maximum allowable charging time, set to 240 minutes. This constraint ensures that charging occurs only if Y_i is activated and limits the charging duration to a realistic maximum. The model enforces a minimum SOC through Equation (7):

$$SOC_i \geq minc \quad \forall i \in I \quad (7)$$

where SOC_i represents the state-of-charge upon arrival at location i , and $minc$ is the minimum SOC allowed, set at 10% of the battery's capacity. This constraint ensures that the SOC remains above 10% when arriving at any charging location. The SOC at the first location ($i=1$) is calculated using Equation (8):

$$SOC_1 = SOC_o - use_1 \quad (8)$$

where use_1 represents the energy consumed while travelling to the first stop. For subsequent locations ($i > 1$), the SOC is updated by accounting for the energy consumed during travel and the energy added during charging at the previous stop, as shown in Equation (9):

$$SOC_i = SOC_{i-1} + \sum_j (ch_{i-1,j} * X_{i-1,j}) - use_i \quad \forall i > 1 \quad (9)$$

where, SOC_{i-1} represents the state-of-charge at the previous location, $ch_{i-1,j}$ is the charging rate in segment j at the previous location, and use_i is the energy consumed travelling to location i . This formulation ensures that the SOC reflects both charging and energy consumption dynamics. To model the piecewise linear charging curve, only one segment can

be active at a time at each location, using Equation (10):

$$\sum_j C_{i,j} = 1 \quad \forall i \quad (10)$$

where $C_{i,j}$ is a binary variable that activates segment j at location i if the SOC falls within that segment. The amount of energy added during charging is constrained by the maximum allowable charging rate for each segment using Equation (11):

$$ch_{i,j} \cdot X_{i,j} \leq charg_{i,j} \cdot \sum_{k=1}^j C_{i,k} \quad \forall i, j \quad (11)$$

where $charg_{i,j}$ represents the maximum charging rate for segment j at location i . This ensures that the added charge remains within the technical limitations of the chargers. The SOC must also stay within the segment-specific limits for each charging session, as defined in Equation (12):

$$SOC_i + ch_{i,j} \cdot X_{i,j} \leq cu_{i,j} + (1 - C_{i,j}) * M \quad \forall i, j \quad (12)$$

where $cu_{i,j}$ represents the upper SOC limit for segment j at location i and M serves as a large upper bound to deactivate the constraint if the segment is not active. This constraint ensures that the SOC remains within the safe operating range of the battery. The model further bounds the SOC using cumulative segment limits. The SOC at any location must not exceed the cumulative energy associated with the active segments as described in Equation (13):

$$SOC_i \leq \sum_j C_{i,j} * cu_{i,j} \quad \forall i \quad (13)$$

Similarly, the SOC must also respect the lower bound of the active segments, ensuring continuity, using Equation (14):

$$SOC_i \geq \sum_j C_{i,j} * cu_{i,j-1} \quad \forall i, j > 1 \quad (14)$$

Finally, the total charge added at each location is calculated by summing the charge contributions from all active segments using Equation (15):

$$XT_i = \sum_j X_{i,j} * ch_{i,j} \quad \forall i \quad (15)$$

where XT_i represents the total charge added at location i , reflecting the combined charging time $X_{i,j}$ and rate $ch_{i,j}$ across all segments. This ensures accurate accounting of the energy added during each stop. Together, these constraints guarantee that the charging process respects the technical, operational, and battery limitations, while optimising the total charging time across all locations.

2.3. Power grid assessment

This section outlines the main concepts used to carry out the power grid assessment, including a brief description of the Icelandic transmission grid, the application of PyPSA as the power flow analysis tool, and the assumptions regarding BET charging loads and case study design.

2.3.1. The Icelandic transmission grid

Iceland's transmission grid is quite unique, relying entirely on renewable energy sources and operating as an isolated system without connections to neighbouring countries. As such, all electricity demand must be met by domestic generation (Apiyo, 2019). The transmission network consists primarily of overhead lines with a total length of 3,343 km, complemented by 245 km of underground cables. As shown in Figure 3, key voltage levels include 220 kV (919.97 km), 132 kV (1,419.6 km), 66 kV (1,161.3 km), and 33 kV (89 km). The system includes 74 substations and 85 supply points, which serve 20 power plants, eight energy-intensive industries, and 59 distributors. A 132 kV ring network connects the country, supported by two strong 220 kV systems in the southwest and east (Apiyo, 2019; Landsnet, 2024). The grid connects hydropower and geothermal plants to residential users and small industrial users, as well as large-scale industries such as aluminium smelters and fish processing plants, which account for 80% of electricity consumption (Fraunhofer ISI, 2020).

To improve the clarity of the analysis, this study makes regional distinctions of the Icelandic power grid, which are shown in Figure 3. The North-West area (Westfjords) is characterised by its sole 132 kV line connection to the general grid, which leaves this area susceptible to power outages, and the region has a set of diesel generators at BOL to support the region when it is isolated from the grid. This region counts several fish farming industries, which are transported to the main export harbours around the country by trucks. The South-West region is defined by its heavy industry and the country's largest urban area, the Reykjavík capital region. Power generation in this region is concentrated on the Reykjanes peninsula, located south of Reykjavík. The West region hosts one significant industrial facility alongside moderate power demands from other consumers. Similar to the Westfjords, the Snæfellsnes (the largest peninsula in the West region) is connected to the general grid through a single 66 kV line. The South contains the majority of Iceland's power generation capacity. However, the region's power demand is relatively low, as there are no significant industrial loads and a relatively small portion of the population lives there. The North is characterised by a mix of important urban areas, industrial facilities, and power generation capacity. Lastly, the East houses Iceland's largest power plant (FLJ) with a capacity of 660 MW, which primarily provides electricity to the aluminium smelter in the East region (Landsnet, 2024).

relevant to this study's goals. The key components and parameters represented in the PyPSA model are defined in Table 3.

Table 3. Components included in the model (PyPSA)

Component	Definition	Parameters modeled
Buses	Nodes representing grid connection points with defined nominal voltages.	Nominal voltage (V_i)
Generators ^a	Electricity production units (e.g. power plant) connected to specific buses. These are defined by nominal power, active and reactive power limits, impedance, and voltage control mode	Bus connection; nominal power (p_nom); voltage control
Loads	Points of power consumption (e.g. industries, urban areas) with defined active and reactive power	Bus connection; Active power load (P_nom); Reactive power load (Q_nom)
Transformers ^b	Components that manage voltage changes with a specified nominal apparent power, primary and secondary nominal voltages, and impedance.	Primary bus (Bus0); Secondary bus (Bus1); resistance (r); reactance (x); thermal limit (S_nom)
Shunt impedances ^c	Electrical elements that compensate reactive power and power losses.	Voltage control
Lines	Connections between buses with a specified thermal resistance and impedance.	Primary bus (bus0); Secondary bus (bus1); resistance (r); reactance (x); thermal transmission limit (S_nom); susceptance (charging B)

^a Búrfell is defined as the slack bus

^b Due to limitations in the data collection, a uniform ratio is applied to the resistance and reactance values for all transformers. Accurate parameters are applied for the rest of the components.

^c Shunt impedances are modelled as generators that can only provide reactive power

The model consists of a two-step approach, consisting of a linear optimisation which focuses on efficient computation through linear optimal power flow (LOPF), followed by a more physically accurate AC power flow analysis through non-linear power flow (PF). The methodology implemented is illustrated in Figure 4.

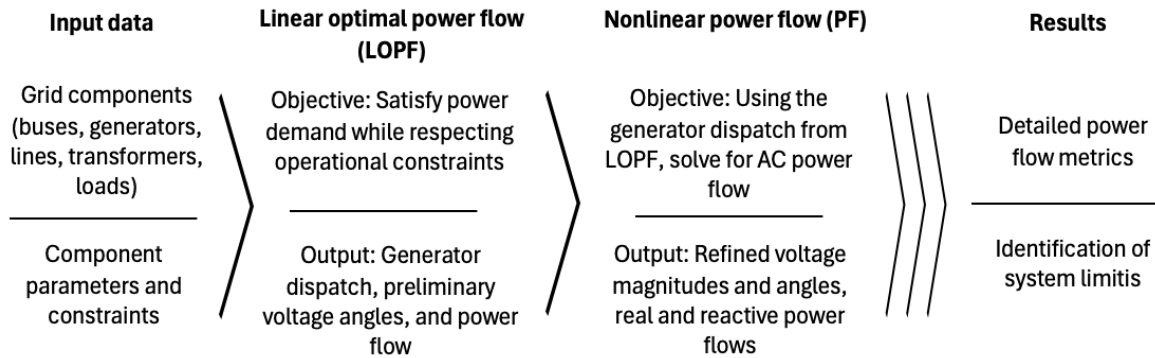


Figure 4. Methodology flowchart, which explains the stepwise process, starting from left and delivering the results shown to the right.

First, the proposed model begins with a LOPF calculation to ensure grid balance and power flow feasibility in the system. This approach simplifies certain aspects of the power system and constant voltage magnitudes, which is suitable for an initial system analysis. It does not include any economic aspects in the analysis, as the primary focus of the model is the technical performance of the grid, especially its ability to handle additional loads from BET charging around the country. Therefore, the simplified approach provides insights into potential system bottlenecks but overlooks complex cost-based questions, which could limit the scope of the analysis. All model constraints are used to ensure technical feasibility rather than economic optimisation, and the sole goal of the model is to meet power demand while respecting operational constraints.

The power balance for each bus is represented in Equation (16):

$$P_g - P_d = \sum_{j \in adj(i)} P_{i,j} \quad \forall i \quad (16)$$

where P_g is the real power output, P_d is the load at the bus, and $P_{i,j}$ is the real power flow on the line connecting buses i and j . The indexes g and d represent generation and demand, respectively, while $adj(i)$ represents the set of all buses that are directly connected to bus i in the power network. The linearised power flow equation is represented in Equation (17):

$$P_{i,j} = \frac{\theta_i - \theta_j}{X_{i,j}} \quad \forall (i,j) \quad (17)$$

where θ_i and θ_j are the voltage angles at bus i and bus j ; and $X_{i,j}$ is the reactance of the line between buses i and j . The generator and line flow constraints are represented in Equation (18) and Equation (19):

$$P_{min} \leq P_g \leq P_{max} \quad \forall g \quad (18)$$

$$|P_{i,j}| \leq S_{nom_{i,j}} \quad \forall (i,j) \quad (19)$$

where $Snom_{i,j}$ is the thermal limit of every line.

The results of the linear optimisation are then used in the non-linear power flow solver. The non-linear solver addresses the limitations of LOPF by incorporating the full AC power flow equations, modelling the complex non-linear relationships between voltage magnitudes, angles, and power flows. The solver uses the Newton-Raphson method to refine voltage magnitudes and angles and to satisfy real and reactive power balance at each bus. These results provide a more accurate representation of the grid's operations, which is crucial for our analysis.

The real and reactive power balance are represented in Equation (20) and (21):

$$P_i = \sum_{j \in adj(i)} V_i V_j (G_{i,j} \cos(\theta_i - \theta_j) + B_{i,j} \sin(\theta_i - \theta_j)) \quad (20)$$

$$Q_i = \sum_{j \in adj(i)} V_i V_j (G_{i,j} \sin(\theta_i - \theta_j) - B_{i,j} \cos(\theta_i - \theta_j)) \quad (21)$$

where P_i and Q_i are real and reactive power injections at bus i ; V_i , V_j and θ_i , θ_j are the voltage magnitudes and voltage angles at buses i and j ; and $G_{i,j}$ and $B_{i,j}$ are the conductance and susceptance of the line. The Newton-Raphson method is used to solve these equations.

Lastly, the net power injected at each bus balances the contributions from generators, loads, and shunt elements. The power injection constraints are defined by Equation (22):

$$P_i = P_g - P_d \text{ and } Q_i = Q_g - Q_d \quad (22)$$

where P_g and Q_g are the real and reactive powers from generators, P_d and Q_d are the real and reactive powers from loads. The power flow through lines and transformers is calculated based on voltage angles and magnitudes.

In the LOPF, soft transmission capacity limits are applied to ensure the model can converge to a solution regardless of potential violations of thermal transmission limits in lines and transformers. This approach finds the generators profile in the system and incorporates a penalty for exceeding the predefined component limits, ensuring that such violations are accounted for within the optimisation framework.

The purpose of this study is to provide an approximate evaluation of the impact of future 2030 load scenarios, including the additional BET charging loads, on the power grid. The developed power grid model aims to offer a realistic approximation of grid behaviour under these conditions. It is not intended to accurately represent the grid's performance, as accurately modelling such behaviour requires accounting for many variables and factors inherent to grid operations. By focusing on a practical and simplified approach, this study seeks to highlight key trends and potential challenges rather than achieving a fully detailed simulation.

2.3.3. BET charging requirements and power grid impact assessment

This study determines the charging requirements for BETs covering the routes illustrated in Figure 5 and evaluates the impact of the derived charging loads on the power grid. The model simulates the initial stages of long-haul freight electrification in Iceland, with North and South routes including 50 BETs, 25 travelling outbound and 25 returning, while the routes to the Westfjords account for 25 BETs to consider the lower-traffic flow (Vegagerðin, 2024). In total, the model simulates 150 BETs operating simultaneously, reflecting early-stage BET deployment conditions.

To reflect varying charging behaviours and avoid congestion at FCS, two sets of on-

route charging requirements are estimated using an iterative optimisation approach. The first iteration identifies the most optimal locations for charging stations based on the BETs energy consumption on the analysed routes. In the second iteration, the charging locations selected in the first iteration are excluded, and the optimisation model is applied again to identify a new set of optimal charging locations. Therefore, the BET charging loads result from two charging profiles for each route, which better reflects real-life freight operations.

The power grid impact assessment is carried out using three scenarios:

- Reference scenario: This baseline scenario represents the state of the power grid in 2023 and serves as a benchmark to assess the impact of additional loads on the Icelandic power grid. The load profile is based on data provided by Landsnet for the 2nd of February at 18:00 PM in 2023, reflecting conditions close to peak system demand. No BET charging loads are included in this scenario.
- 2030 scenario (reference + forecasted demand growth): This scenario builds on the reference scenario by incorporating the projected increase in general electricity consumption for 2030, as reported in the national energy forecast (Orkustofnun, 2024). Total general consumption is increased by 4.8%, while heavy-industry power demand is kept constant. No BET charging loads are included.
- 2030 BET scenario (reference + forecasted demand growth + BET charging): This scenario extends the 2030 scenario by adding the charging loads from BETs, which were calculated using the vehicle energy consumption modelling described in Section 3.1.

Voltage magnitudes and apparent power flows through all system components are then calculated for each scenario using the methods introduced in Section 1.6. By investigating these scenarios, this study aims to assess the impact of the BET charging loads distribution and determine the main challenges derived from the forecasted increased power demand.

3. Results

3.1. BET performance and charging loads

This section outlines the outcomes from the vehicle energy consumption model presented in Section 2.1.3 and the charging optimisation model introduced in Section 2.2, which are used to estimate the charging loads used in the power flow simulations.

Table 4 summarises the main vehicle energy consumption outcomes for the modelled BET across the analysed routes. A map of the routes is given in Figure 2. Overall, the expected energy consumption ranges from 1.53-1.71 kWh/km depending on the route, which aligns with Teichert et al. (2023) and Basma et al. (2019), and the BET range varies between 352 to 392 km. These values are lower than Daimler’s official estimate for the eActros 600, which reports a range of 450 km under full load at -10 ° C in regional driving conditions (Mercedes Trucks, 2024). This difference can be attributed to the inclusion of headwind conditions in this study, which raises energy demand and reduces range.

Table 4. Key BET energy consumption outcomes across the analysed routes.

Parameter	North	South	WF North	WF South
Energy consumption (kWh/km)	1.64-1.71	1.53-1.54	1.53-1.54	1.57-1.70
Total route energy consumption (kWh)	1,300-1,333	1,229-1,260	881-890	954-961
Estimated range (km)	352-367	388-392	378-391	375-383

Figure 5 presents the results of the charging optimisation model, including both iterations. Each iteration represents a different charging plan, which results in different charging profiles for each route. The results are categorised by route and outbound and return trips. The analysis shows that BETs require three stops to complete the north and south routes, whereas the routes to the Westfjords can be completed with a single charging stop. For the northern route, BETs need to charge a total of 495-545 kWh on-route, while the southern route requires around 500 kWh. In contrast, BETs only need 70-160 kWh of on-route charging to cover the Westfjords routes. The outbound trip for the northern route includes up to three locations with more than 200 kWh of charging: AKY, VAR, and MYV. Notably, MYV appears in both charging plans with charging requirements of 207 and 225 kWh, which makes MYV one of the most demanding locations in terms of charging needs. The less-demanding charging locations are BLO and STA, with 46 and 64 kWh, respectively. The return trip for the North route involves only two charges exceeding 200 kWh, at VAR and STA. The South routes also account for two locations that go over 200 kWh of charging demand, this time with Höfn hosting charging sessions in both charging plans. Reyðarfjörður and Selfoss are the locations with less charging demand. The Westfjords routes demand significantly less on-route charging compared to the northern and southern routes, with the route to Bildudalur requiring 70-109 kWh and the route to Ísafjörður 132-160 kWh.

Figure 6 illustrates the calculated power demand per charging location based on the results from the charging optimisation model. The BET charging demand spreads across 19 different FCS locations, with an average charging demand of 3 MW. These loads will be used in the power flow simulations for the 2030 BET scenario to represent BET charging.

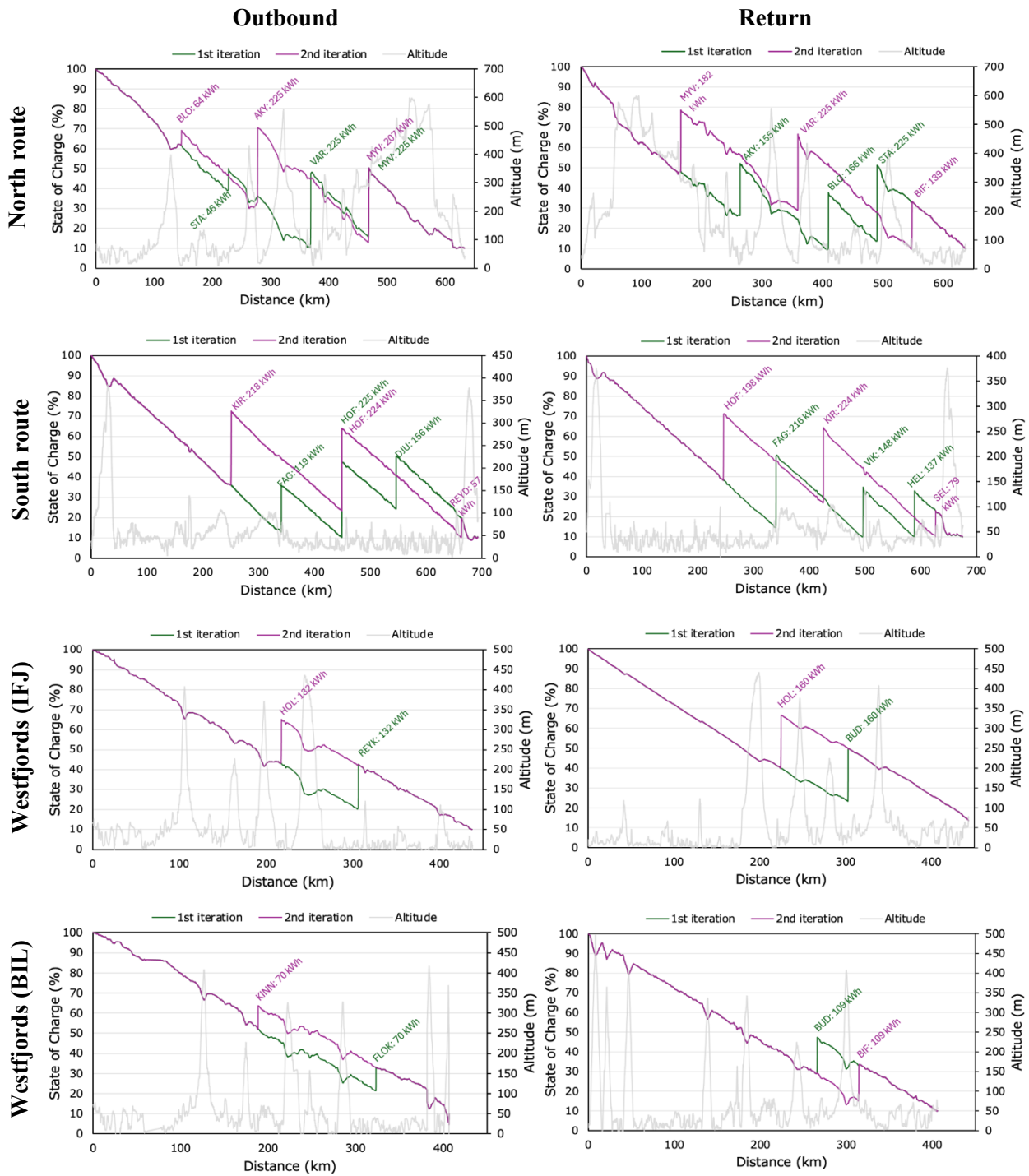


Figure 5. Charging optimisation results for all routes and iterations. Each iteration represents a different BET charging plan for the same route, resulting in different charging profiles.

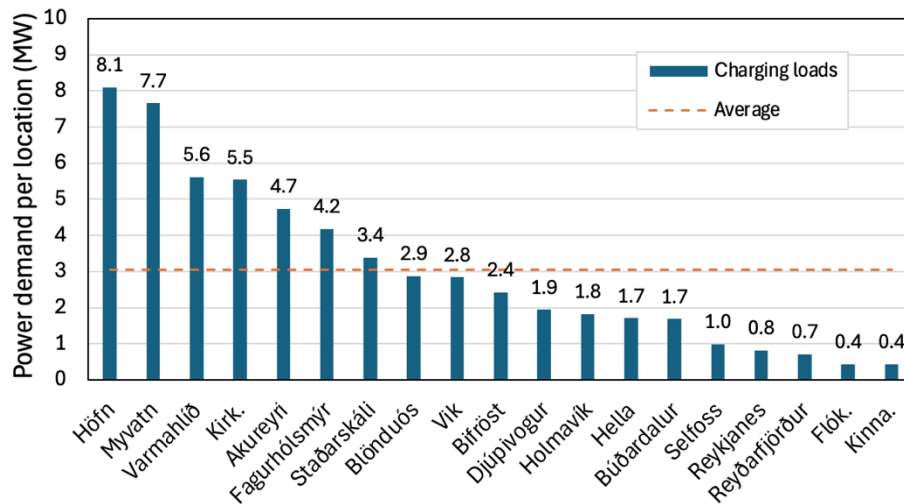


Figure 6. Distributed charging loads scenario, total charging loads per location and average demand

3.2. Power grid assessment

3.2.1. Reference scenario

This section presents the power flow assessment results for the reference scenario using the methods described in Section 2. The results include snapshots for demand, generation, and power flow close to the peak-system demand period, which in Iceland usually happens during winter (Apiyo, 2019). The load data was provided by Landsnet for the 2nd of February at 18:00 PM.

Figure 7 shows the regional distribution of demand and generation for the analysed period. As it can be observed, the power demand and generation are not equally distributed across the different regions, as the major consumption points are focalised in Reykjavík, east and west Iceland, while the remaining regions account for significantly lower demand loads. It is remarkable to point out that the regions comprising the southwest of Iceland (in this study, Reykjavík and West) account for 59% of the national power demand. In terms of generation, the South produces 55% of the total national power output, as the region accumulates a significant share of hydroelectric and geothermal capacity. The East is the second region in terms of power generation, although its contribution is significantly lower compared to the South (26%). The North and Reykjavík regions account for a similar generation with 11% and 7% of the total national output, respectively. Finally, the West and Westfjords barely account for 0.9% of the total power produced nationally. The East and North regions are the only regions with a similar power demand/generation ratio.

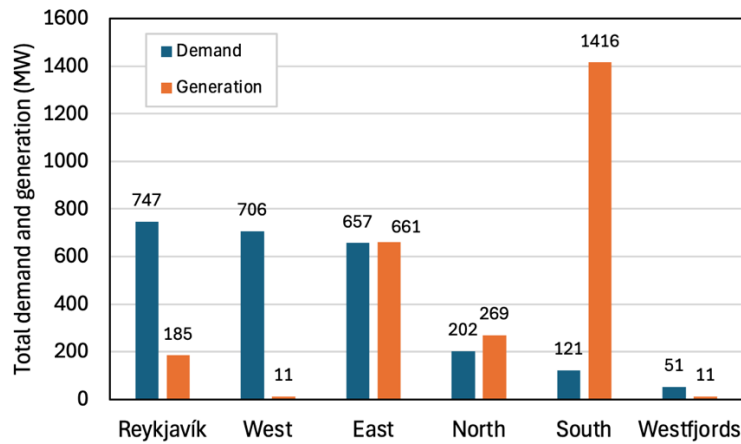


Figure 7. Total demand and generation (MW) in each region

Figure 8 shows the apparent power flow and generation output results from the power flow model for the reference scenario. The figure shows the regional distribution of loads and generators, while the size of the symbols is relative to the power demand magnitude. The line's width represents the relative power flow travelling through each line. Regional delimitations are also drawn to improve the clarity of the results. Figure 8 shows that most power flow occurs in the southwest of Iceland, from the main generation area, the South, to the major industrial and urban demand points, Reykjavik and the West. The East also presents a significant flow, mostly because of the transmission lines from Fljótsdals hydroelectric powerplant to the aluminium smelter in Reyðarfjörður. The North region also presents a relatively important power flow, as the power plants of the area feed the main urban areas of the region of Blönduós, Akureyri, and Húsavík. The South accounts for a moderately low flow through the entire region, excluding the flow going to the West and Reykjavik. Finally, the Westfjords accounts for the lowest power flow due to the small population and industry loads compared to the rest of the country.

The power flow results from the reference scenario showed non-critical voltage drops in Patreksfjörður substation, in the Westfjords regions. These results are considered to fall within acceptable rates since the Westfjords region occasionally operates below optimal conditions due to the long lines and system isolation characteristics from this area, especially during peak system demand periods. The results also showed that the Hnappavellir substation in south Iceland was operating at a maximum voltage limit of 1.05. The results also indicated minor thermal limit violations for transformers in Bolungarvík and Patreksfjörður in the Westfjords. Lastly, the model results showed no overloaded lines in the reference model.

Acknowledging these starting conditions, the results of the baseline model were considered optimal for the purpose of this research. As explained in Section 2.3.2, the developed power grid model aims to highlight key power flow trends rather than achieving a fully detailed simulation.

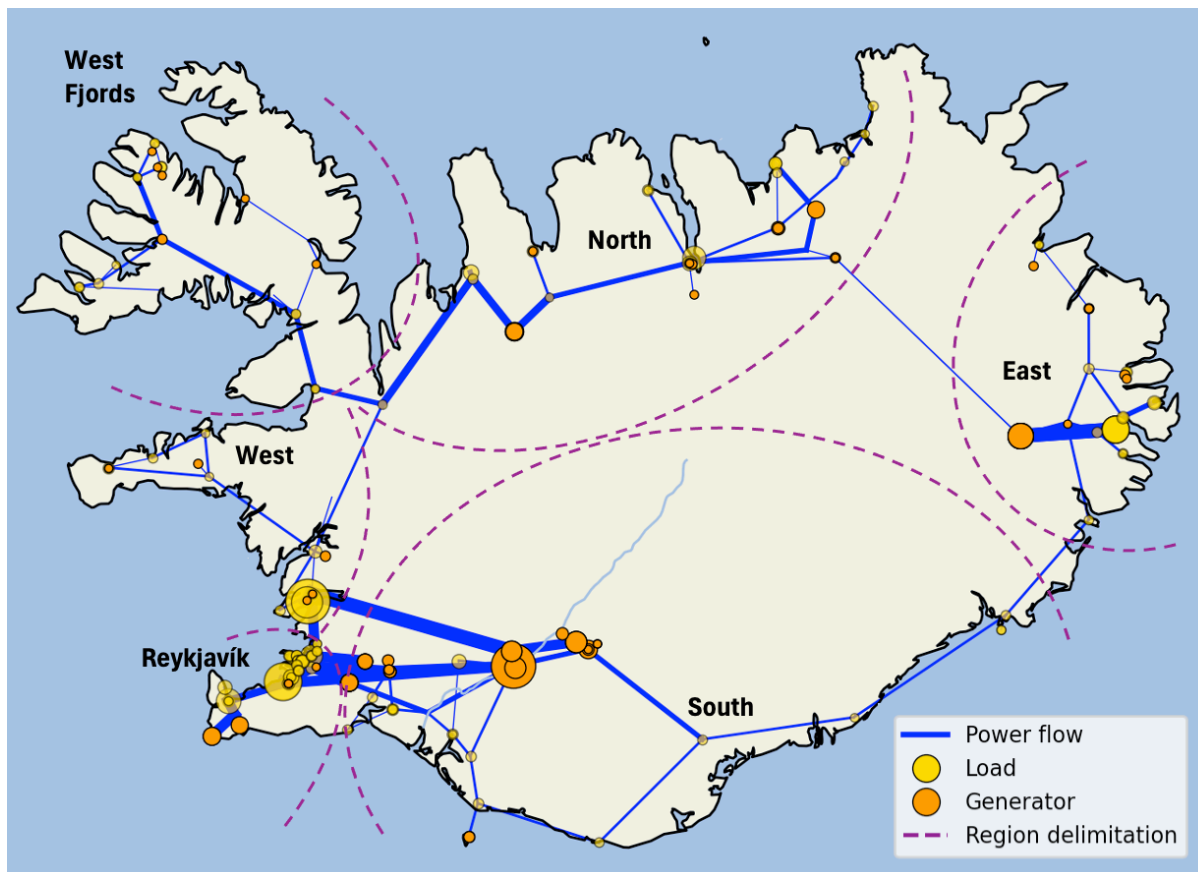


Figure 8. Power flow, loads, and generation for the reference scenario. The width of the lines is adjusted to represent the power flow going through the lines. The size of the loads and generators is relative to the power demand and power output, respectively.

3.2.2. 2030 scenario

This section presents the variations in power flow and generation output in the 2030 scenario. As described in Section 2.3.3, this scenario only includes the increase in general electricity consumption in 2030, representing a 5% rise over the reference scenario.

Table 5 summarises the regional distribution of the additional load and the corresponding difference in regional power demand and generation output compared to the reference scenario. The 2030 scenario accounts for significant increases in load across all regions, particularly in Reykjavík (41.7 MW), and the North (23.4 MW) and South (20.9 MW) regions. However, these load increases correspond to an 11.6% rise in the North region, 17.3% in the South, and only 5.6% in Reykjavík. The East region accounts for a lower total increase in load with 17 MW, representing a 2.6% increase regarding the reference scenario. While the Westfjords region accounts for a relatively moderate total increase in load with 8.9 MW, the region experiences a major load increase with 17.3% regarding the baseline case. Lastly, the West region accounts for the lowest increase in load, with only 7.4 MW and a 1.1% increase compared to the reference scenario.

In terms of generation, the South region experiences the highest additional generation dispatch output with an increase of 79.8 MW, representing a rise of 5.6% compared to the reference scenario. This result is aligned with the significant increase in additional load, which reflects the region's capacity to meet additional demand with local generation. The North region accounts for the second largest increase in generation with 29.8 MW (11.1% variation). The East also experiences a moderate generation increase of 2.9%, which is aligned with its regional load variation. Finally, the Westfjords, West and Reykjavík regions do not account for any additional generation due to reaching peak generation already in the baseline scenario. This indicates that these regions may solely rely on generation from other regions to

accommodate the increase in demand. As explained in Section 2.3.2, the generation results are determined through LOPF and solely controlled by capacity limitation for both transmission and generation. Overall, the 2030 scenario accounts for an increase of 4.8% (119.3 MW) in total power demand and 5.1% (129.1 MW) in total power generation.

Table 5. Regional distribution of additional load and generation in the 2030 BET scenario

Region	Additional load (MW)	Load variation 2030 vs reference (%)	Additional generation (MW)	Generation variation 2030 vs reference (%)
Reykjavík	41.7	5.6%	0	0%
West	7.4	1.1%	0	0%
East	17.1	2.6%	19.4	2.9%
North	23.4	11.6%	29.8	11.1%
South	20.9	17.3%	79.8	5.6%
Westfjords	8.9	17.3%	0	0%
TOTAL	119.3	4.8%	129.1	7.5%

Figure 9 illustrates the impact of the additional loads from the 2030 electricity consumption forecast on the power flow and generation output across Iceland. The thickness of the lines represents the relative magnitude variation in power flow through each line, while the colour indicates increments or reductions in power flow. Similarly, Figure 9 also shows the differences in generator output, using size and colour to represent the magnitude variation of generator dispatch. Only generators that showed variation between the two analysed scenarios are represented in the figure.

The results show that power flow generally increases across Iceland to cope with the additional loads from the 2030 scenario. The main power flow increases can be observed in the Reykjavík and West regions due to the increase of general power demand in this populated area. The power flow in the Westfjords also increases considerably, with the national grid being used to supply power to the increased regional demand.

In addition to the generators that were already at maximum power output in the reference scenario, the outcomes for the 2030 scenario show significant increases in power generation in Búðarháls (BUD), Krafla (KRA), Þeistareykir (THR), Fljótisdals (FLJ), and Lagarfoss (LAG). BUD accounts for the highest increase in power output with 33.6 MW.

Although the power flow results also show increases in most lines, there are a few reductions in power flow, as illustrated in Figure 9. The most unexpected result may be the power flow drop in the lines leading to Djúpvogur (DJU) in the East region. Nevertheless, this could possibly be explained by the way AC power flow is solved in PyPSA. In AC power flow, voltage magnitude and phase angle differences determine the power flow through lines. Changes in load distribution, such as the ones made in the 2030 scenario, can shift the phase angle balance in the network, altering the path of power flows. In the 2030 model, the increased loads around the grid might cause a redistribution of flows, reducing the phase angle difference across the two lines leading to the substation. As a result, these lines carry less power, even though the local load at the substation has increased.

The increase in general power demand also caused additional voltage violations across the national grid. These violations appeared at the substations in the Westfjords at Patreksfjörður (PAT), Bíldudalur (BIL), and Keldeyri (KEL), in the North at Blönduós (BLO), and in the South at Flúðir (FLU) and Hnappavellir (HNA). The results from the power flow analysis also indicate a sole overloaded line, AK1, in the West region.

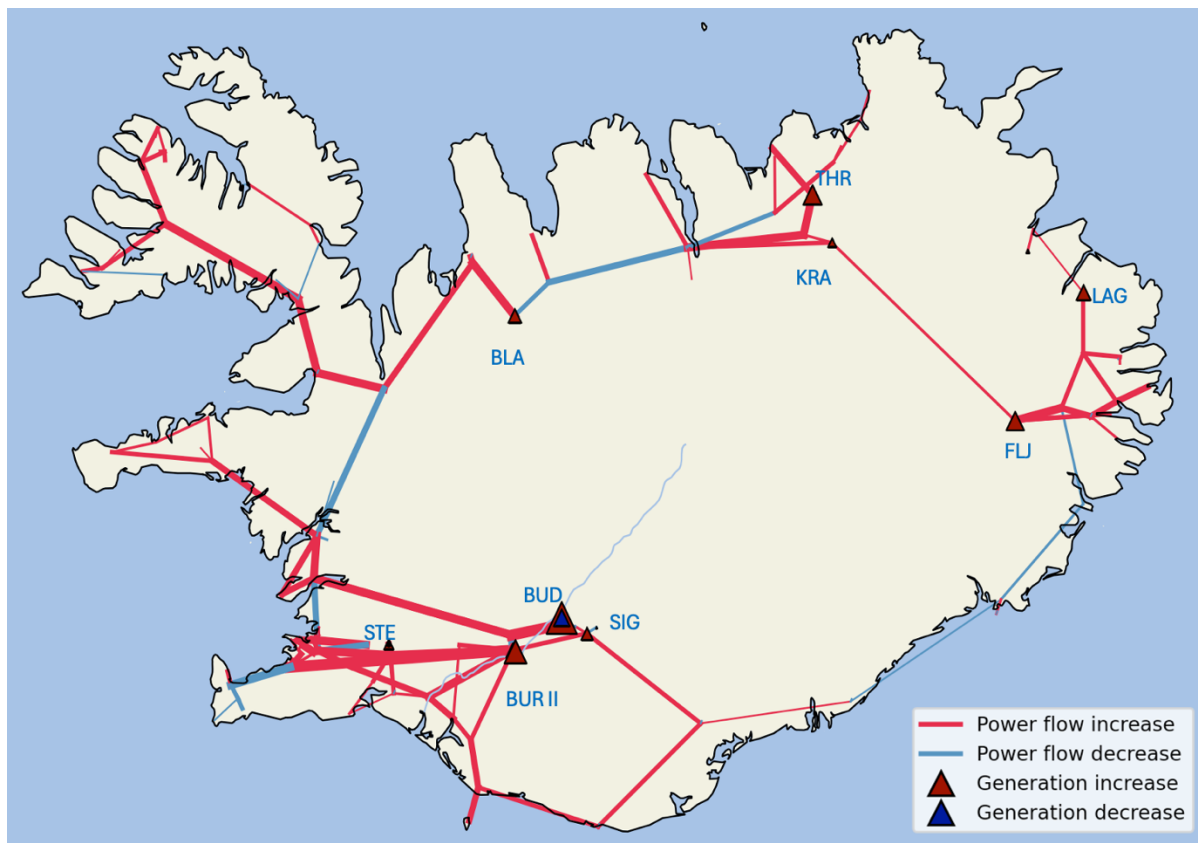


Figure 9. Power flow and generation variation in the 2030 scenario compared to baseline

3.2.3. 2030 BET scenario

This section presents the results of the 2030 BET scenario, which integrates the BET charging loads defined in Section 3.1 on top of the electricity consumption forecasts for 2030 in the power flow simulation.

Figure 10 shows the variations in power flow and generator output in the 2030 BET scenario compared to the reference scenario. The additional BET charging loads are also illustrated in the figure, whose relative magnitude is reflected through the size of the loads. Figure 10 shows the overall increase in power flow compared to the 2030 scenario, which can be observed in most lines leading to the FCS. The results show that the role of generators changes in the 2030 BET scenario as Sigalda (SIG), Krafla (KRA) and Búðarhals (BUD) increase their contribution to take on the additional load, while Búrfell II switches to a more secondary role.

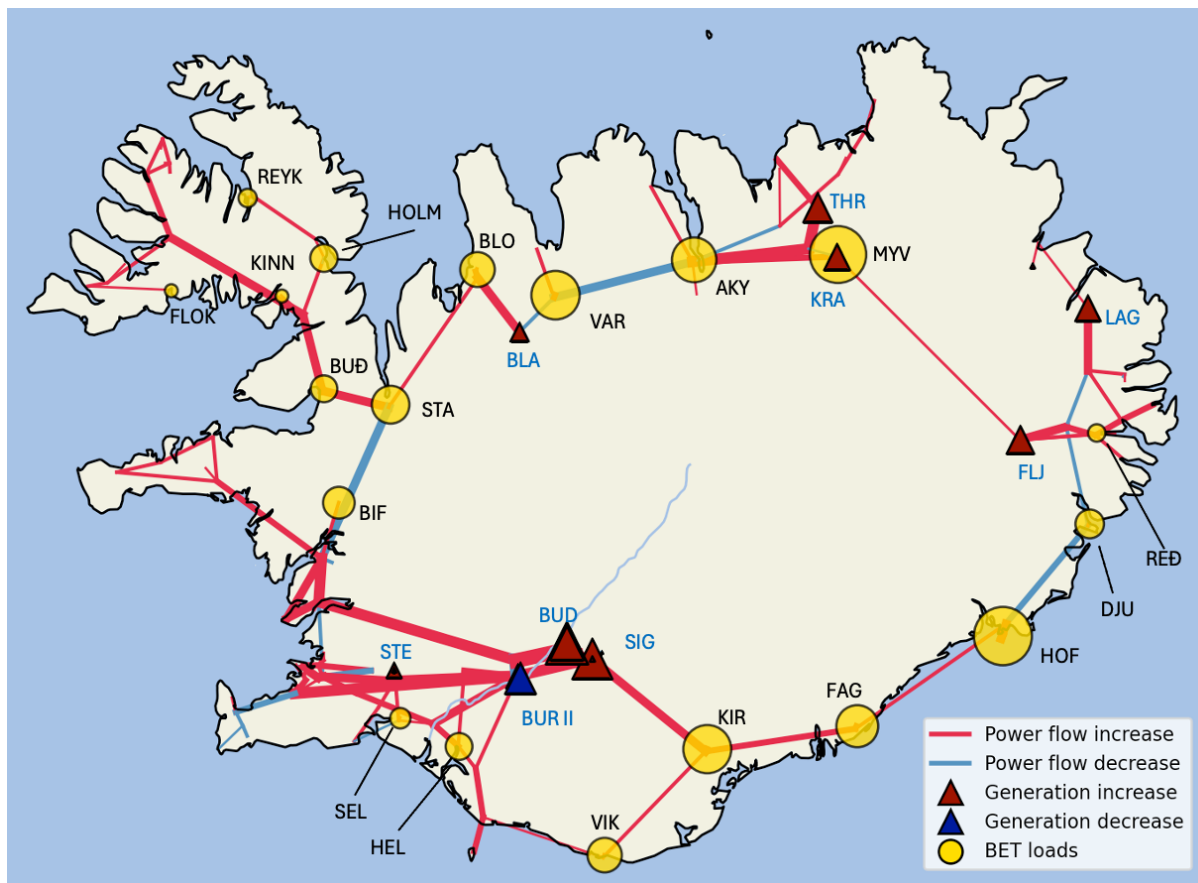


Figure 10. Power flow and generation variation in the 2030 BET scenario compared to the reference scenario

Table 6 shows the distribution, magnitude, and implications of the additional BET charging loads on the power grid. As it can be observed in Table 6, the distribution of BET charging loads across the analysed routes highlights significant regional variations. For instance, since only overnight slow-charging is assumed in Reykjavík, it does not result in BET fast-charging loads, while the North and South regions account for majority of the total BET charging demand. The North and South account for the highest shares of BET charging demand relative to their total 2030 regional electricity demand, with the South at 14.1% and the North at 9.8%. In contrast, the West, East, and Westfjords regions have relatively smaller contributions to the total BET charging demand, with shares ranging from 4.1% to 8.8%. However, their share of BET charging loads relative to total regional electricity demand suggests that even these smaller contributions could stress localised grids, particularly in the Westfjords (7.8%).

Table 6 shows that BETs fast-charging loads will increase the regional load considerably during peak demand periods. The most affected regions are the South, where BET charging loads could increase the load up to 16.5%, followed by the North, with a 10.8% increase in load, and the Westfjords, with a 8.5% increase.

The results also suggest that the power generation required to meet the additional BET charging loads will be distributed over several regions, with the North accounting for the largest increase in production with 6.1%, followed by the South with 2.3%, and the East with 1.5%. Overall, the BET charging loads represent a 2.3% increase in the total generation.

Table 6. Distribution of BET fast-charging loads, magnitude, and regional implications of the 2030 BET scenario. The variations in load and generation are calculated comparing the 2030 BET scenario with the 2030 scenario.

Region/ Parameter	BET fast-charging loads (MW)	BET fast-charging load over total regional electricity demand in 2030 (%)	Increase in load vs 2030 scenario	Increase in generation vs 2030 scenario
Reykjavík	0	0%	0%	0%
West	2.4	0.3%	0.3%	0%
East	2.7	0.4%	0.4%	1.5%
North	24.3	9.8%	10.8%	6.1%
South	23.4	14.1%	16.5%	2.3%
Westfjords	5.1	7.8%	8.5%	0%

Lastly, Figure 11 shows the voltage and line violations in the 2030 BET scenario. In the 2030 scenario, six voltage violations had already been detected. The 2030 BET scenario results in seven additional voltage violations in Reykjanes (REYK), Nauteyri (NAU), Holmavík (HOLM), Staður (STAD), Þverárvirkjun (THV), Flókaludur (FLOK), Myvatn (MYV) and Höfn (HOF). Figure 10 shows that most voltage violations occur in the Westfjords area, although voltage violations are also in the north and south regions.

Out of the 13 voltage violations identified, over half occur in substations with a BET charging station directly connected. Like in the 2030 scenario, the results from the power flow analysis indicate a sole overloaded line, AK1, in the West region.

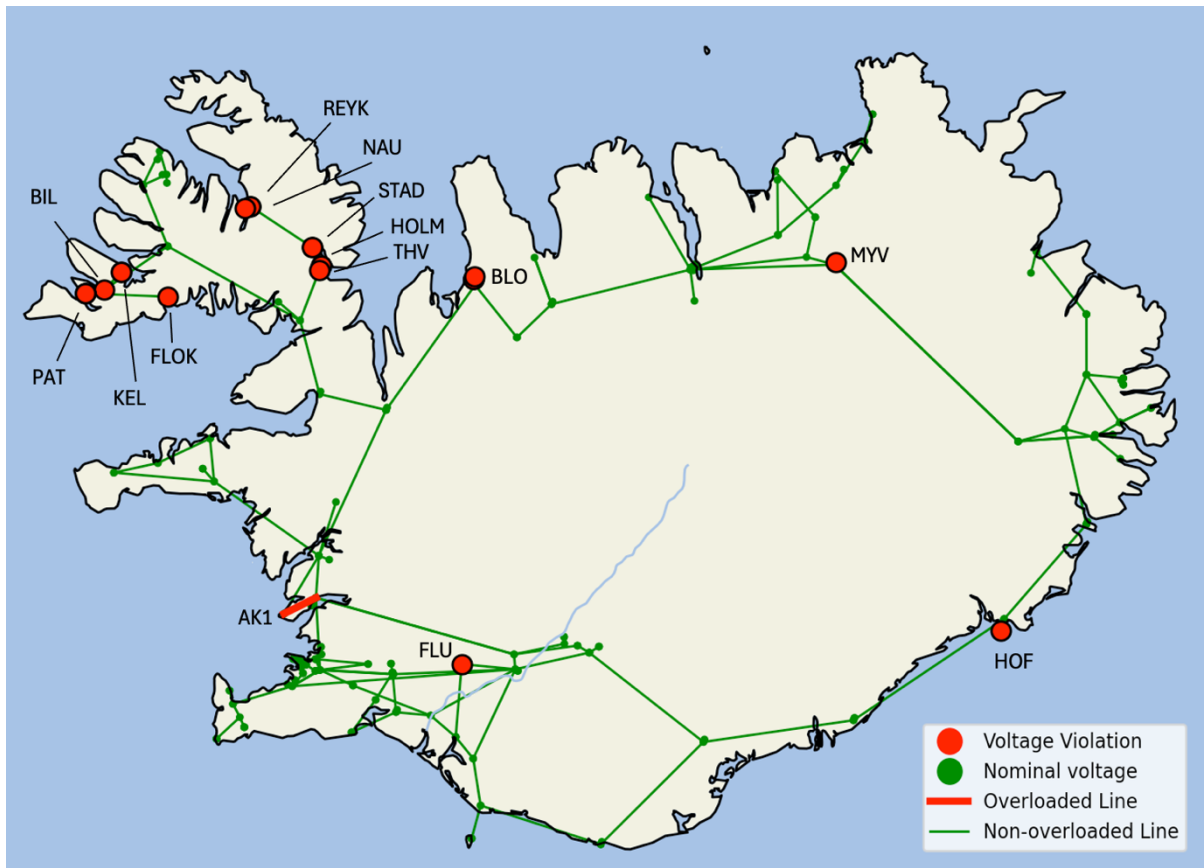


Figure 11. Voltage and lines violations in the 2030 BET scenario

3.2.4. Summary of results

Table 7 summarises the voltage and line violations and the total load and generation for the reference scenario, 2030 scenario, and 2030 BET scenario. The results suggest that the number of voltage violations will increase along with the demand, with the 2030 BET scenario accounting for the largest number of voltage violations in the power grid. The results also suggest that the overall increase in electricity consumption assumed in the 2030 scenario may lead to overloaded lines. Nevertheless, Table 7 indicates that while adding BET charging loads do not cause further critical problems in the lines, these contribute to higher flows on several lines and may aggravate existing bottlenecks.

Table 7. Summary of voltage violations, overloaded lines, and total load and generation for the different scenarios addressed

Parameter/Scenario	Reference	2030 scenario	2030 BET scenario
Voltage violations	2	6	13
Overloaded lines	0	1	1
Total load (MW)	2,484	2,604	2,661
Total generation (MW)	2,554	2,683	2,745

4. Discussion

4.1. Impacts of the combined 2030 and BET loads on the current power grid and operational challenges

The power flow analysis indicates that the projected 2030 demand, driven by both general load growth and BET fast charging, will create significant operational stress on the Icelandic grid, primarily through voltage violations. While transmission and distribution lines are largely sufficient, local bottlenecks emerge, most notably the overloaded line to Akranes and substations in the Westfjords. These findings highlight that system stability in 2030 will depend not only on managing peak demand but also on reinforcing vulnerable regions of the grid.

The power flow analysis outcomes revealed that the increased loads projected for 2030, driven by both general demand growth and BET fast charging, pose significant operational challenges for the current power grid. This increase in power demand causes voltage violations, which is aligned with Haraldsson (2020) and Apiyo (2019) and points out potential congestion issues in the power grid. The results are based on distributed generation approach to cope with the new demand from the 2030 BET scenario, which may be the most optimum way of operating the existing system while resulting in the minimum system impact. Other studies, such as those by Apiyo (2019), investigated different approaches, such as installing a new power plant that takes up the new load.

Table 7 indicates that the increasing loads from general consumption may lead to voltage instability across the national grid, which only gets more pronounced with the addition of BET charging loads, which is aligned with Dharmakeerthi et al., (2014). This implies the critical need to reinforce the grid to ensure system stability. The results also suggest that current transmission and distribution lines are capable of meeting the increasing loads, even with BET charging loads, provided that the overloaded underground line to Akranes can be managed. In addition, Table 7 highlights that the incorporation of BET charging loads does not cause any additional critical problems in the power grid lines.

Figure 10 shows that most of the identified voltage violations at substations in the 2030 BET scenario occurred in the Westfjords, which suggests that the region will likely require the most upgrades and strategic planning to accommodate both the projected increases in

electricity consumption and the peak charging demands associated with BETs.

The Reykjavík region shows no component violations of any sort despite the significant general increase in power demand in the area. These results emphasise the good state of the regional grid in the Reykjavík area, which is handling well the additional load. Similarly, the East region does not show any component violations, which could be explained by the region's relatively moderate increase in general electricity consumption and BET charging demands. According to the results of the analysis, the only overloaded line is AK1 in the West region, which suggests that this region could face considerable challenges to accommodate the forecasted increase in power demand. Lastly, both the North and South regions account for two voltage violation points, which could be explained by the significant increase in both general power demand and the BET charging loads. As shown in Table 6, the North and South regions account for most of the total charging demand from battery-electric trucks.

Overall, the results of this analysis indicate that most component violations are localised in the Westfjords and FCSs, which could be managed through strategic planning aiming to mitigate grid constraints and ensure power flow stability. BET charging loads should be considered when planning future grid developments, and the design of FCS should be aligned with the limitations of the power grid (Shafiei & Ghasemi-Marzbali, 2023).

The potential mitigation strategies discussed in this section are presented at a high-level scope to illustrate possible pathways for supporting BET charging in Iceland. Detailed assessments of localised renewable deployment fall outside the scope of this analysis and are identified as an area for future research.

4.2. Potential mitigation strategies

As explained in the previous section, voltage, line and transformer constraints emerged as critical concerns, particularly in the remote regions of the Westfjords, where grid connectivity is limited. To address these challenges, mitigation strategies such as voltage support devices (e.g., shunt capacitors or synchronous condensers) and transformer capacity upgrades may be necessary (Apiyo, 2019).

The integration of localised renewable energy generation and power storage solutions could also prove helpful in tackling the operational constraints identified in this study. Installing relatively small renewable generation capacity (e.g. wind power) close to main demand points, such as the substations handling the new BET charging stations, could potentially improve the overall power grid performance (Apiyo, 2019). Meeting the BET demand with localised generation could potentially reduce transmission losses and alleviate stress on long-distance lines (Shafiei & Ghasemi-Marzbali, 2023).

On-site battery storage could also help balance peak demand at the FCS, particularly in regions with limited grid capacity like the Westfjords. The on-site storage could be an effective solution to reduce the need for potential upgrades in the distribution lines feeding the charging station. In addition, on-site battery storage could be tailored to the demand of each location, adjusting the installed power storage capacity based on the forecasted peak demand of each FCS (Mouratidis, 2024).

Overall, the results of this analysis suggest that grid upgrades or on-site solutions will be necessary to electrify the long-haul road freight transport in Iceland while accommodating the forecasted increase in electricity consumption.

4.3. Limitations

While this study provides valuable insights into the potential impacts of future 2030 loads and additional BET charging demands on Iceland's power grid, several limitations must

be acknowledged.

A significant limitation lies in the data collection process for the assessment, which did not include the resistance and reactance values for transformers. This prevented the accurate modelling of transformer behaviour under various loading conditions, potentially affecting the precision of the results. Another limitation of this study is the exclusion of economic motivations and operational strategies in the power flow modelling, as the power flow solutions were solely based on technical feasibility constraints. For example, the prioritisation of geothermal or hydroelectric power generation based on water reservoir levels, particularly during winter when water availability is lower, was not considered. These real-world operational factors may significantly influence the grid behaviour and could alter the results under more detailed modelling. The assumptions about the number of BETs travelling the modelled routes and their battery capacities could also represent a limitation. These assumptions were necessary due to a lack of detailed data for road freight transport activity in Iceland and may not fully capture the variability in fleet composition or operational patterns. Similarly, this study only focused on a selected set of long-haul routes, which limits the scope of the findings in understanding the broader impacts of electrified road transport on the grid. Although grid bottlenecks were identified in certain regions, the study did not delve deeply into proposing detailed mitigation strategies. Future research could investigate potential solutions such as on-site energy storage to handle peak demand, grid upgrades like line capacity improvements, or the deployment of advanced grid management technologies.

Another key limitation of this analysis is the lack of studies addressing the energy consumption of long-haul battery-electric trucks in Arctic conditions. As a result, the validation of the BET energy consumption results could only be carried out against a small number of prior publications. This limits the strength of the comparison and underlines the need for future research and data collection in Arctic environments.

Lastly, this study assumes a static representation of the Icelandic transmission grid. Planned reinforcements and expansions outlined in the 2030 energy roadmap were not incorporated into the power flow analysis. As a result, the findings reflect the current grid configuration and may overestimate future constraints. Future research should explicitly model these planned upgrades to provide a more accurate assessment of how the grid can accommodate large-scale BET charging loads. Lastly, future research should account for the planned upgrades in the Icelandic grid to better evaluate strategies to manage the BET charging loads.

These additional steps would provide a more comprehensive roadmap for addressing the challenges of increased load scenarios and BET integration. Despite these limitations, the study offers a foundational understanding of the Icelandic grid's response to future demand scenarios and highlights key areas for further investigation and improvement. Addressing these limitations in subsequent research could significantly enhance the accuracy and applicability of the findings.

5. Conclusion

This study evaluates the impact of integrating BET charging demands into Iceland's national power grid, with a focus on long-haul freight transport. The research proposes a novel approach combining detailed vehicle energy consumption models, a charging optimisation framework, and a comprehensive non-linear power flow analysis to assess the technical feasibility of electrifying long-haul freight routes in Iceland. To the best of our knowledge, this is the first study to apply such an integrated approach to assess the grid impacts of BET charging under Arctic conditions at a national-scale.

The proposed methodology (illustrated in Figure 1) uses real-world driving data to calculate BET energy consumption on the main long-haul freight routes in Iceland, using the

results to optimally allocate BET charging locations. A charging optimisation model was used to determine the correspondent charging load magnitudes for each charging location, which are simulated on the Icelandic grid using a non-linear power flow approach to identify potential component violations.

The findings indicate that charging demand from long-haul BETs will be highly uneven across the country, as more than 80% of the total BET charging demand is concentrated in the North and South regions, significantly altering the load profiles of the regions. The 2030 BET scenario shows that electrification could increase total demand by up to 16.5% in the South and 10.8% in the North relative to the 2030 baseline, reshaping regional demand profiles. Even moderate absolute charging loads can have a major impact in smaller regions such as the Westfjords, where an 8.5% increase adds pressure to an already constrained grid.

The results also highlight that the increase in general power consumption may contribute to voltage instability across the national grid, a challenge that becomes more pronounced with the addition of BET charging loads. Although BET loads do not introduce new line overloads beyond those projected in the 2030 scenario, they raise flows on multiple lines, aggravating weaknesses where the grid is already constrained. Among all regions, the Westfjords experience the most significant difficulties in accommodating rising power demand, as the area's limited grid capacity results in the highest incidence of voltage violations.

The outcomes of this analysis underscore that electrifying long-haul road freight transport in Iceland is technically feasible, although strategic planning will be essential to address regional grid constraints, particularly in the Westfjords and other grid-sensitive areas. Mitigation strategies such as voltage support devices, on-site battery storage, and localised renewable energy generation could be potential solutions to ensure grid stability while supporting BET operations and increased power demand. Overall, these findings provide an integrated perspective that is critical for policymakers and grid operators, as it highlights where BET charging will most strongly affect the grid and what mitigation strategies may be needed. Future research should deepen the analysis of mitigation strategies, including the deployment costs and capacity sizing of on-site renewable capacity and battery storage, as well as the evaluation of demand-side options such as smart charging. It should also address the economic aspects of grid operation and upgrade costs, taking into account Iceland's planned grid reinforcements. In addition, future studies should assess the total system costs of BET deployment and compare them with alternative decarbonization pathways, such as hydrogen fuel-cell trucks.

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6. Discussion

The road freight transport sector is critical to achieving a sustainable transition from fossil fuels, whose environmental impact has been under scrutiny in recent years. Consequently, regulators have enforced stricter GHG emission limits for freight vehicles (European Commission, 2019), and many countries worldwide have established targets aiming at the decarbonisation of the sector to reach the objectives of the Paris Agreement, including carbon neutrality objectives (UNFCCC, 2015) or other goals related to climate change (Kluschke et al., 2019). Heavy-duty Duty Vehicles (HDVs) play an indispensable role in the global economy, facilitating the transportation of goods across diverse and challenging contexts. However, their reliance on fossil fuels has resulted in substantial emissions, contributing to climate change, pollution, and dependency on imported fuels. Additionally, the technical demands of HDVs are characterised by long travel distances, heavy payloads, and tight schedules, which makes their decarbonisation more complex compared to light-duty vehicles. While improvements in powertrain efficiency and optimisation of freight routes can reduce emissions, these measures alone are insufficient to achieve deep GHG emission reduction (European Commission, 2019). Consequently, alternative fuels have gained significant attention due to their potential to reduce emissions (Stančin et al., 2020) while complying with the technical demands of heavy transport (Forrest et al., 2020).

Among the available alternatives, BETs are considered a viable solution to reduce emissions and fossil fuel dependency in the freight transport sector (Transport and Environment, 2022). However, their adoption remains low, with only 0.4% of new medium and heavy-duty truck registrations in the EU in 2020 being electric powertrains such as BET and FCT. This low uptake is primarily explained by high capital costs (Transport and Environment, 2022) and uncertainties around the technical capacities of electric HDVs regarding driving range (Melander et al., 2022), payload capabilities (Khani and Emami, 2022), potential additional time losses due to recharging (Qasim and Csiszar, 2021), and infrastructure availability (Imre et al., 2021), among other barriers.

A major challenge in the transition to alternative fuel HDVs is the uncertainty in selecting the most viable solution and designing the implementation strategy effectively. Making premature decisions without comprehensive feasibility assessments can lead to costly and time-consuming mistakes that could slow down or even halt the transition process. Thus, minimising uncertainties through data-driven modelling approaches is crucial. The use of methodologies such as LCA, TCO, and vehicle and power grid simulation frameworks, as demonstrated in the research, enables stakeholders to assess the feasibility of alternative fuels from technical, environmental, and economic perspectives. These models provide critical insights into fuel performance under real-world conditions, infrastructure needs, and the systemic impacts of adopting new technologies. Without a robust planning framework, the transition to alternative fuel HDVs could face significant setbacks, including underutilised infrastructure, unexpected operational challenges, and financial burdens on stakeholders. Proper planning through the application of comprehensive feasibility assessments ensures that decisions are made based on evidence, reducing the risk of project failure and optimising the allocation of resources.

This thesis works with Iceland as a case study. It provides a comprehensive evaluation of alternative fuel powertrains to identify the most suitable solution for decarbonising road freight transport, incorporating environmental, economic, and technical assessments. The transition in Iceland is particularly complex due to the harsh climate, sparse population, and ageing infrastructure. While the country's abundant renewable energy resources offer a significant opportunity to move away from fossil fuels in the freight sector, the shift requires a thorough understanding of technical feasibility and infrastructure needs. This thesis addresses key concerns regarding the feasibility of decarbonising freight transport in Iceland

by defining the research goals and questions outlined in Section 1.2. Section 5.1 details the research questions and provides answers to each individually. Lastly, the thesis evaluates the overall feasibility of achieving a decarbonised freight transport sector in Iceland.

5.1 Overall feasibility of BET to decarbonise freight transport in Iceland

RQ1: Given the technical demands of HDV in Iceland, what alternative fuel powertrain represents the most feasible solution to transition away from fossil fuels in terms of GHG and air pollutant emissions and total cost of ownership?

Paper I evaluated the technical, environmental, and economic feasibility of using various alternative fuel powertrains to decarbonise the road freight transport sector in Iceland. These alternative fuels included battery-electric trucks (BETs), hydrogen fuel cell vehicles (FCVs), biodiesel, renewable diesel, compressed natural gas (CNG), and liquefied natural gas (LNG). The case-study design considered the unique conditions of Iceland, including its low-carbon electricity, available local feedstocks, and HDV activity.

The results showed that BETs stand out as the most environmentally and economically feasible option to decarbonise freight transport in Iceland in terms of GHG and air pollutant emissions, TCO, and impact on energy security. However, BETs range limitations and high initial capital costs were identified as challenges, particularly for long-haul applications, a common drawback of battery-electric powertrains in the literature (Melander et al., 2022).

The outcomes of this first assessment indicated that the LCA and TCO results are very context-dependent, varying greatly depending on the regional case study, including HDV application and carbon intensity of the power grid (Lajevardi et al., 2019). While the GHG emission reduction achieved by BETs is mostly aligned with the literature (Sen et al., 2017; Lajevardi et al., 2019), Paper I found that the magnitude of emissions reduction was significantly accentuated by Iceland's near-zero carbon electricity grid. Furthermore, BETs showed competitive TCO compared to other alternatives, mostly due to Iceland context-specific significant low electricity prices. This result is aligned with Sen et al., (2017).

RQ2: To what extent do climate and freight conditions impact the electrification potential of heavy-duty vehicles?

The outcomes of Paper II showed that climate, freight demands, and route characteristics significantly influence the electrification potential of HDVs. Paper II quantified the impact on BET performance of sub-zero temperatures, strong headwinds, heavy payloads, tail-lift use, as well as the type of route. The increase in BET energy consumption also intensified the on-route charging demands, making the integration of long-haul BETs particularly challenging in climate contexts like Iceland.

The analysis showed that combined factors could potentially lead to a range reduction of approximately 41-47% on BETs driving in downtown routes, compared to standard operational scenarios. The impact of these factors on BETs travelling regional routes was smaller, resulting in a range decrease of 34-38%.

Moreover, the study highlighted the critical role of infrastructure in mitigating these challenges. Therefore, on-route charging infrastructure needs to account for both the increased energy consumption of BETs and the operational variations caused by weather variability. Paper II showed that low temperatures and battery SOC can significantly reduce the charging capacity of on-route chargers, leading to unexpectedly longer charging times and reducing the overall feasibility of meeting freight operations.

RQ3: Considering unfavourable climate conditions, to what extent can the case study freight activity be carried out with battery-electric trucks?

The outcomes from RQ2 showed that the electrification potential of HDVs is highly dependent on route characteristics, vehicle specifications, and climate conditions. The case study of Ölgerðin's fleet provided valuable insights into how these factors influence the feasibility of using BET for freight operations under the challenging conditions found in Iceland.

Paper II revealed that BETs are well-suited for short and medium-haul routes. The results indicated that BETs with bigger battery capacity could meet all downtown and suburban trips without significant route adjustments or on-route charging, even under challenging scenarios. However, regional routes (referred to as out-of-town in Paper II) were found to pose greater challenges. High-battery capacity BETs proved capable of meeting regional routes, requiring only occasional charging under challenging conditions. In contrast, BETs with lower battery capacities showed significant reliance on on-route charging across all scenarios, including relatively favourable ones. This dependency on on-route charging would likely require route adjustments, particularly on BETs with ageing batteries. The results also suggested that small battery-capacity vehicles, such as delivery vans, would have their applications limited to downtown routes.

Paper II also addressed the environmental and economic implications of transitioning towards an electric HDV fleet from the perspective of the fleet operator, in this case, Ölgerðin. The results suggested that replacing a single diesel semi-trailer with an electric equivalent could imply significant economic benefits and emission savings for the fleet operator. The highly decarbonised national grid and low electricity costs are crucial in these savings, highlighting the advantages of Iceland's renewable energy infrastructure and BETs.

Overall, the findings suggest that short-haul freight transport electrification in Iceland is feasible, even in harsh climates and demanding freight conditions. However, Paper II found that the electrification of long-haul freight presents significant challenges and may require investments in high-power charging infrastructure.

RQ4: What are the charging network requirements to support a 100% battery-electric heavy-duty vehicle fleet in the Reykjavík-Westfjords route?

By addressing RQ4, Paper III laid the foundations for developing an optimisation model to calculate the BET fast-charging requirements along the freight routes in Iceland. The on-route charging infrastructure required to support BETs on the Reykjavík-Westfjords routes should consider the varying battery capacities and the operational conditions of the vehicles. The outcomes from the charging optimisation model developed in Paper III showed that BETs with relatively small battery capacities (360-kWh) would require at least five fast-charging stations to cover the routes, which would be placed around 109 km apart on average, with a maximum gap of 136 km between Ísafjörður and Reykjanes. For vehicles with a larger battery capacity (540-kWh), only three FCSs would be needed, located around 156 km apart on average and with a maximum distance of 172 km between Búðardalur and Flókalundur, which may necessitate emergency charging options to address potential performance drops or unforeseen events.

Mandatory rest regulations, which require a 45-minute break every four hours of driving, provide an opportunity to integrate charging sessions and reduce the impact on total route time. In this context, BETs with 540-kWh batteries and 500-kW charging capacity stand out as the most favourable combination, as the necessary charging sessions would only add 25 minutes to the total routing time. Smaller battery configurations and lower charging rates would result in significant increments in routing time of over an hour, requiring significant

routing adjustments to fit the required charging sessions to meet the route. Overall, the insights provided in Paper III emphasise the importance of aligning charging infrastructure with battery capacity and operational constraints to ensure a functional and efficient network.

RQ5: How can fast-charging infrastructure for battery-electric trucks be optimally designed to support long-haul freight operations in remote and rural regions with harsh climate conditions?

Designing fast-charging infrastructure for battery-electric trucks in remote and rural regions such as Iceland requires careful consideration of location, resilience, and operational efficiency. Paper III used the charging optimisation model proposed to minimise the number of charging stops, while queuing theory was used to balance accessibility and demand under different charging power assumptions. In the context of Iceland, relatively high freight traffic routes would require stations with greater charging capacities to meet the operational demands and avoid queuing. The charging infrastructure optimisation results with 540-kWh BETs suggested fewer but busier stations, which could reduce FCS infrastructure costs while maintaining operational efficiency. However, this approach would lead to higher peak demands and charging load magnitudes, which would pose additional stress on the power grid and potentially lead to upgrade requirements in the transmission and distribution grid. The results from Paper III showed that the distribution of the charging loads from BETs is strongly linked to the BET battery capacity, while the number of required charging plugs per station is linked to the charging power. Additionally, the charging network's operational resilience and robustness are emphasised by considering adverse climate and freight conditions in the BET energy consumption and optimisation models. Overall, the charging network design approach proposed in Paper III can be useful for the early introduction of BETs in remote regions such as the Westfjords.

RQ6: What are the impacts of fast-charging BET loads on the Icelandic power grid?

The integration of fast-charging battery electric trucks (BETs) into the Icelandic power grid presents several challenges and potential impacts, as outlined in Paper IV. The increased electricity demand from BET fast-charging stations, combined with the forecasted rise in national power consumption by 2030, is expected to result in voltage violations and line overloading in the current grid infrastructure. These challenges are further exacerbated by the uneven geographical distribution of on-route fast-charging demand, with the North and South regions accounting for over 80% of the total BET-related electricity consumption.

The analysis reveals that in the 2030 BET scenario, the total load on the grid would increase significantly, contributing to voltage instability, particularly in areas with limited grid capacity, such as the Westfjords. This region exhibits the highest concentration of voltage violations, suggesting that the Westfjords may need the most grid reinforcements to maintain stability.

Furthermore, the study indicates that the current transmission and distribution networks can handle the increased loads. Despite the anticipated increase in electricity consumption, the results from Paper IV indicate that incorporating BET fast-charging loads does not introduce additional critical failures in the power grid.

In conclusion, while the outcomes suggest that the electrification of long-haul freight transport in Iceland is technically feasible, it will require strategic planning and investments in grid upgrades to address potential challenges. The findings underscore the importance of adopting a coordinated approach to infrastructure development to ensure the successful integration of BETs into the Icelandic power grid.

What's the overall feasibility of BETs to decarbonise freight transport in Iceland?

The findings of this thesis indicate that BETs represent the most feasible solution for decarbonising freight transport in Iceland, primarily due to the country's near-zero carbon electricity grid and relatively low electricity costs. BETs demonstrate a clear advantage over other alternative powertrains in terms of GHG emissions, TCO, and energy security. However, while their feasibility is strong in short and medium-haul applications, significant challenges remain for long-haul operations, particularly under Iceland's demanding climatic and freight conditions.

The research highlights that Iceland's cold temperatures, strong winds, and heavy payloads significantly impact BET energy consumption, reducing vehicle range by up to 47% in extreme conditions. This increased energy demand outlines the need for a well-planned on-route charging network, as long-haul BET operations would be highly limited without a supporting charging infrastructure. The optimisation model developed in this thesis demonstrates that strategic placement of fast-charging stations can enable long-haul BET operations without substantially disrupting freight operations, but this would require significant investment in infrastructure.

For short and medium-haul routes, BETs are highly feasible. Vehicles with larger battery capacities can operate effectively without major route modifications or excessive reliance on on-route charging, even under challenging conditions. However, smaller battery-capacity vehicles may be limited to urban deliveries. Fleet-level analysis suggests that transitioning towards BETs can offer substantial economic benefits for freight operators due to lower energy costs, reinforcing the economic feasibility of electrification in Iceland's context.

The integration of BETs into Iceland's power grid is technically feasible but will require strategic grid reinforcements, particularly in regions with limited capacity such as the Westfjords. Although the overall grid can accommodate the additional electricity demand, localised investments will be required to prevent voltage instability and network congestion in constraint areas.

In summary, the electrification of freight transport in Iceland is highly feasible for short and medium-haul applications, with clear environmental and economic benefits. However, for long-haul operations, feasibility is contingent on the development of a robust fast-charging network and targeted grid reinforcements. The success of BET deployment will depend on a coordinated approach involving infrastructure investment, policy support, and operational adjustments to address the challenges posed by Iceland's unique climate and freight conditions.

5.2 Main contributions of the thesis and practical implications

This thesis makes several key academic contributions to the field of sustainable freight transport, particularly in the performance of battery-electric powertrains in regions with harsh climates. These contribute to meet the identified research gaps in the literature, including alternative fuel HDV powertrain assessments, climate influence on BET performance, and BET integration implications on the power grid.

This study provides a comprehensive assessment of BETs as a decarbonisation solution for freight transport in Iceland, considering technical, environmental, and economic factors. Unlike generalised assessments that focus on broader European or North American contexts, this research offers a case study in a region with near-zero carbon electricity, harsh climate conditions, and a relatively small yet geographically challenging freight network. The findings highlight the extent to which regional characteristics influence BET viability, contributing to

the academic discourse on the context-dependence of sustainable transport solutions. In addition, by using Iceland as case study, this research provides insights into the implications of transitioning towards BETs in regions with a highly decarbonised electricity mix. As the global electricity production sectors shifts from fossil fuels, this study offers a forward-looking perspective of the advantages of BETs over other alternative fuels, highlighting their potential benefits in a future with a high share of renewable and low-carbon electricity.

Another significant contribution of this research is the quantification of adverse climate and freight conditions over BET energy consumption and operational range. By calculating the range reduction associated to low temperatures, headwinds, tail-lift usage, heavy payloads, as well as the combined effects of these factors, this research provides valuable insights on the challenges of road freight transport electrification in regions with Arctic-like climates. As the literature review from Paper II revealed, not many studies consider the range variation of BETs when evaluating their technical capability to meet freight demands. Therefore, this research expands the existing literature on BET performance by providing a deeper understanding of their operational feasibility in real-world freight activities under demanding conditions. These insights are especially useful for fleet operators considering the integration of BETs into their fleets but uncertain about their operational capability in challenging conditions. The collaboration with Ölgerðin is a great example, whose freight activity was used as a case study for our research purposes in Paper II. The results of our study, which were presented in detail to the company, provided valuable insights that directly informed their decarbonisation strategy. As a result, Ölgerðin recently incorporated several battery-electric trucks into their fleet, demonstrating the practical impact of this study in guiding fleet electrification investments.

This research also contributed to enhancing the understanding of the interaction between BET adoption and power grid stability, which has been mostly overlooked in the literature. Although some studies addressed similar fast-charging conditions for passenger vehicles, including high-power and concentrated inflexible demand, the literature has not exclusively studied the impacts of BET fast-charging loads. By modelling the grid impacts of BET fast-charging demand, this thesis provides insights into the potential voltage violations and power line network stress, which contribute to the discussion of the grid planning role in transport decarbonisation. Specifically, this thesis highlighted the regional disparities of fast-charging demand along the main freight routes in Iceland and identified the regions which will potentially require the most infrastructure upgrades. These contributions provide crucial information for stakeholders working towards freight transport decarbonisation in Iceland, including grid operators and policymakers, which could be used to guide infrastructure investments.

The insights provided by this thesis could be used to inform investments and policy development aimed at decarbonising road freight transport in Iceland and regions with similar conditions. In particular, the outcomes of this thesis could be used to develop a technology roadmap for battery-electric trucks, similar to the hydrogen and e-fuels roadmap report developed by the Ministry of Environment, Energy and Climate in Iceland. The insights of this thesis could be used to inform a phased implementation strategy for BETs, prioritising BET deployment for short and medium-haul freight, where operational feasibility is the highest, while proposing a gradual long-haul BET roll-out aligned with infrastructure goals. The thesis outcomes in BET fast-charging requirements provide a foundation for planning a nation-wide BET fast-charging network, outlining strategic locations of stations along key freight corridors, as well as the optimal fast-charger capacity for aligning the charging sessions duration with the mandatory driver rest periods. The roadmap could use the insights of this thesis to design pilot projects to test BET performance in long-haul applications.

Lastly, one of the main contributions of the work is the methodologies developed throughout the papers included in the thesis, which include the novel combination of detailed models on vehicle energy consumption, non-linear charging, charging infrastructure

optimisation, and power flow analysis. These models offer a comprehensive approach to evaluating the technical feasibility of freight transport electrification in any sort of context, including BET performance, charging infrastructure design, load profile calculation and impact on the grid. The methods used in this thesis are explained in detail in the corresponding papers and are based on open-source nature programs, which have been included in the appendix. Therefore, these methods can be used by researchers and customised to fit other contexts, contributing to the global efforts for the electrification of freight transport.

5.3 Limitations and future work

A primary limitation is the almost exclusive focus on battery-electric trucks throughout this thesis, which lacks a detailed comparison with other alternatives, such as fuel-cell trucks. After a review of alternative fuels and techniques with feasibility and economic assessment, in the first paper, a decision was made to focus on the most favourable candidate. The exclusion of other relevant powertrains in the assessments carried out in Paper II, III, and IV provides an incomplete analysis for identifying the optimal solution to decarbonise road freight transport in Iceland. The promising results of fuel-cell trucks presented in Paper I highlight the need to explore further the performance of these powertrains in Arctic-like climates, as well as the refuelling requirements of long-haul FCTs and the implications of producing hydrogen fuel to supply the road freight transport over the power grid. Similarly, other promising alternative fuel solutions for HDVs were not addressed in this thesis, such as e-fuels (i.e. methanol from hydrogen and direct carbon air capture) or catenary-electric trucks. Further research should investigate and compare the feasibility of using these solutions in HDVs. Another important limitation of this thesis is the exclusion of future improvements in powertrain technology, which could play a relevant role in their potential implementation in the near future. Advancements in battery energy density, cost reductions, and faster charging solutions (e.g. megawatt charging systems) could significantly influence the outcomes in BET feasibility. Future assessments should incorporate scenarios that consider potential developments in battery technology and hydrogen fuel production costs to provide a more comprehensive evaluation of the analysed decarbonisation pathways.

The lack of a detailed economic assessment for BET deployment remains one of the major limitations of this thesis. While this thesis includes a TCO analysis in Paper I, the economic assessment was based on current costs for alternative fuel powertrains including battery costs, electricity, fuel costs, and operational expenses, and does not account for long-term cost trends and technological developments that could influence the TCO results.

Another limitation of this thesis is the absence of the economic implications of the development of fast-charging infrastructure. The thesis lacks a detailed capital investment analysis for the charging stations, including construction and equipment costs, as well as the operational costs, with maintenance and grid connections expenses. The utilisation rates of the different charging stations may play a critical role into their individual financial feasibility, especially in low-traffic regions such as the Westfjords, potentially requiring for subsidies to ensure service in remote regions. Further investigation should be carried out to determine the total fast-charging infrastructure costs and compare it to other alternatives such as hydrogen refuelling infrastructure.

This thesis highlights potential power grid upgrade requirements to accommodate BET fast-charging loads, but it does not quantify the economic costs of the necessary grid component reinforcements. The expenses of upgrading substations, transformers, transmission and distribution lines should be addressed in further research and compared to other strategies, such as on-site storage. The total system costs, including fast-charging network and power grid infrastructure upgrades, should be compared to other alternative fuel infrastructure systems.

Another major limitation of this thesis is the no-consideration of the future power grid development specified in Landsnet's System Plan 2023-2032 which includes several grid reinforcement projects across the entire national grid (Orkustofnun, 2025). Future studies should address different power demand scenarios accounting for the planned grid developments and evaluate the impact of BET fast-charging loads.

Lastly, the availability of Icelandic-specific data on road freight activity (e.g., traffic flows) represents a limitation of this research. This thesis used several assumptions on freight activity, which were necessary due to a lack of detailed data for road freight transport activity in Iceland, which may not fully capture the variability in fleet composition or operational patterns. Additionally, this study only focused on the main set of long-haul routes, which limits the scope of the findings in understanding the broader impacts of electrified road transport on the grid.

7. Conclusion

This thesis presents a comprehensive evaluation of alternative fuel powertrains to identify the most suitable solution for decarbonising road freight transport in Iceland, including environmental, economic, and technical assessments. Based on this initial assessment, the thesis focuses on Battery-Electric Trucks (BETs) as the most promising solution to achieve the decarbonisation goals, conducting a detailed assessment of the feasibility and implications of HDV electrification in Iceland. Consequently, the thesis focuses on an in-depth feasibility analysis of BET deployment, addressing the unique challenges posed by Iceland's Arctic-like climate, geographic remoteness, and freight transport characteristics. The main goal of this thesis is to answer the question, "Are BETs a feasible option to decarbonise the road freight transport sector in Iceland?"

A comprehensive novel approach combining detailed vehicle energy consumption modelling, non-linear charging, charging optimisation, and power flow analysis is proposed and applied to assess the feasibility of BET deployment. The findings are then used to optimise charging infrastructure placement and determine charging load magnitudes, which are subsequently simulated on the national power grid using a non-linear power flow approach to identify potential system constraints. This integrative methodology provides a comprehensive understanding of the technical feasibility, infrastructure requirements, and systemic impacts of freight transport electrification, which proves essential for a successful transition to alternative fuel HDVs, as inadequate planning can lead to underutilised infrastructure, operational challenges and financial burdens. Comprehensive feasibility assessments using data-driven modelling are crucial to minimise uncertainties and avoid costly mistakes that could delay or halt such transition. This methodological approach can be summarised as a systematic process consisting of four steps: evaluate potential alternative fuel solutions based on environmental and economic implications and identify the most favourable solution/s, evaluate the powertrain performance in relevant climate and freight contexts, explore the infrastructure required to support its integration in freight transport, and lastly investigate the impacts on the power grid or other relevant infrastructures. The regional context plays a crucial role in alternative fuel HDV feasibility, making it essential to conduct tailored assessments.

The outcomes of the analysis emphasise the feasibility of electrifying road freight transport in Iceland. However, key infrastructure investments in fast-charging networks and grid reinforcements will be required to enable full BET implementation. The results highlight the crucial need to consider BET range variation under adverse conditions, which can impact the electrification feasibility of freight transport regionally and the on-route fast-charging requirements. Incorporating BET fast-charging loads into the power grid is one of the main challenges of freight transport electrification in Iceland. The main challenges arise from the

uneven distribution of charging demands, which significantly impacts the regional load profiles and causes voltage violations.

In a more general context, the insights provided by this thesis contribute to expanding the global understanding of freight transport decarbonisation feasibility, especially in remote regions with harsh climates. The methods proposed by this thesis can be adapted by researchers, policymakers and other relevant stakeholders to inform their local freight decarbonisation efforts.

Overall, this thesis highlights that while BETs offer a viable pathway for decarbonising Iceland's freight transport, strategic infrastructure planning is essential to ensure smooth integration. Investments in high-power charging stations, grid reinforcements, and load management strategies will be necessary to address the operational challenges derived from road freight electrification. The challenging conditions found in Iceland, such as the harsh climate and freight travel to remote regions, deeply influence the outcomes of this thesis. Future research should further explore the economic implications of transitioning towards electric road freight transport in Iceland, especially regarding the total system costs. A comparative study with other promising technologies, such as the fuel-cell trucks pathway, should also be carried out, considering potential advancements in battery technology or hydrogen fuel production costs.

The outcomes of this thesis directly contribute to Iceland's Climate Action Plan goals in GHG emissions reduction and Iceland's sustainable energy transition. The outcomes also support several UN Sustainable Development Goals (3, 7, 8, 11, 12, 13) and aid with the fulfilment of the Paris Agreement.

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9. Appendix

9.1 Charging optimisation model

Charging optimisation model

#Optimisation model. Code example for the IFJ-RVK route using a 540 kWh BET and 350 kW charger

```
import gurobipy as gp
from gurobipy import GRB
```

```
# Data
```

```
I = [1, 2, 3, 4, 5, 6, 7] # Charging locations
```

```
J = [1, 2] # Number of breakpoints/segments on the nonlinear charging curve
```

```
f = 10 # Time needed to start and finish each charging stop [minutes]
```

```
# Number of kw added to the battery per minute of charging at location i within segment j
```

```
ch = [[7.48, 3.74],
      [7.48, 3.74],
      [7.48, 3.74],
      [7.48, 3.74],
      [7.48, 3.74],
      [7.48, 3.74],
      [7.48, 3.74],
      [7.48, 3.74]]
```

```
# Max SOC of segment j at location i [kwh]
```

```
cu = [[461.7, 513],
      [461.7, 513],
      [461.7, 513],
      [461.7, 513],
      [461.7, 513],
      [461.7, 513],
      [461.7, 513],
      [461.7, 513]]
```

```
# The max charging in kwh added to SOC in segment j at location i [kwh]
```

```
charg = [[461.7, 51.3],
         [461.7, 51.3],
         [461.7, 51.3],
         [461.7, 51.3],
         [461.7, 51.3],
         [461.7, 51.3],
         [461.7, 51.3],
         [461.7, 51.3]]
```

```
soc0 = 513 # Initial state of charge [kwh]
```

```
cap = 513 # Total capacity of the battery (only usable battery size) [kwh]
```

```
# The reduction in SOC when driving from i-1 to i [kwh]
```

```
use=[50.37, 256.87, 207.21, 181.82, 113.78, 65.97, 151.54] #IFJ_RKV (ONLY 7 STOPS)
```

```
minc = 51.3 # Minimum allowed SOC [kwh]
```

```

# Model
model = gp.Model("charging_optimization")

# Decision Variables
Y = model.addVars(I, vtype=GRB.BINARY, name="Y") # Binary variable =1 if charging at
location i, else 0
X = model.addVars(I, J, vtype=GRB.CONTINUOUS, lb=0, name="X") # Charging time at location
i within segment j
XT = model.addVars(I, vtype=GRB.CONTINUOUS, lb=0, name="XT") # Total charging in kwh at
location i
SOC = model.addVars(I, vtype=GRB.CONTINUOUS, lb=0, name="SOC") # State of charge at
location i
C = model.addVars(I, J, vtype=GRB.BINARY, name="C") # Binary variable for SOC segment
activation

# Objective Function
model.setObjective(gp.quicksum(f * Y[i] + X[i,j] for i in I for j in J), GRB.MINIMIZE)

# Constraints
# Activation of fixed starting time
model.addConstrs((X[i,j] <= Y[i] * 240 for i in I for j in J), name="start_time_activation")

# Constraint on the minimum allowed state of charge
model.addConstrs((SOC[i] >= minc for i in I), name="min_charge_constraint")

# Calculation of state of charge when arriving at location i
model.addConstr(SOC[1] == soc0 - use[0])
model.addConstrs((SOC[i] == SOC[i-1] + gp.quicksum(ch[i-2][j-1] * X[i-1, j] for j in J) - use[i-1] for
i in I if i > 1), name="State_of_charge_calculation")

# Constraint on maximum charging in each segment
model.addConstrs((ch[i-1][j-1] * X[i, j] <= charg[i-1][j-1] * gp.quicksum(C[i, k] for k in range(1,
j+1)) for i in I for j in J), name="Max_charging_in_segment")
#model.addConstrs((ch[i-1][j-1] * X[i, j] <= charg[i-1][j-1] * gp.quicksum(C[i, k] for k in J) for i in I
for j in J), name="Max_charging_in_segment")
model.addConstrs((SOC[i] + ch[i-1][j-1] * X[i, j] <= cu[i-1][j-1] + (1 - C[i, j]) * 1000 for i in I for j
in J), name="Max_charging_in_segment_with_SOC")

# Constraints for activation of the Ci,j variables
model.addConstrs((gp.quicksum(C[i, j] for j in J) == 1 for i in I), name="C_sum_1")
model.addConstrs((SOC[i] <= sum(C[i, j] * cu[i-1][j-1] for j in J) for i in I),
name="SOCUpperSegment")
model.addConstrs((SOC[i] >= sum(C[i, j] * cu[i-1][j-2] for j in J if j > 1) for i in I for j in J),
name="SOCLowerSegment")

# Constraint to calculate the value of the total charging variable in kwh
model.addConstrs((XT[i] == gp.quicksum(X[i, j] * ch[i-1][j-1] for j in J) for i in I),
name="total_charging_calculation")

# We can use the lp file to verify the model
model.write('non_lin_charging_v2.lp')

# Solve
model.optimize()

# Print the objective value
print("Optimal Objective Value:", model.objVal)

```

```

# Print the values of decision variables
print("\nDecision Variables:")
for i in I:
    print("Y[{}] = {}".format(i, Y[i].x))
    print("SOC[{}] = {}".format(i, SOC[i].x))
    for j in J:
        print("C[{}, {}] = {}".format(i, j, C[i, j].x))
        print("X[{}, {}] = {}".format(i, j, X[i, j].x))
    print("XT[{}] = {}".format(i, XT[i].x))

```

9.2 PyPSA model

Simplified PyPSA model used in Paper IV

```

import pypsa
import pandas as pd

# Create a new network
network = pypsa.Network()

# BUSES #
# Parameters: Voltage, latitude and longitude (for plots)

buses = {
}

#Add buses to the network
for bus,attrs in buses.items():
    network.add("Bus", bus, v_nom=attrs["v_nom"])

# GENERATORS #
# Parameters: Connected bus (voltage), nominal power (MW), max/min reactive power
(MVAR), nominal voltage (kV), and voltage control
generators = [
]

for generator in generators:
    network.add("Generator",
        bus=generator["bus"], # Bus name where the generator is connected
        name=generator["name"], # Bus name where the generator is connected
        p_nom=generator["p_nom"], # Nominal power (MW)
        p_max_pu=generator.get("p_max_pu", 1.0), # Max generation in p.u. (default is 1)
        p_min_pu=generator.get("p_min_pu", 0.0), # Min generation in p.u. (default is 0)
        max_q_pu=generator.get("q_max"), # Max reactive power in p.u.(Mvar)
        min_q_pu=generator.get("q_min"), # Min reactive power in p.u. (Mvar)
        control=generator.get("control", "PV"), # Control mode (default is 'pq')
        v_nom=generator.get("v_nom", None), # Nominal voltage (optional)
        v_set=generator.get("v_set", None), # Voltage setpoint (optional)
        # marginal_cost=generator.get("marginal_cost", 0), # Marginal cost (optional)
    )

```

```

# LOADS #
# Parameters: Bus connected, active power load (MW), reactive power (MVAR)

loads = {
}

for load,attrs in loads.items():
    network.add("Load", load, bus=attrs["bus"], p_set=attrs["p_set"], q_set=attrs["q_set"])

# TRANSFORMERS #
# Define the transformers from the dataset including all windings (r and x in pu, s_nom in
mva) - aligned with pypsa documentation

transformers = [
]

for transformer in transformers:
    network.add("Transformer", transformer['name'],
        bus0=transformer['bus0'],
        bus1=transformer['bus1'],
        s_nom=transformer['s_nom'],
        #v_nom0=transformer['v_nom0'],
        #v_nom1=transformer['v_nom1'],
        r=transformer.get('r', None), #
        x=transformer.get('x', None), #
        #tap_pos=0, #
        tap_ratio=1 #
    )

# SWITCHED SHUNTS -- VOLTAGE CONTROL #
# Switched shunts were modeled as generators that only provide reactive power

shunt_data = [
]

# Add shunt components as reactive power generators
for shunt in shunt_data:
    if shunt["bus"] in network.buses.index:
        network.add(
            "Generator",
            name=f"shunt_gen_{shunt['bus']}",
            bus=shunt["bus"],
            p_nom=0.001, # Small active power capacity to model reactive-only behaviour
            min_pu=-1.0, # Allow full reactive power absorption
            max_pu=1.0, # Allow full reactive power injection
            marginal_cost=0, # Low cost for reactive power adjustment
            control="PV" # Control mode for reactive power
        )
    else:
        print(f"Bus {shunt['bus']} not found in network")

```

```

# LINES #
# Parameters: reactance (ohms), resistance (ohms), apparent power (MVA), susceptance (b)
transmission_lines = [
]

default_b = 0

for line in transmission_lines:
    network.add("Line", line["name"], bus0=line["bus0"], bus1=line["bus1"], x=line["x"],
r=line["r"], s_nom=line["s_nom"],b=line.get("b", default_b))

# SOFT LIMITS #

# Define the cost per unit of s_nom violation
line_violation_cost = 1000 # Cost (e.g., $/MW above s_nom)

# Allow soft limits by adding a slack variable for each line
for line in network.lines.index:
    network.lines.at[line, "s_nom_extendable"] = True # Make s_nom extendable
    network.lines.at[line, "capital_cost"] = line_violation_cost # Penalty per MW

# Define the cost per unit of s_nom violation for transformers
transformer_violation_cost = 1000 # Cost per MVA exceeding s_nom

# Allow soft limits on transformers
for transformer in network.transformers.index:
    network.transformers.at[transformer, "s_nom_extendable"] = True # Allow s_nom to
increase
    network.transformers.at[transformer, "capital_cost"] = transformer_violation_cost #
Penalty cost

# Set voltage magnitude
network.buses['v_mag_pu_min'] = 0.95
network.buses['v_mag_pu_max'] = 1.05

# Set same ratio for all transformers
network.transformers['r'] = 0.01
network.transformers['x'] = 0.05

# Run optimal power flow (OPF)
network.lopf(network.snapshots)

# Fix the generator outputs to the OPF results
network.generators.p_set = network.generators_t.p.loc[network.snapshots[0]]
# Run non-linear power flow (PF)
pf_results = network.pf()

```



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