Degree project in Industrial Management

Second cycle, 30 credits

Economic Viability of Vehicle-to-Grid Participation for a Swedish Housing Cooperative

An Economic Analysis Considering New Power-Based Tariffs

BASIMA KAMIL

MELKER WIDLUND

Economic Viability of Vehicle-to-Grid Participation for a Swedish Housing Cooperative

by

Basima Kamil
Melker Widlund

Master of Science Thesis TRITA-ITM-EX 2025:313
KTH Industrial Engineering and Management
Industrial Economics and Management
SE-100 44 STOCKHOLM

Ekonomisk lönsamhet för Vehicle-to-Grid deltagande i en svensk bostadsrättsförening

av

Basima Kamil
Melker Widlund

Examensarbete TRITA-ITM-EX 2025:313
KTH Industriell teknik och management
Industriell ekonomi och organisation
SE-100 44 STOCKHOLM

Master of Science Thesis TRITA-ITM-EX 2025:313

Industriell ekonomi
och organisation

Economic Viability of Vehicle-to-Grid Participation for a Swedish Housing Cooperative

Basima Kamil
Melker Widlund

Approved	Examiner	Supervisor
2025-06-16	Emrah Karakaya	Fabian Levihn
	Commissioner	Contact person
	PEAK Energy AB	Michal Stala

Abstract

Sweden's energy transition is challenged by rising electricity demand, grid capacity constraints and the need for increased flexibility. Power-based tariffs have been introduced to encourage more responsive consumption but pose challenges for consumers such as housing cooperatives. In this context, Vehicle-to-Grid (V2G) technology offers a promising solution by enabling electric vehicles (EVs) to charge from and discharge to the grid. While V2G has been widely studied, its economic viability, without synergies from complementary technology, under Sweden's evolving market conditions remains underexplored.

This thesis evaluates the economic viability of V2G in Swedish housing cooperatives using a mixed-integer optimization model in GAMS. The model simulates ten EVs under three charging strategies - uncontrolled, controlled, and bidirectional - across two network contracts from Ellevio and Vattenfall Eldistribution. It assesses cost savings through peak shaving and energy arbitrage, including the impact of battery degradation.

Results show that V2G can reduce annual electricity costs by up to 10.3%, with payback periods between 4.5 and 8.8 years. Savings are mainly driven by peak shaving, which prove especially effective during high-load months, reducing peak power costs by up to 37.2%. Energy exports, without ancillary services, yield limited returns under current price spreads. Cost-effectiveness is closely tied to tariff design, as poorly structured tariffs may encourage behaviors that conflict with system efficiency. Sensitivity analysis further shows that battery degradation has minimal impact on peak shaving and only moderate effects on arbitrage.

The study concludes that V2G is economically viable for housing cooperatives, especially for behind-the-meter optimization. However, unlocking its full potential requires smart tariff design, accessible infrastructure and supportive policy measures.

Key-words: Vehicle-to-Grid, Vehicle-to-Building, Electric vehicles, Charging strategies, Bidirectional charging, Peak shaving, Energy arbitrage, Cost optimization, Power-based tariffs, Battery degradation

Examensarbete TRITA-ITM-EX 2025:313

Industrial economics and management

Ekonomisk lönsamhet för Vehicle-to-Grid deltagande i en svensk bostadsrättsförening

Basima Kamil
Melker Widlund

Godkänt	Examinator	Handledare
2025-06-16	Emrah Karakaya	Fabian Levihn
	Uppdragsgivare	Kontaktperson
	PEAK Energy AB	Michal Stala

Sammanfattning

Sveriges energiomställning står inför utmaningar såsom ökande elbehov, begränsad nätkapacitet och ett växande behov av flexibilitet. Effektbaserade tariffer har införts för att uppmuntra en mer flexibel elanvändning men innebär utmaningar för elkonsumenter såsom bostadsrättsföreningar. I detta sammanhang framstår Vehicle-to-Grid (V2G)-teknik som en lovande lösning genom att möjliggöra för elbilar att både ladda från och till elnätet. Trots omfattande forskning kring V2G i integrerade system är dess ekonomiska lönsamhet, utan synergier från annan teknik, i det svenska elsystemet, fortfarande otillräckligt utforskad.

Denna studie undersöker V2G-teknikens ekonomiska lönsamhet i svenska bostadsrättsföreningar genom en blandad heltalsoptimeringsmodell i GAMS. Modellen simulerar laddningsprofiler för tio elbilar under tre laddstrategier – okontrollerad, kontrollerad och bidirektionell – samt analyserar dessa under två nätavtal från Ellevio och Vattenfall Eldistribution. Kostnadsbesparingar genom effekttoppavlastning (peak shaving) och elprisarbitrage utvärderas, inklusive påverkan av batteridegradering.

Resultaten visar att V2G kan minska årliga elkostnader med upp till 10.3 %, med återbetalningstider på mellan 4.5 och 8.8 år. Besparingarna drivs främst av peak shaving, vilket visar sig särskilt effektivt under högbelastningsmånader med effektkostnadsminskningar på upp till 37.2 %. Export av el till nätet, utan tillägg från stödtjänster, ger begränsade intäkter under rådande prisnivåer. Kostnadseffektiviteten är starkt kopplad till tariffstrukturen, då bristfälligt utformade tariffer kan uppmuntra beteenden som motverkar systemeffektivitet. Känslighetsanalysen visar vidare att batteridegradering har minimal påverkan på peak shaving och endast måttlig påverkan på arbitrage.

Studien drar slutsatsen att V2G är ekonomiskt lönsamt för bostadsrättsföreningar, särskilt vid användning för optimering bakom mätaren. För att fullt ut realisera dess potential krävs dock smart tariffutformning, tillgänglig infrastruktur och stödjande policyåtgärder.

Nyckelord: Vehicle-to-Grid, Vehicle-to-Building, Elbilar, Laddstrategier, Bidirektionell laddning, Effekttoppavlastning, Energi-arbitrage, Kostnadsoptimering, Effekttariffer, Batteridegradering

Contents

1 Introduction **1**

1.1 Relevance of Thesis 2
1.2 Research Aim and Questions 3
1.3 Scope and Delimitations 4

2 Empirical Background **6**

2.1 Overview of the Swedish Electricity System 6
2.1.1 Electricity Market Structure 6
2.1.2 Grid Infrastructure and Regional Differences 7
2.1.3 Electrification and Energy Transition 8
2.1.4 Power-Based Grid Tariffs 9
2.2 Electric Vehicles in Sweden 10
2.3 Charging Infrastructure and Technical Requirements 11
2.3.1 Alternating Current (AC) Bidirectional Charging 11
2.3.2 Direct Current (DC) Bidirectional Charging 11
2.3.3 Cost and Infrastructure Comparison 12
2.4 Vehicle-to-Grid Technology 13
2.4.1 Vehicle-to-Grid (V2G) Opportunities for Housing Cooperatives 14

3 Economic Implications of Vehicle-to-Grid **16**

3.1 Vehicle-to-Grid Configurations 17
3.2 Vehicle-to-Building and Vehicle-to-Home Configurations 19
3.3 Renewable Energy Integration 21
3.4 Different Charging Strategies 23
3.5 Electrical Vehicles for Different Services 26
3.5.1 Energy Arbitrage Trading 26
3.5.2 Peak Shaving and Load Shifting 27
3.6 Cost Considerations and Barriers to Adoption 28

3.6.1 Infrastructure and Standardization Challenges 28
3.6.2 Business Models and Regulatory Gaps 29
3.6.3 Tariffs and Pricing Models 30
3.6.4 Willingness to Pay and Decision-Making 31
3.7 Summary 31

4 Method **33**
4.1 Research Design 33
4.2 Optimization Model in General Algebraic Modeling System (GAMS) . . 34
4.3 System Overview 35
4.4 Data Collection 37
4.4.1 Electricity Purchases 37
4.4.2 Electricity Sales 40
4.4.3 Housing Cooperative Profile 41
4.4.4 Electrical Vehicle and Charger Setup 42
4.4.5 Operational Costs 44
4.4.6 Driving Profiles and Patterns 44
4.4.7 Assumptions 46
4.5 Case Study Scenarios 47
4.6 Model Equations and Constraints 48
4.6.1 Objective Function 48
4.6.2 Power Balance 49
4.6.3 State-of-Charge Evolution 50
4.6.4 State-of-Charge Boundaries 50
4.6.5 Arrival and Departure 50
4.6.6 Battery Degradation Cost 51
4.6.7 Differences Between Charging Strategies 52
4.7 Data Analysis 53
4.8 Limitations 54

5 Results **57**
5.1 Economic Results of Ellevio's Network Contract 57
5.1.1 Charging Strategies 60
5.2 Economic Results of Vattenfall's Network Contract 64
5.3 Effects of Varied Battery Degradation 67

5.3.1 Ellevio 67
5.3.2 Vattenfall 69
5.4 Cost-Benefit Analysis 70
5.5 System and Non-Monetary Benefits 72

6 Conclusions **74**
6.1 Key Findings 74
6.2 Policy and Practical Implications 76
6.3 Final Reflections 78

Bibliography **79**

Appendix **90**

List of Figures

2.1 Map of Sweden's transmission grid (Svenska Kraftnät, 2025) 7
2.2 Vehicle-to-Everything (V2X) ecosystem (Khezri et al., 2024) 14

4.1 System configuration with energy flows 36

5.1 Cost results under Ellevio's network contract 58
5.2 Peak cost results under Ellevio's network contract 58
5.3 All three charging strategies against spot prices 62
5.4 Cost results under Vattenfall's network contract 65
5.5 Peak cost results under Vattenfall's network contract 65

1 Demand curves with uncontrolled charging. 93
2 Demand curves with controlled charging. 94
3 Demand curves with V2G charging 94
4 Peak power for all three charging strategies 94

List of Tables

4.1 Ellevio's network contract 38
4.2 Vattenfall's network contract 38
4.3 Fortum's variable supply contract 40
4.4 Electricity sales with Ellevio 41
4.5 Electricity sales with Vattenfall 41
4.6 Electric Vehicle (EV), battery and charging specifications 44
4.7 Weekday availability and State-of-Charge (SoC) of EVs 45
4.8 Weekend availability and SoC of EVs 46
4.9 Overview of modeled scenarios 48

5.1 Peak power demand for the months with the highest and lowest total cost savings 61
5.2 Results of varied battery degradation 67
5.3 Results of varied battery degradation 69
5.4 Annual costs and cost savings comparison (SEK/year) 70
5.5 Charging infrastructure investment and operational costs 70
5.6 Net profit, investment and payback time comparison 71

1 Monthly costs and savings for Ellevio 93
2 Monthly costs and savings for Vattenfall 95
3 December cost comparison: 2x and 0.5x degradation scenarios 96
4 July cost comparison: 2x and 0.5x degradation scenarios 96
5 January cost comparison: 2x and 0.5x degradation scenarios 97
6 July cost comparison: 2x and 0.5x degradation scenarios 97

Acronyms

AC	Alternating Current
BEV	Battery Electric Vehicle
CAPEX	Capital Expenditure
CBA	Cost-Benefit Analysis
DC	Direct Current
DER	Distributed Energy Resource
DSO	Distribution System Operator
ESS	Energy Storage Systems
EV	Electric Vehicle
FCR	Frequency Containment Reserve
FCR-D	Frequency Containment Reserve for Disturbances
GAMS	General Algebraic Modeling System
IRR	Internal Rate of Return
LCOE	Levelized Cost of Energy
LCOS	Levelized Cost of Storage
LMO	Lithium Manganese Oxide
MILP	Mixed-Integer Linear Programming
NPV	Net Present Value
OBC	Onboard Bidirectional Converter
OCPP	Open Charge Point Protocol
OEM	Original Equipment Manufacturers
PB	Payback
PV	Photovoltaics
RES	Renewable Energy Systems
SEMS	Smart Energy Management System
SoC	State-of-Charge

SoH State-of-Health
ToU Time-of-Use
TPT Two-Part Tariff
TSO Transmission System Operator
VAT Value Added Tax
VRE Variable Renewable Energy
V2B Vehicle-to-Building
V2G Vehicle-to-Grid
V2H Vehicle-to-Home
V2L Vehicle-to-Load
V2V Vehicle-to-Vehicle
V2X Vehicle-to-Everything

List of Symbols

C_{inv}	is the total initial investment cost
C_{deg}	total battery degradation cost
c_{bat}	battery cost per kWh
t	time step in hours
v	electric vehicle
$ET_{\text{exp}}(t)$	energy exported to the grid at time t
$ET_{\text{imp}}(t)$	energy imported from the grid at time t
N_{EFC}	number of equivalent full cycles before battery end-of-life
$P_{\text{load}}(t)$	electricity demand at time t
p_{peak}	peak net power (kW) drawn from the grid
$\delta_{avail,v}(t)$	binary parameter: if vehicle v is connected at t
$\delta_{ch,v}(t)$	binary parameter: if charging allowed for v at t
$\delta_{dh,v}(t)$	binary parameter: if discharging allowed for v at t
η_{ch}	charging efficiency
η_{dh}	discharging efficiency
cap_{EV}	total battery capacity per vehicle v (kWh)
$soc_v(t)$	state of charge of vehicle v at time t
$soc_v^{\max}(t)$	upper SoC limit for v at t
$soc_v^{\min}(t)$	lower/minimum SoC limit for v at t
$soc_v^{entry}(t)$	SoC of v at arrival time t
$soc_v^{exit}(t+1)$	required SoC of v at departure $t+1$
PB	is the payback period in years

Π_{annual}	is the annual net profit or savings generated by the system
$p_{ch,v}(t)$	power charged into vehicle v at t
$p_{dh,v}(t)$	power discharged from vehicle v at t
$\pi_{\text{buy}}(t)$	electricity purchase price at t
$\pi_{\text{sell}}(t)$	electricity sale price at t
π_{peak}	peak tariff rate

Acknowledgments

We would like to express our gratitude to our supervisor, Fabian Levihn, and our examiner, Emrah Karakaya, for their continuous guidance and constructive feedback throughout this project. Your critical evaluations and suggestions have significantly improved the quality and depth of this work. We are also thankful to our fellow students, whose valuable discussions and challenging questions helped shape the direction and rigor of this thesis.

We would also like to thank Michal Stala at PEAK Energy AB for sharing his practical insights and support during the development of this thesis. His industry perspective has been essential in grounding our research in real-world applications.

Finally, we would like to thank Mikael Amelin and Per Lundqvist at KTH Royal Institute of Technology for their genuine interest in our work and their support.

In light of the rapid development of Vehicle-to-Grid technology, we hope this thesis sheds new light on its practical applications and strategic implications, fostering new discussions in the field and supporting the integration of sustainable and intelligent energy solutions in the Swedish energy system. We also hope this work offers meaningful guidance for policymakers, energy companies and housing cooperatives as they navigate the ongoing energy transition.

Stockholm, June 2025
Basima Kamil
Melker Widlund

Chapter 1

Introduction

The global energy system faces increasing pressure to transition from fossil fuels to renewable energy sources, in response to the urgent challenges posed by climate change. Sweden's renewable energy capacity is expected to grow by 90% by 2030 to meet climate targets (International Energy Agency, 2024b). However, the expansion of renewable energy introduces new complications due to its intermittent nature, contributing to an inflexible energy system.

This transition is complicated by rising energy demand driven by electrification, digitalization and the expansion of energy-intensive technologies such as Artificial Intelligence (International Energy Agency, 2025). In this global context, Sweden and the European Union are faced with new energy challenges, including increased electricity consumption, power deficiencies, capacity constraints, high electricity prices and the need for greater grid flexibility (Holmberg & Tangerås, 2023).

To address these issues, the Swedish Energy Markets Inspectorate has introduced time-differentiated power-based tariffs with the aim of incentivizing more flexible and demand-responsive consumption, shifting loads to relieve the grid (Emulate Energy, 2024; Energimarknadsinspektionen, 2025). These tariffs charge customers based on their maximum power usage in kW during peak hours, resulting in higher costs for customers who fail to respond to such measures. Adapting to this pricing model may be particularly challenging for larger residences under collective electricity contracts, such as housing cooperatives, where coordinating individual residents' energy usage is complex.

Along with this, local grid operators have emphasized the need to increase local

electricity production and adopt innovative solutions to meet growing demand (Ellevio, 2024). One such solution lies in the potential of V2G technology, which utilizes EV batteries to both charge from and discharge electricity back to the grid. With the transport sector being a key driver in electrification, it enables great potential for EVs to be utilized as flexible assets. In 2024, EVs accounted for 35%, about 94 000 units, of Sweden's car registrations, reflecting its growing adoption (European Commission, 2025b). By storing energy during low-demand periods and supplying it to the grid or residential buildings during peak hours, V2G can help meet demand, shifting electricity consumption and shaving peak loads, thus alleviating stress on the grid (Englberger et al., 2021).

This bidirectional energy flow also offers potential economic benefits including lower system costs through peak shaving and load shifting, as well as reduced need for short-term grid investments (Bibak & Tekiner-Moğulkoç, 2021; Greaker et al., 2022; Haikola & Söderberg, 2020; Jiang et al., 2025). Further, taking advantage of hourly price signals with energy arbitrage trading can further lower costs and create new revenue streams (Leijon et al., 2024). Additionally, it can help optimize the use of renewable energy, lowering electricity costs and reducing dependence on more expensive energy sources (Blumberg et al., 2022; Nagel et al., 2024).

1.1 Relevance of Thesis

The benefits of V2G have been widely discussed in research, particularly in the context of integrated renewable energy systems and microgrids. Much of existing research focuses on its role within integrated smart energy systems, emphasizing the strong synergies between V2G and complementary technologies. For example, Kern et al. (2022) and Ouammi (2021) highlight that when V2G is combined with technologies such as solar Photovoltaics (PV) and Energy Storage Systems (ESS), it can significantly reduce electricity costs, lower peak loads, enhancing self-consumption and supporting grid stability. However, there remains limited understanding of the economic viability of V2G as a standalone technology. This makes it difficult to isolate and evaluate the specific value that V2G provides independently. As this technology is still emerging, it becomes particularly important to understand its potential as an independent technology.

In the Swedish context, there has been limited research on how V2G performs within

the current electricity market structure, especially under the new policies around power-based tariffs. While some studies have explored V2G in various technical and regulatory settings, their findings do not fully reflect the unique market conditions and pricing structures found in Sweden's four electricity bidding areas. This suggests that further investigation is needed to better understand how V2G could be effectively integrated into the Swedish energy system, especially for housing cooperatives aiming to manage electricity costs and consumption more efficiently.

1.2 Research Aim and Questions

This study analyzes the economic viability of V2G technology in Sweden, with a particular focus on its implementation in housing cooperatives. It evaluates cost structures, potential revenue streams from peak shaving, energy arbitrage trading and self-consumption to evaluate whether V2G can serve as an effective solution to support Sweden's transition toward a more resilient and sustainable energy system. Additionally, the study explores how the evolving power-based tariffs impact V2G's profitability. By simulating various charging strategies and identifying key factors influencing economic viability, the research aims to provide insights into the conditions necessary for the successful integration of V2G into Sweden's electricity system. To achieve this, this study seeks to answer the following research questions:

- Is Vehicle-to-Grid, as a standalone technology, an economically viable investment for Swedish housing cooperatives?
  - What are the key factors in reducing electricity costs?
- How do new pricing models with power-based tariffs influence the profitability of Vehicle-to-Grid?
- How do different charging strategies impact financial outcomes?

1.3 Scope and Delimitations

This study focuses on Sweden, using specific case studies and assumptions in modeling to evaluate the economic viability of V2G technology. The analysis is limited to the Swedish energy market and its unique regulatory and infrastructure context.

Furthermore, the study does not investigate how potential cost savings are distributed among individual stakeholders, such as EV owners. Specifically, mechanisms for sharing savings, user compensation models or incentives for participation are not considered. Instead, the analysis is conducted entirely from the perspective of the housing cooperative as a centralized actor. The focus lies solely on evaluating the total system-level costs, investment requirements and net savings for the cooperative as a collective entity.

This thesis focuses on EVs interacting with and delivering power to both the grid and residential buildings, referring to two distinct concepts: V2G and Vehicle-to-Building (V2B). However, V2G will be used throughout this thesis as a general term to also include the energy service V2B. This is done for simplification, consistency and to reflect the fact that the core concept being analyzed is the bidirectional flow of electricity between EVs and external systems. Further, Vehicle-to-Home (V2H) specifically refers to single households and involved residential profiles, which are relevant in the context of residential buildings. V2B and V2H will respectively be used when required to specify something, particularly in the literature review, to accurately cover the research in the field. Although V2H systems operate on a smaller and more controllable scale than V2B, the modeling approaches are similar. Therefore, literature on V2H will be included where it helps illustrate practices and findings relevant to the thesis.

It also excludes participation in the Frequency Containment Reserve (FCR) markets and other ancillary services as they introduce additional layers of complexity, regulatory uncertainty and infrastructure requirements that fall outside the scope of this thesis. While previous literature and real-world testing have shown such services to be both profitable and technically feasible, they do not reflect the short-term economic viability of V2G for a typical Swedish housing cooperative. Participation in FCR would require bidirectional grid-export capabilities and significant upgrades to internal electrical infrastructure, such as increased fuse capacities and advanced metering equipment-costs that are difficult to estimate due to immature technology

and regulatory frameworks. Moreover, these markets are relatively limited in size and risk becoming saturated as battery penetration increases, further reducing their long-term profitability. This would add yet another layer of uncertainty without fundamentally altering the core conclusion regarding V2G's economic viability. Modeling participation would also require much more complex bidding strategies and supporting technical infrastructure, such as aggregator coordination and real-time communication systems.

Chapter 2

Empirical Background

This chapter provides the empirical foundation for the thesis by outlining the key features of the Swedish electricity system and the broader energy transition. It highlights challenges such as increased electrification, grid imbalances and the introduction of power-based tariffs, while exploring the role of EVs and the emerging potential of V2G technology.

2.1 Overview of the Swedish Electricity System

2.1.1 Electricity Market Structure

Sweden's electricity market operates within a deregulated framework, designed to promote competition in electricity generation and supply, while transmission and distribution networks remain under regulatory control (Energimarknadsinspektionen, 2021). The market is integrated into the larger Nordic electricity market through the Nord Pool power exchange, where electricity is traded on both the day-ahead and intraday markets (Holmberg & Tangerås, 2023). Price-setting in Nord Pool is based on a supply-and-demand mechanism, with hourly electricity prices fluctuating depending on production levels, consumption patterns and transmission capacities (Svenska Kraftnät, 2024c). This market-based system enables Sweden to import and export electricity, contributing to overall grid stability but also exposing the country to price volatility and external market fluctuations. The Swedish power grid consists of two grid levels (Svenska Kraftnät, 2024d):

- Transmission Grid: Managed by the Transmission System Operator (TSO) Svenska Kraftnät, it operates at high voltages (220-400 kV) and is responsible for transporting electricity over long distances from power plants to regional distribution networks.
- Distribution Grid: Managed by the Distribution System Operator (DSO)s.
  - The regional distribution grid operates at medium voltage (around 130 kV).
  - The local distribution grid operates at low voltages (about 0.4-40 kV), delivering electricity to households, businesses and industries

2.1.2 Grid Infrastructure and Regional Differences

With regional differences in production and consumption, the Swedish electricity system is divided into four bidding areas (SE1-SE4), reflecting physical transmission constraints (Svenska Kraftnät, 2024b). The northern regions (SE1 and SE2) have abundant electricity production, primarily from hydropower, while the southern regions (SE3 and SE4) experience high electricity demand due to industrial activities, population density and urbanization. These regional imbalances are reflected in Figure 2.1, which maps the structure of the transmission grid, leading to price disparities, with southern Sweden typically facing higher electricity prices than the north. Further, the growing strain on the transmission grid is exacerbating these price differences.

Ryssland
Sverige
Finland
Norge
Danmark
Estland
Lettland
Litauen
Belarus
Polen
Tyskland
Stockholm
Helsingfors
Oslo
Göteborg
Malmö
Kopenhamn
Tallinn
Riga
Vilnius
Luleå
Umeå
Sundsvall
Örnsköldsvik
Karlstad
Örebro
Linköping
Norrköping
Jönköping
Växjö
Karlskrona
Kalmar
Visby
Gotland
Gävle
Uppsala
Västerås
Eskilstuna
Nyköping
Kristianstad
Helsingborg
Lund
Trelleborg
Ystad
Ronneby
Oskarshamn
Ringhals
Forsmark
Oskarshamn
Ringhals
Karlshamn
Simrishamn
Ängelholm
Halmstad
Varberg
Borås
Trollhättan
Vänersborg
Skövde
Mariestad
Lidköping
Falköping
Mjölby
Motala
Norrtälje
Nynäshamn
Södertälje
Enköping
Hudiksvall
Sundsvall
Härnösand
Örnsköldsvik
Skellefteå
Piteå
Boden
Gällivare
Kiruna
Narvik
Bodø
Mo i Rana
Mosjøen
Namsos
Steinkjer
Trondheim
Kristiansund
Molde
Ålesund
Florø
Sogndal
Førde
Stavanger
Haugesund
Bergen
Arendal
Kristiansand
Lillesand
Porsgrunn
Skien
Tønsberg
Sandefjord
Larvik
Drammen
Hamar
Lillehammer
Gjøvik
Kongsvinger
Elverum
Rena
Kongsberg
Hønefoss
Fredrikstad
Sarpsborg
Halden
Moss
Ås
Lysaker
Oslo
Hamburg
Wilster
Lübeck
Rostock
Güstrow
Neder-länderna
Amsterdam
Rotterdam
Den Haag
Utrecht
Arnhem
Nijmegen
Eindhoven
Tilburg
Breda
Groningen
Leeuwarden
Zwolle
Enschede
Almelo
Hengelo
Apeldoorn
Amersfoort
Hoorn
Alkmaar
Haarlem
Leiden
Dordrecht
Middelburg
Vlissingen
Terneuzen
Roosendaal
Bergen op Zoom
Breda
Tilburg
Eindhoven
Helmond
Venlo
Roermond
Sittard
Maastricht
Heerlen
Kerkrade
Aachen
Düsseldorf
Duisburg
Essen
Dortmund
Bochum
Wuppertal
Solingen
Remscheid
Leverkusen
Köln
Bonn
Koblenz
Trier
Mainz
Wiesbaden
Frankfurt
Darmstadt
Mannheim
Ludwigshafen
Heidelberg
Karlsruhe
Pforzheim
Stuttgart
Ludwigsburg
Esslingen
Reutlingen
Tübingen
Ulm
Augsburg
München
Ingolstadt
Regensburg
Passau
Landshut
Rosenheim
Kempten
Memmingen
Lindau
Konstanz
Freiburg
Offenburg
Baden-Baden
Kehl
Landau
Speyer
Worms
Kaiserslautern
Saarbrücken
Metz
Nancy
Strasbourg
Colmar
Mulhouse
Belfort
Besançon
Dijon
Chalon-sur-Saône
Mâcon
Lyon
Grenoble
Chambéry
Annecy
Genève
Lausanne
Fribourg
Bern
Biel
Neuchâtel
Basel
Zürich
Winterthur
St. Gallen
Chur
Davos
Bregenz
Innsbruck
Salzburg
Linz
Wels
Steyr
Graz
Leoben
Klagenfurt
Villach
Udine
Trieste
Venezia
Padova
Verona
Brescia
Bergamo
Milano
Como
Varese
Novara
Torino
Asti
Alessandria
Genova
La Spezia
Pisa
Livorno
Firenze
Prato
Pistoia
Lucca
Siena
Arezzo
Perugia
Terni
Rieti
Roma
Latina
Frosinone
Napoli
Caserta
Salerno
Avellino
Benevento
Foggia
Bari
Taranto
Brindisi
Lecce
Potenza
Matera
Cosenza
Catanzaro
Reggio Calabria
Messina
Catania
Siracusa
Ragusa
Trapani
Palermo
Agrigento
Caltanissetta
Enna
Cagliari
Sassari
Nuoro
Olbia
Ajaccio
Bastia
Porto-Vecchio
Bonifacio
Calvi
Corte
Propriano
Sartène
Figari
Solenzara
Lumio
Vescovato
Ghisonaccia
Aléria
Bonifacio
Porto-Vecchio
Sartène
Propriano
Figari
Solenzara
Ghisonaccia
Aléria
Corte
Calvi
Lumio
Vescovato
Ajaccio
Bastia
Olbia
Nuoro
Sassari
Cagliari
Trapani
Palermo
Agrigento
Caltanissetta
Enna
Ragusa
Siracusa
Catania
Messina
Reggio Calabria
Catanzaro
Cosenza
Potenza
Matera
Taranto
Brindisi
Lecce
Bari
Foggia
Benevento
Avellino
Salerno
Caserta
Napoli
Frosinone
Latina
Rieti
Roma
Terni
Perugia
Arezzo
Siena
Lucca
Pistoia
Prato
Firenze
Livorno
Pisa
La Spezia
Genova
Alessandria
Asti
Novara
Torino
Varese
Como
Milano
Bergamo
Brescia
Verona
Padova
Venezia
Trieste
Udine
Klagenfurt
Villach
Leoben
Graz
Steyr
Wels
Linz
Salzburg
Innsbruck
Bregenz
Davos
Chur
St. Gallen
Winterthur
Zürich
Basel
Neuchâtel
Biel
Bern
Fribourg
Lausanne
Genève
Annecy
Chambéry
Grenoble
Lyon
Mâcon
Chalon-sur-Saône
Dijon
Besançon
Belfort
Mulhouse
Colmar
Strasbourg
Nancy
Metz
Saarbrücken
Kaiserslautern
Landau
Speyer
Worms
Mainz
Wiesbaden
Frankfurt
Darmstadt
Mannheim
Ludwigshafen
Heidelberg
Karlsruhe
Pforzheim
Stuttgart
Ludwigsburg
Esslingen
Reutlingen
Tübingen
Ulm
Augsburg
München
Ingolstadt
Regensburg
Passau
Landshut
Rosenheim
Kempten
Memmingen
Lindau
Konstanz
Freiburg
Offenburg
Baden-Baden
Kehl
Koblenz
Trier
Bonn
Köln
Leverkusen
Solingen
Remscheid
Wuppertal
Bochum
Dortmund
Duisburg
Essen
Düsseldorf
Aachen
Kerkrade
Heerlen
Maastricht
Sittard
Roermond
Venlo
Helmond
Eindhoven
Tilburg
Breda
Roosendaal
Bergen op Zoom
Terneuzen
Vlissingen
Middelburg
Dordrecht
Leiden
Haarlem
Alkmaar
Hoorn
Amersfoort
Apeldoorn
Zwolle
Enschede
Almelo
Hengelo
Leeuwarden
Groningen
Arnhem
Nijmegen
Eindhoven
Tilburg
Breda
Utrecht
Den Haag
Rotterdam
Amsterdam
Neder-länderna
Wilster
Lübeck
Rostock
Güstrow
Hamburg
Kopenhamn
Malmö
Helsingborg
Lund
Trelleborg
Ystad
Ronneby
Karlskrona
Kalmar
Visby
Gotland
Gävle
Uppsala
Västerås
Eskilstuna
Nyköping
Kristianstad
Ängelholm
Halmstad
Varberg
Borås
Trollhättan
Vänersborg
Skövde
Mariestad
Lidköping
Falköping
Mjölby
Motala
Norrtälje
Nynäshamn
Södertälje
Enköping
Hudiksvall
Sundsvall
Härnösand
Örnsköldsvik
Skellefteå
Piteå
Boden
Gällivare
Kiruna
Narvik
Bodø
Mo i Rana
Mosjøen
Namsos
Steinkjer
Trondheim
Kristiansund
Molde
Ålesund
Florø
Sogndal
Førde
Stavanger
Haugesund
Bergen
Arendal
Kristiansand
Lillesand
Porsgrunn
Skien
Tønsberg
Sandefjord
Larvik
Drammen
Hamar
Lillehammer
Gjøvik
Kongsvinger
Elverum
Rena
Kongsberg
Hønefoss
Fredrikstad
Sarpsborg
Halden
Moss
Ås
Lysaker
Oslo

This increasing demand for electricity places significant stress on the grid, with grid congestion and power deficiencies emerging in the south, creating challenges for industrial expansion and urban electrification efforts (Göteborg Energi, 2024). These challenges are driven by transmission capacity limitations, resulting in congestion and bottlenecks, especially during peak demand periods, when electricity supply cannot meet consumption needs. Critical upgrades to the national transmission grid are underway, but are not expected to be completed before 2035. In response to these challenges, efforts such as regional flexibility markets and time-based power tariffs have been developed to incentivize customers to use energy more efficiently, encouraging them to shift and reduce their consumption. However, there remains an urgent need to accelerate the deployment of new local generation and explore innovative, decentralized solutions to support this ongoing energy transition. According to Svenska Kraftnät, these measures could help increase the capacity from north to south by 10% (Svenska Kraftnät, 2022).

2.1.3 Electrification and Energy Transition

Sweden has set ambitious climate and energy goals, aiming to achieve a fossil-free electricity system, with net-zero greenhouse gas emissions by 2045, as part of its commitment to the Paris Agreement in 2015 (Naturvårdsverket, 2025). A key component of this transition is the electrification of various sectors, including transportation and industry, which are driving a significant increase in electricity demand (Göteborg Energi, 2024; Krönert et al., 2025). Sweden's electrification across these sectors is accelerating, driven by policy incentives and climate goals. Electric mobility is rapidly expanding, increasing pressure on the grid, while heavy transport and industrial sectors are shifting to electricity-intensive solutions (Krönert et al., 2025).

This transition relies on expanding renewable energy sources such as hydropower, wind and solar energy, which are essential for Sweden's long-term energy security and grid stability. The current energy mix is diverse, with hydropower and nuclear power contributing 40% and 29.1% of total electricity generation, respectively (International Energy Agency, 2024a). Wind power has expanded rapidly, accounting for about 20.5%, with bioenergy, solar and coal making up the remaining share. A key challenge associated with the expansion of renewable energy is its intermittent nature, where

wind and solar power depend on weather conditions. This variability can lead to a mismatch between supply and demand, where electricity is generated in surplus when demand is low and vice versa, complicating efforts to maintain grid stability.

Capacity limitations and congestion further complicate renewable integration, especially in regions with high demand. To address these fluctuations and achieve the climate goals, the effective integration of renewable energy sources requires significant infrastructure investments, increased grid flexibility and technological advancements (Svenska Kraftnät, 2024a). While electrification plays a crucial role in achieving climate goals and reducing fossil fuel dependence, it also necessitates strategic investments in grid infrastructure and flexibility solutions (Göteborg Energi, 2024).

2.1.4 Power-Based Grid Tariffs

To promote more efficient grid usage, all DSOs are mandated to implement time-differentiated power-based tariffs by January 1, 2027 (Energimarknadsinspektionen, 2025). Unlike previous electricity contracts, where the costs are based primarily on energy consumption in kWh, the new pricing model charges customers based on their peak power demand in kW. To reduce grid congestion, customers are charged based on their maximum hourly power usage during high-load periods, for example between 06:00 and 22:00 on weekdays, during the winter months (November to March).

This marks a fundamental shift in how electricity costs are allocated, from energy consumption to demand intensity, encouraging users to avoid high, simultaneous electricity use. Some DSOs, such as Ellevio, have already introduced these tariffs, while others are gradually phasing them in (Ellevio, 2025c). However, tariff structures vary between operators depending on local grid conditions, which adds additional complexity for end-users and can make it difficult to anticipate and manage costs. As higher peak demand can lead to increased costs under the new model, smart energy solutions such as V2G offer potential to mitigate these peaks. By shifting electricity strategically, V2G becomes particularly relevant under these new policies.

2.2 Electric Vehicles in Sweden

As a part of its net-zero emission targets, Sweden aims to reduce domestic transportation emissions by 70% by 2030 compared to 2010 levels (Naturvårdsverket, 2024). With the transport sector accounting for nearly one-third of Sweden's total emissions, this represents the greatest challenge in meeting climate objectives, making sector electrification essential to reach this goal (International Energy Agency, 2024c; Yang, 2023).

In recent years, EV adoption has accelerated rapidly in Sweden, now accounting for approximately 12% of all cars (Guttman, 2024). This growth is driven by climate targets, stronger consumer demand and advancements in charging infrastructure (Enode, 2025; Statista, 2025). This shift is also supported by regulatory support with incentives, including subsidies for installation and material of charging infrastructure and tax deductions on travel expenses (Skatteverket, 2025a, 2025b). However, as the state subsidies for purchasing electrical vehicles was eliminated in 2022, adoption has slowed, contributing to a rebound in emissions (European Commission, 2025b; Guttman, 2024; Quatrin, 2022).

EV penetration growth is still strong, with 35% of 2024 passenger car registrations being from battery driven vehicles, expecting to reach 40% of registrations in 2025 (out of a total 275,000 car registrations) (European Commission, 2025b). As for May 2025, Sweden is close to the yearly forecast, with 36.9% of registrations being battery driven (Mobility Sweden, 2025). Although the market has been slowing down, new car model launches and cuts in interest rate are expected to drive adoption (CTEK, 2025; European Commission, 2025b). Further, Goldman Sachs Research (2024) predicts a drop in battery prices between 2023 and 2026 to be nearly 50%, driven by technological innovation and decrease in metal prices for cobalt and lithium. With EVs becoming more affordable and seeing technological developments, this will ultimately increase adoption rates (Blumberg et al., 2022).

The increasing number of EVs also present new challenges for the energy system, where rising electricity demand from charging further strains the grid. To address this, smart charging solutions and demand-response mechanisms need to be implemented to optimize grid loads (Göteborg Energi, 2024; Krönert et al., 2025). V2G technology offers an additional layer of flexibility by enabling EVs to store excess electricity and discharge it when needed, helping balance supply and demand. Given Sweden's

increased reliance on renewable energy, the growing EV market presents significant opportunities to reduce emissions, enhance energy efficiency and support grid stability. Focus should shift to scaling near-future technologies such as V2G and creating robust frameworks and standardization protocols for EVs to be utilized, further supporting the climate goals (Swedish Electromobility Centre, 2025).

2.3 Charging Infrastructure and Technical Requirements

Bidirectional charging can be implemented through either AC or DC charging systems, each with distinct technical, economic and regulatory implications.

2.3.1 AC Bidirectional Charging

In AC V2G setups, the conversion from DC (vehicle battery) to AC (grid) and vice versa takes place inside the vehicle, through the Onboard Bidirectional Converter (OBC). This configuration simplifies the grid-side infrastructure and is typically more cost-effective for residential and low-power applications. The AC approach leverages the vehicle's OBC and can be deployed using wallboxes with V2G-enabled communication protocols like ISO 15118-20. According to Steen et al. (2025), a 22 kW AC bidirectional charger was successfully tested in the HSB Living Lab, demonstrating the feasibility of AC V2G for building-level energy services.

However, AC V2G is limited by the capacity of the OBC, typically offering power levels between 7-22 kW, which may be insufficient for high-power or commercial applications. Moreover, the standardization and availability of ISO 15118-20 compliant onboard bidirectional converters are still in early stages, with many EVs yet to fully support this functionality (Steen et al., 2025).

2.3.2 DC Bidirectional Charging

In contrast, DC V2G systems shift power conversion to the charging station, enabling higher power outputs (20-50 kW or more). This makes DC V2G better suited for commercial fleets, fast-charging environments and locations with higher energy service demands. The V2X-MAS project by Steen et al. (2025) included a 20 kW DC

bidirectional charger from Ferroamp, which offered higher flexibility in grid services such as frequency regulation and local congestion management.

While DC systems offer greater control and power output, they are more expensive. Further, the study by Kühnbach et al. (2024) estimates that DC V2G stations involve higher upfront costs due to added hardware like inverters and safety systems, making them less attractive for private users.

2.3.3 Cost and Infrastructure Comparison

Kühnbach et al. (2024) emphasize that AC V2G is generally more cost-effective and scalable for residential users, especially when combined with rooftop PV and Time-of-Use (ToU) tariffs. DC V2G, by contrast, is advantageous where faster charging/discharging rates or centralized control are prioritized, such as in aggregated fleet operations or microgrid services.

Importantly, AC-based V2G systems shift part of the investment costs from the charging infrastructure to the vehicle itself. DC-based setups require expensive off-board bidirectional chargers, while the AC alternative makes use of a bidirectional onboard converter integrated in the vehicle. Although this increases the costs and complexity of the EV, it significantly reduces the cost of the charger, allowing the use of simpler, cheaper AC wallboxes. From a behavioral economics perspective, this cost shift is not only technically logical but also psychologically favorable for consumers. Adding for example 50,000 SEK to an EV with a base price of 450,000 SEK represents only an 11% increase. However, adding the same amount to a charger costing 10,000 SEK represents a 500% price increase. While the total investment is the same, the latter is disproportionately expensive. This phenomenon is consistent with Thaler (1999) theory of mental accounting, which shows that people evaluate costs relative to the base price of a product rather than in absolute terms.

Notable recent developments reinforce the maturity of the AC-based V2G pathway, for example:

- Volvo Cars conducted a successful pilot project in Gothenburg in 2025, where four AC-charged EVs delivered 111 kWh to the grid using standard low-cost wallboxes. This demonstrated both technical feasibility and market potential for residential V2G participation in local flexibility markets such as *Effekthandel*

Väst (Westerheide, 2025).

  - Volvo's Wallbox charger (22kW AC), is "prepared for V2G" but requires a compatible EV such as the EX90 or other upcoming models. Likely because other models lack the OBC (Volvo Cars, 2025).

- DEFA Power, a commercially available AC charger with a capacity of up to 22 kW, supports both Open Charge Point Protocol (OCPP) 2.0.1 and ISO 15118, ensuring readiness for bidirectional energy transfer and smart grid integration (Defa, 2025).
- Nissan announced it will deploy onboard bidirectional AC chargers in select vehicles from 2026, starting in the United Kingdom. This approach, likely supported by ISO 15118-20 and OCPP 2.1, reduces cost barriers by removing the need for external inverters and enables seamless grid interaction via standardized communication protocols. Nissan aims to price the onboard V2G solution comparable to today's unidirectional chargers, significantly lowering the entry costs for households and promoting mass adoption (Nissan Motor Corporation, 2024).
- In 2025, the OCPP 2.1 protocol was officially released, extending OCPP 2.0.1 with added support for bidirectional energy transfer, ISO 15118-20 integration and Distributed Energy Resource (DER) control. These updates enable smarter and more grid-responsive EV charging infrastructure, providing the communication capabilities necessary for reliable AC-based V2G operation in both residential and commercial environments (Open Charge Alliance, 2025).

2.4 Vehicle-to-Grid Technology

V2G is part of the umbrella term V2X, which (Thompson & Perez, 2020) describe as the broader concept where electric vehicles are used for more than just transportation but also to provide energy services when parked. V2X encompasses services such as feeding electricity back to the grid (V2G), powering buildings (V2B), homes (V2H), vehicles (Vehicle-to-Vehicle (V2V)), and other electrical loads (Vehicle-to-Load (V2L)), thereby enabling more flexible energy management across the system. These configurations can be seen in Figure 2.2 below, where the services are delivered through bidirectional charging. A key advantage of V2X is its ability to leverage the

existing capacity of EV batteries, which typically remain unused more than 90% of the time, creating an opportunity to unlock additional value without requiring new storage infrastructure (Kabir et al., 2022).

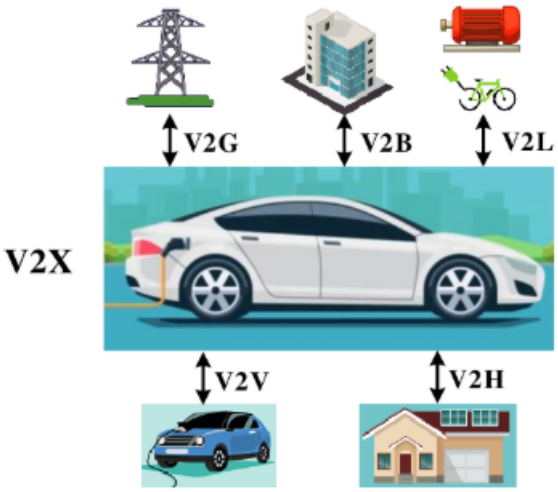


Figure 2.2: V2X ecosystem (Khezri et al., 2024)

V2G technology can play a significant role in providing a range of essential grid services that help maintain the stability and reliability of the electricity grid. This includes services such as frequency regulation and voltage support as well as revenue driven opportunities like energy arbitrage trading (Mastoi et al., 2023). In addition, V2G can contribute to grid optimization by offering ancillary services, such as spinning reserve, which provide additional backup capacity in case of unforeseen grid disruptions.

2.4.1 V2G Opportunities for Housing Cooperatives

The current V2G market remains in its early stages of technical and commercial development, with uncertainties around the profitability and feasibility of various business models (Kabir et al., 2022). Nevertheless, Sweden presents strong potential for V2G integration due to rising EV adoption, high shares of renewable energy and underutilized capacity of parked vehicles.

In V2G systems, EVs serve dual roles as both transport and flexibility assets, supporting the shift toward a sustainable energy system. This aligns with the European Union's vision of Energy Communities, which promotes decentralized energy production and increases local resilience (European Commission, 2025a). By functioning as mobile storage units, EVs can power buildings, reduce peak demand,

lower electricity costs during peak hours and enhance grid stability (Stockholm Exergi, n.d.).

For Swedish housing cooperatives, it is increasingly common to adopt collective electricity agreements, where all residents are included under a single electricity contract (Nettbureau, n.d.). This approach has become standard in new constructions and is also being implemented in older residences due to the financial benefits (Infometric, n.d. Rehnberg, 2024). By aggregating under the same electricity contract, the housing cooperative can reduce administrative burdens for residents and often negotiate a lower electricity price per kWh, typically through fixed-price contracts (HSB, 2025; Vattenfall, 2025a). However, it is also more difficult to steer individual behavior as residents are no longer in control of their electricity contracts, limiting their ability to respond to hourly price signals and reducing incentives for load shifting. While some cooperatives still provide individual metering and billing based on actual consumption, the network contract containing the power tariff is collective, blurring the connection between personal usage and costs (Elbyte, n.d.).

The debate over fixed versus variable electricity contracts is common for housing cooperatives (HSB, 2025). However, it is often overlooked that the electricity supply contract is just one part of the total cost. Since all DSOs are required to implement power-based tariffs by January 1, 2027, electricity network contracts will see great changes. Reviewing network contracts is therefore becoming increasingly important, as cooperatives must start looking at how to reduce their power demand and related costs.

Without the ability to shift demand, high peaks can lead to significantly higher costs. Shifting daily routines and daily load profiles could be difficult for a collective of residents to do in a meaningful way, especially without incentives. This is where EVs can play a crucial role, where they could be utilized to provide power for self-consumption or discharging to the grid, thereby shaving peak loads and reducing tariff costs. The EVs are going to be at the residence either way, requiring substantial power for charging, which adds to the peak power and associated costs. Smart charging management could therefore be key to avoid the high charges. To utilize the technology even further, housing cooperatives could still employ variable supply contracts, taking advantage of price fluctuations through energy arbitrage (since V2G systems require hourly, or at least periodically, control management).

Chapter 3

Economic Implications of Vehicle-to-Grid

This chapter reviews key research contributions in the field, outlining the economic implications of various V2G configurations. It covers V2G participation in energy systems, integration into V2B setups and their potential for cost savings and revenue across services like energy arbitrage and peak shaving. It also addresses challenges such as battery degradation and infrastructure requirements, concluding with insights on market structure and willingness to adopt V2G.

In recent years, V2G technology has gained increasing attention in literature for its potential to support grid stability, enhance sustainability and reshape energy markets (Thompson & Perez, 2020). Researchers have explored its implementation across residential, commercial and industrial settings, considering a range of economic and regulatory conditions. A comprehensive review by Bibak and Tekiner-Moğulkoç (2021) synthesizes two decades of literature on the economic implications of V2G technology. Their analysis outlines both the opportunities and limitations of V2G, particularly in relation to their integration with Renewable Energy Systems (RES) and smart grid infrastructures. Many studies emphasize the technical feasibility and environmental benefits of V2G, yet the economic viability remains a subject of debate. Few studies address the economic drivers required for widespread adoption, such as financial incentives for EV owners, cost savings for businesses and the impact on grid operation costs.

3.1 Vehicle-to-Grid Configurations

Vehicle-to-Grid technology enables bidirectional energy exchange between electrical vehicles and the grid, creating opportunities on different system-levels and under different use cases. At its core, V2G adoption has the potential to reduce energy costs and generate revenue through services such as energy arbitrage, peak shaving and participation in ancillary services like frequency regulation. These mechanisms leverage EV capabilities to optimize energy use, allowing them to respond to market signals and support grid stability. However, the profitability of V2G depends on a range of factors, including electricity price volatility, battery degradation costs, market design and participation scale.

Several studies demonstrate that V2G can create viable revenue streams under favorable conditions. For example, Leijon et al. (2024) simulate ten EVs in Sweden and find that V2G-enabled vehicles can generate profits by discharging during peak price periods since they experience large SoC fluctuations. The economic benefits are strongest during high price volatility, particularly in winter or under high renewable energy variability. However, they also find that these benefits are offset to some extent by increased battery wear due to frequent cycling. With perfect market conditions, Menchaca Santos et al. (2025) demonstrate the economic value of stacking EV services, showing that residential users in eastern Denmark could have annual savings of 6-11% depending on high or low driving demand. The study employs a techno-economic Mixed-Integer Linear Programming (MILP) optimization model, finding that V2G setups are especially attractive for users with flexible charging patterns, highlighting that battery degradation is a minimal cost factor. For heavy-duty fleets, savings are more limited, but combined with Frequency Containment Reserve for Disturbances (FCR-D), annual savings can reach €330,000 (26% reduction compared to unidirectional charging). Similarly, Greaker et al. (2022) study a perfectly projected case for Belgium in 2040, suggesting that even limited V2G participation could yield significant cost reductions, especially for infrastructure investment needs. The authors develop an analytical model to show that V2G can encourage battery investments, lower system costs and reduce the need for new generation capacity by alleviating peak demand. This also contributes to price convergence between peak and off-peak hours, improving electricity market efficiency and social welfare.

Despite these opportunities, some caution against overestimating V2G's current profitability. For instance, Vallinder and Carlsson (2022) assess the economic feasibility of V2G for a car-sharing fleet in Sweden, optimizing the costs under different charging strategies - uncontrolled, smart charging and V2G. While smart charging alone led to notable annual cost savings (7.3-8.4%), V2G provided only marginal additional benefits (up to 8.7-9.9% savings), depending on charger type. They also find that participating in Swedish frequency regulation markets is more profitable than simple energy arbitrage, yet overall net revenues remain relatively low. Results emphasize that under current economic conditions, V2G is not yet a viable standalone business model for fleet operators. Battery degradation is identified as the key cost barrier. However, with the right incentives or evolving market structures, its feasibility could improve. These findings align with Zheng et al. (2022), who assess aggregator-led V2G services in the New York market. Their optimization model, maximizing aggregate profits, shows that battery costs currently make V2G unprofitable, but future cost reduction could change this. They also find that in the current market landscape, revenue from frequency regulation services are limited. They emphasize that electricity prices strongly influence charging strategies and are, along with market design, determining factors on profitability.

By examining both the large-scale V2G adoption for home charging and small-scale implementation at public airport parking, Nagel et al. (2024) evaluate the economic and operational effect in Denmark and Norway in 20240 - two countries with contrasting energy mixes. The findings show that V2G reduces electricity price volatility, lowers the systems operations costs, decreases renewable curtailment and supports the integration of wind and solar power, especially in regions with high shares of variable renewable energy (like Denmark). In less flexible systems, V2G is found to be profitable at smaller scales, while large-scale usage flattens price differences, thereby lowering financial returns for participants. In flexible systems (like Norway), V2G may even raise average electricity prices despite reducing peak prices, revealing tensions between system efficiency and user-level economics.

3.2 Vehicle-to-Building and Vehicle-to-Home Configurations

As the number of EVs continues to grow, increasing attention is being paid to their role not just as transportation, but as flexible energy assets. V2B and V2H technologies have gained attention for their potential to enhance energy efficiency and reduce electricity costs for households. These configurations enable EVs to store surplus electricity during off-peak hours and release it back to buildings and households during periods of high demand, thereby shifting load and shaving peaks. This not only reduces household electricity bills but also alleviates stress on local grids and contributes to more sustainable energy use.

Some of the literature highlights the strong synergy between EVs in V2B/V2H setups and renewable energy sources, particularly solar PV. When paired with smart energy systems, EVs can dynamically support building loads, enhance self-consumption of locally produced renewable electricity and improve the overall environmental footprint of residential and commercial energy systems. This potential is highlighted in a study by Bjurek and Hagman (2022), who examine the role of EVs in supporting both grid operations and household energy needs, addressing two major challenges of the energy transition: the growing strain on electricity grids and the intermittency of renewable energy generation. Their study applies a V2H setup to reduce peak demand in Swedish households, showing that it can lower household electricity costs by 13.3-35.9% while also reducing battery calendar aging compared to uncontrolled charging. Moreover, they show that combining with V2G setups can support frequency regulation, highlighting the broader role of EVs. However, the study also notes that battery degradation remains a significant economic trade-off, potentially offsetting up to 30.2% of the realized savings. Despite this, the authors highlight that both V2H and V2G present substantial opportunities for cost reduction and grid support, offering tangible benefits to EV owners and aggregators.

In a broader system context, Ouammi (2021) finds that using V2B to manage a microgrid equipped with rooftop solar PV, battery storage and EV infrastructure, effectively reduces peak loads with EV contributing to 18% and batteries to 7%. This also lowers demand costs. They highlight that EVs play a key role due to their flexibility and that the system successfully manages user requirements while supporting the

variability of renewable energy sources. Lo et al. (2023) propose a Smart Energy Management System (SEMS) that integrates EVs, solar PV and ESS to reduce grid dependence and carbon emissions in buildings. Using real-world EV parking patterns, their system achieves a 65% reduction in grid power demand and a 64% cut in carbon emissions under the PV+V2B+ESS scenario. Notably, the PV+V2B configuration emerges as the most cost-effective, balancing a 6% cost reduction with a 59% emissions reduction. The study also underscores the importance of accounting for EV battery degradation, which was excluded in their analysis. Similarly, Kobashi et al. (2020) evaluate four system configurations in residential buildings - PV only, PV with battery storage, EV charging only and PV with EVs - in the context of projected energy prices in Japan and China in 2030. With two different electricity price structures, their findings indicate that PV+EV systems are the most cost-effective, especially in high-electricity-price regions like Kyoto, offering a net present value of around $6 900 $\pm$ 1,600. In contrast, in Shenzhen, where electricity is cheaper, the economic advantage is delayed. However, they find that in both cases, the integration of EVs contributes to decarbonization, emphasizing an environmental value of such systems. The study underlines that economic viability depends heavily on local electricity prices, regulatory support and integrated policy design.

Literature also reveals the complementary role of stationary batteries, underlying the value of integrated configurations. For instance, Ahsan et al. (2022) suggest that stationary batteries play a valuable supporting role and that shared infrastructure can maximize financial potential and enable optimized EV scheduling and energy utilization. The study examines a smart building network in New Zealand where a primary building with solar PV and stationary storage supplies electricity to secondary buildings via bilateral contracts. Their results highlight substantial economic benefits across all assets: daily profits for primary buildings of up to 62%, cost savings of 8-20% for secondary buildings and 35-65% charging cost reductions for EVs. These outcomes were found to mostly be driven by real-time pricing mechanisms, local tariff design and optimized load contracts. Including stationary batteries in the system was found to further enhance the economic performance. Similarly, Higashitani et al. (2021) find that while V2H is generally more profitable than using stationary batteries alone, combining both technologies yield even greater returns, particularly for households with large PV capacity and high electricity demand. Their study evaluates the economic and energy performance of V2H in Japanese residential settings, simulating variations

in electricity demand, EV usage patterns and PV installation areas under favorable conditions where both EV and PV costs are low.

Several studies emphasize the economic gains from EV-PV systems. Luo et al. (2024) report Levelized Cost of Energy (LCOE) reductions of 38.9% for an office building system in Chengdu, along with EV charging cost reductions of over 18%, even when accounting for battery degradation costs (5.2% annually). For the overall system, cost savings can reach up to 26.4-31.8%. Similarly, Barone et al. (2020) highlight operating cost savings of 8.1% and electricity demand reductions of 20% in a V2B configuration between multiple office buildings in Naples, underscoring the potential of interconnected EV-building ecosystems to support zero-energy goals. With improved self-consumption across the system, the electricity consumption was reduced by 20%. However, they point out that economic benefits depend largely on electricity prices, necessitating supportive policy measures. Zhou (2022) also points out the pivotal role of pricing mechanisms in shaping economic outcomes. The study demonstrates that dynamic pricing and incentives for electricity exports can effectively encourage commercial building participation in V2B networks, despite the risks of battery wear (which is found to be 15.8%). Lastly, Kern et al. (2022) demonstrate how PV self-consumption and revenue generation can be significantly enhanced through smart charging and bidirectional charging strategies. Shifting from uncontrolled to smart or bidirectional charging increases PV self-consumption from 23% to 45% and 65% respectively, as well as yielding cost reductions of 25% to 36% annually. With arbitrage, revenue can rise from €310/year to €530/year. These findings illustrate how coordinated charging can monetize otherwise curtailed solar generation and reduce grid reliance.

3.3 Renewable Energy Integration

A recurring theme in the literature is the significant potential of V2G technology to enhance the integration of renewable energy sources by addressing the inherent mismatch between renewable generation and electricity consumption. V2G enables EVs to store surplus renewable energy during periods of high generation and discharge it during peak demand, thereby increasing self-consumption and reducing reliance on grid-supplied power (Bibak & Tekiner-Moğulkoç, 2021; Blumberg et al., 2022; Nagel et al., 2024). This flexibility is particularly valuable in power systems with a high share

of Variable Renewable Energy (VRE), such as wind and solar, where managing supply fluctuations is critical.

In countries with substantial renewable penetration, such as Denmark, Nagel et al. (2024) report that V2G strategies can reduce renewable energy curtailment by up to 30%, highlighting the important role EVs can play in balancing supply and demand. Similarly, Bibak and Tekiner-Moğulkoç (2021) emphasize that V2G contributes to overall grid stability by storing excess renewable energy and releasing it when demand rises. Supporting these findings, Blumberg et al. (2022) demonstrate through a German case study that smart charging algorithms within V2G systems optimize energy flow, enhance grid stability and enable more efficient use of renewable generation - thereby reducing the need for costly infrastructure investments. They estimate that widespread V2G adoption across Europe could unlock an additional 475 TWh of renewable electricity annually while reducing the need for up to 244 GW of new VRE capacity.

From an economic perspective, high shares of renewable generation often lead to price volatility, which can diminish its market value if adequate storage solutions are not in place. V2G mitigates these challenges by shifting demand to better align with renewable supply, smoothing peak loads and stabilizing electricity prices (Blumberg et al., 2022; Nagel et al., 2024). This dynamic not only strengthens the business case for renewables but also lowers overall system costs by decreasing dependence on fossil-fueled power plants and reducing the need for additional grid infrastructure. Fachrizal et al. (2024) find that V2G increases self-consumption of on-site renewables, resulting in direct economic benefits for consumers. Q. Chen et al. (2025) further show that integrating EVs into building energy systems significantly reduces net load variability, especially when solar PV penetration exceeds 20%, suggesting that EVs can serve as a more flexible and cost-effective alternative to stationary battery storage.

However, the magnitude of V2G's benefits is closely linked to the level of renewable penetration in the energy system. Yang et al. (2025) demonstrate that V2G becomes economically and environmentally advantageous primarily when renewable generation exceeds 80% of total electricity supply. Under such high-renewable scenarios, V2G can substantially reduce reliance on conventional backup systems, improve price stability and accelerate the phase-out of coal-fired power plants. Additionally, V2G supports the variability of renewables by providing critical grid

services traditionally supplied by centralized power plants, including frequency regulation, voltage control and congestion management (Blumberg et al., 2022). While unidirectional charging may be more effective in coal-dependent systems, bidirectional V2G offers greater flexibility and benefits in renewable-rich contexts.

Nevertheless, Blumberg et al. (2022) caution that even with widespread V2G adoption, some level of controllable backup capacity remains necessary to maintain system reliability. This highlights the need for supportive regulatory frameworks and policy incentives to encourage investment not only in V2G infrastructure but also in complementary flexibility resources, ensuring a resilient and sustainable energy system.

3.4 Different Charging Strategies

Bidirectional charging is not only about discharging to the grid or to households, it requires smart energy management to fully reach its potential, where many studies have compared controlled bidirectional charging to controlled unidirectional charging as well as uncontrolled unidirectional charging.

Uncontrolled charging tends to exacerbate peak loads and misalign with renewable energy availability. As Fachrizal et al. (2024) demonstrate in a Swedish net-zero energy city scenario, this strategy achieves only about 68% load matching, leading to increased grid stress and a greater need for stationary storage. Q. Chen et al. (2025) similarly find uncontrolled charging to be the least flexible, failing to provide grid-friendly behavior or economic advantages.

In contrast, smart unidirectional charging introduces controlled scheduling of when and how EVs charge, aligning energy consumption with lower-price periods or higher renewable generation. Fachrizal et al. (2024) find that this strategy improves load matching to 73% with moderate economic benefits from timing charging and discharging better to prices, which Drommi (2022) supports with finding modest but consistent cost savings. Smart charging also contributes to peak shaving and reduces peak grid exchanges where P. Huang et al. (2022) find 8.8-16.3% reduction in peak energy exchanges, benefiting both grid stability and energy costs. Its relative simplicity and lower impact on battery degradation compared to bidirectional charging make it a practical, economically viable solution under current conditions. Vallinder and

Carlsson (2022) highlight that smart unidirectional charging alone can yield annual cost reductions of 8.4% compared to uncontrolled charging, making it attractive for fleet operators even without regulatory incentives. Adding V2G functionality offers only marginal additional savings, increasing total savings to 9.9% for a 22 kW charger, due to battery degradation costs.

Bidirectional charging takes smart charging a step further where Mastoi et al. (2023) find that EV flexibility can enhance grid balancing, provide ancillary services and create additional revenue streams beyond energy arbitrage. They highlight that carefully coordinated and scheduled charging and discharging are essential to maximize economic benefits. Fachrizal et al. (2024) observe that V2G achieves the highest load matching of 84%, significantly reducing the reliance on costly stationary storage. Moreover, Q. Chen et al. (2025) affirm that bidirectional charging maximizes flexibility and return on investment, particularly when grid capacity or budget constraints limit other storage options.

However, the economic and technical feasibility of V2G is more nuanced. Battery degradation is highlighted as a critical concern, where Leijon et al. (2024) find that V2G-enabled EVs experience larger SoC fluctuations (between 20-80%) than those using passive charging strategies, leading to accelerated battery wear. According to P. Huang et al. (2022), bidirectional charging similarly induces greater SoC variation than regular or controlled charging due to increased charging-discharging cycles, which tend to accelerate degradation. Commuting distances are found to have the greatest impact on battery degradation, going from 1.1%/year to 6.6%/year when going from 40 km/day to 140 km/day for smart charging. While increasing charging power limits can improve grid services such as peak shaving, it also exacerbates battery wear, creating a trade-off between system flexibility and battery lifespan. Their study also found the daily average degradation rate to be 0.003-0.02% for the 65 scenarios.

Several studies emphasize that battery degradation remains a core cost barrier. Vallinder and Carlsson (2022) argue that degradation significantly limits economic returns, making the savings from V2G marginal. Comparing two charging capacities (11kW and 22kW), they found battery degradation to range from 63-75% for V2G. Zheng et al. (2022) similarly find that current battery costs likely make V2G unprofitable, where battery degradation is the key factor to EV aggregator losses. Simulating three scenarios, the study found total battery wear costs to range from $108

to $168.2. Bjurek and Hagman (2022) acknowledge V2G's role in FCR but report that degradation can offset up to 30.2% of the potential financial benefits. This concern is further reinforced by Rahman et al. (2023), who include degradation in Levelized Cost of Storage (LCOS) calculations, showing that it remains a major cost driver, especially in colder climates where battery efficiency declines. The study concluded that reducing lithium-ion battery prices will also reduce LCOS. In their research, battery life was found to be reduced from 10 years to 6 years, needing more frequent replacement and significantly impacting V2Gs overall economic performance.

Nonetheless, several studies suggest that the extent of battery degradation may be less severe than initially anticipated, or that it can be effectively mitigated through appropriate management strategies. Menchaca Santos et al. (2025) report that degradation is a minimal cost factor under controlled conditions, with only 2.8% reduction in battery State-of-Health (SoH) when going from unidirectional to bidirectional charging. Calendar degradation almost stays the same in this transition too. Luo et al. (2024) find that economic gains from V2G are achievable even when degradation is considered, with 5.2% extra degradation annually. This stems from 210 discharges from the EV to the building. Authors also add that higher outdoor temperatures can decrease degradation, with 0.112% as maximum degradation when below 5°C. Similarly, Malya et al. (2021) further show that V2G does not necessarily reduce battery life and can in some cases even extend it for certain chemistries, such as Lithium Manganese Oxide (LMO) batteries, depending on battery chemistry and usage patterns. Englberger et al. (2021) support this by demonstrating that optimizations that account for degradation costs can extend battery health while allowing participation in services like peak shaving, self-consumption and market trading. Without control strategies, degradation can lead to 6 year lifetime reduction. While technical challenges exist, Mastoi et al. (2023) conclude that a well-managed V2G system can offer significant cost savings and grid benefits.

Profitability is further found to depend on electricity price volatility and access to ancillary service markets. Leijon et al. (2024) find that winter months in Sweden are more favorable for V2G due to energy arbitrage utilization. Drommi (2022) reports that bidirectional V2G alone is not profitable but becomes financially attractive when combined with FCR services, generating up to 22 000 SEK annually per vehicle in a Swedish energy community. Vallinder and Carlsson (2022) further underline that V2G cost-effectiveness is highly sensitive to electricity price volatility. They argue

that to realize the full potential of V2G, financial incentives and supportive regulatory frameworks are needed; otherwise, smart charging remains the more cost-effective and practical solution for EV fleet operators.

3.5 Electrical Vehicles for Different Services

3.5.1 Energy Arbitrage Trading

Energy arbitrage is a key economic benefit of V2G, enabling EV owners or aggregators to take advantage of electricity price fluctuations, particularly under dynamic pricing. By charging during low-price periods and discharging during high-price periods, V2G systems can generate cost savings and potential revenue. This strategy allows households to store energy during off-peak hours and utilize or export it when prices peak. Several studies explore the viability of energy trading using different modeling approaches and geographic contexts. For example, Malya et al. (2021) estimate that EV owners in Germany could earn up to €662 annually through energy arbitrage with a 100 kWh battery, factoring in a dynamic model for battery degradation and EV driving behavior. The study finds that profitability stems from both energy trading and extended battery life, but highlights that outcomes are sensitive to battery type, usage patterns and market conditions. Similarly, Kern et al. (2022) show that combining energy arbitrage with PV self-consumption in an V2G+V2H setup can yield up to €530 annually during winter months (€310 is from optimized PV usage). Their findings suggest that while arbitrage is a promising opportunity, its effectiveness depends more on household load profiles and PV system size than on EV battery capacity.

However, other studies point to the relative limitations of arbitrage trading when considered in isolation. Vallinder and Carlsson (2022) focus on a future Swedish context, finding that energy arbitrage only yields modest returns, especially when battery degradation is taken into account - 7-14 SEK per year per vehicle using 11kW and 22kW chargers respectively. In contrast, participation in FCR-D markets provides significantly higher revenues, around 275 SEK and 195 SEK per vehicle. The authors conclude that arbitrage alone may not justify V2G investments unless supported by complementary revenue streams or new policy frameworks and incentives. This conclusion is supported by Tepe et al. (2022), who analyze revenue optimization for EV aggregators in Germany. They find that while arbitrage trading yields between €28

and €203 per vehicle in 2020, participation in FCR markets is far more profitable, at around €380 per vehicle. Their study also reveals a trade-off: higher V2G activity increases battery wear, but the additional revenue can justify the degradation costs, particularly with growing EV adoption and smart aggregation strategies. Heilmann and Friedl (2021) also point to frequency regulation as a promising opportunity for economic return, especially for vehicle owners. Further Jiang et al. (2025) and Thompson and Perez (2020) argue that while energy arbitrage can contribute to cost reductions, it is most effective when combined with other applications. Jiang et al. (2025) propose a value-stacking framework combining V2G (for arbitrage) and V2B (for self-consumption) for residential communities, using real-world data from the United States and Australia. Their results indicate that V2B offers the greatest savings by leveraging stored energy to offset high electricity tariffs during peak periods. Thompson and Perez (2020) introduce a V2X Value Stream Framework, evaluating the economic potential of different EV services, suggesting that power-based services (such as bill management, resource adequacy and network deferral) yield greater economic returns than commonly studied mechanisms like energy arbitrage. They further find that these services also lead to less battery degradation while offering better opportunities for revenue stacking.

3.5.2 Peak Shaving and Load Shifting

Beyond this, V2G technology can be leveraged to reduce peak electricity demand (peak shaving) and shift energy consumption to off-peak hours (load shifting). By charging EVs during low-demand periods and discharging them to power household needs during peak hours, users can lower their maximum power demand and reduce grid fees tied to peak loads. Research highlights the strong economic potential of these applications where Yeoh et al. (2025), for example, demonstrate that V2B systems in urban Taiwan can reduce electricity costs by 51.2%, decrease grid energy usage by 46.8% and cut peak demand by 63.5% compared to a non-V2B baseline. These reductions are achieved through the integration of V2B with solar PV and ESS, offering a total cost savings of 40.8%. The model's flexibility allows adaptation to various urban layouts and seasonal variations, making it applicable to both residential and commercial contexts. Borge-Diez et al. (2021) explore the integration of V2B in Spain and demonstrate how leveraging stored EV energy during high-demand or high-price periods can reduce peak demand by as much as 50%. This not only decreases

energy costs for buildings but also delivers environmental benefits and contributes to greater grid efficiency and reliability. Further, Englberger et al. (2021) find that peak shaving combined with self-consumption are the most profitable V2G applications for commercial EV fleets in Germany. By stacking multiple energy services together, it could generate up to €2,224 annually per EV. Moreover, the model also reveals that battery degradation can be mitigated through optimized charging behavior. Lastly, Liu et al. (2024) find that V2B in a Chinese microgrid effectively shifts peak loads to off-peak periods, with battery capacity and the number of charging stations being the most influential factors. The study identifies optimal PV penetration rates of 30–40% in summer and 40–50% in winter for maximum peak smoothing. Furthermore, it emphasizes that reducing battery costs by 65% or improving battery life can make V2B economically competitive with centralized storage solutions.

3.6 Cost Considerations and Barriers to Adoption

Despite the economic potential of V2G technologies, its widespread adoption remains constrained by a variety of cost-related, structural challenges, stemming from technical, financial and regulatory complexities that affect the feasibility and long-term profitability of V2G systems.

Battery degradation is a major concern in literature due to frequent charging and discharging cycles in V2G applications. Mojumder et al. (2022) highlight that accelerated battery wear can potentially discourage EV owners from participation due to worries about battery lifespan and replacement costs, where users bear most of the long-term risks. Adding to battery management, Qiu (2023) further identifies safety, security and privacy concerns to complicate adoption and increase operational risks.

3.6.1 Infrastructure and Standardization Challenges

Another critical barrier is the lack of standardization in communication and charging infrastructure, where concerns about compatibility complicates integration further. Without fully developed and universally adopted standards, ensuring interoperability among vehicles, charging infrastructure, aggregators and grid operators is difficult (Steen et al., 2025). Studies such as Alsharif et al. (2021), Mojumder et al. (2022),

and Ravi and Aziz (2022) emphasize key barriers to include high upfront investment costs and the need of costly grid upgrades to support high EV penetration. These factors increase the operational and investment costs of V2G systems, limiting their widespread implementation. Mojumder et al. (2022) conclude that overcoming these barriers needs improved battery technology, supportive policies, clear business frameworks and enhanced grid compatibility to make V2G commercially feasible.

Steen et al. (2025) did a pilot project in Sweden, V2X-MAS, where they enabled a 22 kW AC-AC charger through custom back-end modifications to the OCPP 1.6, allowing negative current values for discharging. These workarounds were necessary due to the lack of native bidirectional support. With the recent release of OCPP 2.1, such functionality is now standardized, solving most of the technical barriers they encountered, with improved security and seamless backend integration (Open Charge Alliance, 2025). Along with this a communication interface standard ISO 15118-20 has emerged for bidirectional power transfer. However, full implementation remains limited, as partial and inconsistent adoption across industry actors continues to hinder large-scale V2G deployment (Steen et al., 2025).

3.6.2 Business Models and Regulatory Gaps

Goncearuc et al. (2024) point out that current EV charging business frameworks are not well-aligned with V2G's value propositions, presenting the highest risk for implementation. A key issue is the lack of clear and functional business models that fairly distribute costs and benefits across stakeholders. Qiu (2023) notes that the immaturity of current models results in cost burdens mostly falling on power and grid companies, while EV users receive small financial incentives, leading to weak motivation to participate. Mojumder et al. (2022) add that immature business models and unclear policies limit investment incentives. To address these limitations, Kabir et al. (2022) propose a structured business model that positions EV owners as flexibility providers through different services. Their findings call for political support, financial incentives and increased public awareness to overcome these barriers. They also highlight that high costs and limited market maturity, as well as battery degradation concerns, range anxiety and infrastructural needs hinder adoption. Mojumder et al. (2022) even argue that creating viable business models and revising market structures should be the priority for V2G to become profitable, as well as developing

energy management strategies that balance economic benefits with battery health. Complementing these perspectives, Sovacool et al. (2020) argue that the successful deployment of V2G depends not only on technical innovation but also on economic and regulatory factors. They emphasize the importance of clear business models with stakeholders roles and harmonized governance across the energy and mobility sectors. The authors suggest that regulatory incentives such as dynamic tariffs, support for mobility-as-a-service platforms and the development of second-hand EV battery markets could enhance participation and efficiency. Ultimately, they conclude that the long-term viability of V2G lies in financial, business and policy dimensions that are well-designed and functioning.

3.6.3 Tariffs and Pricing Models

Dynamic pricing models, such as ToU or Two-Part Tariff (TPT), are identified as factors affecting the economic viability of V2G participation. Jiang et al. (2025) show that coordinated V2X services (V2B, V2G and peer-to-peer trading) can significantly reduce energy costs by 19.9% under ToU and 17.3% under TPT where V2B yields the greatest economic benefit through effective peak shaving. In the Swedish context, Haikola and Söderberg (2020) identify ToU capacity charges with free electricity during off-peak hours as particularly effective. These tariffs encourage demand shifting and support distributed energy resources such as solar PV and batteries. However, their study also notes that regulatory constraints, such as conflicting taxation rules and revenue caps for grid operators, limit the broader deployment of these pricing models. Ravi and Aziz (2022) and Signer et al. (2024) also point to regulatory and market barriers that often limit the practical application of such pricing models. Ravi and Aziz (2022) argue that while dynamic tariffs can increase revenue through optimized charging/discharging, V2G adoption is held back by a lack of standardized business models and regulatory uncertainty. They call for governmental support through subsidies, tax breaks or even free parking, emphasizing that long-term adoption requires infrastructural developments and social acceptance. Similarly, Signer et al. (2024) highlight that high taxes, surcharges and low compensation for discharging significantly reduce financial incentives, making V2G not economically viable under Germany's current conditions. The study emphasizes the need for tax reform, suggesting integrating V2G into capacity-based tariffs to enhance flexibility and lower wholesale electricity prices. However, they warn that misaligned policies may introduce new systemic risks

as adoption grows. Bjørndal et al. (2025) offer a critical perspective on the design of grid tariffs, warning that poorly designed grid tariffs such as capacity-based ones, eliminate price signals and can significantly reduce incentives for users to respond to system needs. In this Norwegian study, they find that cost savings depend heavily on electricity price levels and volatility and that effective price signals are essential for aligning user behavior with system constraints.

3.6.4 Willingness to Pay and Decision-Making

Studies agree that user acceptance of V2G depends on several dimensions, including financial, behavioral, technical and regulatory factors. Helferich et al. (2024) did a study on smart charging tariff designs, revealing that financial incentives such as cost savings or clear tariff structures, play a central role in consumer acceptance and decision-making, especially when paired with user control and flexible pricing schemes in Germany. Similarly B. Huang et al. (2021) and C.-F. Chen and Lai (2024) emphasize that willingness to participate increases when V2G offers benefits based on economic value and performance, such as fast charging and minimum battery guarantees, while concerns over battery degradation, range anxiety and data privacy serve as significant barriers that reduce adoption. Demuth et al. (2024) and Ramic and Nyström (2024) point to broader systemic barriers such as regulatory uncertainty, lack of standardization and insufficient collaboration across market actors. These barriers limit consumer acceptance, requiring collaboration, consumer education and policy advocacy to overcome challenges and capitalize on business opportunities. Demuth et al. (2024) add recommendations for user-friendly technology, clear communication of benefits, policy support, investment in charging infrastructure and the development of business models that align with user preferences. While V2G shows strong potential for grid load management and new revenue streams, overcoming regulatory and business model barriers is essential for its widespread implementation.

3.7 Summary

The literature highlights the potential of V2G technology to provide grid services, offer economic incentives for EV owners and support the integration of renewable energy. Numerous studies have demonstrated the significant economic benefits of implementing V2G in various economic and regulatory contexts, with revenue streams

from services such as energy arbitrage, peak shaving and ancillary services. Various charging strategies and system configurations can unlock these benefits, though challenges such as battery degradation and operational complexities remain barriers to its full adoption.

As the electricity market is evolving in response to new policies, goals and protocols, the standalone viability of V2G technology remains uncertain. Many studies indicate that relying on single revenue streams may not be sufficient, pointing to the need to combine multiple services and adapting to market conditions. Overall, while V2G holds considerable promise, further research is needed to better understand how this technology can be integrated effectively into specific markets, such as the Swedish electricity market, under specific economic and regulatory conditions.

Chapter 4

Method

This chapter outlines the methodological approach of the optimization model, designed to simulate the charging and discharging behavior of EVs and a residential load profile. The simulation results, combined with a battery degradation cost analysis, are analyzed to evaluate the economic viability of V2G participation for a Swedish housing cooperative. The chapter provides the research design, model structure, data collection and analytical methods to ensure transparency and replicability throughout the study.

4.1 Research Design

This study employs a mono-method quantitative approach, as recommended by Saunders et al. (2015) for research focused on model testing, numerical analysis and outcome quantification. The research simulates EV charging and discharging behavior to assess cost-effectiveness under fluctuating spot prices and varying vehicle availability.

An optimization framework is employed to quantify potential revenue streams from V2G-enabled services such as energy arbitrage, peak shaving and self-consumption, evaluating how various charging strategies influence economic performance. The model considers two tariff designs, reflecting emerging dynamic pricing structures in the Swedish electricity market. Additionally, battery degradation costs are incorporated to account for the long-term impact of bidirectional charging on EV battery lifespan. The simulation results are further supported by a Cost-Benefit

Analysis (CBA) to comprehensively evaluate V2G's financial potential within existing energy market structures.

The case study strategy centers on a specific Swedish housing cooperative, enabling context-sensitive insights into V2G's practical implementation. This approach aligns with Saunders et al. (2015) emphasis on real-world applicability, particularly in residential settings where market conditions, grid constraints and user behaviors shape economic outcomes. The full-year time horizon ensures that temporal variability in electricity prices and consumption patterns is adequately represented.

The study relies on secondary data sources, including historical spot prices, EV and charger specifications and academic literature, as well as empirical electricity consumption data from the selected cooperative. This real-world load profile serves as the foundation for simulating demand-side behavior and evaluating the potential of V2G to manage residential peaks and shift loads.

4.2 Optimization Model in GAMS

The optimization model is developed in GAMS, a high-level algebraic modeling language specifically designed for formulating and solving large-scale mathematical programming problems. GAMS is particularly suitable for energy systems modeling due to its support for time-indexed variables, linear and non-linear formulations and complex constraint handling (Rosenthal, 2007). The model is constructed as a MILP problem where the primary objective is to minimize total electricity costs for the cooperative by treating EV batteries as flexible assets that can store and supply electricity in response to hourly price signals and user behavior.

The model is inspired by the research of Drommi (2022), who similarly studied V2G integration in a Swedish housing cooperative. However, several key differences can be found in this study. Drommi incorporates on-site solar PV generation and explores the potential of participating in ancillary service markets, which this study excludes. This study focuses solely on price-based optimization and V2G as an independent technology. Further, the bidding area as well as the studied year differ (SE2 and 2021), which makes a difference in market conditions, including variations in spot prices, volatility and local grid constraints. Further, Drommi employs a quasi-linear optimization. Several parts of the modeling have therefore been adjusted to align with

this specific study, however, the logic behind it has been inspired by that research.

The model operates over a yearly horizon with hourly resolution (8,760 time steps) for each EV, to capture both electricity price fluctuations and residential EV usage patterns. Within this setup, the model consists of decision variables and parameters.

- Decision variables: Include, for example, the charging and discharging power levels and the SoC for each EV battery. These are indexed by each time step and across the electric vehicles individually.
- The parameters of the model consist of historical spot electricity prices, residential base load, EV battery and charger specifications, vehicle availability schedules, required SoC at departure and other technical constraints.

The model follows a deterministic approach where all input data, such as spot electricity prices, vehicle availability and initial SoC values, are predefined before the optimization is carried out. This ensures that the model produces consistent, reproducible results and allows for a clear interpretation of how different parameters and constraints affect the economic performance of the V2G system.

4.3 System Overview

The modeled system represents an integrated energy environment for a real-world Swedish housing cooperative, comprising three interconnected components: (1) household energy consumption, (2) electric grid interaction and (3) V2G-enabled EVs (see Figure 4.1). These components interact dynamically to manage energy flows and costs in response to electricity prices and the operational behavior of the vehicles.

The objective function aims to minimize the cooperatives annual net electricity costs by leveraging:

- Peak shaving: Helps flatten the cooperatives electricity demand curve, reducing peak loads and alleviating grid strain.
- Energy arbitrage: Exploits temporal price fluctuations in the electricity market, charging vehicles during periods of low electricity prices and discharging them during periods of high prices.

The optimization is subject to constraints related to battery operation, EV availability, charging/discharging limits and required SoC at departure.

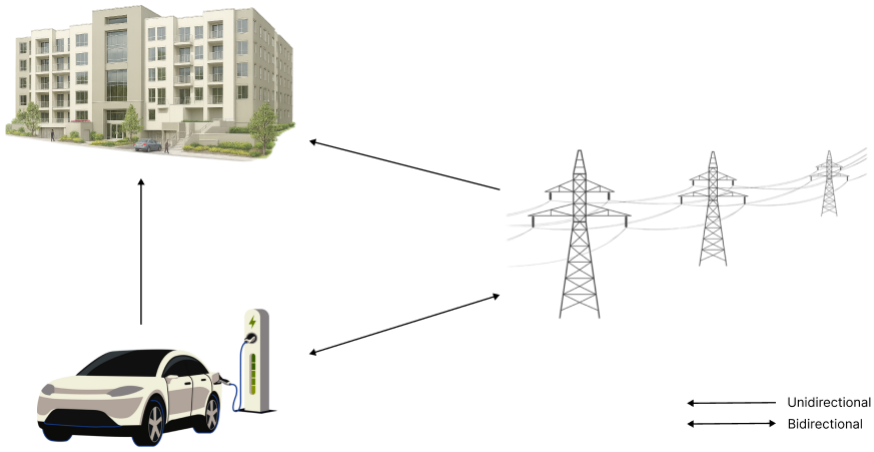


Figure 4.1: System configuration with energy flows

Household Energy Consumption

The cooperative's base load is derived from real measured data which was acquired through a professor at KTH Royal Institute of Technology. The housing cooperative is located in SE3, outside of Gothenburg. This base load is augmented by the energy/electricity demand of ten individual EVs, each with unique weekly driving profiles and availability patterns. While randomly generated, these patterns reflect realistic user behavior and contribute to fluctuations in the cooperative's total energy demand.

Electric Grid Interaction

The system allows for bidirectional connectivity between the EVs and the external electricity grid. Electricity can be imported when local supply (from EVs) is insufficient or when spot market prices are low. Conversely, the system can export electricity back to the grid during periods of surplus, when prices are favorable. The technical limitations on energy trading are based on the chosen fuse of the housing cooperative and the discharge power of the EVs. However, the grid interaction decisions are controlled purely by economic signals, with real-time hourly spot prices guiding optimal import and export decisions.

V2G enabled EVs

Each of the ten EVs is individually modeled with specific characteristics:

- Battery capacity and current SoC
- Arrival and departure times based on probabilistic behavior (for example overnight parking and daily commuting)
- Power limits for charging and discharging
- A minimum required SoC to guarantee driving needs upon departure

4.4 Data Collection

This section outlines the data collection for the simulation model, describing how key inputs were sourced, verified and used. The model draws from a diverse mix of data, including empirical measurements, statistical datasets, academic literature and publicly available documentation. These inputs cover real-world electricity consumption, literature-based estimates for components such as battery degradation and infrastructure costs, historical electricity prices and technical specifications for EVs and charging hardware. Together, they provide a solid foundation for accurately modeling energy flows, economic outcomes and the role of V2G technology in residential energy systems.

4.4.1 Electricity Purchases

The electricity purchasing costs incurred by the housing cooperative consist of two main components: the electricity network contract and the electricity supply contract. Both elements are modeled to reflect real-world pricing mechanisms and regulatory structures applicable in Sweden as of 2025. To assess the impact of different electricity pricing models on the economic viability of V2G participation, two different tariff designs are considered in the analysis: One from Ellevio and one from Vattenfall Eldistribution.

Electricity Network Contract

Both Ellevio and Vattenfall Eldistribution have introduced time-differentiated tariff structures which were last updated on January 1, 2025 (Ellevio, 2025a; Vattenfall Eldistribution, 2025a). Due to regulatory changes that mandates such structures across these contracts, power tariffs have become a central component of network pricing, with less emphasis on traditional energy-based transmission fees. Since such

pricing models were not available in 2023, the last updated models will be used.

To evaluate how this shift affects V2G profitability, the model includes both the *Lågspänning L04S* contract from Ellevio and the *Lågspänning N3T* contract from Vattenfall. Both feature peak and off-peak pricing, but differ significantly: Ellevio has higher power charges and lower transmission fees, while Vattenfall offers lower power charges but higher transmission fees. Comparing these helps assess how different tariff designs influence V2G outcomes. The contracts are shown in Table 4.1 and 4.2 below. The low-load and high-load charges are paid monthly based on the cooperative's highest power peak.

Table 4.1: Ellevio's network contract

Category	**Value**	**Unit**
Low-Load Charge	81	SEK/kW
High-Load Charge	85	SEK/kW
Transmission Fee (Peak hours)	9.0	öre/kWh
Transmission Fee (Off-peak hours)	9.0	öre/kWh
VAT	25	%

For Ellevio, the high-load charge of 85 SEK/kW is additive to the low-load charge, resulting in 166 SEK/kW during peak hours. Similarly, peak and off-peak hour transmission fees are additive.

Table 4.2: Vattenfall's network contract

Category	**Value**	**Unit**
Low Load Charge	34	SEK/kW
High Load Charge	86	SEK/kW
Transmission Fee (Peak hours)	27.2	öre/kWh
Transmission Fee (Off-peak hours)	10.8	öre/kWh
VAT	25	%

For both Ellevio and Vattenfall, the high-load charge and transmission fee (peak hours) apply on weekdays, during the peak hours 06:00 to 22:00 for the months of November, December, January, February and March.

It is important to note that the fixed fees associated with each network contract are excluded from this analysis. Consequently, this study does not compare the total annual electricity costs between Ellevio and Vattenfall. Instead, the focus is exclusively on the variable components (power charges, transmission fees and consumption-based tariffs), as these are directly influenced by the modeled charging strategies and have a meaningful impact on optimization outcomes.

Electricity Supply Contract

For the electricity supply contract, the model uses an agreement from Fortum, Sweden's largest electricity retailer (Hitta Elavtal, 2025). To take advantage of price fluctuations for energy arbitrage trading, a variable supply contract is applied where hourly spot-prices guide the operational decisions within the system, determining when to charge or discharge EVs, import electricity from the grid, or export excess energy.

The variable contract is indexed to hourly Nord Pool spot prices, in this case for bidding area SE3, which represents the marginal cost of electricity and reflects real-time market conditions (Vattenfall, 2025b). Since the electricity consumption data for the housing cooperative is taken from 2023, the retrieved spot-price data is also for that full calendar year. However, due to lack of historical contract data, the contract used in the model is valid for the year 2025 and goes under the name *Rörligt elpris* (Fortum, 2025). The spot price is supplemented by the contract specific surcharges and regulated fees, as well as national taxes. The price data is collected as a time-series and synchronized to the simulation's hourly resolution to ensure temporal accuracy. Table 4.3 below summarizes the cost components included in the contract:

Table 4.3: Fortum's variable supply contract

Category	Value	Unit
Spot Price	Nord Pool	öre/kWh
Surcharge	4.7	öre/kWh
Electricity certificate	2.93	öre/kWh
Fixed Fee	49	SEK/month
VAT	25	%

In addition to this, the Swedish Tax Agency (Skatteverket) has set an energy tax that for the year 2023 is 39.2 öre/kWh and with the VAT of 25% it is valued to 49 öre/kWh (Skatteverket, 2025c).

4.4.2 Electricity Sales

Electricity sold back to the grid through V2G operations is compensated through two contract types, an electricity production contract and an electricity feed-in contract. As there are no contracts available for V2G sell back, the production contract for micro-production is used in this case.

For sales, Fortum is once again applied as the electricity retailer. The production contract includes the selling price of Fortum which is set as the Nord Pool spot price for the SE3 bidding area (Fortum, n.d.). This is paid directly to the housing cooperative for every kWh sold to the retailer.

For grid compensation, once again Ellevio and Vattenfall Eldistribution will be compared as DSOs. The feed-in contract from Ellevio and Vattenfall provide a compensation for electricity injected into the low-voltage grid, differentiating for peak and off-peak hours (Ellevio, 2025b; Vattenfall Eldistribution, 2025b). For Ellevio the compensation applies for *Västra Svealand* and *Västergötland*, which is where the housing cooperative is located. As the cooperative is VAT-registered, both the spot price and feed-in compensation are subject to 25% VAT, which is added to the income received.

Moreover, the housing cooperative qualifies for a refund of the energy tax that was paid during purchase (39.2 öre/kWh without VAT) for all electricity that is re-exported

to the grid (Skatteverket, 2025c). This ensures that the cooperative is not taxed on electricity that is not ultimately consumed on-site. These components form a comprehensive pricing structure for electricity sales, which supports cost recovery and revenue maximization from grid-feed-in services such as V2G. A complete overview of the electricity sales for the Ellevio and Vattenfall is found in Table 4.4 and Table 4.5.

Table 4.4: Electricity sales with Ellevio

Category	**Value**	**Unit**
Spot Price	Nord Pool	öre/kWh
Grid Compensation (Peak hours)	7.8	öre/kWh
Grid Compensation (Off-peak hours)	6.8	öre/kWh
VAT	25	%
Energy Tax Refund	39.2	öre/kWh

Table 4.5: Electricity sales with Vattenfall

Category	**Value**	**Unit**
Spot Price	Nord Pool	öre/kWh
Grid Compensation (Peak hours)	13.2	öre/kWh
Grid Compensation (Off-peak hours)	13.2	öre/kWh
VAT	25	%
Energy Tax Refund	39.2	öre/kWh

4.4.3 Housing Cooperative Profile

To model the baseline residential electricity demand, real-world consumption data from a housing cooperative located in bidding area SE3 is used. The cooperative consists of multiple residential apartments distributed across several multi-story buildings with shared facilities. The dataset includes hourly electricity consumption for the full calendar year of 2023, capturing detailed and typical energy demand patterns.

The total annual electricity consumption was approximately 420 MWh, where the cooperative does not use electric space heating. The load profile follows typical household consumption trends with higher demand in the morning and evenings, and lower consumption during midday and night hours. However, the seasonal variation in electricity consumption is relatively moderate as a consequence of non electric heating.

By relying on actual consumption data rather than synthetic or generalized profiles, the model captures realistic variability, behavioral patterns and seasonal dynamics. This is crucial for accurately evaluating the performance and potential of V2G integration under actual operating conditions. The housing cooperative had a max load of 132 kW during 2023. With all EVs installed and a safety margin added, the chosen fuse of the model was 385 A (240 kW).

4.4.4 Electrical Vehicle and Charger Setup

The EV parameters implemented in the model are based on the Renault Scenic E-Tech Evolution+, with each charging strategy having its own charger. This was selected based on relative affordability and compatibility.

The Renault Scenic E-Tech Evolution+ serves as a representative Battery Electric Vehicle (BEV) profile, with publicly available specifications such as battery capacity, charging speed and energy consumption rates (Renault, 2025). The technical characteristics derived from the manufacturer data for the EV and the different chargers are summarized in Table 4.6. These parameters define the technical limits and capabilities of each modeled EV, including maximum charging and discharging power, battery size and charging/discharging efficiency, ensuring that the simulation reflects a feasible and scalable real-world scenario.

To estimate the total investment cost of enabling V2G functionality in the housing cooperative, an AC-based V2G integration is used due to its growing potential regarding standardization, infrastructure compatibility, cost-efficiency and the increasing momentum seen in pilot projects and commercial deployments (see Section 2.3). This focus reflects current industry trends and provides a technically viable and scalable foundation for modeling residential V2G systems.

Three charger configurations are used in the cost comparison; a basic unidirectional

charger, a smart unidirectional charger and a bidirectional charger. Their costs, including installation, is presented in Table 4.6, which includes total configuration costs after tax deductions for green technology and with 25% VAT added (Skatteverket, 2025b).

- The basic charger is a Zaptec Go model with a 22 kW AC charging capacity.
- The smart charger, also a Zaptec Go, includes the same hardware, but adds Zaptec Sense for load balancing.
- The bidirectional charger is the DEFA Power model, also rated at 22 kW AC, and includes the DEFA Balancer for load management. It supports ISO 15118 for bidirectional communication and V2G compatibility (Defa, 2025).

An OBC is required when using the DEFA Power wallbox for V2G functionality, as the DEFA unit operates with AC power and relies on the vehicle itself to perform the conversion and control needed to discharge electricity back to the grid. Unlike DC V2G systems, which include external inverters, AC-based V2G shifts that complexity to the vehicle, making a compliant onboard bidirectional converter essential. However, the cost of an OBC is difficult to estimate, as it is not publicly available and is typically integrated by Original Equipment Manufacturers (OEM)s into select EV models. Prices vary depending on power level, integration complexity and whether the vehicle supports ISO 15118-20.

In order to estimate a price range of the OBC, similar DC setups are considered. A comparable 20 kW DC charger (Ferroamp V2X) is expected to be priced at 52 750 SEK, also including installation, green technology tax write offs and excluding VAT (Ferroamp, 2025). These figures reflect current market conditions and are expected to decrease over time through standardization, economies of scale et cetera. Since both approaches ultimately require similar hardware capabilities and complexity, just allocated differently, this thesis assumes the cost of the onboard converter in the AC case to be approximately 42,000 SEK with a +/- 20% cost range to account for price variation and uncertainty.

Table 4.6: EV, battery and charging specifications

Category	Value	Unit	Reference
Battery Capacity (cap_{EV})	60	kWh	(Renault, 2025)
Battery Cost (c_{bat})	1,500	SEK/kWh	(BloombergNEF, 2024)
Total Cycles (N_{EFC})	3,000	Cycles/Lifetime	(Bellantuono, 2023) (Saft, 2022)
Consumption	16.4	kWh/100 km	(Renault, 2025)
Charging Power	22	kW	(Renault, 2025)
Charge Efficiency (η_{ch})	93	%	(Khezri et al., 2024)
Discharge Efficiency (η_{dh})	93	%	(Khezri et al., 2024)
Installation Cost	2,750	SEK	(Laddboxbolaget, 2025a)
OBC	33,600 – 50,400	SEK	(Ferroamp, 2025)
Charger			
Basic Price	9,325	SEK	(Laddboxbolaget, 2025b)
Smart Price	10,820	SEK	(Laddboxbolaget, 2025b)
Bidirectional Price	11,575	SEK	(Laddboxbolaget, 2025a)

4.4.5 Operational Costs

The operational costs of the V2G setup include both software for optimized charging control and maintenance of the hardware. It is assumed that maintenance costs are equivalent across all configurations since the physical hardware is comparable in terms of upkeep requirements. The cost of the control software, which enables controlled or V2G operation, is assumed to correspond to 15% of the cost savings achieved through controlled or V2G charging, relative to uncontrolled charging. This estimation is provided by the commissioner of this thesis, Peak Energy.

4.4.6 Driving Profiles and Patterns

For the weekdays (Monday through Friday) the driving profile is the same for all weeks of the year, all ten vehicles and across all simulations. The red cells in Table 4.7 illustrate when the vehicles are not available at the residence, while the

green represents availability (plugged in). The number 30 represents the required SoC at departure, which is set to 30 kWh (50% of the battery capacity) for all vehicles. Departures are between 06:00 and 10:00 with different SoC at arrival. This mechanism is further explained in Section 4.6. The numbers to the right of the red areas show the SoC when every vehicle arrives at the residence, at hours between 16:00 and 21:00. This is to reflect different driving patterns and instances for the different EV users.

Table 4.7: Weekday availability and SoC of EVs

	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12	t13	t14	t15	t16	t17	t18	t19	t20	t21	t22	t23	t24
v1							30									17								
v2									30								25							
v3								30										19						
v4							30												25					
v5									30							27								
v6						30											23							
v7						30										16								
v8								30												21				
v9									30										22					
v10										30											18			

The charging profiles for the weekends are different, with vehicles being available and unavailable at more random times than regular commuting during weekdays (see Table 4.8). SoC when departing is again set to 50% (30 kWh) for all ten vehicles, with arrival SoC to the right of the red areas being different for all vehicles to reflect on different behaviors.

Table 4.8: Weekend availability and SoC of EVs

	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12	t13	t14	t15	t16	t17	t18	t19	t20	t21	t22	t23	t24
v1									30			23												
v2									30							21								
v3											30			25										
v4																	30				23			
v5							30			27														
v6													30			24								
v7								30		26														
v8												30		25										
v9																			30					19
v10																	30			23				

The average daily driving distance of all vehicles is roughly 50 km, which is higher than the national average of 30.8 km/day in 2023 (Trafikanalys Statistik, 2024). This is because the housing cooperative is located in a rural area, where commuting distances are assumed to be longer. Consequently, this assumption is embedded in the vehicle SoC at arrival.

4.4.7 Assumptions

The model is built on several key assumptions to simplify the system while maintaining realism.

- There are 10 EVs in the model setup.
- All EVs are assumed to be V2G-enabled and connected to bidirectional chargers, allowing both charging from the grid and discharging to the buildings or the grid.
- For each EV it is assumed that the user permits grid-discharge, but only within defined technical and behavioral constraints, specifically, a minimum SoC is always preserved before departure to ensure user mobility is not compromised.
- Vehicles are considered available for energy services based on probabilistic behavior patterns, reflecting typical usage such as being parked overnight.
- All EV owners require a 50% SoC at departure, corresponding to 30 kWh in this

case.

- EV batteries charge and discharge between 20-80% SoC to maintain battery health.

These assumptions enable a controlled and consistent evaluation of V2G potential without modeling complex user heterogeneity or participation reluctance, which may vary in real-world implementations.

4.5 Case Study Scenarios

Six case scenarios are constructed by combining the pricing models of two DSOs with three different charging strategies. Each mechanism is described below and summarized in Table 4.9. The simulations explore the economic outcomes of controlled charging and V2G under current market and pricing conditions.

Electricity Pricing Model These represent two distinct power-based tariff designs, differing in their balance between power charges and transmission fees.

- *E - Ellevio*
- *V - Vattenfall*

Charging Strategies

1. *Uncontrolled Charging*
   EVs begin charging immediately at full power after being plugged in, regardless of electricity prices or increased peak loads. This represents the baseline scenario where no optimization is applied.

2. *Controlled Charging*
   Charging is scheduled to minimize costs or reduce peak demand, based on price signals and system constraints. However, discharging is not enabled, meaning EVs act as flexible loads only.

3. *V2G*
   Controlled charging that also allows bidirectional power flow. EVs can optimize charging and discharge to minimize system costs through both energy arbitrage and peak shaving.

Table 4.9: Overview of modeled scenarios

Scenario	Pricing Model	Charging Strategy	Enabled Functions
E1	Ellevio	Uncontrolled	Baseline, no optimization
E2	Ellevio	Controlled	Peak shaving and load shifting
E3	Ellevio	V2G	Peak shaving + Energy arbitrage
V1	Vattenfall	Uncontrolled	Baseline, no optimization
V2	Vattenfall	Controlled	Peak shaving and load shifting
V3	Vattenfall	V2G	Peak shaving + Energy arbitrage

4.6 Model Equations and Constraints

This section presents the mathematical formulation of the GAMS model, which uses linear expressions to simulate energy flows and EV behavior. The objective is to minimize total costs for the housing cooperative. The key decision variables include EV charging and discharging rates, SoC and power flows to and from the grid. The model's feasibility is ensured through a set of constraints that account for practical limitations designed to reflect the system's boundaries at each time step. The primary ones are found below in this section, while some additional ones are found in Appendix 1 to 8. These include setting the initial SoC (Equation 1), limiting charging/discharging power (Equations 2–3) and ensuring that SoC does not drop below 20% (Equation 4). Simultaneous charging and discharging is prevented (Equation 5). A peak power cap reflects tariff structures (Equation 6) and grid sell limits ensure discharges do not exceed EV capacity or fuse limits (Equations 7–8).

4.6.1 Objective Function

The objective of the optimization model is to minimize the total cost incurred by the housing cooperative over the modeling time period. This is achieved by coordinating energy flows in a way that leverages price fluctuations and system flexibility. The total cost consists of electricity purchases, revenues from sales, peak tariff charges and battery degradation costs. The cost function is expressed as:

$$\min C = \sum_{t} \left(ET_{\text{imp}}(t) \cdot \pi_{\text{buy}}(t) - ET_{\text{exp}}(t) \cdot \pi_{\text{sell}}(t) \right) + \pi_{\text{peak}} \cdot p_{\text{peak}} + C_{\text{deg}} \tag{4.1}$$

$ET_{\text{imp}}(t)$ is the energy imported from the grid at time t
$\pi_{\text{buy}}(t)$ is the price for purchased electricity at time t
$ET_{\text{exp}}(t)$ is the energy exported to the grid at time t
$\pi_{\text{sell}}(t)$ is the revenue for sold electricity at time t
p_{peak} is the peak net power drawn from the grid during the billing period
π_{peak} is the peak tariff rate
C_{deg} is the costs associated with battery degradation due to cycling

4.6.2 Power Balance

The power balance equation ensures that the energy supplied by the grid and the discharging EVs meets the total energy demand of the housing cooperative. It also accounts for the energy required for charging, including efficiency losses represented by the charging and discharging efficiency factors η_{ch} and η_{dh}. The equation is given by:

$$ET_{\text{imp}}(t) - ET_{\text{exp}}(t) = P_{\text{load}}(t) + \sum_{v} \frac{p_{ch,v}(t)}{\eta_{ch}} - \sum_{v} p_{dh,v}(t) \cdot \eta_{dh} \tag{4.2}$$

$P_{\text{load}}(t)$ is the electricity demand (power consumption) of the housing cooperative at time t
$p_{ch,v}(t)$ is the power charged into vehicle v at time t
$p_{dh,v}(t)$ is the power discharged from vehicle v at time t
η_{ch} is the charging efficiency
η_{dh} is the discharging efficiency

4.6.3 State-of-Charge Evolution

This constraint describes how the SoC of each vehicle's battery evolves over time. It captures the battery dynamics for hour t by updating the SoC from the previous time step $t-1$, based on the energy charged and discharged in hour t, accounting for their respective efficiencies. The equation applies only when the vehicle is plugged in at both $t-1$ and t (no arrival or departure occurs). The SoC evolution is given by:

$$soc_v(t) = soc_v(t-1) + \eta_{ch} \cdot p_{ch,v}(t) - \frac{p_{dh,v}(t)}{\eta_{dh}} \tag{4.3}$$

$soc_v(t)$ is the state of charge of vehicle v at time t
$soc_v(t-1)$ is the state of charge of vehicle v at time $t-1$

4.6.4 State-of-Charge Boundaries

To preserve the battery health of the EV fleet, charging and discharging are limited within recommended operational boundaries. This constraint ensures that the SoC for each vehicle remains between 20% and 80% of its total battery capacity at all times. It is expressed as:

$$soc_v^{\min}(t) = 0.2 \cdot cap_{\text{EV}}, \quad soc_v^{\max}(t) = 0.8 \cdot cap_{\text{EV}} \tag{4.4}$$

cap_{EV} is the total battery capacity of each vehicle v
$soc_v^{\min}(t)$ is the lower SoC limit for vehicle v at time t
$soc_v^{\max}(t)$ is the upper SoC limit for vehicle v at time t

4.6.5 Arrival and Departure

This constraint governs how the SoC is managed when an EV arrives at or departs from the charging station. These behaviors depend on the binary parameter $\delta_{avail,v}(t)$, which indicates whether vehicle v is plugged in at time t.

Arrival: When a vehicle plugs in after being away, the availability transitions from $\delta_{avail,v}(t-1) = 0$ to $\delta_{avail,v}(t) = 1$. At this moment, the SoC is set to a predefined value $soc_v^{entry}(t)$, which represents the vehicle's battery level upon return from driving.

Departure: When a vehicle is about to unplug, the transition occurs from $\delta_{avail,v}(t-1) = 1$ to $\delta_{avail,v}(t) = 0$. In this case, the model ensures that the SoC at time t is no less than a predefined value $soc_v^{exit}(t+1)$, guaranteeing the vehicle has sufficient energy for its next trip.

The arrival and departure conditions are expressed as:

$$soc_v(t) = soc_v^{entry}(t) \quad \text{(if arrival)} \tag{4.5}$$

$$soc_v(t) \geq soc_v^{exit}(t+1) \quad \text{(if departure)} \tag{4.6}$$

$soc_v^{entry}(t)$ is the state of charge of vehicle v at the time of arrival t
$soc_v^{exit}(t+1)$ is the minimum required SoC for vehicle v at the upcoming departure time $t+1$

4.6.6 Battery Degradation Cost

To account for the long-term wear of EV batteries caused by V2G cycling, the model adopts a linear approximation of battery degradation. The degradation cost is estimated based on the total energy passing through, under the assumption that each kWh of energy throughout contributes proportionally to battery wear. By restricting operations to the conservative 20-80% SoC window, a simplified linear relationship between energy cycled and battery aging can be assumed (Lee & Kim, 2022). This simplification allows the model to remain linear while still capturing the dominant mechanism of cycle life degradation.

This simplification is deemed acceptable since recent studies have found battery degradation to be significantly lower than previously estimated. In the V2X-MAS-pilot project in Sweden, Steen et al. (2025) found that battery degradation from shallow V2G cycling within the 20-80% SoC range is minimal compared to potential revenue streams, especially when using modern lithium-ion chemistries. Moreover, the authors show that incremental degradation from bidirectional charging is small

enough to be neglected in many economic analyses. It is also important to distinguish between cycle aging and calendar aging. Calendar aging, which is the battery degradation due to time rather than usage, is not considered in this cost formulation. While both cycle life and calendar life affect the lifetime of a battery, calendar life, especially in colder climates, has a smaller impact and is the same regardless of charging strategy (Rahman et al., 2023). Thus, the model is simplified to only include cycle life degradation costs.

The degradation cost is calculated as:

$$C_{\text{deg}} = \sum_{v,t} \left(\frac{p_{dh,v}(t)}{\eta_{dh}} + p_{ch,v}(t) \cdot \eta_{ch} \right) \cdot \frac{100 \cdot c_{\text{bat}}}{N_{\text{EFC}} \cdot cap_{\text{EV}}} \tag{4.7}$$

c_{bat} is the battery cost per kWh
N_{EFC} is the total number of equivalent full cycles the battery can perform before end-of-life

4.6.7 Differences Between Charging Strategies

To evaluate the impact of different charging strategies on system costs and grid interaction, three distinct simulation models were developed in GAMS. Each model represents a scenario with different levels of flexibility and system intelligence regarding how electric vehicles (EVs) are charged or discharged. The V2G model includes all the equations found in Section 4.6 and in Appendix 1 to 8.

The Controlled scenario only allows unidirectional charging, but still has the optimization capabilities regarding when charging should occur. Vehicles follow smart scheduling based on spot prices and peak periods. The goal remains to minimize the total cost, including peak charges and battery degradation, but without any revenue from energy export or added peak shaving. Constraints are simplified accordingly, discharge-related variables and equations are removed and charging is managed through vehicle availability and price responsiveness.

The Uncontrolled scenario represents a baseline where vehicles begin charging immediately upon arrival, regardless of price signals or grid load. The model includes a custom constraint called *Immediate Charge* which makes sure that charging starts as soon as the EV is plugged in.

All three models share core assumptions regarding EV battery capacity, efficiency and the overall structure of the simulation. The input data for electricity prices, load profiles and vehicle availability are the same for each scenario. By comparing these simulations, the relative benefits of controlled charging and V2G are evaluated in terms of reduced grid costs, peak shaving and improved system efficiency.

4.7 Data Analysis

The data analysis is carried out using a CBA framework to evaluate the economic viability of V2G participation for housing cooperatives. This approach allows for a structured assessment by comparing quantifiable costs, such as infrastructure investment, installation, ongoing maintenance and battery degradation, against expected financial benefits, including revenue from spot market arbitrage and peak shaving.

The analysis is conducted from the perspective of the housing cooperative as the system owner, under the assumption that it owns the charging infrastructure but outsources both maintenance and optimized charging software. Since installation costs and ongoing maintenance can be assumed to be constant for all three charging setups, these are excluded from the analysis. The cooperative is assumed to bear the Capital Expenditure (CAPEX) for chargers and installation, while benefiting from reduced electricity bills and revenue from energy sales back to the grid.

To assess financial viability and investment attractiveness, the Payback (PB)-time will be calculated.

Payback Time (PB): Measures the time required for the cooperative to recover its initial investment based on net annual savings and revenue. A shorter payback period indicates a more attractive investment.

$$PB = \frac{C_{\text{inv}}}{\Pi_{\text{annual}}} \tag{4.8}$$

PB is the payback period in years
C_{inv} is the total initial investment cost (SEK)
Π_{annual} is the annual net profit or savings generated by the system

The core inputs for the CBA are drawn from the GAMS simulation results, which provide annual energy costs and revenues under each operational scenario. These are combined with capital and operational cost assumptions, as outlined in Section 4.4.4 and 4.4.5, to calculate annual net benefits.

4.8 Limitations

There are several limitations in the model that were necessary to ensure feasibility while still capturing the complexities of the system as a whole. These simplifications affect the generalizability and realism of the results, but are considered acceptable within the scope of this study. The most important limitations are outlined below.

Assumption of perfect foresight

The model assumes perfect foresight of hourly spot prices, enabling the optimization to align charging and discharging with the most favorable hours. While this assumption simplifies the modeling process, it deviates from real-world conditions, where electricity prices must be forecasted with some degree of uncertainty. Nevertheless, in practical applications, even limited foresight or the use of trend-based strategies (such as avoiding peak hours or aligning with solar production) can lead to profitable decisions. Furthermore, given the relatively short time required to complete a full charging cycle (from 20 to 80% SoC in under two hours at 22 kW), this simplification is unlikely to have a substantial impact on arbitrage results. Accurate forecasting is only necessary over short time horizons to respond effectively to price signals.

Ideal market conditions

Regulatory constraints, market participation rules and transaction costs are not included in the model, due to immature state of technology and the lack of reliable real-world data. In practice, these factors may introduce barriers to V2G-adoption, including minimum bid sizes, licensing requirements or metering regulations. By assuming ideal market access, the model isolates the technical and economic performance of V2G under optimal conditions, which may overestimate its real-world feasibility and profitability.

Treatment of public holidays

Public holidays that fall on weekdays are modeled using standard weekday driving patterns, as defined in Section 4.4.6. This simplification ignores potential deviations

in vehicle usage and household load on such days, which might slightly affect cost estimates and demand profiles.

Simplified driving behavior

The driving profiles used in the model assume relatively short daily trips, resulting in higher SoC upon arrival and a lower charging demand per session. As a result, the simulated charging is often brief and distributed, leading to flatter load profiles. In reality, more varied behavior, such as skipping daily charging or arriving with a nearly depleted battery, would result in larger charging peaks, particularly in the uncontrolled scenario. This could impact both the peak demand costs and the relative benefits of controlled or V2G charging.

Excluded additional battery degradation for uncontrolled charging

The analysis does not account for potential added battery degradation costs associated with the uncontrolled charging scenario, when charging reaches 100% SoC. In practice, such charging behavior likely contributes to cycle-related battery wear. However, these degradation effects are assumed to be negligible in this thesis due to their relatively minor impact over the study horizon. While this simplification may slightly underestimate the long-term costs of uncontrolled charging, it is not expected to significantly affect the overall comparison between the charging strategies.

Mismatch in input data years

The model uses input data from different years, which may introduce some inconsistencies. Household electricity load profiles and spot prices are based on real data from 2023, while other parameters, such as grid tariffs, supply contracts and energy tax rates, are based on real data from 2025. This mix was necessary due to limited availability of data. However, the alignment between household consumption and spot prices is the most critical factor for preserving the internal consistency of the simulation. Since both are taken from the same year, their correlation reflects actual behavioral responses to market signals and outdoor temperature et cetera. The main concern with this limitation is that household consumption patterns might have differed if the 2025 grid contracts and pricing structures had been in place in 2023. For instance, high power tariffs or new incentive structures could have influenced load shifting behavior of the housing cooperative itself. While this introduces some uncertainty, the overall impact on model validity is expected to be minor.

Limited financial indicators

While indicators such as Net Present Value (NPV) and Internal Rate of Return (IRR) are commonly used to assess long-term investment performance, their application in this context is limited. The uncertainty regarding investment costs and future revenue streams for services such as grid support and flexibility provision makes it difficult to produce reliable NPV and IRR estimates for V2G projects. Therefore, the analysis is limited to PB-time and as a result, a much shorter investment timeline.

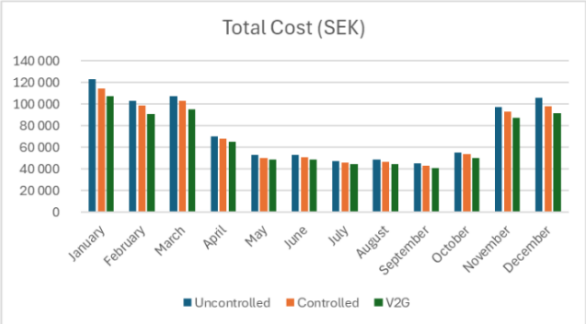
Chapter 5

Results

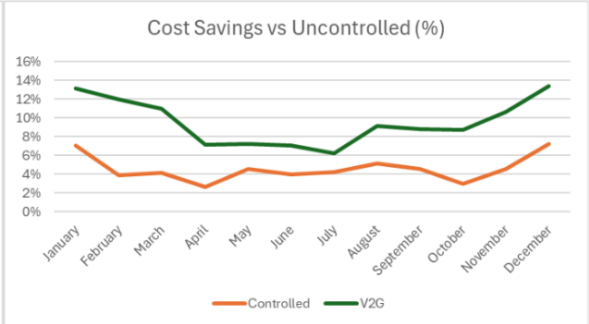
This chapter presents the outcomes of the optimization model over the six simulation scenarios. The analysis focuses on the economic performance of each charging strategy and the impact of the different electricity network contracts. The impact of varying battery degradation parameters is also presented in order to illustrate its impact on the results, followed by a CBA for the housing cooperative.

5.1 Economic Results of Ellevio's Network Contract

The total costs for the housing cooperative when simulating the three charging strategies are presented in Figure 5.1a, along with the cost savings from controlled and V2G charging in comparison to uncontrolled charging in Figure 5.1b. To further understand the effect of the power tariffs and the peak shaving potential of controlled and V2G charging, Figure 5.2a and 5.2b present the peak power costs as well as the peak cost savings, again plotted against uncontrolled charging. For a full overview and exact values, see Appendix B.1.

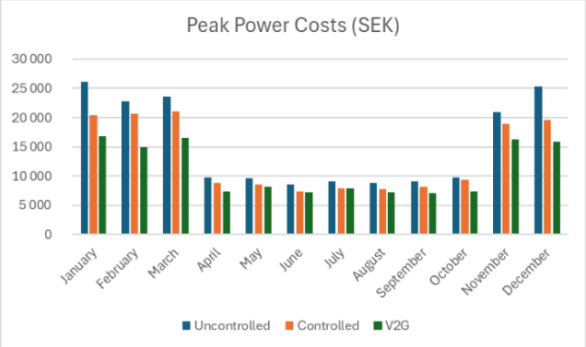


(a) Total cost for all strategies

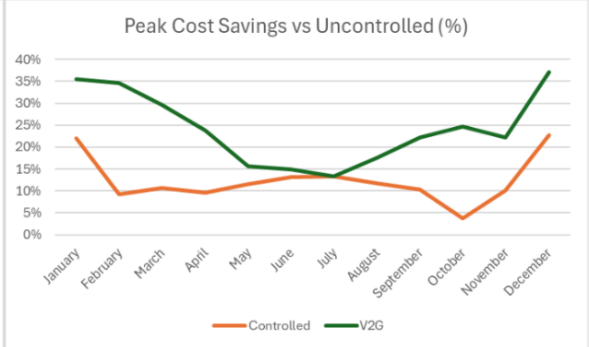


(b) Total cost savings from base scenario

Figure 5.1: Cost results under Ellevio's network contract



(a) Peak power cost for all strategies



(b) Peak power cost savings from base scenario

Figure 5.2: Peak cost results under Ellevio's network contract

As shown in Figure 5.1a, all three strategies unsurprisingly result in significantly higher costs during high-load months (November to March) than low-load months, showcasing the effect of the time-differentiated power tariffs and transmission fees. Although there is a slight rise in household load, the higher costs are primarily due to higher spot prices and increase tariff fees. With a total annual cost of 908,941 SEK, the uncontrolled charging scenario consistently yields the highest monthly costs throughout the year. In contrast, controlled charging reduced total annual cost to 865,140 SEK and V2G further reduces costs to 815,416 SEK.

The cost savings from controlled and V2G charging are visualized relative to the baseline scenario of uncontrolled charging in Figure 5.1b, which plots each month's total cost savings throughout the year. Controlled charging leads to significant cost reductions with a total annual cost savings of 4.8%, compared to uncontrolled charging. This is primarily from shifting consumption to off-peak hours and thereby minimizing electricity purchase and power tariff costs. Similarly, Vallinder and Carlsson (2022) find controlled charging to yield 8.4% cost savings. The larger savings

in that report likely stem from modeling a more price-volatile year (2021), differences in market structure where peak tariffs were not yet implemented, or more favorable assumptions. However, Kern et al. (2022) find even larger cost reductions of 25%, potentially explained by the synergic effect of using solar PV and stationary batteries. In this model, results still show that controlled charging alone manages to shave peaks significantly and produce financial benefits.

The V2G scenario yields cost savings of 10.3% annually, compared to the base scenario. This added benefit is achieved mainly through discharging EVs to meet household demand and thereby shift the purchasing costs to more favorable hours or flatten out the power curve additionally during high-cost periods. Sold electricity to the grid is very limited since charging and discharging energy losses and the buy-sell price spread make it less favorable, which supports Vallinder and Carlsson (2022)s findings that discharging back to the grid generates limited profits without revenue from ancillary services. Their study finds 9.9% annual cost savings under a V2G setup, close to this study. However, the added benefits in this study are significantly greater for V2G over controlled charging (an increase from 4.8% to 10.3%), whereas Vallinder and Carlsson (2022) suggest only marginal additional gains due to less favorable battery degradation cost. It is important to note that the literature regarding battery degradation costs is evolving rapidly, potentially explaining the differences in outcomes.

For peak power costs even larger reductions can be seen in the V2G scenario, where the housing cooperative achieves a 27.5% reduction in annual peak tariff costs. This supports the findings of previous research which highlights that peak shaving through V2G has significant economic effects (Bjurek & Hagman, 2022; Englberger et al., 2021). However, the extent of the cost savings are lower in this case; for example, Yeoh et al. (2025) reported a 63.5% reduction in peak demand in a V2B system integrated with solar PV and ESS, while Borge-Diez et al. (2021) found a 50% decrease. Those setups include synergetic technologies that enhance system performance, potentially explaining the disparity. Even so, this study demonstrates that V2G as a stand-alone technology significantly reduces power peaks and produces financial benefits.

The reductions that are achieved are particularly significant during winter months. In December V2G reduced the peak tariff costs by 37.2%, compared to 13.3% in July, likely caused by the high peak power costs during the winter which provides stronger incentives to reduce peak demand. These seasonal differences align with

Liu et al. (2024)s findings of 30-40% peak reductions during summer and 40-50% in the winter, consistent with the finding that peak shaving is most valuable during high-tariff periods. For that study, V2G is again modeled in a microgrid setup, likely explaining the different results. Furthermore, the seasonal difference in total cost savings reflects the higher price volatility during the winter, which the Swedish study by Leijon et al. (2024) also note can generate greater economic benefits, particularly through arbitrage.

In summary, these findings imply that maximizing self-consumption and peak shaving is more profitable than selling electricity back to the grid under current market structures. This supports the findings of Signer et al. (2024), who note that high taxes and low compensation rates reduce the financial incentives for discharging to the grid, limiting the ability of V2G to be economically viable and contribute to enhanced system flexibility. Additionally, Englberger et al. (2021) support this, concluding that peak shaving in combination with self-consumption yields the most profit for V2G setups. These results suggest that policymakers should consider revising current tax structures and compensation schemes to better align economic incentives with the broader goals of energy flexibility and grid support. Specifically, policies could be adjusted to reward grid-discharge additionally, thereby encouraging greater participation in demand-response markets. Without such reforms, the economic rationale for V2G remains limited primarily to behind-the-meter applications such as peak shaving and self-consumption, potentially undermining the broader potential of V2G to contribute to grid stability and renewable integration.

5.1.1 Charging Strategies

To illustrate how the charging behavior changes between the different charging strategies and how the peaks and loads change during high- and low-load periods, two months of the Ellevio contract are displayed in Table 5.1: December and July. These months represent the highest and lowest monthly cost savings for the V2G scenario, capturing the dynamic of seasonal fluctuations. For graphical illustration, see Appendix B.2 for the power demand curves for all three charging strategies in both December and July.

Table 5.1: Peak power demand for the months with the highest and lowest total cost savings

	Peak Power (High-demand)	Peak Power (Low-demand)
Uncontrolled – Dec	153 kW	–
Controlled – Dec	118 kW	135 kW
V2G – Dec	96 kW	197 kW
Uncontrolled – July	–	112 kW
Controlled – July	–	97 kW
V2G – July	–	97 kW

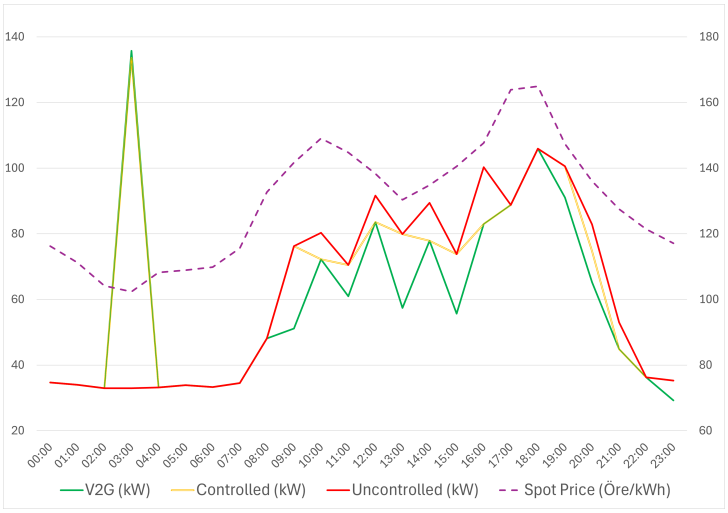
The controlled scenario clearly demonstrates that it is possible to achieve significant cost savings and peak power reductions without the added capabilities of V2G. For example, in December, controlled charging lowers the high-demand peak to 118 kW, while still allowing the low-demand peak to reach 135 kW. As low-demand peaks are not as penalized by the tariffs, the model takes advantage of these hours to charge the vehicles. In July, controlled charging lowers the power peak to 97 kW from 112 kW, when there are no high-demand penalties.

The V2G scenario shows further peak reductions in December to 96 kW during high-demand hours. However, the model allows for a substantial increase in power demand during low-load hours (197 kW), taking advantage of the low-tariff fees and low spot prices. In July, no further peak reduction is achieved since the model already achieves the lowest cost-beneficial peak shaving with just the controlled charging strategy. This is an extreme case which results in the lowest monthly cost savings among all scenarios. For a complete view of the peak power loads of each month and charging strategy, see Appendix B.3.

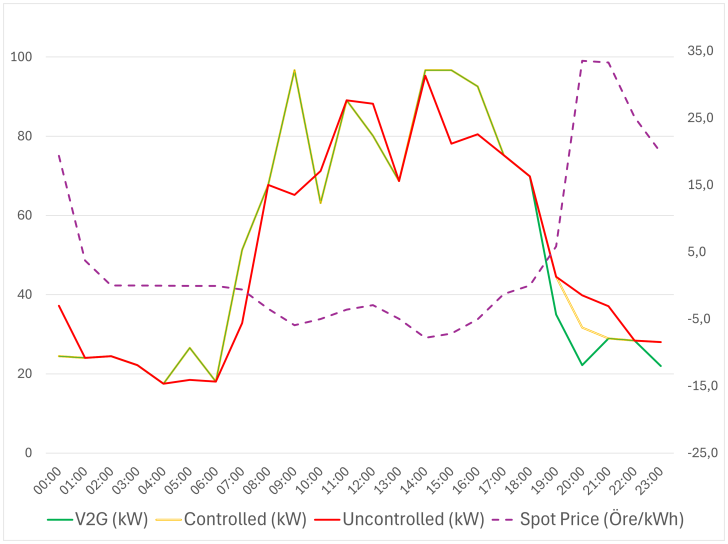
These results highlight that strategic load shifting based on tariff prices can lead to significant cost savings, even if it results in higher absolute peaks during the low-demand periods. The model shows that dynamic pricing models have a large impact on the economic outcome of V2G participation, which Haikola and Söderberg (2020) and Ravi and Aziz (2022) also identify. As research points to, as well as the specific purpose of the time-differentiated power-based tariffs that are being implemented in Sweden, they appear effective in shifting load to low-demand hours. However, the model does not account for the strain that load shifting creates on the grid. It is crucial that smart charging systems also consider grid constraints and congestion, rather than

purely financial indicators. Otherwise, large amounts of aggregated smart systems may create unsustainable peaks during hours that have been previously defined as low demand hours. This demonstrates a trade-off to cost minimization where the system prioritizes financial efficiency with minimal consideration to physical effects on the grid, underlining the importance of balancing and managing peak loads in several dimensions. It is increasingly important to align user behavior with system constraints, as poorly designed tariffs shift the focus of EV users (Bjørndal et al., 2025).

To further visualize the charging strategies, a representative 24-hour period from December and July is presented in Figure 5.3a and 5.3b. They plot charging strategies against hourly spot prices, showcasing how each strategy responds to price signals and how their behaviors differ on how the load is managed throughout the day.



(a) December



(b) July

Figure 5.3: All three charging strategies against spot prices

In July, when high-load tariffs are not applied, the load profiles for all three charging strategies align closely with the spot prices. The net power curve is low when spot prices are high and high when prices are low. This indicates that in the absence of high-demand power tariffs, the model focuses solely on minimizing electricity purchase costs and taking advantage of energy arbitrage. It is important to note that only the controlled and V2G scenario actually respond to spot market fluctuations while the uncontrolled scenario just naturally aligns since the aggregated needs of all SE3 consumers affect the spot prices.

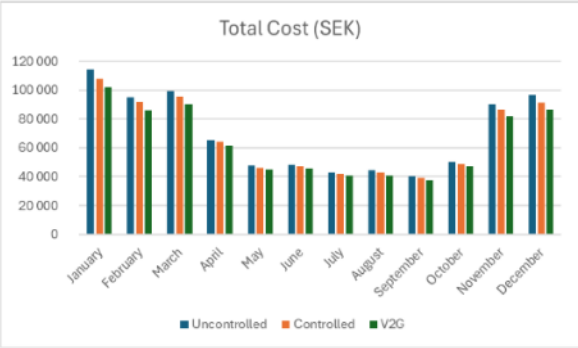
In December, a clear shift in charging behavior occurs due to the high-load tariffs imposed between 06:00 and 22:00. During this period, the optimization no longer follows spot price signals as closely. Instead, it prioritizes minimizing the net power load to avoid incurring high-tariff charges. Both controlled and V2G strategies demonstrate a marked increase in charging activity around 03:00, capitalizing on the absence of high-tariff fees and the presence of low spot prices. During high-tariff hours, the load profile focuses more on balancing and flattening demand rather than responding directly to spot price variations. This illustrates how tariff structures can override price signals in determining optimal charging schedules. Such dynamics align with the findings of Bjørndal et al. (2025), who argue that misaligned economic incentives can distort user behaviors and create broader system challenges. Poorly designed grid tariffs, especially overly broad time-differentiated power tariffs, risk neutralizing spot price signals, encouraging behavior that is economically rational for the consumer, but misaligned with system needs.

The literature consistently emphasizes the potential of V2G to support renewable-heavy systems by charging during periods of high generation and discharging during scarcity (Bibak & Tekiner-Moğulkoç, 2021; Blumberg et al., 2022; Nagel et al., 2024). However, this requires that tariff and market structures preserve and enhance the value of flexibility to utilize VRE sources more efficiently. If tariff-induced load flattening becomes the dominant objective, as observed in December, the system may fail to leverage synergies between V2G and VRE sources. To enhance system efficiency and support renewable integration, it may be beneficial to implement more dynamic power tariffs, for instance 06:00-10:00 and 18:00-22:00, to allow smart systems to absorb solar generation. Without such reforms, the system risks underutilizing distributed flexibility resources like V2G and may continue to rely unnecessarily on fossil-based or stationary backup capacity (Blumberg et al., 2022; Yang et al., 2025).

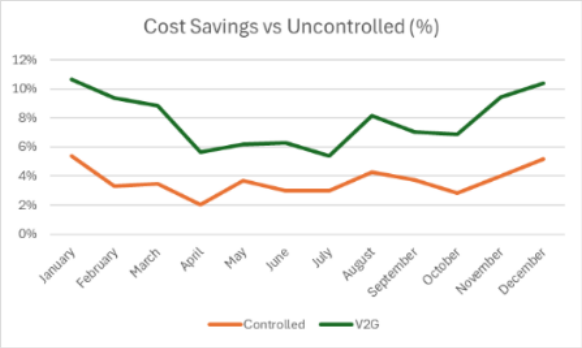
These findings highlight that housing cooperatives need to look beyond simply choosing fixed or variable electricity contracts and focus on understanding the specific tariff structures behind their grid fees. Since many cooperatives use collective contracts where individual residents are not directly exposed to price signals, it becomes essential for the cooperative to actively manage electricity use during high-tariff hours to avoid extra costs. In practice, this means adopting smart technologies like V2G, which can lead to significant cost savings, if managed strategically with full awareness of both electricity prices and grid tariffs. The key to reducing costs is not just about cutting overall consumption or peak demand, but avoiding usage specifically during the most expensive tariff periods. This is supported by Jiang et al. (2025) that similarly conclude that offsetting high electricity tariffs during peak periods offers the greatest cost savings. To unlock V2G's full potential, cooperatives should invest in advanced energy management systems that can automatically respond to tariff signals, as these are shown to have great effect on the economic outcomes. At the same time, policymakers need to align tariff designs, taxation and market rules that encourage grid-friendly behaviors, which is also highlighted by Signer et al. (2024). Without such alignment, cost-saving efforts by cooperatives could unintentionally increase stress on the grid or harm system reliability, underlining the importance of balancing economic efficiency with systemic responsibility.

5.2 Economic Results of Vattenfall's Network Contract

The total costs for the housing cooperative when simulating the three charging strategies are presented in Figure 5.4a, along with the cost savings from controlled and V2G charging in comparison to uncontrolled charging, in Figure 5.4b. To further understand the effect of the power tariffs and the peak shaving potential of controlled and V2G charging, Figure 5.5a and 5.5b presents the peak power costs as well as the peak cost savings, plotted against uncontrolled charging. For a full overview and exact values, see Appendix C.1.

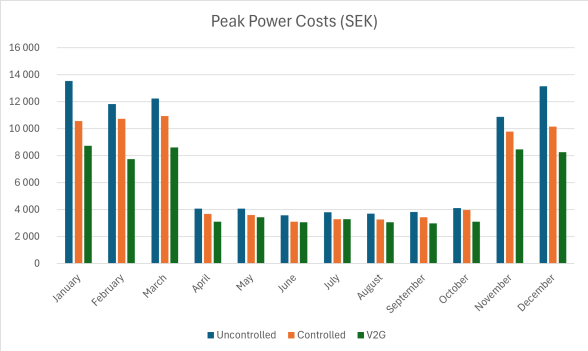


(a) Total cost for all strategies

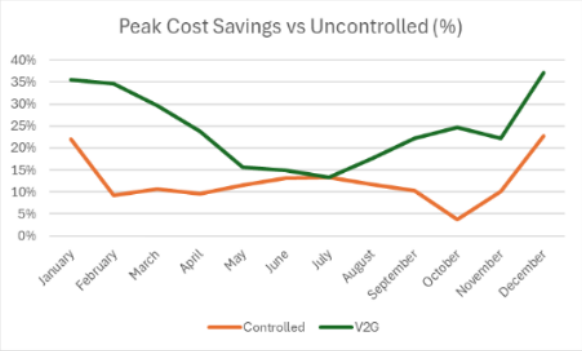


(b) Total cost savings from base scenario

Figure 5.4: Cost results under Vattenfall's network contract



(a) Peak power cost for all strategies



(b) Peak power cost savings from base scenario

Figure 5.5: Peak cost results under Vattenfall's network contract

The total annual cost of uncontrolled charging was 835,361 SEK, which is slightly lower than for Ellevio. Controlled charging reduced total annual costs to 803,363 SEK and V2G charging further reduced them to 764,997 SEK.

When comparing the results with Ellevio's network contract, notable differences in outcome can be seen. Under Vattenfall's contract, total annual cost savings are slightly lower across both optimized scenarios. For controlled charging, savings decrease from 4.8% under Ellevio to 3.8% with Vattenfall. Similarly, the savings from the V2G scenario drop from 10.3% to 8.4%. This suggests that overall, Ellevios pricing model is more efficient at incentivizing flexibility through V2G (note that the fixed prices differ between the contracts and are excluded from the analysis). These differences stem from the design of each network tariff. Ellevio's model places a much greater emphasis on power-based charges, with relatively high fees based on peak load and comparatively low energy consumption rates. In contrast, Vattenfall's model relies more heavily on energy-based fees, applying higher charges per kWh, while keeping

the power-based fees significantly lower.

As a result of Ellevio's cost structure, it leads to greater reductions in total system costs, making V2G more profitable overall through higher cost avoidance. However, the most expensive peak power levels in kW are identical for all months and charging strategies under both Ellevio's and Vattenfall's contracts (for a detailed chart of all peak powers see Appendix B.3). This explains why the financial impact of those peaks differs significantly as reducing a peak under Ellevio yields greater absolute value savings due to the higher SEK/kW charges. Another interesting difference between the contracts is that Vattenfall's tariff structure allows for higher peaks during low-demand periods without increasing costs. This is due to its wider ratio between high-load and low-load charges (86/34 = 2.53), compared to Ellevio's tighter spread (166/81 = 2.05). A broader ratio provides greater flexibility for off-peak charging, potentially enabling EVs to absorb surplus energy, such as midday solar or wind, without triggering additional cost penalties. However to utilize this, high-demand tariffs would have to be split up in morning- and evening-intervals, reinforcing the results in 5.1.1.

These results highlight how network contract design, particularly the balance between energy and power charges, in addition to the ratio between peak- and off-peak power tariffs, determines how effectively V2G and controlled charging can translate technical performance, such as peak reduction, into financial value. As Helferich et al. (2024) also found, smart tariff structures are essential for aligning technical benefits with economic incentives which encourages user participation.

While housing cooperatives cannot choose their DSO, both Ellevio and Vattenfall impose different tariff structures that significantly impact financial outcomes. Even though peak loads are reduced to the same level, the financial savings differ significantly depending on the provider, underscoring the need for cooperatives to understand and adapt to their specific network contracts. Regardless of the provider, both controlled charging and V2G consistently demonstrate cost saving potential.

5.3 Effects of Varied Battery Degradation

Battery degradation is one of the most commonly cited barriers to the large-scale implementation of V2G technology. While V2G offers potential savings through peak shaving and energy arbitrage, frequent battery cycling can accelerate wear and reduce battery lifespan. This section evaluates how changes in the assumed degradation cost parameter affects the model's economic and technical outcomes, specifically focusing on how robust the cost savings remain under varying degradation parameters. To do so, the model is re-run with both halved and doubled degradation costs, under both network contracts. By comparing cost savings across high- and low-load months, specifically the most extreme ones for each contract, the analysis aims to assess whether battery wear assumptions significantly impact V2G's overall economic viability. The analysis focuses on whether arbitrage and peak shaving potential is impaired or if the primary difference lies in battery degradation cost itself.

5.3.1 Ellevio

To capture the most pronounced and minimal effects of battery degradation, December and July are selected for illustration, representing the months with the highest and lowest total cost savings, respectively. Table 5.2 presents the results (in SEK and %) of doubling and halving the assumed degradation cost parameters.

Table 5.2: Results of varied battery degradation

Ellevio	Total Cost	Δ Base	Battery Deg	Δ Base	Peak Tariff	Δ Arbitrage	Δ Arbitrage
Dec 2x	94,980	**3,426**	5,641	**1,877**	15,922	1,549	1.7
Dec Base	91,553	–	3,764	–	15,922	–	–
Dec 0.5x	89,585	**-1,968**	2,093	**-1,671**	15,922	-297	-0.3
July 2x	47,312	**2,773**	4,006	**590**	7,832	2,182	4.9
July Base	44,539	–	3,416	–	7,832	–	–
July 0.5x	42,725	**-1,814**	1,864	**-1,551**	7,832	-263	-0.6

The results show that large variations in battery degradation have a measurable but relatively limited impact on the profitability of energy arbitrage (0.3-4.9%) and do not constrain the model's ability to perform peak shaving as these costs remain unchanged. See Appendix D.1 for more detailed results from both December and July.

This demonstrates that peak reduction is primarily achieved by shifting and spreading out charging during low-demand periods, rather than relying heavily on discharging, as this would increase battery wear. While some studies, such as Zhou (2022), Bjurek and Hagman (2022) and P. Huang et al. (2022) have expressed skepticism about V2G's profitability due to battery degradation, this optimization model shows that it is less severe than initially anticipated. Even when battery degradation costs are doubled in the model, V2G shows significant cost reductions versus uncontrolled charging. These findings are supported by more recent literature from Menchaca Santos et al. (2025) and Luo et al. (2024) who both find degradation as a minimal cost factor where economic gains from V2G are still achievable. Battery wear can be effectively mitigated through appropriate management strategies, which is also highlighted in these studies, along with Mastoi et al. (2023) that conclude that a well-managed V2G system can offer significant cost savings and grid benefits. Since willingness to participate in V2G has been shown in the literature to depend heavily on battery degradation concerns, such results need to be communicated for public awareness, to further increase consumer acceptance and technology deployment.

Notice that the total degradation cost incurred by the system does not scale linearly with the cost parameter in the model. When the degradation cost in the model is doubled, the actual degradation cost in December increases from 3,764 SEK to 5,641 SEK, an increase of about 50%, not 100%. Likewise, halving the degradation cost reduces the total degradation cost to 2,093 SEK, a decrease of approximately 44%. This could be explained with the model adapting its behavior. When degradation becomes more expensive, it reduces battery cycling to limit costs and when it is cheaper, the battery cycles more which is why arbitrage is impaired or improved.

This optimization adaptation explains why total system costs change only moderately despite large parameter shifts. In December, doubling the degradation cost of the model increases the total cost by 3.7%, while halving the cost reduces it by 2.2%. In July, the effects are slightly more noticeable due to the relatively greater role of arbitrage as a result of lower tariff costs. Total costs increases by 6.2% when

degradation costs are doubled and drop by 4.1%, when halved. These findings reinforce the conclusion that battery degradation costs primarily affect arbitrage-related savings but have little to no impact on the system's ability to reduce peaks. The model continues to perform peak shaving effectively, demonstrating that one of the main value propositions of V2G, reducing power-based charges, remains robust even under varying assumptions about battery wear.

5.3.2 Vattenfall

For Vattenfall, the highest total cost savings were achieved for January while the lowest was again achieved during July, thus Table 5.3 presents the results from these two months in SEK and %. For more detailed results, see Appendix D.2.

Table 5.3: Results of varied battery degradation

Vattenfall	Total Cost	Δ Base	Battery Deg	Δ Base	Peak Tariff	Δ Arbitrage	Δ Arbitrage
Jan 2x	105,669	**3,632**	6,479	**2,406**	8,718	**1,226**	1.2
Jan Base	102,037	–	4,073	–	8,718	–	–
Jan 0.5x	99,609	**-2,429**	3,180	**-893**	8,718	**-1,536**	-1.5
July 2x	43,465	**2,815**	4,097	**659**	3,287	**2,157**	5.3
July Base	40,650	–	3,438	–	3,287	–	–
July 0.5x	38,829	**-1,821**	1,865	**-1,573**	3,287	**-247**	-0.6

These results again indicate that battery degradation costs have a measurable but relatively limited impact on arbitrage (0.6-5.3%) and no impact on peak shaving as the peak tariff costs are unaffected. As with Ellevio, this demonstrates that peak shaving is primarily achieved through optimized charging patterns, rather than through aggressive discharging that would accelerate battery wear.

Once again, the total degradation cost incurred by the system does not scale linearly with the cost parameter in the model due to the model's adaptive behavior. When degradation costs are doubled, the system reduces cycling to limit additional wear. Conversely, when degradation becomes cheaper, the system increases cycling to

capitalize on arbitrage opportunities. As a result, in January, doubling the degradation costs increases the total degradation cost significantly, but the overall system costs only rises with 3.6%, while halving the degradation cost reduces the system costs by 2.4%. In July, where arbitrage is more important due to lower peak-related fees, the effects are again more pronounced. The total system costs increases by 6.9% when degradation costs were doubled and decreased by 4.5% when degradation was halved.

5.4 Cost-Benefit Analysis

This section evaluates the economic viability of V2G integration for a Swedish housing cooperative, comparing it to both uncontrolled and controlled charging strategies. The analysis is based on the annual results of the optimization model and includes both direct monetary impacts and system-level effects. The total costs and the cost savings relative to the base scenario are presented in Table 5.4.

Table 5.4: Annual costs and cost savings comparison (SEK/year)

	E1	**E2**	**E3**	**V1**	**V2**	**V3**
Total Annual Cost	908,941	865,140	815,416	835,361	803,363	764,997
Cost Savings from E1 & V1 respectively	–	43,801	93,525	–	31,998	70,364

The investment costs for the different charging setups can be found in Section 4.4.4. Furthermore, the operational costs for the controlled and V2G charging scenarios, as mentioned in Section 4.4.5, are assumed to be 15% of the cost savings compared to the uncontrolled scenario. These are summarized in Table 5.5 below.

Table 5.5: Charging infrastructure investment and operational costs

	Charging Setup x10 (SEK)	**Software E2/E3 (SEK/Year)**	**Software V2/V3 (SEK/Year)**
Uncontrolled	93,250	0	0
Controlled	108,200	6,570	4,800
V2G (Low/High End)	451,750 – 619,750	14,029	10,555

The values from Table 5.4 and 5.5 form the basis for the PB-time calculations, providing

a clear comparison of the financial returns of controlled/V2G-enabled charging. The analysis focuses on the annual cost savings generated by controlled/V2G-enabled charging, compared to their additional investment and operational costs, in relation to the uncontrolled scenario. The net profit is the savings subtracted by the operational costs. The additional costs are the increased investment costs compared to a basic charger setup. These results are presented in Table 5.6.

Table 5.6: Net profit, investment and payback time comparison

	Net Profit (SEK/year)	Additional Costs (SEK)	Low-End PB-Time (years)	High-End PB-Time (years)
E2	37 231	14 950	0.4	–
E3	79 497	358 500 – 526 500	4.5	6.6
V2	27 198	14 950	0.6	–
V3	59 809	358 500 – 526 500	6.0	8.8

The results show that controlled charging strategies (E2 and V2) offer very short payback times due to relatively high net profits and low upfront costs. In contrast, V2G participation requires substantially higher investments in bidirectional charging infrastructure, leading to longer payback periods that range from 4.5 to 8.8 years, depending on tariff structure and investment assumptions. The high-end PB time in the V3 scenario (almost 9 years) raises concerns about the financial risk and long-term commitment required. This aligns with findings in the literature, which consistently highlight high upfront infrastructure costs as a major barrier to V2G adoption (Alsharif et al., 2021; Mojumder et al., 2022; Ravi & Aziz, 2022). To enhance the economic feasibility of V2G, infrastructure costs must decline further, driven by economies of scale, standardization and targeted subsidies.

Moreover, a key obstacle remains in the absence of mature and scalable business models, adding uncertainty to investment decisions and cost recovery. Without well-defined frameworks for fairly distributing costs and benefits among stakeholders, the commercial viability of V2G remains constrained (Goncearuc et al., 2024; Kabir et al., 2022). As emphasized by Steen et al. (2025), a lack of standardization, particularly in communication protocols and charging infrastructure, continues to delay widespread deployment of the technology. Long-term success therefore depends not only on technological readiness but also on coordinated policy support, financial incentives and viable business models (Mojumder et al., 2022; Sovacool et al., 2020).

Nevertheless, under favorable conditions, both unidirectional and bidirectional charging strategies produce positive net annual profits. Tariff design plays a critical role in shaping these outcomes as the Ellevio contract consistently outperforms Vattenfall's in terms of profitability and payback time. These results support earlier findings that dynamic pricing models have a substantial impact on economic performance (C.-F. Chen & Lai, 2024; Helferich et al., 2024), which also reinforces arguments by Sovacool et al. (2020) and Mojumder et al. (2022) that tariff designs must evolve alongside technological advances to fully unlock the value of V2G.

For housing cooperatives, where decision-making is made collectively, overcoming the behavioral barriers is also important. Gaining resident support depends on clear communication of benefits and user-friendly systems. As Demuth et al. (2024) and Ramic and Nyström (2024) emphasize, consumer education, aligned infrastructure planning and policy clarity are essential to encourage adoption in shared residential settings and beyond.

5.5 System and Non-Monetary Benefits

While the primary focus of this study is the economic viability of V2G systems for housing cooperatives, it is also important to acknowledge the broader system and non-monetary benefits that extend beyond direct financial savings.

Grid Peak Load Reduction

A key benefit of V2G lies in its ability to reduce electricity demand during peak hours. The simulation results demonstrate that during the high-load period, November to March, the V2G scenario consistently achieved an average peak power reduction of 46 kW compared to uncontrolled charging (see Appendix B.3 for all peak loads). This peak shaving potential is particularly important in areas like Gothenburg, where power grid capacity shortages have been flagged as critical bottlenecks for urban development and electrification efforts (Göteborg Energi, 2024). When scaled up across multiple housing cooperatives, such reductions could significantly relieve stress on local distribution networks and delay costly grid reinforcements.

Renewable Energy Integration and Emission Reduction

Another important benefit is the improved alignment between electricity demand and renewable energy supply. Although the EVs in this study are not connected during the

daytime of weekdays, limiting their ability to capture solar surplus, the reduced power peaks and load shifting through V2G still potentially allows for greater utilization of low-cost, low-emission electricity. As discussed in Chapter 3 by Nagel et al. (2024) and Blumberg et al. (2022), V2G technologies support the broader decarbonization of the electricity system by smoothing out variability in renewable generation and enabling more efficient energy use.

Avoided Environmental Disruption from Grid Expansion

By reducing peak loads and enabling local balancing, V2G can delay or reduce the need for upgrading physical grid infrastructure. Grid expansions, such as new substations or power lines, often require extensive permitting, land use changes and construction, all of which carry environmental, economic and social costs. Through better utilization of existing infrastructure, V2G represents a decentralized, lower-impact alternative to support Sweden's energy transition.

Policy Implications

Maximizing the system-level benefits of V2G requires tariff structures that provide clear and effective price signals. The results highlight that both the ratio between high-load and low-load power charges and the specific timing of peak tariff periods significantly influence load-shifting behavior. Therefore, to promote adoption and guide user behavior, policymakers and network operators should ensure that peak pricing is both meaningful and confined to narrower windows, such as 06:00-10:00 and 18:00-22:00, while maintaining low costs during off-peak periods.

Chapter 6

Conclusions

This chapter summarizes the key findings of the study and reflects on the broader implications of Vehicle-to-Grid participation for a Swedish housing cooperative. By combining optimization modeling with a cost-benefit analysis, the study offers a comprehensive evaluation of its standalone economic viability under current market conditions. Building on the results from a full-year simulation under real-world conditions, it highlights the implications of how power-based tariffs, charging strategies and battery degradation influence the overall viability of V2G systems. The findings are followed by recommendations for policy and practice in enabling V2G adoption.

6.1 Key Findings

This study finds that V2G participation is economically viable for Swedish housing cooperatives under current market conditions. Simulations demonstrate that bidirectional charging (V2G) leads to significant cost savings compared to both uncontrolled and controlled unidirectional charging. Annual savings can reach up to 10.3% under Ellevio's tariff structure and 8.4% under Vattenfall's, which translate into competitive payback periods of 4.5-6.6 years and 6-8.8 years respectively. Even in the absence of additional revenue from ancillary services or complementary setups (such as PV-integration), the study finds V2G participation to be a financially attractive investment, adding to existing research on V2G's potential. The main cost savings are found in the ability to strategically reduce peak power demand, particularly during high-load months and shift consumption away from expensive tariff hours. However,

the model shows limited benefits from selling electricity back to the grid with current price spreads and without additional revenue streams, making self-consumption (V2B) and peak shaving more financially attractive.

The profitability of V2G is found to be directly influenced by the design of power tariffs. When comparing Ellevio's and Vattenfall's network contracts, it becomes evident that emphasis on power charges instead of electricity transmission charges leads to more effective V2G performance. This implies that if policymakers and grid operators want to incentivize V2G integration, Ellevio's model is more effective in creating economic benefits for flexible electricity use. Additionally, the model shows that tariff signals can override spot price signals, shifting the optimization objective from minimizing electricity purchase costs to avoiding periods with high tariff fees. This can have substantial implications for system-level efficiency if not managed properly. While V2G has the potential to support local load management and cost control, poorly designed tariffs can drive behavior that is economically rational for the consumer, but misaligned with overall system needs, diminishing the broader value of V2G flexibility. This suggests that power tariffs should thoughtfully align economic incentives with system needs, such as grid congestion and VRE generation, by adopting more targeted tariff structures.

The results show clear differences between charging strategies. Uncontrolled charging results in the highest system and peak costs, whereas controlled charging significantly reduces costs by shifting load to off-peak, low-price hours. V2G offers even greater benefits, achieving more than twice the annual cost savings of controlled charging alone. These benefits are most pronounced during the winter, when time-differentiated tariffs apply. In December, V2G reduced peak costs by up to 37.2%, compared to 21.5% for controlled charging. During low-load months such as July, the difference between strategies narrows. While controlled charging systems have shorter PB periods and thus strong short-term appeal, V2G delivers additional long-term, highlighting its potential for long-term value.

Finally, battery degradation is found to have a relatively limited economic impact on V2G's viability. Even when degradation cost parameters are doubled in the model, total system savings are only moderately affected. While higher degradation costs slightly impair arbitrage performance, they do not compromise the systems ability to shave peaks or maintain required SoC levels for mobility. The model adapts to more

conservative cycling behavior under more costly degradation assumptions, reinforcing that peak shaving through V2G can be achieved through strategic discharge rather than aggressive cycling.

6.2 Policy and Practical Implications

This study demonstrates that V2G technology can contribute to both cost savings for housing cooperatives and broader system-level benefits such as peak load reduction and improved grid flexibility. However, realizing this potential at scale depends not only on the technology itself, but also on the regulatory and market environment in which it operates. Several policy and practical implications emerge from the results.

Prioritizing local energy optimization over grid interaction

In the current regulatory and market environment, where economic incentives for selling electricity back to the grid remain limited, housing cooperatives should focus on V2B rather than full V2G participation. Similarly, EV manufacturers, charging infrastructure companies and energy management software developers should prioritize solutions that support local energy optimization. This means designing systems that integrate well with building energy profiles, enhance on-site consumption of stored or generated electricity (such as solar PV) and enable flexible, demand-responsive charging schedules. By concentrating on self-consumption and internal load balancing, this can deliver more immediate value to residential buildings, while laying the groundwork for broader grid interaction once supportive policies emerge.

Design tariffs to incentivize flexibility while aligning with system needs

The study shows that power-based tariffs can effectively encourage peak shaving and load shifting, but their structure significantly influences user behavior. If tariff windows are too broad, such as 06:00-22:00, they may lead to new, unintended peaks during hours that are technically “off-peak” but still require stability. Instead, tariff windows should be aligned more closely with actual system bottlenecks (for example 06:00-10:00 and 18:00-22:00), ensuring that economic signals reflect operational realities. Moreover, the ratio between high-load and low-load charges plays a crucial role in guiding charging behavior. A higher ratio encourages off-peak usage without penalizing flexibility, enabling EVs to absorb surplus renewable energy during midday

or nighttime hours. Policymakers and DSOs should therefore strive to balance strong peak pricing with sufficiently low off-peak charges to maximize both economic and grid-level benefits.

Shift cost burden to EVs rather than infrastructure

From a practical deployment perspective, AC-based V2G systems are potentially more accessible for housing cooperatives since the main cost of bidirectional capability is embedded in the vehicle rather than in the charger. This lowers the perceived cost of participation and aligns with behavioral economics insights around "mental accounting". Incentivizing OEMs to include onboard bidirectional converters, or providing tax credits for V2G-ready vehicles, would potentially lower adoption barriers.

Simplify access to flexibility markets for small-scale actors

Currently, residential actors face significant barriers to participate in ancillary service markets such as FCR. Unlocking the full economic potential of V2G requires policy and regulatory changes that reduce market entry thresholds. This could include enabling aggregator participation, harmonizing technical requirements and introducing simplified bid structures. Creating value-stacking opportunities across self-consumption, peak shaving and ancillary services would further enhance economic viability.

Provide planning guidance and funding for cooperatives

Housing cooperatives are key actors in the residential energy transition but often lack the technical and financial capacity to implement emerging technologies. Municipalities or energy agencies could provide targeted support through planning templates, funding schemes or pilot programs focused on V2G deployment. This could include simplified procurement frameworks and bundled offers for hardware, installation and smart charging services.

Support pilot projects and evidence-building

Finally, further real-world testing is needed to validate economic assumptions, technical reliability and user behavior. Policymakers and grid operators should fund and support more V2G demonstration projects, especially in multifamily housing settings, to develop best practices, address implementation barriers and build public confidence.

6.3 Final Reflections

This study confirms that V2G technology holds promise not only as a technical solution but also as an economically viable investment for Swedish housing cooperatives, particularly under evolving power-based tariff structures. By simulating realistic charging behavior, pricing models and degradation effects, the analysis provides a nuanced understanding of how V2G performs under current conditions.

While the results are promising, it is important to recognize that profitability remains sensitive to local tariff designs, hardware costs, spot price volatility and market access limitations. Furthermore, the value of V2G is not confined to direct monetary savings. System-level benefits such as peak reduction, improved grid flexibility and better alignment with renewable generation add further justification for broader adoption, particularly in densely populated or capacity-constrained urban areas like Gothenburg.

However, economic potential alone will not be enough. To enable widespread deployment, V2G must be supported by clear policy signals, accessible infrastructure and user-friendly business models. Strategic collaboration between policymakers, DSOs, technology providers and housing cooperatives will be essential to bridge the gap between pilot-scale success and large-scale implementation.

Ultimately, V2G is not the solution to all of Sweden's energy problems, but it is potentially a significant part of future flexibility solutions. If properly integrated, it can help transform EVs from passive consumers into active grid participants, supporting a smarter, more resilient and sustainable energy system.

Bibliography

Ahsan, S. M., Khan, H. A., & Ul-Hassan, N. (2022). Optimized power dispatch for smart building(s) and electric vehicles with v2x operation. *Energy Reports*, *8*, 10849–10867. https://doi.org/10.1016/j.egyr.2022.08.221

Alsharif, A., Tan, C. W., Ayop, R., Dobi, A., & Lau, K. Y. (2021). A comprehensive review of energy management strategy in Vehicle-to-Grid technology integrated with renewable energy sources. https://doi.org/10.1016/j.seta.2021.101439

Barone, G., Buonomano, A., Forzano, C., Giuzio, G. F., & Palombo, A. (2020). Increasing self-consumption of renewable energy through the Building to Vehicle to Building approach applied to multiple users connected in a virtual micro-grid. *Renewable Energy*, *159*, 1165–1176. https://doi.org/10.1016/j.renene.2020.05.101

Bellantuono, J. (2023). Electric vehicle battery maintenance: Tips for long-lasting power. https://www.dynamicmanufacturinginc.com/unveiling-the-lifespan-of-electric-car-batteries-how-long-do-they-truly-last/

Bibak, B., & Tekiner-Moğulkoç, H. (2021). A comprehensive analysis of Vehicle to Grid (V2G) systems and scholarly literature on the application of such systems. *Renewable Energy Focus*, *36*, 1–20. https://doi.org/10.1016/j.ref.2020.10.001

Bjørndal, E., Bjørndal, M., Tøllefsen Søndrol, I., & Woie, W. (2025). Electricity tariffs and temporal trading opportunities from bidirectional charging of electric vehicles. *Energy Policy*, *203*. https://doi.org/10.1016/j.enpol.2025.114614

Bjurek, K., & Hagman, V. (2022). *Vehicle-to-Everything Optimization Considering Battery Degradation* [Doctoral dissertation]. www.chalmers.se

BloombergNEF. (2024). Lithium-Ion Battery Pack Prices See Largest Drop Since 2017, Falling to $115 per Kilowatt-Hour: BloombergNEF. https://about.bnef.com/insights/commodities/lithium-ion-battery-pack-prices-see-largest-drop-since-2017-falling-to-115-per-kilowatt-hour-bloombergnef/

Blumberg, G., Broll, R., & Weber, C. (2022). The impact of electric vehicles on the future European electricity system – A scenario analysis. *Energy Policy*, *161*. https://doi.org/10.1016/j.enpol.2021.112751

Borge-Diez, D., Icaza, D., Açıkkalp, E., & Amaris, H. (2021). Combined vehicle to building (V2B) and vehicle to home (V2H) strategy to increase electric vehicle market share. *Energy*, *237*. https://doi.org/10.1016/j.energy.2021.121608

Chen, C.-F., & Lai, C.-M. (2024). Understanding the acceptance of vehicle-to-grid (V2G) services: Evidence from Taiwan. *Transport Policy*, *159*, 230–240. https://doi.org/10.1016/j.tranpol.2024.10.025

Chen, Q., Liu, X., & Zhang, T. (2025). Quantifying the flexibility potential of electric vehicles in buildings and determining the investment strategy for charging infrastructure. *eTransportation*, *24*. https://doi.org/10.1016/j.etran.2025.100403

CTEK. (2025). Brighter Times Ahead for Sweden's EV Market and Charging Infrastructure. https://www.ctek.com/ctek-magazine/brighter-times-ahead-for-sweden-s-ev-market-and-charging-infrastructure?srsltid=AfmBOoqzPoac5YoyKtb47nkU_LKrejP4IcIxqEKiGyIVcUONouSJzneS

Defa. (2025). Laddning i BRF - det här kan vi erbjuda Framtidens smarta laddning är här nu! https://www.defa.com/se/framtidens-smarta-laddning-ar-har-nu/

Demuth, J. L., Buberger, J., Huber, A., Behrens, E., Kuder, M., & Weyh, T. (2024). Unveiling the Power of Data in Bidirectional Charging: A Qualitative Stakeholder Approach Exploring the Potential and Challenges of V2G. *Green Energy and Intelligent Transportation*, 100225. https://doi.org/10.1016/j.geits.2024.100225

Drommi, C. (2022). *The local potential of V2G - Estimation of the benefits of Vehicle to Grid in the energy community of Stenberg* [Doctoral dissertation]. https://kth.diva-portal.org/smash/get/diva2:1678466/FULLTEXT01.pdf

Elbyte. (n.d.). Gemensamt Elavtal i Brf (Bostadsrättsförening. https://elbyte.se/gemensamt-elavtal-brf

Ellevio. (2024). How the electricity market works. https://www.ellevio.se/en/about-us/electricity-grid/How-the-electricity-market-works/

Ellevio. (2025a). Elnätspriser från och med 1 januari 2025. https://www.ellevio.se/globalassets/content/priserabonnemang-pdf/2025/lokalnat/effekt%7B%5C_%7D250101.pdf

Ellevio. (2025b). Mikroproduktion över 63 A. https://www.ellevio.se/globalassets/content/priserabonnemang-pdf/2025/lokalnat/prislista%7B%5C_%7Dmikroprod%7B%5C_%7Dover%7B%5C_%7D63a%7B%5C_%7D250101.pdf

Ellevio. (2025c). Ny prismodell baserad på effekt. https://www.ellevio.se/abonnemang/ny-prismodell-baserad-pa-effekt/

Emulate Energy. (2024). A new project explores dynamic power tariffs from a psychological perspective. https://emulate.energy/a-new-project-explores-dynamic-power-tariffs-from-a-psychological-perspective/

Energimarknadsinspektionen. (2021). The electricity market. https://ei.se/ei-in-english/electricity/the-electricity-market

Energimarknadsinspektionen. (2025). Effektavgift. https://ei.se/konsument/el/elnatsavgiften-och-elnatsreglering/effektavgift

Englberger, S., Abo Gamra, K., Tepe, B., Schreiber, M., Jossen, A., & Hesse, H. (2021). Electric vehicle multi-use: Optimizing multiple value streams using mobile storage systems in a vehicle-to-grid context. *Applied Energy*, *304*. https://doi.org/10.1016/j.apenergy.2021.117862

Enode. (2025). Vattenfall and Enode bring smart charging to EV owners in Sweden. https://enode.com/blog/customers/vattenfall-and-enode-bring-smart-charging-to-ev-owners-in-sweden

European Commission. (2025a). Energy communities. https://energy.ec.europa.eu/topics/markets-and-consumers/energy-consumers-and-prosumers/energy-communities%7B%5C_%7Den

European Commission. (2025b). Sweden: 35% BEV market share in 2024. https://alternative-fuels-observatory.ec.europa.eu/general-information/news/sweden-35-bev-market-share-2024

Fachrizal, R., Qian, K., Lindberg, O., Shepero, M., Adam, R., Widén, J., & Munkhammar, J. (2024). Urban-scale energy matching optimization with smart EV charging and V2G in a net-zero energy city powered by wind and solar energy. *eTransportation*, *20*. https://doi.org/10.1016/j.etran.2024.100314

Ferroamp. (2025). Beställ ferroamp v2x. https://ferroamp.com/kampanj/bestall-v2x-laddare/

Fortum. (2025). Elavtal för företag. https://www.fortum.com/se/el/foretag/elavtal

Fortum. (n.d.). Sälja el från solceller. https://www.fortum.com/se/el/behov/salja-el-fran-solceller

Goldman Sachs Research. (2024). Electric vehicle battery prices are expected to fall almost 50% by 2026. https://www.goldmansachs.com/insights/articles/electric-vehicle-battery-prices-are-expected-to-fall-almost-50-percent-by-2025

Goncearuc, A., De Cauwer, C., Sapountzoglou, N., Kriekinge, G. V., Huber, D., Messagie, M., & Coosemans, T. (2024). The barriers to widespread adoption of vehicle-to-grid: A comprehensive review. *Energy Reports*, *12*, 27–41. https://doi.org/10.1016/j.egyr.2024.05.075

Göteborg Energi. (2024). *Göteborgs elektrifiering - Rapport nr 2 2024* (tech. rep.). Göteborg. https://online.flippingbook.com/view/204099333/

Greaker, M., Hagem, C., & Proost, S. (2022). An economic model of vehicle-to-grid: Impacts on the electricity market and consumer cost of electric vehicles. *Resource and Energy Economics*, *69*. https://doi.org/10.1016/j.reseneeco.2022.101310

Guttman, B. (2024). EV Charging Index: Expert insight from Sweden 2024. https://www.rolandberger.com/en/Insights/Publications/EV-Charging-Index-Expert-insight-from-Sweden-2024.html

Haikola, M., & Söderberg, M. (2020). *Grid tariff design for efficient utilisation of the distribution grid - A qualitative study with actors on the Swedish electricity market* [Doctoral dissertation]. https://www.diva-portal.org/smash/get/diva2%7B%5C%%7D3A1460445/FULLTEXT01.pdf

Heilmann, C., & Friedl, G. (2021). Factors influencing the economic success of grid-to-vehicle and vehicle-to-grid applications—A review and meta-analysis. https://doi.org/10.1016/j.rser.2021.111115

Helferich, M., Tröger, J., Stephan, A., Preuß, S., Pelka, S., Stute, J., & Plötz, P. (2024). Tariff option preferences for smart and bidirectional charging: Evidence from battery electric vehicle users in Germany. *Energy Policy*, *192*. https://doi.org/10.1016/j.enpol.2024.114240

Higashitani, T., Ikegami, T., Uemichi, A., & Akisawa, A. (2021). Evaluation of residential power supply by photovoltaics and electric vehicles. *Renewable Energy*, *178*, 745–756. https://doi.org/10.1016/j.renene.2021.06.097

Hitta Elavtal. (2025). Sveriges största elbolag 2025. https://hittaelavtal.se/sveriges-storsta-elbolag/

Holmberg, P., & Tangerås, T. P. (2023). *The Swedish electricity market – today and in the future* (tech. rep. No. 1). https://www.riksbank.se/globalassets/media/rapporter/pov/artiklar/engelska/2023/230512/2023%7B%5C_%7D1-the-swedish-electricity-market--today-and-in-the-future.pdf

HSB. (2025). ”Är det dags att binda elpriset i vår brf?”. https://www.hsb.se/nyheter-och-tips/nyheter/2025/ar-det-dags-att-binda-elpriset/

Huang, B., Meijssen, A. G., Annema, J. A., & Lukszo, Z. (2021). Are electric vehicle drivers willing to participate in vehicle-to-grid contracts? A context-dependent stated choice experiment. *Energy Policy*, *156*. https://doi.org/10.1016/j.enpol.2021.112410

Huang, P., Tu, R., Zhang, X., Han, M., Sun, Y., Hussain, S. A., & Zhang, L. (2022). Investigation of electric vehicle smart charging characteristics on the power regulation performance in solar powered building communities and battery degradation in Sweden. *Journal of Energy Storage*, *56*. https://doi.org/10.1016/j.est.2022.105907

Infometric. (n.d.). Gemensam el för BRF:er. https://infometric.se/gemensam-el/

International Energy Agency. (2025). Growth in global energy demand surged in 2024 to almost twice its recent average. https://www.iea.org/news/growth-in-global-energy-demand-surged-in-2024-to-almost-twice-its-recent-average

International Energy Agency. (2024a). Energy system of Sweden. https://www.iea.org/countries/sweden

International Energy Agency. (2024b). Global overview. https://www.iea.org/reports/renewables-2024/global-overview

International Energy Agency. (2024c). Sweden 2024. https://www.iea.org/reports/sweden-2024

Jiang, C., Liebman, A., Jie, B., & Wang, H. (2025). Dynamic rolling horizon optimization for network-constrained V2X value stacking of electric vehicles under uncertainties. *Renewable Energy*, *244*. https://doi.org/10.1016/j.renene.2025.122668

Kabir, S., Sjöberg, K., & Östling, M. (2022). *Affärsmöjligheter för V2G - Vardagens elbilar som en flexibilitetstjänst för elnätet* [Doctoral dissertation]. https://www.diva-portal.org/smash/get/diva2:1694183/FULLTEXT01.pdf

Kern, T., Dossow, P., & Morlock, E. (2022). Revenue opportunities by integrating combined vehicle-to-home and vehicle-to-grid applications in smart homes. *Applied Energy*, *307*. https://doi.org/10.1016/j.apenergy.2021.118187

Khezri, R., Steen, D., Wikner, E., & Tuan, L. A. (2024). Optimal V2G Scheduling of an EV With Calendar and Cycle Aging of Battery: An MILP Approach. *IEEE Transactions on Transportation Electrification*, *4*(10), 10497–10507. https://doi.org/https://doi.org/10.1109/tte.2024.338429

Kobashi, T., Say, K., Wang, J., Yarime, M., Wang, D., Yoshida, T., & Yamagata, Y. (2020). Techno-economic assessment of photovoltaics plus electric vehicles towards household-sector decarbonization in Kyoto and Shenzhen by the year 2030. *Journal of Cleaner Production*, *253*. https://doi.org/10.1016/j.jclepro.2019.119933

Krönert, F., Lenasson, M., Telin, F., Atsmon, D., Huang, Y., Koziel, S., & von Essen, E. (2025). *Effektrapporten 2025* (tech. rep.). https://blobs.reformsociety.se/Effektrapporten.pdf

Kühnbach, M., Klobasa, M., Stephan, A., Lux, B., Frank, F., Surmann, A., Kähler, J., Biener, W., Kamaci, Z., & John, R. (2024). *Potential of a full EV-power-system-integration in Europe & how to realise it* (tech. rep.). Fraunhofer Institute for Solar Energy Systems ISE & Fraunhofer Institute for Systems and Innovation Research ISI. Freiburg & Karlsruhe. https://www.transportenvironment.org/uploads/files/2024_10_Study_V2G_EU-Potential_Final.pdf

Laddboxbolaget. (2025a). DEFA Power. https://laddboxbolaget.se/laddboxar/defa-power/

Laddboxbolaget. (2025b). Zaptec Go. https://laddboxbolaget.se/laddboxar/zaptec-go/

Lee, J.-O., & Kim, Y.-S. (2022). Novel battery degradation cost formulation for optimal scheduling of battery energy storage systems. *International Journal of Electrical Power and Energy Systems*, *137*. https://doi.org/https://doi.org/10.1016/j.ijepes.2021.107795

Leijon, J., Santos Döhler, J., Hjalmarsson, J., Brandell, D., Castellucci, V., & Boström, C. (2024). An Analysis of Vehicle-to-Grid in Sweden Using MATLAB/Simulink †. *World Electric Vehicle Journal*, *15*. https://doi.org/10.3390/wevj15040153

Liu, Q., Li, Y., Xu, T., Qian, F., Meng, H., Yao, Y., & Ruan, Y. (2024). Peak shaving potential and its economic feasibility analysis of V2B mode. *Journal of Building Engineering*, *90*. https://doi.org/10.1016/j.jobe.2024.109271

Lo, K.-Y., Yeoh, J. H., & Hsieh, I.-Y. L. (2023). Towards Nearly Zero-Energy Buildings: Smart Energy Management of Vehicle-to-Building (V2B) Strategy and Renewable Energy Sources. *Sustainable Cities and Society*, *99*. https://doi.org/10.1016/j.scs.2023.104941

Luo, J., Cao, X., & Yuan, Y. (2024). Comprehensive techno-economic performance assessment of PV-building-EV integrated energy system concerning V2B impacts on both building energy consumers and EV owners. *Journal of Building Engineering*, *87*. https://doi.org/10.1016/j.jobe.2024.109075

Malya, P. P., Fiorini, L., Rouhani, M., & Aiello, M. (2021). Electric vehicles as distribution grid batteries: a reality check. *Energy Informatics*, *4*. https://doi.org/10.1186/s42162-021-00159-3

Mastoi, M. S., Zhuang, S., Munir, H. M., Haris, M., Hassan, M., Alqarni, M., & Alamri, B. (2023). A study of charging-dispatch strategies and vehicle-to-grid technologies for electric vehicles in distribution networks. *Energy Reports*, *9*, 1777–1806. https://doi.org/10.1016/j.egyr.2022.12.139

Menchaca Santos, D., Thüne, P., Zepter, J. M., & Marinelli, M. (2025). Business cases for degradation-aware bidirectional charging of residential users and heavy-duty vehicle fleets. *eTransportation*, *23*. https://doi.org/10.1016/j.etran.2024.100389

Mobility Sweden. (2025). Laddhybriderna driver på elektrifieringen i en svag återhämtning av marknaden. https://mobilitysweden.se/statistik/Nyregistreringar%7B%5C_%7Dper%7B%5C_%7Dmanad%7B%5C_%7D1/nyregistreringar-2025/laddhybriderna-driver-pa-elektrifieringen-i-en-svag-aterhamtning-av-marknaden

Mojumder, M. R. H., Antara, F. A., Hasanuzzaman, M., Alamri, B., & Alsharef, M. (2022). Electric Vehicle-to-Grid (V2G) Technologies: Impact on the Power Grid and Battery. *Sustainability (Switzerland)*, *14*. https://doi.org/10.3390/su142113856

Nagel, N. O., Jåstad, E. O., & Martinsen, T. (2024). The grid benefits of vehicle-to-grid in Norway and Denmark: An analysis of home- and public parking potentials. *Energy*, *293*. https://doi.org/10.1016/j.energy.2024.130729

Naturvårdsverket. (2024). Sustainable transports. https://www.naturvardsverket.se/en/international/research/the-environmental-research-fund/research-efforts-climate/sustainable-transports/

Naturvårdsverket. (2025). Sweden's Climate Act and Climate Policy Framework. https://www.naturvardsverket.se/en/international/swedish-environmental-work/swedens-climate-act-and-climate-policy-framework/

Nettbureau. (n.d.). Hitta ett bra elavtal till din BRF. https://el.se/brf

Nissan Motor Corporation. (2024). Nissan lanserar prisvärd Vehicle to Grid-teknik från 2026. https://sweden.nissannews.com/sv-SE/releases/nissan-lanserar-prisvard-vehicle-to-grid-teknik-fran-2026

Open Charge Alliance. (2025). OCPP 2.1 is now available! https://openchargealliance.org/ocpp-2-1-is-now-available/

Ouammi, A. (2021). Peak load reduction with a solar PV-based smart microgrid and vehicle-to-building (V2B) concept. *Sustainable Energy Technologies and Assessments*, *44*. https://doi.org/10.1016/j.seta.2021.101027

Qiu, Z. (2023). Research and Analysis on V2G Technology and Its Application. *Highlights in Science, Engineering and Technology*, *68*, 141–149. https://doi.org/10.54097/hset.v68i.12052

Quatrin, F. (2022). Mobility Sweden: "The decision to remove subsidies for EVs will slow down electrification". https://mobilityportal.lat/mobility-sweden-the-decision-to-remove-subsidies-for-evs-will-slow-down-electrification/

Rahman, M. M., Gemechu, E., Oni, A. O., & Kumar, A. (2023). The development of a techno-economic model for assessment of cost of energy storage for vehicle-to-grid applications in a cold climate. *Energy*, *262*. https://doi.org/10.1016/j.energy.2022.125398

Ramic, D., & Nyström, J. (2024). *Vehicle-to-Grid in Sweden: Industry Challenges and Strategic Opportunities* [Doctoral dissertation]. www.kth.se

Ravi, S. S., & Aziz, M. (2022). Utilization of Electric Vehicles for Vehicle-to-Grid Services: Progress and Perspectives. https://doi.org/10.3390/en15020589

Rehnberg, Y. (2024). Bra att tänka på för brf:ens ekonomiansvariga. https://www.vattenfall.se/fokus/tips-rad/ekonomiansvar-i-brf/

Renault. (2025). Scenic. https://www.renault.se/bilar/elbilar/scenic-e-tech-electric/versioner-och-priser

Rosenthal, R. (2007). *GAMS - A User's Guide* (tech. rep.). Washington, DC. https://www.un.org/en/development/desa/policy/mdg%7B%5C_%7Dworkshops/training % 7B % 5C _ %7Dmaterial / gams % 7B % 5C _ %7Dusers % 7B % 5C _ %7Dguide.pdf

Saft. (2022). Lithium-ion batteries in use: 5 more tips for a longer lifespan. https://saft.com/en/energizing-iot/lithium-ion-batteries-use-5-more-tips-longer-lifespan

Saunders, M., Lewis, P., & Thornhill, A. (2015). *Research Methods for Business Students* (7th ed.). Pearson Education Limited.

Signer, T., Baumgartner, N., Ruppert, M., Sandmeier, T., & Fichtner, W. (2024). Modeling V2G spot market trading: The impact of charging tariffs on economic viability. *Energy Policy*, *189*. https://doi.org/10.1016/j.enpol.2024.114109

Skatteverket. (2025a). Common deductions in the tax return. https://www.skatteverket.se/servicelankar/otherlanguages/inenglishengelska / individualsandemployees / declaringtaxesforindividuals / commondeductionsinthetaxreturn.4.7be5268414bea064694c75e.html

Skatteverket. (2025b). Grön teknik. https : / / www . skatteverket . se / privat / fastigheterochbostad/gronteknik.4.676f4884175c97df4192860.html

Skatteverket. (2025c). Skatt på el. https : / / www . skatteverket . se / foretag / skatterochavdrag / punktskatter / energiskatter/skattpael.4.15532c7b1442f256bae5e4c.html?q=batterileekim

Sovacool, B. K., Kester, J., Noel, L., & Zarazua de Rubens, G. (2020, October). Actors, business models, and innovation activity systems for vehicle-to-grid (V2G) technology: A comprehensive review. https://doi.org/10.1016/j.rser.2020.109963

Statista. (2025). Electric Vehicles - Sweden. https://www.statista.com/outlook/mmo/electric-vehicles/sweden

Steen, D., Sjölander, J., Forsgren, H., Sabbouh, M., Bjerkliden, C., Gabrielsson, S., Wallin, E., & Jernström, B. (2025). *V2X-MAS A study of the possible applications of bidirectional electric vehicle charging. Final report* (tech. rep.). www.chalmers.se

Stockholm Exergi. (n.d.). Batterier för energilagring. https://www.stockholmexergi.se / bostadsrattsforening / vara - energitjanster / ellosningar / batterier - for - energilagring/

Svenska Kraftnät. (2022). *Så arbetar vi för att öka överföringskapaciteten Kortsiktiga åtgärder* (tech. rep.). https://www.svk.se/siteassets/om-oss/rapporter/2022/kapaciteteshojande%7B%5C_%7Datgarder%7B%5C_%7Dq2.pdf

Svenska Kraftnät. (2025). Map of the national grid. https://www.svk.se/en/national-grid/map-of-the-national-grid/

Svenska Kraftnät. (2024a). Drivkrafter bakom utvecklingen av transmissionsnätet. https://www.svk.se/utveckling-av-kraftsystemet/transmissionsnatet/drivkrafter/

Svenska Kraftnät. (2024b). Elområden och prisskillnader. https://www.svk.se/om-kraftsystemet/om-elmarknaden/elomraden/elomraden-och-prisskillnader/

Svenska Kraftnät. (2024c). Operations and Electricity Markets. https://www.svk.se/en/national-grid/operations-and-electricity-markets/

Svenska Kraftnät. (2024d). Sveriges elnät. https://www.svk.se/om-kraftsystemet/oversikt-av-kraftsystemet/sveriges-elnat/

Swedish Electromobility Centre. (2025). *Aannual report 2024* (tech. rep.). https://emobilitycentre.se

Tepe, B., Figgener, J., Englberger, S., Sauer, D. U., Jossen, A., & Hesse, H. (2022). Optimal pool composition of commercial electric vehicles in V2G fleet operation of various electricity markets. *Applied Energy*, *308*. https://doi.org/10.1016/j.apenergy.2021.118351

Thaler, R. H. (1999). *Mental Accounting Matters* (tech. rep. No. 3). https://people.bath.ac.uk/mnsrf/Teaching%7B%5C%%7D202011/Thaler-99.pdf

Thompson, A. W., & Perez, Y. (2020). Vehicle-to-Everything (V2X) energy services, value streams, and regulatory policy implications. *Energy Policy*, *137*. https://doi.org/10.1016/j.enpol.2019.111136

Trafikanalys Statistik. (2024). *Körsträckor 2023* (tech. rep.). https://www.trafa.se/globalassets/statistik/vagtrafik/korstrackor/2023/korstrackor-2023---2024-09-19.pdf

Vallinder, I. S., & Carlsson, M. (2022). *Electric cars for grid services - A system perspective study of V2G in a future energy system of Sweden and a local perspective study of a commercial car fleet* [Doctoral dissertation]. https://kth.diva-portal.org/smash/get/diva2:1697452/FULLTEXT01.pdf

Vattenfall. (2025a). Elavtal för Bostadsrättsföreningar (BRF). https://www.vattenfall.se/foretag/elavtal/elavtal-for-bostadsrattsforeningar/

Vattenfall. (2025b). Teckna elavtal med timpris. https://www.vattenfall.se/elavtal/elpriser/timpris/

Vattenfall Eldistribution. (2025a). Avtal och elnätsavgifter för företag. https://www.vattenfalleldistribution.se/foretag/abonnemang-och-avgifter/avtal-och-elnatsavgift/

Vattenfall Eldistribution. (2025b). Elproduktionsersättning och avgifter för företag. https://www.vattenfalleldistribution.se/foretag/abonnemang-och-avgifter/avtal-och-elnatsavgift/elproduktionsersattning-och-avgifter/

Volvo Cars. (2025). Volvo wallbox med laddkabel. https://www.volvocars.com/se/shop/additionals/volvo-wallbox-with-cable/?showBackButton=true

Westerheide, C. (2025). Volvo Cars deliver power to the grid in Gothenburg. https://www.electrive.com/2025/04/09/volvo-cars-deliver-power-to-the-grid-in-gothenburg/

Yang, C. (2023). Accelerating Sweden's climate action in transportation. https://www.sei.org/perspectives/swedens-transport-climate-action/

Yang, C., Zhao, Y., Li, X., & Zhou, X. (2025). Electric vehicles, load response, and renewable energy synergy: A new stochastic model for innovation strategies in green energy systems. *Renewable Energy*, *238*. https://doi.org/10.1016/j.renene.2024.121890

Yeoh, J. H., Lo, K.-Y., & Hsieh, I.-Y. L. (2025). Optimizing urban energy flows: Integrative vehicle-to-building strategies and renewable energy management. *Energy Conversion and Management: X*, *26*. https://doi.org/10.1016/j.ecmx.2025.100974

Zheng, Y., Shao, Z., Lei, X., Shi, Y., & Jian, L. (2022). The economic analysis of electric vehicle aggregators participating in energy and regulation markets considering battery degradation. *Journal of Energy Storage*, *45*. https://doi.org/10.1016/j.est.2021.103770

Zhou, Y. (2022). Energy sharing and trading on a novel spatiotemporal energy network in Guangdong-Hong Kong-Macao Greater Bay Area. *Applied Energy*, *318*. https://doi.org/10.1016/j.apenergy.2022.119131

Appendix

A Model Equations and Constraints

A.1 Initial SoC

This equation defines the initial battery level of each EV at the start of the simulation, denoted as $t1$, to a SoC of 25% of the total battery capacity.

$$soc_v(t_1) = 0.25 \cdot cap_{\text{EV}} \tag{1}$$

A.2 Charge and Discharge Limits

These constraints limit the maximum charging and discharging power of each EV based on technical specifications and availability status. An EV can only charge or discharge when plugged in and the power level is capped at the maximum rated charging/discharging capacity, which is assumed to be 22 kW. The respective equations are:

$$p_{ch,v}(t) \leq \delta_{ch,v}(t) \cdot 22 \tag{2}$$

$$p_{dh,v}(t) \leq \delta_{dh,v}(t) \cdot 22 \tag{3}$$

$\delta_{ch,v}(t) \in \{0,1\}$ is a binary parameter indicating whether charging is allowed for vehicle v at time t (1 if plugged in, otherwise 0)
$\delta_{dh,v}(t) \in \{0,1\}$ is a binary parameter indicating whether discharging is allowed for vehicle v at time t (1 if plugged in, otherwise 0)

A.3 Discharge Energy Limited by SoC

To protect battery health and reduce degradation, EV batteries are not allowed to discharge below a certain minimum SoC, set to 20% of total capacity. This constraint ensures that at any time t, the energy discharged from the battery does not reduce the SoC below this threshold. This is expressed as:

$$p_{dh,v}(t) \leq \left(soc_v(t) - soc_v^{\min}(t)\right) \cdot \eta_{dh} \tag{4}$$

A.4 No Simultaneous Charging/Discharging

To prevent an EV from charging and discharging at the same time, a constraint is set for each time step t. It is governed by the binary variable $\delta_{avail,v}(t)$. Since both $\delta_{ch,v}(t)$ and $\delta_{dh,v}(t)$ are binary, their sum must not exceed $\delta_{avail,v}(t)$, which also takes values in $\{0,1\}$.

If an EV is not plugged in, $\delta_{avail,v}(t) = 0$, which enforces $\delta_{ch,v}(t) = 0$ and $\delta_{dh,v}(t) = 0$ — i.e., no charging or discharging can occur.

If an EV is plugged in, there are three valid states:

- Charging: $\delta_{ch,v}(t) = 1$, $\delta_{dh,v}(t) = 0$
- Discharging: $\delta_{ch,v}(t) = 0$, $\delta_{dh,v}(t) = 1$
- Idle: $\delta_{ch,v}(t) = 0$, $\delta_{dh,v}(t) = 0$

The constraint is formulated as:

$$\delta_{ch,v}(t) + \delta_{dh,v}(t) \leq \delta_{avail,v}(t) \tag{5}$$

$\delta_{avail,v}(t) \in \{0,1\}$ is a binary parameter indicating whether vehicle v is connected at time t (1 if connected, otherwise 0)

A.5 Peak Power Constraint

To reflect real-world electricity pricing structures, where peak power tariffs apply, this model includes a constraint on p_{peak}, defined as the highest level of net power drawn from the grid across all hours t. A high peak leads to increased costs, since p_{peak} is multiplied by a scalar peak tariff in the objective function. The model therefore aims to reduce it.

The constraint tracking net power at each time step is formulated as:

$$p_{\text{peak}}(t) = ET_{\text{imp}}(t) - ET_{\text{exp}}(t) \tag{6}$$

A.6 Sell Grid Limits

The first equation ensures that the amount of electricity sold to the grid at any given hour cannot exceed the total discharging capacity of all EVs combined. This prevents the model from overselling beyond what the vehicles are capable of supplying.

The second equation ensures that the total power sent back to the grid at any hour does not exceed the remaining capacity of the fuse (max 240 kW), after serving the building's own load. It is a physical constraint reflecting the grid connection limit of the cooperative.

$$ET_{\text{exp}}(t) \leq \sum_{v} p_{dh,v}(t) \cdot \eta_{dh} \tag{7}$$

$$ET_{\text{exp}}(t) \leq 240 - P_{\text{load}}(t) \tag{8}$$

B Results under Ellevio's Contract

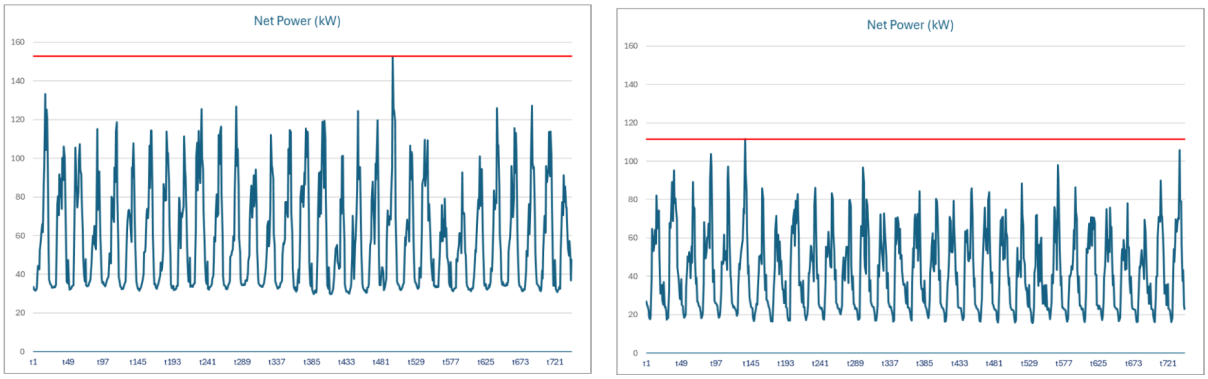
B.1 Cost Results

Table 1: Monthly costs and savings for Ellevio

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
						Total Cost (SEK)							
E1	123,368	103,021	107,152	70,171	52,791	52,686	47,508	49,017	44,943	55,231	97,333	105,722	908,941
E2	114,632	99,003	102,708	68,307	50,381	50,580	45,523	46,519	42,890	53,604	92,882	98,112	865,140
E3	107,132	90,676	95,425	65,187	48,996	48,958	44,539	44,549	40,987	50,424	86,990	91,553	815,416
						% Reduction on Total Cost							
E1	-	-	-	-	-	-	-	-	-	-	-	-	-
E2	7.1%	3.9%	4.1%	2.7%	4.6%	4.0%	4.2%	5.1%	4.6%	2.9%	4.6%	7.2%	4.8%
E3	13.2%	12.0%	10.9%	7.1%	7.2%	7.1%	6.2%	9.1%	8.8%	8.7%	10.6%	13.4%	10.3%
						Peak Power Cost (SEK)							
E1	26,123	22,831	23,597	9,693	9,676	8,518	9,035	8,821	9,077	9,782	20,989	25,350	183,494
E2	20,365	20,720	21,102	8,757	8,552	7,394	7,832	7,790	8,141	9,416	18,878	19,592	158,539
E3	16,827	14,940	16,600	7,385	8,169	7,255	7,832	7,272	7,068	7,366	16,318	15,922	132,953
						% Reduction Peak Power Cost							
E1	-	-	-	-	-	-	-	-	-	-	-	-	-
E2	22.0%	9.2%	10.6%	9.7%	11.6%	13.2%	13.3%	11.7%	10.3%	3.7%	10.1%	22.7%	13.6%
E3	35.6%	34.6%	29.7%	23.8%	15.6%	14.8%	13.3%	17.6%	22.1%	24.7%	22.3%	37.2%	27.5%

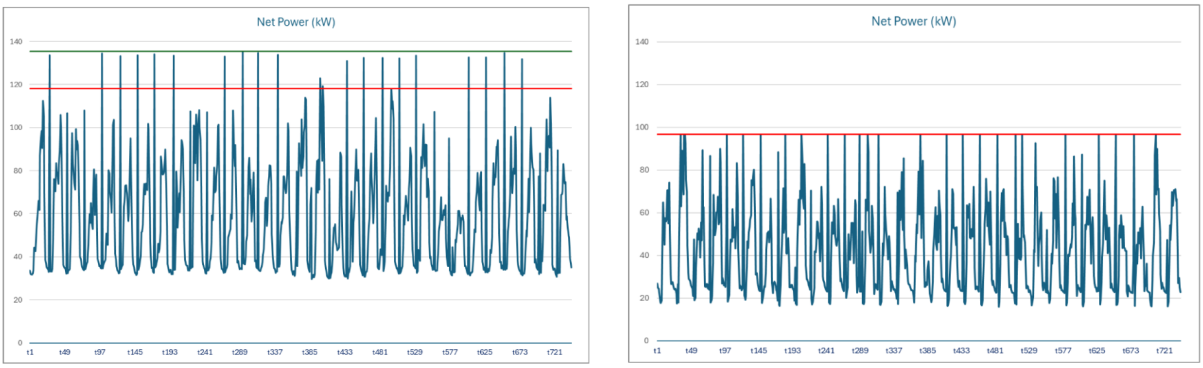
B.2 Net Power Demand Curves

In Figure 1a to 3b, the red lines indicate the most expensive power peak while the green lines indicate low demand period peaks, that are the same or lower cost than the red one.



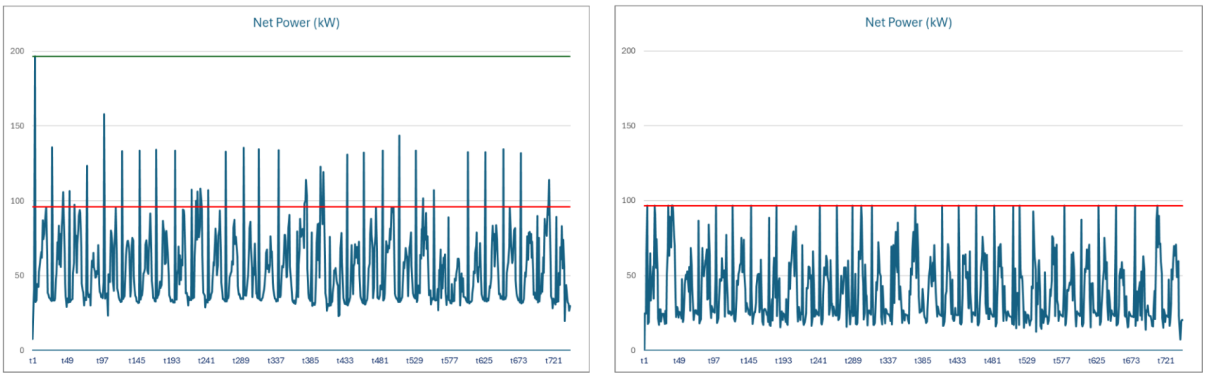
(a) December (b) July

Figure 1: Demand curves with uncontrolled charging.



(a) December (b) July

Figure 2: Demand curves with controlled charging.



(a) December (b) July

Figure 3: Demand curves with V2G charging

B.3 Peak Power - Ellevio and Vattenfall

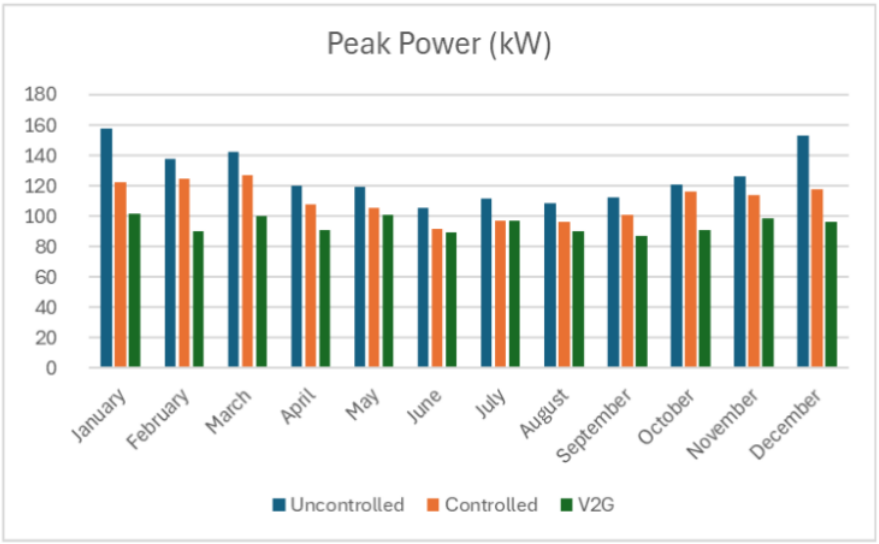


Figure 4: Peak power for all three charging strategies

C Results under Vattenfall's Contract

C.1 Cost Results

Table 2: Monthly costs and savings for Vattenfall

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
						Total Cost (SEK)							
V1	114,217	95,106	99,158	65,397	47,942	48,438	42,973	44,614	40,411	50,399	90,138	96,570	835,361
V2	108,077	91,942	95,729	64,075	46,182	46,982	41,684	42,713	38,899	48,982	86,533	91,565	803,363
V3	102,037	86,172	90,370	61,695	44,974	45,388	40,650	40,991	37,575	46,949	81,642	86,555	764,997
						% Reduction on Total Cost							
V1	-	-	-	-	-	-	-	-	-	-	-	-	-
V2	5.4%	3.3%	3.5%	2.0%	3.7%	3.0%	3.0%	4.3%	3.7%	2.8%	4.0%	5.2%	3.8%
V3	10.7%	9.4%	8.9%	5.7%	6.2%	6.3%	5.4%	8.1%	7.0%	6.8%	9.4%	10.4%	8.4%
						Peak Power Cost (SEK)							
V1	13,533	11,828	12,225	4,069	4,061	3,576	3,793	3,703	3,810	4,106	10,874	13,133	88,711
V2	10,550	10,735	10,932	3,676	3,590	3,104	3,287	3,270	3,417	3,952	9,780	10,150	76,444
V3	8,718	7,740	8,600	3,100	3,429	3,045	3,287	3,053	2,967	3,092	8,454	8,249	63,733
						% Reduction Peak Power Cost							
V1	-	-	-	-	-	-	-	-	-	-	-	-	-
v2	22.0%	9.2%	10.6%	9.7%	11.6%	13.2%	13.3%	11.7%	10.3%	3.7%	10.1%	22.7%	13.8%
V3	35.6%	34.6%	29.7%	23.8%	15.6%	14.8%	13.3%	17.6%	22.1%	24.7%	22.3%	37.2%	28.2%

D Battery Degradation Analysis

D.1 Degradation Results under Ellevio's Contract

Table 3: December cost comparison: 2x and 0.5x degradation scenarios

Metric	2x Degradation			0.5x Degradation		
	Scenario	Regular	Difference	Scenario	Regular	Difference
Total Cost (SEK)	94,980	91,553	3,426	89,585	91,553	-1,968
Degradation Cost (SEK)	5,641	3,764	1,877	2,093	3,764	-1,671
% of Total	5.9%	4.1%	1.8%	2.3%	4.1%	-1.8%
Peak Power Cost (SEK)	15,922	15,922	0	15,922	15,922	0
Increased Purchase Cost (SEK)	1,549	–	–	-297	–	–
% of Total	1.7%	–	–	-0.3%	–	–
High Load Peak (kW)	96	96	0	96	96	0
Low Load Peak (kW)	197	197	0	197	197	0
Charging (kWh)	2,759	2,810	-51	3,146	2,810	336
Discharging (kWh)	1,720	3,048	-1,328	3,372	3,048	324
Sold (kWh)	0	0	0	9	0	9

Table 4: July cost comparison: 2x and 0.5x degradation scenarios

Metric	2x Degradation			0.5x Degradation		
	Scenario	Regular	Difference	Scenario	Regular	Difference
Total Cost (SEK)	47,312	44,539	2,773	42,725	44,539	-1,814
Degradation Cost (SEK)	4,006	3,416	590	1,864	3,416	-1,551
% of Total	8.5%	7.7%	0.8%	4.4%	7.7%	-3.3%
Peak Power Cost (SEK)	7,832	7,832	0	7,832	7,832	0
Increased Purchase Cost (SEK)	2,182	–	–	-263	–	–
% of Total	4.9%	–	–	-0.6%	–	–
High Load Peak (kW)	–	–	–	–	–	–
Low Load Peak (kW)	97	97	0	97	97	0
Charging (kWh)	2,720	2,720	0	2,785	2,720	65
Discharging (kWh)	563	2,619	-2,056	3,019	2,619	400
Sold (kWh)	0	0	0	32	0	32

D.2 Degradation Results under Vattenfall's Contract

Table 5: January cost comparison: 2x and 0.5x degradation scenarios

Metric	2x Degradation			0.5x Degradation		
	Scenario	Regular	Difference	Scenario	Regular	Difference
Total Cost (SEK)	105,669	102,037	3,632	99,609	102,037	-2,429
Degradation Cost (SEK)	6,479	4,073	2,406	3,180	4,073	-893
% of Total	6.10%	4.00%	2.10%	3.20%	4.00%	-0.80%
Peak Power Cost (SEK)	8,718	8,718	0	8,718	8,718	0
Increased Purchase Cost (SEK)	1,226	–	–	-1,536	–	–
% of Total	1.2%	–	–	-1.5%	–	–
High Load Peak (kW)	101	101	0	101	101	0
Low Load Peak (kW)	210	224	-14	255	224	31
Charging (kWh)	2,785	3,074	-289	4,998	3,074	1,924
Discharging (kWh)	2,306	3,270	-964	4,934	3,270	1,664
Sold (kWh)	0	0	0	1	0	1

Table 6: July cost comparison: 2x and 0.5x degradation scenarios

Metric	2x Degradation			0.5x Degradation		
	Scenario	Regular	Difference	Scenario	Regular	Difference
Total Cost (SEK)	43,465	40,650	2,815	38,829	40,650	-1,821
Degradation Cost (SEK)	4,097	3,438	659	1,865	3,438	-1,573
% of Total	9.40%	8.50%	1.00%	4.80%	8.50%	-3.70%
Peak Power Cost (SEK)	3,287	3,287	0	3,287	3,287	0
Increased Purchase Cost (SEK)	2,157	–	–	-247	–	–
% of Total	5.3%	–	–	-0.6%	–	–
High Load Peak (kW)	–	–	–	–	–	–
Low Load Peak (kW)	97	97	0	97	97	0
Charging (kWh)	2,720	2,720	0	2,785	2,720	65
Discharging (kWh)	629	2,651	-2,022	3,019	2,651	368
Sold (kWh)	0	0	0	0	0	0

TRITA – ITM-EX-2025:313
Stockholm, Sverige 2025

www.kth.se