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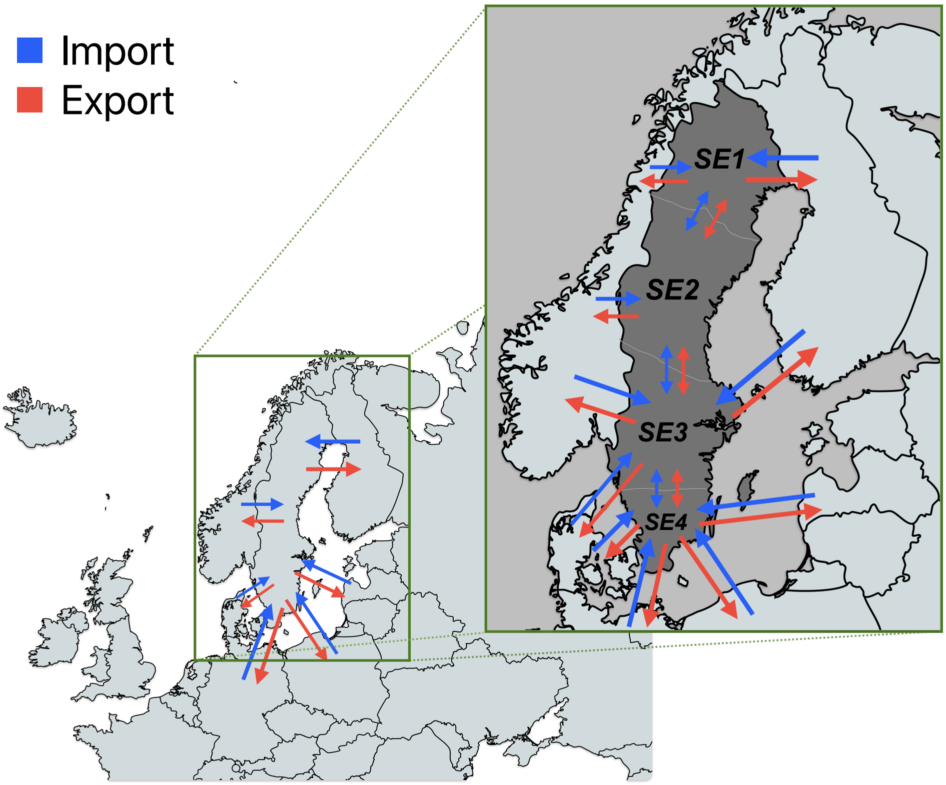

Vertical integration in energy system modelling

Understanding the effects of European energy trading on the Swedish energy system

Master's thesis in Sustainable Energy Systems and Complex Adaptive Systems

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Gothenburg, Sweden 2026
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Abstract

Understanding a country's future energy system requires modelling, yet national energy system models typically treat countries as isolated systems, ignoring cross-border interdependencies. Fully resolving this limitation is computationally intractable, as adequately representing neighbouring countries requires their neighbours in turn, rapidly producing models too large to solve.

This project addresses this by developing a vertical integration methodology that couples a national sub-model with a surrounding macro-level model. Cross-border trade flows are extracted from the macro-level model and applied as boundary conditions in the sub-model, allowing the national system to respond to external energy market pressures without requiring a fully resolved continental model. The methodology is implemented within the GENeSYS-MOD framework and evaluated through a Swedish case study, using a newly constructed dataset divided into Sweden's four electricity bidding zones.

The results demonstrate that vertical integration fundamentally reshapes Sweden's optimal energy configuration in ways an isolated model cannot capture. Hydrogen export demand to Finland emerges as the dominant driver, cascading through the power system and redirecting electricity away from domestic industry, slowing its electrification. Access to imported natural gas further reinforces this pattern, as fossil-fired heating becomes more competitive than electric alternatives. Although net emissions remain comparable between the models, the vertically integrated model shifts toward a greater dependency on carbon capture technologies rather than emissions reduction at source. The sub-model also exposed a spatial resolution mismatch: trade patterns optimised at the European level can produce infrastructure investments that are impractical at the national scale.

The study highlights that what is optimal from a European perspective may not align with national climate goals, a tension that isolated national models cannot reveal. Addressing this through more sophisticated vertical integration methodologies represents an important direction for future research.

Keywords: Energy system optimisation, vertical integration, cross-border energy trade, GENeSYS-MOD, national energy modelling, hydrogen, energy transition research

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Viktor Rosenberg, Leo Roslund, Gothenburg, June 2026.

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

ATR	Autothermal Reforming
BECCS	Bioenergy with Carbon Capture and Storage
CCS	Carbon Capture and Storage
CGE	Computable General Equilibrium
CHP	Combined Heat and Power
DIW	German Institute for Economic Research (Deutsches Institut für Wirtschaftsforschung)
ECMWF	European Centre for Medium-Range Weather Forecasts
EFOM	Energy Flow Optimisation Model
ENTSO-E	European Network of Transmission System Operators for Electricity
ENTSO-G	European Network of Transmission System Operators for Gas
ERA5	Fifth generation of the ECMWF atmospheric reanalysis
ESOM	Energy System Optimisation Model
ETSAP	Energy Technology System Analysis Program
GAMS	General Algebraic Modelling System
GENeSYS-MOD	The Global Energy System Model
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
MARKAL	Market Allocation Model
NECP	National Energy and Climate Plan
NUCS	Nordic Unavailability Collection System

Continued on next page...

NUTS-3	Nomenclature of Territorial Units for Statistics, level 3
OSeMOSYS	The Open Source Energy Modelling System
PV	Photovoltaics
SCB	Statistics Sweden (Statistiska Centralbyrån)
SINTEF	The Foundation for Industrial and Technical Research (Stiftelsen for Industriell og Teknisk forskning)
SMR	Steam-Methane Reforming
TIMES	The Integrated MARKAL–EFOM System
TSO	Transmission System Operator
TYNDP	The Ten-Year Network Development Plan
WIP	Workgroup for Economic and Infrastructure Policy (Wirtschafts- und Infrastrukturpolitik)

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Introduction

Climate change remains one of the most pressing challenges of our time. From the latest synthesis report of the Intergovernmental Panel on Climate Change (IPCC), AR6 (IPCC, 2023), it is evident that we are on our way towards increasing the global temperature beyond 1.5°C compared to pre-industrial levels already during the 2030s. Even the goal from the Paris agreement of keeping the warming under 2°C within the 21st century seems out of reach. In 2024 the global energy-related CO_2 emissions reached 37.8 Gt CO_2 (including transport) (International Energy Agency, n.d.), which is 71% of the global CO_2 emissions in total (Joint Research Centre European Comission, 2025). Even though we have seen an immense increase in renewable power generation in recent years there has also been an increase in the use of fossil fuels globally (Institute, 2025). In Europe the energy-related emissions of about 1 Gt CO_2 account for 30% of the CO_2 emissions of the region. The EU Green Deal aims to reduce greenhouse gas (GHG) emissions by 50% until 2030 and achieve climate neutrality by 2050 (European Commission, 2019). Sweden, as part of EU, took on ambitious climate goals in 2017 aiming to have net-zero emissions by 2045 (Klimatpolitiska rådet, 2017). While this includes investments in reduced emissions abroad, domestic emissions in Sweden still need to be at least 85% lower than the levels of 1990. In Sweden the largest share of emissions stems from transport and industry, accounting for 35% and 30% respectively while the heat and power sector only accounts for 8% of the national CO_2 emissions of 47.5 Mt CO_2 in 2024 (Naturvårdsverket, 2025a).

Meeting these targets across transport, industry, heat and power simultaneously requires navigating a system of great complexity. Energy systems are characterised by high infrastructural investment costs and operational lifetimes extending over multiple decades, meaning that decisions made today shape the system far into the future. With multiple interacting sectors and actors involved, it becomes impossible to empirically test different transition strategies and simply choose the best one. Instead, to make sound decisions, both politically and in terms of investment, we need tools that can represent the system as a whole and explore how it may evolve under different conditions. Energy system optimisation models (ESOM) serves exactly this purpose: by representing the real world through mathematical formulations, it allows us to investigate different scenario pathways, understand how the system behaves under certain constraints, and identify what is most critical for the transition to take place.

One such ESOM is the Global Energy System Model (GENeSYS-MOD) developed at the

Workgroup for Economic and Infrastructure Policy (WIP) at Technische Universität Berlin (TU Berlin). It is a linear optimisation model, stemming from the Open Source Energy Modelling System (OSeMOSYS) (Löffler, Burandt, et al., 2026). It takes multiple sectors and their interactions into account, finding the solution which meets the exogenously set up demands while minimising total system costs. The model can be applied to energy systems of varying sizes, from the level of a small local energy system to, as the name implies, the global energy system.

When modelling these energy systems, the ideal approach would be to capture large geographical areas while maintaining a fine, granular resolution of the data. For example, it is preferable to model the European energy system while simultaneously accounting for regional differences within each country. However, achieving this level of detail requires adding a substantial number of nodes. In this context, a ”node” represents a specific geographic region, the scale of which depends on the model's scope; for instance, a node might represent an entire country in a continental European model, or a single federal state (Bundesland) within a national German model. Like many optimisation models, GENeSYS-MOD is heavily limited by the number of nodes it can investigate. Adding nodes increases model complexity and the computational power required. When the goal is to model a specific country in detail, this creates a particular challenge around where to draw the boundaries of the model: correctly representing neighbouring countries requires including their neighbours in turn, and so on, rapidly making the model too large to solve.

This thesis aims to solve this issue and contribute to energy transition research by introducing a new methodology of vertically integrating cross-border trade flows from a broad, macro-level model into a geographically confined, high-resolution sub-model. Alternative approaches exist but carry significant drawbacks: a fully integrated model covering both scales simultaneously remains computationally infeasible, while soft-linking, a method of iteratively exchanging outputs between two separate models, introduces additional complexity and convergence challenges. Vertical integration offers a more tractable middle ground, extracting trade flows from an existing macro-level model and applying them as constraints in the sub-model, without requiring a separate modelling infrastructure. This methodology is implemented in two distinct ways within the GENeSYS-MOD framework, designed to be applicable across various spatial scales. To demonstrate its utility, this report focuses on a case study of Sweden. It compares an isolated national model (the current standard approach) with the new methodology, integrating the necessary European-level trade flows into the Swedish energy system model.

1.1 Background

In order to reach the set goals of limiting CO_2 and GHG emissions, changes in the energy sector will play a vital role as one of the primary emitters. Plazas-Niño et al. (2022) states that energy planning must play a vital role in decarbonisation, while also taking affordability and energy security into account. As the energy system grows more complex, driven by the need of reduced GHG emissions and being formed by liberalised energy markets, energy system planning must be able to deal with these complexities (Pfenninger et al., 2018). Meanwhile we are seeing an increase in sector coupling and distribution of energy providers and consumers, increasing the need of accurate energy models (Majidi et al., 2025).

As a support to energy planning, ESOMs are utilised, finding the optimal system by minimising costs under certain environmental restrictions while ensuring the demands are met. ESOMs, as simplifications of the real energy system, can be used to investigate possible decarbonisation pathways and evaluate different alternatives (Plazas-Niño et al., 2022). Thus can ESOMs provide support for policy and decision making. The realisation of this lead to the formation of the Energy Technology System Analysis Program (ETSAP) in 1976 resulting in the development of the Market Allocation Model (MARKAL) (Plazas-Niño et al., 2022).

MARKAL is an energy sector model based on linear programming which is designed to be used to model an entire nation (Fishbone & Abilock, 1981). The model represents the energy chain from primary resources to the final energy demand (Loulou et al., 2024), and further follows a market logic where the price of fuels are endogenously explored taking scarcity into account, following classical equilibrium theory. MARKAL is still one of the most used ESOMs and has been further developed into other models, such as the successor The Integrated MARKAL–EFOM System (TIMES) (Plazas-Niño et al., 2022). TIMES is, like MARKAL, also a model based on the concept of market equilibriums, introducing inter-regional trade, more detailed age tracking of technologies, and greater flexibility in time slicing (Loulou et al., 2016).

Over the past 20 years we have seen a great increase in ESOMs due to the development within computing capabilities (Prina et al., 2022). We have also seen the development of open source energy modelling, leading to more transparent models and research. Pfenninger et al. (2018) highlights how open source models enables more collaboration between researchers while also opening up decision making, making the process more publicly accessible. The process of making models more accessible is not only limited to the access of the mathematical formulations, programmes and scripts but also the input data used. Free access to input data is of major importance in making modelling processes more accessible, transparent and up to questioning, although it also comes with the process of allocating intellectual property (Pfenninger et al., 2018). One highly developed open source framework is the Open Source Energy Modelling System (OSeMOSYS), a model built for long term energy planning optimisation. Due to the frameworks accessibility and work on relationships with policy makers by the OSeMOSYS team the framework have been adopted by national governments, such as South Africa, Cyprus and Bolivia, for their energy sector planning (Pfenninger et al., 2018).

The developers behind OSeMOSYS Howells et al. (2011) present the model as an optimisation model used for long run planning of energy systems. It is, unlike other predecessors in ESOMs, not built around equilibrium assumptions, but is rather based on a linear optimisation framework where the goal is to find the lowest net present value of a system while a given demand is met under certain constraints (Howells et al., 2011). Based on this modelling framework the Global Energy System Model (GENeSYS-MOD) has been developed by Löffler et al. (2017), adding new features to the existing OSeMOSYS framework. Amongst other differences between the models, some of the major ones are that GENeSYS-MOD takes the transport sector into further and more detailed consideration, while also further developing the structure of accounting for storage potential and sector coupling. The addition and further development of sector coupling is an important feature as it allows to reach a deeper understanding of the current energy system which is becoming all more integrated and complex (Löffler et al., 2017).

Previously the energy system of Sweden has been modelled using primarily MARKAL and TIMES, as exemplified by Krook Riekkola (2015). They used the TIMES-Sweden model using mostly aggregated national data, rather than regional, looking at several topics, such as the importance of including cross-border trade, the representation and inclusion of combined heat and power (CHP) plants and district heating as well as ancillary benefits from climate policy and soft-linking a national Computable General Equilibrium (CGE) model. In their research they highlight the importance of trade and electricity transmission between Sweden and its neighbouring countries, being interconnected since the late 1800s. Furthermore, they argue that the cross border trade in the Nordics changes and is dependent on seasonal and daily factors, arguing for investigating cross border trade using a time granularity that captures these factors. In addition it is stated by Krook Riekkola (2015) that cross border trade may well affect the investments in installed capacity in Sweden.

An issue within linear optimisation of energy system models lies in the spatial resolution. A model is limited in how many nodes it can handle in its computation, this creates the trade-off in choosing between the size and boundaries of the system studied and its spatial resolution (Brinkerink et al., 2024). Global models provide insight into the future global energy system, but its lack of regional detail may result in misconceptions regarding the local possibilities (Oei et al., 2020). Oei et al. (2020) exemplifies this by comparing the results from a global model, showing an even distribution of solar and wind power across the continents, while a European model reveals that this distribution is not even at all. The European model suggests more solar power in the southern parts with more wind power in the north. Another example of how the spatial granularity may affect the results was provided by Brandes et al. (2024), who found that in their analysis of Germany that if treated as ten regions rather than one they had about 6% more renewable capacity being installed in the optimal solution. This motivates the implementation of finer granularity, although it generally limits the size of the system studied, for example to national models. However, since cross border trade is an important feature for many national energy systems, as the case for Sweden described by Krook Riekkola (2015), there is a need for models to be able to take both cross border trade and international system features into account without compromising national and local conditions. Thus motivating the need of creating new tools and methodologies which allows for such things to be considered while studying energy systems with higher spatial granularity.

Other studies have attempted to solve this issue by utilising proxy representations of neighbouring regions or by soft-linking separate models to expand the analytical scope. Mertens et al. (2020) directly address the problem of geographically restricted boundaries in long-term planning models, assessing two methodologies using Belgium as a case study. The first extends the model's geographical scope while fixing capacity variables in neighbouring countries based on pre-designed scenarios; the second reduces computational cost further by using tailored import and export curves to represent each country's trade opportunities. While the trade curve approach successfully reduced computational costs, their results show that for highly interconnected systems, neglecting or oversimplifying cross-border trade leads to inaccurate welfare estimates and technology biases. They concluded that endogenising dispatch decisions in neighbouring countries remains the most accurate approach. However, as previously established, expanding a model's scope to endogenise these neighbouring regions rapidly leads to computational issues when a high spatial resolution is required.

A second strategy for maintaining tractability without sacrificing scope is soft-linking, where outputs from one model are passed as inputs to another. Rosendal et al. (2025) explored a bi-directional soft-linking framework coupling an investment model with an hourly-resolution operational model for a pan-European electricity and hydrogen system. While their results demonstrate that soft-linking enables large-scale problems to be investigated, they also highlight that model harmonisation, convergence issues, and the tuning of specific linking strategies present significant challenges. Soft-linking is not limited to spatial coupling; Krook-Riekkola et al. (2017) soft-linked a macroeconomic CGE model with the bottom-up TIMES-Sweden model, finding that dynamically capturing top-down economic shifts resulted in lower reference CO_2 emissions due to adjusted industrial demand, highlighting how external system influences can meaningfully alter national modelling outcomes. While these approaches each advance the field, they introduce considerable complexity in implementation. This project proposes an alternative: a one-directional vertical integration that extracts cross-border trade flows from a macro-level model and apply them as constraints in a sub-model. This approach captures the broader system dynamics without the computational burden of endogenising neighbouring regions. It also avoids the convergence and harmonisation challenges of iterative soft-linking while remaining easily implementable within an existing open-source framework.

1.2 Aim & purpose

The aim of this project is to develop and implement a new methodology of vertical integration within the GENeSYS-MOD framework and evaluating its impact on country-level energy system modelling. Specifically, this methodology allows lower spatial levels (national models) to inherit boundary conditions and trade flows from higher spatial levels (continental models).

The thesis uses Sweden and Europe as a case study. A core component of the work is a comparative analysis between the results of the existing model, running a country in isolation, and the results from a vertically integrated model where European trade is taken into account for the Swedish national modelling. This comparison will evaluate how the structural change affects the understanding of the system's dynamics.

The research questions of this study are:

- How can vertical integration be implemented within the GENeSYS-MOD framework to effectively transfer boundary conditions and trade flows from higher to lower spatial levels?

- How does the inclusion of European cross-border dynamics, enabled by vertical integration, alter the optimal energy system configuration for Sweden compared to an isolated national model?

1.3 Demarcations

This project focuses on the vertical integration of spatial levels within energy system modelling. While the developed methodology is theoretically applicable to other regional configurations, the scope of this study is strictly demarcated geographically, temporally, and methodologically.

The geographical scope is limited to the established European system boundaries of the GENeSYS-MOD framework; countries or regions outside of this are not considered. Within Sweden, the spatial resolution is limited to the four national electricity bidding zones (SE1–SE4). The temporal scope spans from a base year of 2018 to 2060, the standard modelling horizon of GENeSYS-MOD, operating in primarily 5 year intervals (2018, 2025, 2030,..., 2060). Years outside this range are not considered. Furthermore, while GENeSYS-MOD supports varying temporal resolutions within the year, this study applies a single time slice configuration and the effects of alternative resolutions are not examined.

Regarding the sectoral and technological scope, this study does not include any sectors or technologies that are not currently within the GENeSYS-MOD framework. Additionally, alternative scenario pathways are not considered. Due to data availability limitations, not all input data could be sourced directly at the regional level. Where bidding zone data was unavailable, national data was either disaggregated or lower-level regional data was aggregated to fit the four bidding zones. The implications of this are discussed but the effects of alternative data assumptions are not examined within this study. Since the focus of this study is the development and comparison of methodological implementations rather than the accuracy of absolute results, formal empirical validation of input data and model output falls outside the current scope.

Finally, because the objective of this methodology is to implement cross-border trade, the model adopts a techno-economic optimisation approach rather than an equilibrium market approach. Consequently, dynamic market pricing is explicitly excluded from the scope. Trade is instead governed by the existing GENeSYS-MOD cost framework, utilising exogenous, fixed costs for both the expansion of interconnection capacity and the physical transmission of fuels and electricity between regions.

2

Theory

This chapter establishes the theoretical foundation upon which the modelling work in this thesis rests upon. It begins with an introduction to systems theory, providing the conceptual vocabulary needed to describe and reason about complex, interacting structures. The chapter then turns to energy systems as a specific domain of application, characterising their components, behaviour, and the particular challenges they pose to analysis. Finally, energy system modelling is introduced as a methodology, ending with a description of the modelling framework GENeSYS-MOD, which is used in this work.

2.1 Systems theory

The field of General Systems Theory (GST), with roots in cybernetics, provides a framework to effectively analyse complex societal and infrastructural phenomena by establishing a common language (Ingelstam, 2002). The nature of systems, as said by Fredrich Hegel (1770-1831), comes from the holistic view that the whole is greater than the sum of its parts, and that the parts cannot be fully understood in isolation from the whole (Skyttner, 2001).

A system can broadly be defined as a set of interacting units or elements that form an integrated whole intended to perform a specific function (Skyttner, 2001). More specifically, a system consists of two primary entities: components and the relationships between them (Ingelstam, 2002). These components and relationships can take various forms depending on the context. For instance, in a biological system, components may be cells or organs interacting through physical or chemical transport, whereas in a sociotechnical system, the components comprise both human actors and technical artifacts interacting through shared resources or social relations (Ingelstam, 2002).

Crucial to the definition of any system is the establishment of a system boundary, which separates the system from its surrounding environment. While an isolated system, completely closed to external inputs, will theoretically move toward maximum entropy and a steady state, most practical systems are open and interact with their surroundings (Skyttner, 2001). In the context of this thesis, the primary system is defined as the Swedish national energy system, while the surrounding European energy system constitutes the environment, making cross-boundary interaction a focal point of analysis.

2.2 Energy systems

Applying systems theory to the energy sector requires defining the specific components and relationships that create an energy system. The primary function of an energy system is to deliver necessary energy services, such as electricity, heating, cooling, and transportation, to end-users (Dincer & Abu-Rayash, 2020).

The architecture of an energy system is built upon a flow of energy that transitions through several stages. In systems theory terms, it originates with primary energy sources as initial inputs, which include both fossil fuels (coal, oil, natural gas), and renewable or nuclear sources. These primary sources are then processed through energy conversion facilities acting as transformative components, such as power plants (hydro, wind, nuclear, solar), heating plants, and refineries, transforming raw materials into useful forms of energy (Dincer & Abu-Rayash, 2020). Finally, the physical relationships between these components are realised through transmission and heating networks or other means of transport, distributing energy to end-users across the residential, industrial, commercial, and transportation sectors.

What makes energy systems particularly complex is the degree of interdependency between these components. A decision or change in one part of the system inevitably propagates through the others. Meaning that increasing electricity production from wind, for instance, affects the utilisation of thermal power plants, storage requirements, and transmission flows simultaneously. Similarly, a shift in demand in one sector, such as the electrification of transport, places new pressures on power generation and grid infrastructure. These cascading effects mean that the system cannot be meaningfully understood by studying its parts in isolation.

Underlying these physical flows is an economic dimension. Energy systems are capital-intensive, requiring substantial long-term investments in infrastructure whose operational lifetimes span decades. At the same time, the system must continuously balance supply and demand in a cost-efficient manner, meeting the energy needs of end-users at the lowest possible cost while respecting technical, environmental, and political constraints. This dual challenge of long-term investment planning and short-term operational efficiency is what makes energy system analysis both complex and important for policy and investment decisions.

Applied to Sweden, the system components include power plants, transmission infrastructure, heating networks, and end-users across residential, commercial and transport sectors, with their relationships realised through energy flows, market interactions and physical transmission constraints. Sweden is clearly an open system, it exchanges electricity and fuel with neighbouring countries through interconnections and pipelines, meaning conditions in the surrounding European environment directly influence domestic system behaviour. Studying Sweden in isolation therefore risks an incomplete picture of how the system operates, directly motivating the vertical integration methodology developed in this project.

2.3 Modelling

A model can be understood as a representation of a system, constructed with the purpose of being able to answer questions about that system without performing the experiment itself (Ingelstam, 2002). This may be necessary because the experiment is impossible, prohibitively expensive, or ethically questionable. Models can take several forms: mental, verbal, physical, or mathematical. The latter, consisting of a set of equations that describe the behaviour of a system, is the form relevant to this work. As Einstein observed, however, mathematical models carry an inherent tension: when their propositions refer to reality, they are not certain, and when they are certain, they do not refer to reality (Skyttner, 2001). This serves as an important reminder that any model is a simplification, a tool to examine system effects under certain conditions rather than an exact representation of the real world.

Energy systems, as described in the previous section, are complex sociotechnical systems spanning numerous actors, technologies, and sectors across large spatial and temporal scales. Decisions regarding energy infrastructure and policy play out over decades, and the consequences of those decisions, in terms of cost, emissions, and security of supply, cannot be tested empirically before they are made. This makes energy systems a domain where modelling is not merely useful but necessary.

As Ingelstam (2002) notes, the system boundary and its relationships to the surrounding environment are just as important to define as the system itself. For a national energy system such as Sweden's, this is particularly important: the system does not operate in isolation, but is embedded in and continuously interacting with the broader European energy system through various cross-border trade and interconnected infrastructure.

What an energy system model represents, in practice, is the chain from primary energy resources through conversion technologies to final energy demand (Loulou et al., 2024). In doing so, it necessarily abstracts away a degree of real-world detail, aggregating across time, space, and technology in order to remain computationally feasible. These abstractions constitute deliberate design choices and they determine what questions a given model can and cannot answer.

2.4 Mathematical optimisation and linear programming

To optimise means to do something in the most optimal or best way, whatever that is depends on the context. It could be optimising your intake of energy during a long run to maximise performance, how you would optimise your work-life-balance to minimise stress or, as in our case, minimise energy system costs while still meeting the desired energy demands. The thing being optimised is within the field of optimisation known as the objective value.

Optimisation often refers to mathematical optimisation which as, presented by Boyd and

Vandenberghe (2004), has the form

$$\begin{aligned} &\text{minimize} && f_0(x) \\ &\text{subject to} && f_i(x) \leq b_i, \quad i = 1, \ldots, m. \end{aligned} \tag{2.1}$$

Here $x = (x_1, \ldots, x_n)$ is the optimisation variable of the problem while the function $f_0 : \mathbf{R}^2 \to \mathbf{R}$ is the objective function. The functions $f_i : \mathbf{R}^n \to \mathbf{R}, \quad i = 1, \ldots, m$ are the constraint functions with constant bounds $b_1, \ldots, b_m$. In other words, the function f_0 is what we try to minimise while still adhering to the constraints set by f_i. The solution to the problem, or the optimal, is the value of x^* that when used in f_0 has the smallest value among all possible values of x^* that satisfy the constraints.

Depending on how you formulate the objective function and the constraint we can classify the optimisation problem into different classes or families (Boyd & Vandenberghe, 2004). What we will focus on here is the version of the problem (2.1) where the objective and constraint functions $f_0, \ldots, f_m$ are linear, i.e., satisfy

$$f_i(\alpha x + \beta y) = \alpha f_i(x) + \beta f_i(y) \tag{2.2}$$

for all $x, y \in \mathbf{R}^n$ and all $\alpha, \beta \in \mathbf{R}$. In simpler terms this means two things, one is that if you multiply the input, x, by 2 the objective value would also be multiplied by 2. The other thing is that if you add 10 to x, that would also add 10 to the objective value, the function is a sum of its parts. If the problem is linear it is called a *linear program*. They are the simplest form of optimisation in terms of mathematics, however, with many variables and constraints it can form a complex system, requiring substantial computing power to solve.

2.5 Energy system optimisation models

Energy system optimisation models (ESOM) are mathematical models used to identify an optimal configuration of an energy system under a set of defined constraints. Typically, the objective is to minimise the total system cost over a planning horizon, while ensuring that energy demand is met and that relevant technical, physical, and policy constraints are satisfied (Howells et al., 2011). As simplifications of the real energy system, ESOMs can incorporate a wide range of technologies, sectors, and energy carriers across the full energy chain, and are used to investigate future energy pathways and support policy and investment decisions (Plazas-Niño et al., 2022). The model used in this thesis is GENeSYS-MOD, developed as a further extension of the OSeMOSYS framework, and is described in detail in Section 2.5.1.

2.5.1 GENeSYS-MOD

GENeSYS-MOD, with the full name Global Energy System Model, is a model originally developed to analyse the global energy system (Löffler, Burandt, et al., 2026). It is an linear programming model which was developed by WIP at TU Berlin as a further development of OSeMOSYS. The model is available in the programming language Julia and in the

General Algebraic Modelling System (GAMS) software, which is the version used in this thesis.

The model aims to minimise total system cost where the energy demands of various sources for different regions are provided as input to the model (Löffler, Burandt, et al., 2026). The model then calculates the necessary capacities to meet those demands. Even though the name suggests a global model setting it is not limited to be used only for a global energy system. Depending on the input data the framework could in theory calculate and optimise everything from single households to a global level of regions.

The sectors which are covered by the model are: electricity, industry, buildings and transport. The model includes flexibility options such as regional trade, energy storage as well as sector coupling using linking technologies. See Figure 2.1 for a simplified representation of the model.

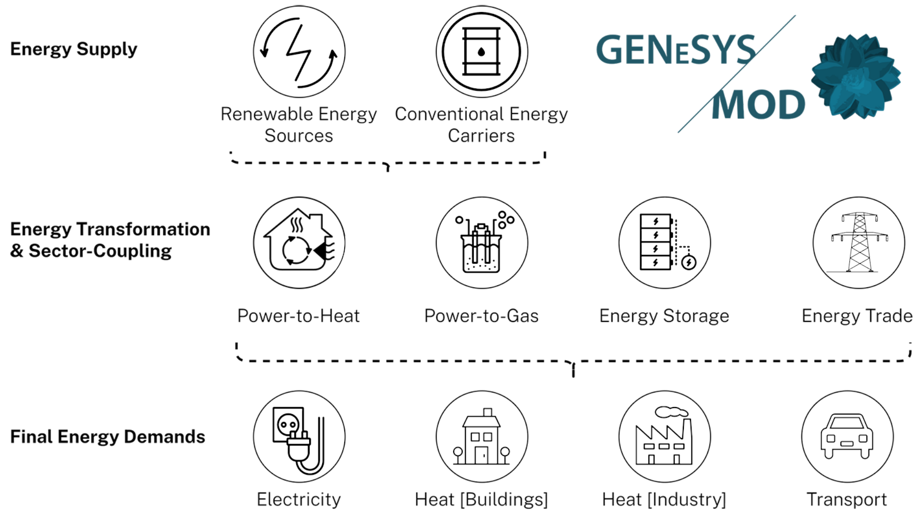

Figure 2.1: Simplified image of the GENeSYS-MOD structure (Löffler, Burandt, et al., 2026). Source: Technische Universität Berlin, DIW Berlin, and SINTEF Energy Research. Licensed under Apache 2.0 (see Appendix A).

2.5.1.1 Mathematical formulation

The model is a linear program which can be used for different spatial and temporal resolutions. The temporal resolution can be adjusted to match the spatial resolution. For example, in a global setting you might not need to know the development of the system at every hour, rather a couple of times a year, while for a more detailed local application you may want hourly results (Löffler et al., 2025a).

The model is set up with these sets:

r = set of Regions,
y = set of Modelled Years,
f = set of Fuels,
e = set of Emissions,
se = set of Sectors,
t = set of Technologies
s = set of Storages
m = set of Mode of Operation
mt = set of ModalType
l = set of TimeSlice

Most of the sets are quite self-explanatory, the regions define the geographical scope of the model, it could for example be regions to cover a global setting, regions in terms of countries for a European model or regions within a country for a higher resolution model.

The technologies defines all processes that can convert, move, store, or use energy (or in some cases other things, such as transport demand). Some example technologies are power and heat generation, industrial processes, transportation, energy conversion and resource supply. In total there are around 150 different technologies. While there are a lot of technologies involved there are quite few storages, only about nine. These are usually linked to technologies in one way or another and includes different batteries and gas storages, such as hydrogen or methane.

Fuel defines all inputs and outputs of technologies. Typically it represents some kind of energy carrier, such as electricity or gas, which is measured in petajoules. Although fuels can also represent other units such as energy proxies like kilometres travelled or surface area available for different technologies. An example of such a fuel is ”Mobility Freight”, representing the amount of goods transported by different transport technologies. Mode of operation is used to distinguish between different modes that the technologies can work in, for example a gas power plant could use either natural gas in mode 1 and biogas in mode 2. Emission defines the types of emission tracked, currently carbon dioxide (CO_2) is the only emission.

ModalType is the set to define or group transportation demands into different categories. Firstly it is divided by freight or passenger transport, then by rails, road, air or ship as well as by renewable or conventional. There are 18 different modal type combinations integrated in the model. The sector set puts different technologies into different sectors. The sectors are; Power, Industry, Buildings, Transportation, Resources, Storages, Transformation and CHP (Combined Heat and Power), which are cohering to sector specific constraints.

As for time we have the Year and TimeSlice sets, the Year set defines the temporal resolution of the model on an annual basis. It is used to track all time-dependent variables. The TimeSlice set defines the temporal resolution within the year. Input data is expected to be on an hourly basis but to reduce the computational complexity a timeseries reduction algorithm (based on Gerbaulet and Lorenz (2017)) is used to aggregate the data into a smaller number of time steps, usually around 150-300 instead of the 8760 hours in a year, while still maintaining the hourly and seasonal representations.

The objective function of GENeSYS-MOD is:

$$
\begin{aligned}
\min z = & \sum_{r}\sum_{t}\sum_{y} \text{DiscountedTechnologyCosts}_{r,t,y} \\
& + \sum_{r}\sum_{s}\sum_{y} \text{DiscountedStorageCosts}_{r,s,y} \\
& + \sum_{r}\sum_{y} \text{DiscountedTradeCosts}_{r,y} \\
& - \sum_{r}\sum_{t}\sum_{y} \text{DiscountedTechnologySalvageValue}_{r,t,y} \\
& - \sum_{r}\sum_{s}\sum_{y} \text{DiscountedStorageSalvageValue}_{r,s,y}
\end{aligned}
$$

This objective function is developed to provide a cost-optimal system while still maintaining relevant constraints. The constraints consists of many different relationships, the most fundamental one is energy balances to make sure supply meets demand, however; they could also be political, for example limitations set in order to phase out certain technologies, capacity restrictions due to physical limitations or emission targets which can be modelled in various ways. In total there are roughly 120 different equations in the model.

To account for these equations there are numerous parameters and variables involved, there are too many to list them here but they can be found at the official GENeSYS-MOD documentation (Löffler et al., 2025b).

2.5.1.2 Trade system in GENeSYS-MOD

GENeSYS-MOD incorporates an inter-regional trade system that allows energy carriers to flow between modelled regions, enabling the optimisation of energy supply across a spatially disaggregated system. Trade is not governed by a market mechanism; rather, all costs associated with trade reflect the physical infrastructure required to build capacity and move energy between regions. The model determines trade flows endogenously as part of the overall cost minimisation.

Network topology and commodities

A wide range of energy carriers can be traded within the system. These include solid fuels (e.g., hard coal, biomass), liquid fuels (e.g., oil, liquefied gases), gaseous fuels (e.g., natural gas, biogas, hydrogen), and electricity. The possibility to trade between regions is defined through the parameter *TradeRoute*, which specifies whether a any fuel may flow between two regions and the travel distance. This exogenous parameter effectively defines the topology of the trade network. Typically, trade routes are only defined between neighbouring regions that share existing infrastructure. Consequently, long-distance trade is achieved implicitly through a chain of bilateral flows across intermediate regions, each constrained by its own trade route definitions.

Infrastructure and capacity constraints

Not all fuels are treated equally regarding infrastructure. A primary distinction is made between grid-bound carriers and freight-bound carriers:

- **Grid-bound carriers (electricity and gas):** These require dedicated physical infrastructure (transmission lines or pipelines) and are subject to explicit trade capacity constraints. The total available capacity between region r and region rr for fuel f in year y is tracked via *TotalTradeCapacity*, which evolves according to:

  $$\begin{aligned}\text{TotalTradeCapacity}_{y,f,r,rr} &= \text{TotalTradeCapacity}_{y-1,f,r,rr} + \\ &+ \text{NewTradeCapacity}_{y,f,r,rr} + \text{CommissionedTradeCapacity}_{y,f,r,rr}\end{aligned}$$

  This ensures that capacity in any given year relies on the previous year's capacity, plus any endogenously built capacity (*NewTradeCapacity*), plus any planned, exogenous build-out defined by the modeller (*CommissionedTradeCapacity*). Expansion is bounded by *GrowthRateTradeCapacity*, which caps the maximum annual increase. Gas trade allows for slightly more flexibility; in addition to expanding the current network, the model can invest in building entirely new regional connections.

- **Freight-bound carriers (liquids and solids):** Commodities like oil, coal, and biomass do not require fixed, point-to-point infrastructure as they are transported by ship or rail. Therefore, they are not subject to strict capacity constraints. Trade flows for these fuels are bounded primarily by the existence of a valid trade route and the broader regional energy balances. The cost for trading these fuels are based solely on the distance and a specific *TradeCostFactor* given for each fuel. Important to note is that the freight-bound trade should not be confused with the modelled fuel ”Mobility freight” representing the exogenously decided demand for transport of goods.

Temporal resolution and balancing

The trade system also distinguishes between time-dependent and time-independent balancing. Because electricity and gas cannot be easily stored without dedicated storage technologies, trade for grid-bound carriers must physically balance within each individual time slice. Imports in any given time slice are constrained not to exceed the available annual capacity scaled by the length of that time slice.

Conversely, liquid and solid fuels are calculated on an annual energy balance. Because these commodities can be stockpiled, shipped on flexible schedules, and consumed across seasons, the model aggregates their trade over the full year rather than enforcing strict time-slice constraints.

Import technologies

Beyond internal inter-regional trade, GENeSYS-MOD includes import technologies representing trade with the rest of the world. For commodities that the modelled system cannot produce domestically in sufficient quantities, dedicated import options are provided (e.g., *Z_Import_Oil*, *Z_Import_Hardcoal*, *Z_Import_Gas*, *Z_Import_LNG*, and *Z_Import_H2*). These technologies allow the model to satisfy residual demand that cannot be met through internal production or the defined inter-regional trade network. These technologies are set to have high pricing in order to minimize the models use of the technologies. From here on will import technologies be referred to as ”the global energy market” as they represent a regions access to buying certain fuels on a global market.

3

Method

This chapter describes the methodology developed to model Sweden's energy system at the bidding zone level within the GENeSYS-MOD framework. The work consisted of two main components. First, a regional dataset was constructed for the four Swedish bidding zones, as GENeSYS-MOD had not previously been applied at this spatial resolution for Sweden. Second, a vertical integration methodology was developed and implemented within the framework, enabling the Swedish sub-model to be coupled to the European macro-level model. Finally, the model setup applied across all runs is described, including scenario selection, temporal configuration, and emission constraints.

3.1 Data compilation

Constructing a dataset for Sweden's four bidding zones within the GENeSYS-MOD framework required combining newly collected regional data with existing Swedish data already present in the European model. Since GENeSYS-MOD was not previously applied at this spatial resolution for Sweden, many parameters had no readily available regional data, requiring either disaggregation from national-level sources or aggregation from county and municipality level sources. The following section describes how this dataset was constructed, the assumptions made, and where data limitations remain.

Many parameters in GENeSYS-MOD can be assumed consistent across regions, such as discount rates, infrastructure pricing, and technology lifetimes. However, 21 parameters require region-specific values to adequately represent a new area. These were compiled in primarily two different ways, depending on if regional data was obtainable or not. When regional data could be obtained, new values were sourced from statistical databases and yearly reports, primarily from Statistics Sweden and the Swedish Energy Agency, covering parameters such as trade capacities and routes, energy demands for power, heat and transport, residual capacities, and selected capacity limits. When regional data could not be obtained, existing Swedish values from the European dataset (Löffler, Moskalenko, et al., 2026) were used as a basis, either applied uniformly across all bidding zones or disaggregated using appropriate splits. Table 3.1 lists all 21 parameters with the method and main source for each, with full descriptions in Appendix C, the different splits are documented in Appendix Table B.2 and the complete datasets used for the isolated Swedish model, the vertically integrated Swedish model and the European model can be found at the Zenodo repository (Rosenberg & Roslund, 2026a).

Table 3.1: Necessary parameters to find when adding new regions.

Parameter	**Method**	**Main source**
Par_AnnualExogenousEmission	Swedish value from the European model disaggregated between bidding zones based on energy use of Swedish industries.	GENeSYS-MOD data github repository.
Par_AvailabilityFactor	Assumed to be the same for all bidding zones as for Sweden in the European model.	GENeSYS-MOD data github repository.
Par_CommissionedTradeCapacity	Compiled from databases by NUCS and ENTSOG as well as a report by Svenska kraftnät.	Nordic Unavailability Collection System (NUCS), Svenska kraftnät (TSO of Sweden) & European Network of Transmission System Operators for Gas (ENTSOG).
Par_DistrictHeatDemand	District heat production by municipality aggregated to Swedish bidding zones and then converted to demand by comparing to demand data for Sweden as a whole.	Statistics Sweden (Statistiska centralbyrån, SCB).
Par_DistrictHeatSplit	District heating for non-residential premises, single-family houses and apartment buildings were assumed to make up ”buildings” while the rest, compared to total use, were assumed to be ”industry”.	Swedish Energy Agency.
Par_GrowthRateTradeCapacity	Assumed to be the same for all bidding zones as for Sweden in the European model.	GENeSYS-MOD data github repository.
Par_ModalSplitByFuel	Freight transport by road, ship, rail and loaded tonnes in each county aggregated to Swedish bidding zones. Passenger transport by road, rail, air and passenger kilometres.	Transport Analysis & Eurostat.
Par_ModelPeriodActivityMaxLimit	Assumed to be the same for all bidding zones as for Sweden in the European model.	GENeSYS-MOD data github repository.
Par_ModelPeriodEmissionLimit	European value disaggregated to Sweden based on population.	GENeSYS-MOD data github repository.
Par_RegionalBaseYearProduction	Swedish values from the European model disaggregated between bidding zones based on different assumptions for each technology.	GENeSYS-MOD data github repository.
Par_RegionalCCSLimit	Based on results from analysis made on the potential CO_2 storage sites in Sweden	GENeSYS-MOD data github repository & Geological Survey of Sweden
Par_REMinProductionTarget	Assumed to be the same for all bidding zones as for Sweden in the European model.	GENeSYS-MOD data github repository.

Continued on the next page...

Table 3.1: Necessary parameters (continued)

Parameter	**Method**	**Main source**
Par_ResidualCapacity	Capacities compiled and aggregated from different sources. Power plant capacities assumed to follow pattern of power consumption in regions. Capacities for non-power generating technologies are determined by making a model run only for the year 2018.	Statistics Sweden, Swedish Energy Agency & European Network of Transmission System Operators for Electricity (ENTSOE) Transparency Platform.
Par_ResidualStorageCapacity	No extensive capacities for energy storage could be found.	-
Par_SpecifiedAnnualDemand	Data of demand for power and building heating collected from Statistics Sweden, other Swedish values taken from the European model and disaggregated between bidding zones based on different assumptions for each technology.	Statistics Sweden & GENeSYS-MOD data github repository.
Par_TotalAnnualMaxActivity	Swedish value from the European model disaggregated between bidding zones based on land area, except for residues and cardboard which was based on population.	GENeSYS-MOD data github repository.
Par_TotalAnnualMaxCapacity	Swedish value from the European model disaggregated between bidding zones based on land area, except for off-shore wind which used length of coastline and hydropower which was limited to the size of residual capacities.	GENeSYS-MOD data github repository.
Par_TotalAnnualMinCapacity	Swedish value from the European model disaggregated between bidding zones based on residual capacity distribution, except for Li-ion batteries which used new data.	GENeSYS-MOD data github repository.
Par_TradeCapacity	Compiled from NUCS database and a report by the Swedish Energy Markets Inspectorate (Energimarknadsinspektionen, Ei).	NUCS & Ei.
Par_TradeCapacityGrowthCosts	Assumed to be the same for all bidding zones as for Sweden in the European model.	GENeSYS-MOD data github repository.
Par_TradeRoute	Distance between central points in bidding zones were calculated.	-

3.1.1 Regional aggregation and disaggregation

During the compilation of the data for the Swedish bidding zones most sources provided information on a county or municipality level which made it necessary to aggregate the data into the four bidding zones we modelled. Since the different regional levels do not align to the division of the bidding zones we had to establish a split when regions were present in more than one. For municipalities we chose the bidding zone based on where the seat was situated. The counties were divided based on the municipalities they hosted and the population of the municipalities. The split in full can be found in Appendix B.

Where only national Swedish values were available, these were disaggregated into the four bidding zones using 13 different splits, constructed based on proxies such as residual capacity, registered cars, power consumption or industrial energy use. The appropriate split varied by parameter, technology, and fuel type. A complete description of all splits and how they were constructed is provided in Appendix Table B.2, with specific descriptions for regional base year production and specified annual demand in Appendix C.10 and C.15 respectively.

3.1.2 Time series

Time series data was generated using the Python Jupyter Notebook script provided in the GENeSYS-MOD tools repository (Löffler, 2025), which uses the atlite package to process weather data from the the fifth generation of the European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis dataset (ERA5) (Copernicus Climate Change Service, 2025). Weather data from 2018 was used, consistent with the model's base year. The script generated intra-year profiles for onshore wind, offshore wind, solar PV, heat pump coefficient of performance, and heating and cooling demand, each produced separately for the four bidding zones to capture regional variation. The onshore and offshore wind capacity factors were based on the Vestas V112 3MW and Vestas V164 7MW turbine models respectively, and solar photovoltaic capacity factors were based on a crystalline silicon panel configuration.

3.1.3 Data calibration

As the final step, the dataset required calibration to ensure internal consistency and model feasibility. Despite thorough data collection, gap and mismatches remained. This is primarily due to the limited availability of some parameters and because of the inconsistencies between different data sources with some being aggregated and some disaggregated.

The first calibration step addressed the missing residual capacities for certain technologies that could not be found in available statistics. To estimate these, a constrained model run made for calibration was performed in which the model was permitted to invest in the missing capacity types of the base year, such as industrial heat divided into different heat categories and transport capacities for different subtypes. The resulting capacities were then increased by 10% before being set as residual capacities. This is standard procedure within GENeSYS-MOD in order to provide a buffer to ensure feasibility in subsequent model runs.

The second calibration step involved adjusting the base year production values to achieve consistency between the installed capacities and the specified annual demands. This was carried out iteratively, starting from the Swedish dataset in the European model disaggregated between regions. The model was then run multiple times with a calibration option which allowed us to know if any technology was producing too much or too little in order for the model to reach the optimal solution. While this process introduces some uncertainty into the absolute values, it was a necessary step given the data constraints, and the resulting dataset represents an internally consistent starting point for the comparative analysis.

3.2 Vertical integration of spatial levels

This section describes the development of the vertical integration methodology, which constitutes the core technical contribution of this work. The methodology enables a higher-resolution sub-model to be coupled to a macro-level model by transferring trade flows from the macro-level solution as constraints to the sub-model. The conceptual framework underlying this approach is first presented, followed by its mathematical formulation and finally the two implementations developed within GENeSYS-MOD.

3.2.1 Conceptual framework

Energy system models applied at the national or sub-national level are inherently limited in how they represent the surrounding energy system. In an isolated model, the studied region is modelled as a self-contained system, where internal trade between regions is optimised freely but external energy flows are not grounded in any broader system optimisation. However, through the import technologies in Section 2.5.1.2, the model can still resort to importing from a global energy market for certain commodities. Those imports do not reflect actual trade relationships with specific neighbouring systems, the source of the imported commodity is effectively unknown. Figure 3.1 illustrates this isolated model structure, where trade flows exist only between the Swedish bidding zones internally.

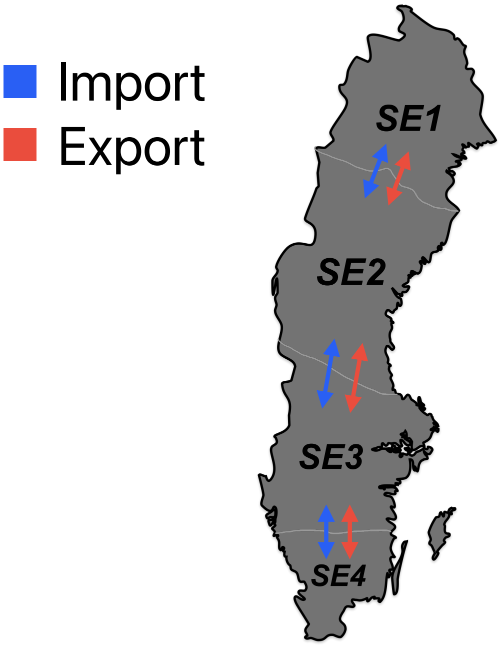

Figure 3.1: Isolated model.

The vertical integration approach addresses this limitation by grounding the sub-model's external trade in the results of a macro-level model, here the European version of GENeSYS-MOD. The European model is first solved as an optimal solution for the full European energy system. A Python script then extracts the relevant trade flows between Sweden and its neighbouring countries and reformulates them as constraints in the Swedish sub-model. The sub-model is subsequently run incorporating these constraints, with no iteration or feedback between the two models. This one-directional coupling reflects the assumption that the European model represents the best available estimate of how the broader system will operate, and that Sweden's internal configuration does not meaningfully alter European-level outcomes. Figure 3.2 illustrates this vertically integrated structure, where the Swedish bidding zones now also trade with the surrounding European system.

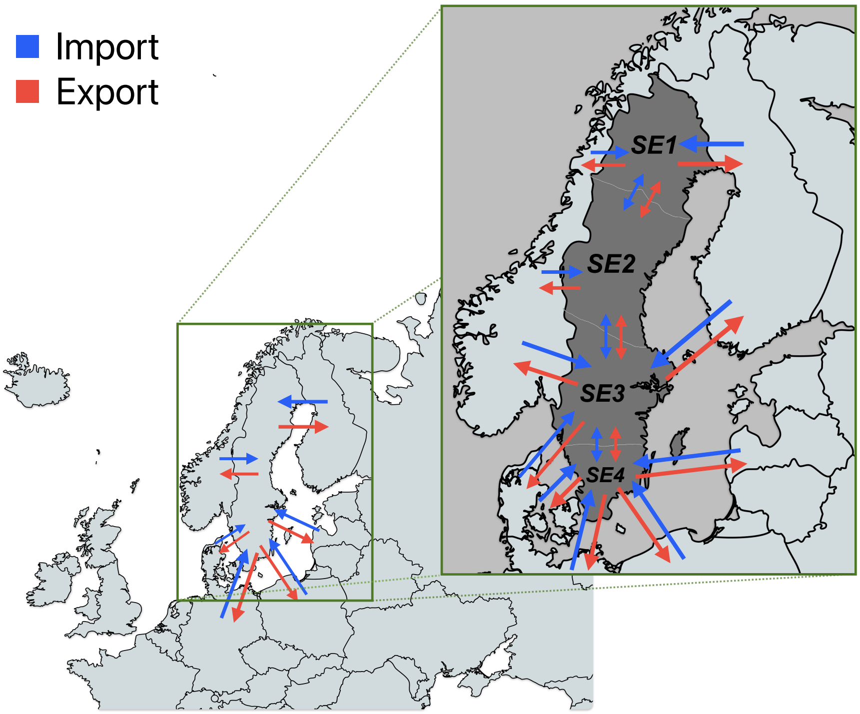

Figure 3.2: Vertically integrated model.

Two formulations of the coupling constraints are considered. In the primary formulation, trade flows are treated as hard constraints: the sub-model must export exactly the amount exported in the macro-level run, and must import exactly the amount imported. This is motivated by the argument that the European model solution represents what actually occurred in the broader system, and the sub-model should therefore reproduce those flows exactly. A second formulation treats the flows as bounds: exports from the sub-model serve as a lower bound, it must export at least as much as the macro-level solution, while imports serve as an upper bound, it may import at most as much as the macro-level solution. This gives the sub-model more freedom to find an internally optimal solution while still being consistent with the broader European system. Since the change between the two formulations is mathematically straightforward, both are implemented and compared.

In both formulations, the constraints are applied at the broader Swedish level rather than per bidding zone. For a given trade route, for example between Sweden and Norway, the sum of exports across all Swedish bidding zones with a route to Norway must together satisfy the constraint. The sub-model then determines which bidding zones contribute to that total, selecting the most cost-efficient distribution. A limitation of this approach is that it does not specify which region within Norway has the corresponding demand, the exogenous regions are treated as single nodes with no internal structure.

3.2.2 Mathematical formulation

The vertical integration is formalised through two sets of constraints added to the sub-model, with the primary one using hard constraints. The formulation relies on the following indices, input data, and decision variables.

3.2.2.1 Indices

The sub-model operates over a set of modelling years y, time slices l, and fuels f. The Swedish electricity bidding zones SE1, SE2, SE3, and SE4 form the index of sub-model regions r. The neighbouring countries that Sweden trades with in the European model form the index of exogenous regions exr. The valid trade routes between sub-model regions and exogenous regions are defined per fuel, reflecting both geographical constraints and which fuels can be traded on each route, denoted $\mathrm{TR}(f, r, exr)$.

3.2.2.2 Input data

Two data inputs are derived from the macro-level European model solution and passed as fixed constants to the sub-model:

- $\mathrm{ExogenousDemand}(y, l, f, exr)$ — the total amount of fuel f that Sweden must export to exogenous region exr in time slice l and year y.
- $\mathrm{ExogenousProduction}(y, l, f, exr)$ — the total amount of fuel f available for Sweden to import from exogenous region exr in time slice l and year y.

3.2.2.3 Decision variables

- $\mathrm{ExogenousExport}(y, l, f, r, exr)$ — export of fuel f from sub-model region r to exogenous region exr, defined only where $\mathrm{TR}(f, r, exr)$ exists, zero otherwise.
- $\mathrm{ExogenousImport}(y, l, f, r, exr)$ — import of fuel f to sub-model region r from exogenous region exr, defined only where $\mathrm{TR}(f, r, exr)$ exists, zero otherwise.

3.2.2.4 Coupling Constraints

The primary formulation, and what is used in the analysis, is a hard constraint formulation that enforces trade flows to match the macro-level solution exactly:

$$\begin{aligned}
\sum_{r:\mathrm{TR}(f,r,exr)} \mathrm{ExogenousExport}(y, l, f, r, exr) &= \mathrm{ExogenousDemand}(y, l, f, exr) \\
\sum_{r:\mathrm{TR}(f,r,exr)} \mathrm{ExogenousImport}(y, l, f, r, exr) &= \mathrm{ExogenousProduction}(y, l, f, exr)
\end{aligned} \tag{3.1}$$

for all y, l, f, exr, and only active when $ExogenousDemand > 0$ and $ExogenousProduction > 0$ respectively.

A secondary bounds formulation treats exports as a lower bound and imports as an upper bound, giving the sub-model freedom to find an internally optimal solution while remaining consistent with the broader European system:

$$\begin{aligned} \sum_{r:\mathrm{TR}(f,r,exr)} \mathrm{ExogenousExport}(y,l,f,r,exr) &\geq \mathrm{ExogenousDemand}(y,l,f,exr) \\ \sum_{r:\mathrm{TR}(f,r,exr)} \mathrm{ExogenousImport}(y,l,f,r,exr) &\leq \mathrm{ExogenousProduction}(y,l,f,exr) \end{aligned} \tag{3.2}$$

for all y, l, f, exr, and only active when $ExogenousDemand > 0$ and $ExogenousProduction > 0$ respectively.

In both formulations, the constraints are defined at the time slice level, requiring the macro-level model and sub-model to use the same temporal resolution. The distribution of trade flows across Swedish bidding zones is determined by the model itself, subject to the route constraints in *TR*.

3.2.3 Implementation

The vertical integration was implemented in two distinct ways within the GENeSYS-MOD framework, referred to here as the separate implementation and the tag implementation. The separate implementation, as the name suggests, handles the trade with exogenous regions within a separate system which is added to the overall GENeSYS-MOD framework. The idea of the tag implementation is to instead incorporate the exogenous regions among the existing sub-model regions to then exclude those regions from certain equations, see Figure 3.3 for a visualised comparison. Both are supported by a Python script that automates the extraction and formatting of data from the macro-level model and the sub-model making it ready for vertical integration. The separate implementation is the only currently working system, and is therefore used throughout the rest of the report. However, the tag implementation is retained here as a proposed alternative for future work.

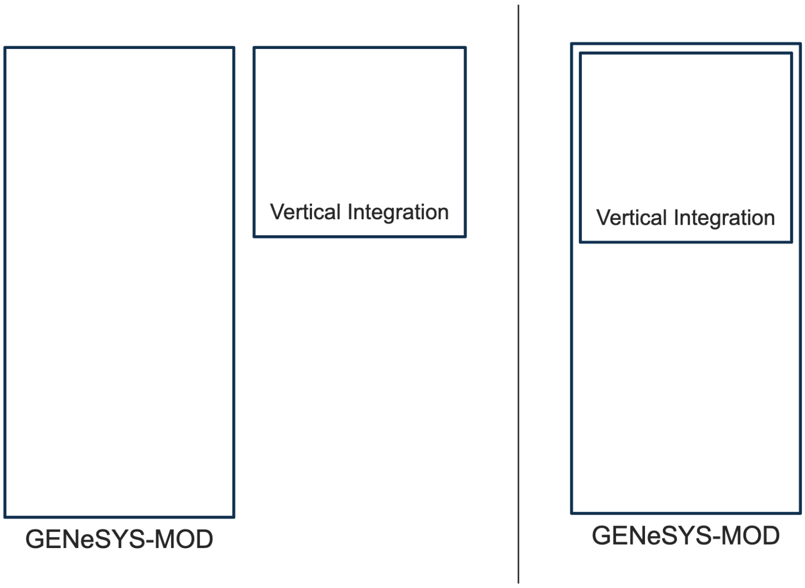

Figure 3.3: Visualisation of the two different implementations within GENeSYS-MOD. To the left is a representation of the separate implementation and to the right is the tag implementation.

3.2.3.1 Python script and data preparation

The script, available at GitHub (Rosenberg & Roslund, 2026b), utilises three specific input files in order to prepare an input file ready for vertical integration. Those are the input and output of the marco-level model and the input of the sub-model that is supposed to be vertically integrated. While the input files of the macro-level model and sub-model needs to be Excel, the output file of the macro-level model could be GDX, Excel or CSV format. The modeller specifies the region to vertically integrate, in this case Sweden, and the script handles the rest automatically, see Figure 3.4 showing a visualisation of the script.

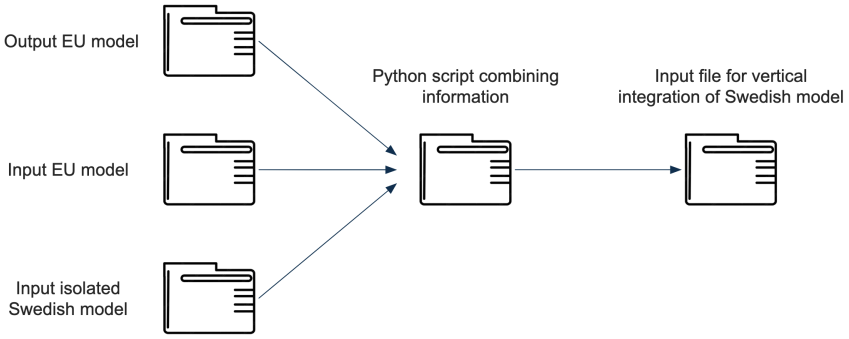

Figure 3.4: Visualisation of the Python script creating the input file for a vertically integrated model.

The script identifies which neighbouring regions the chosen region trades with in the macro-level model and extracts the corresponding import and export flows at time slice level, which becomes the *ExogenousDemand* and *ExogenousProduction* parameters. Trade capacity growth costs and growth rates for the relevant trade routes are also extracted from the macro-level input file and transferred to the sub-model. The exogenous regions identified during this process are added to the relevant sets and parameters in the sub-model input file.

Three parameters cannot be inferred automatically and must be filled in by the modeller: the trade routes between sub-model regions and exogenous regions (*ExogenousTradeRoute*), typically represented by the distance between the centroids of the regions, the residual trade capacity for those routes (*ResidualExogenousTradeCapacity*), and any already commissioned trade capacity (*CommissionedExogenousTradeCapacity*). These reflect geographical and infrastructural constraints that require domain knowledge to specify.

3.2.3.2 Implementation 1 – Separate system

In the separate implementation, exogenous regions are kept entirely separated from the regular model regions. The script creates a dedicated set of exogenous regions in the sub-model input file, and all trade-related parameters for these regions are stored in separate, newly created parameter sheets rather than being merged into the existing model parameters. The additional parameters created for this implementation are: *Par_ExoTradeCapacityGrowthCosts*, *Par_GrowthRateExoTradeCapacity*, *Par_ExogenousTradeRoute*, *Par_ResidualExoTradeCapacity* and *Par_CommissionedExoTradeCap*. For simplicity, a single trade capacity value is used per route, meaning import and export capacities are not distinguished, as building capacity in one direction automatically provides capacity in the other. In GAMS, a parallel trade system is constructed by reproducing the relevant trade equations specifically for the exogenous regions, with the coupling constraints applied on top. The core GENeSYS-MOD code is only modified to a very limited extent, making this implementation modular and transparent.

3.2.3.3 Implementation 2 – Tag system

The tag implementation takes a more integrated approach. Rather than maintaining a separate set, the exogenous regions are added directly into the existing region sets alongside the standard sub-model regions. Trade capacity parameters are merged into the existing parameter sheets rather than stored separately. To distinguish exogenous regions from fully modelled ones, a tag parameter (*Par_TagExogenousRegion*) is introduced with a value of 1 for each exogenous region. In GAMS, the existing equations are modified to include or exclude exogenous regions based on this tag, and the coupling constraints are added as new equations. This results in a more deeply integrated implementation that avoids duplicating model equations. However, this implementation is not currently functional. Due to the deeper integration with existing model equations, identifying the source of issues is more difficult, and insufficient time has been available to resolve them.

3.3 Model Setup

The following describes the configuration applied to both the isolated and vertically integrated model runs. Unless stated otherwise, parameters and assumptions are taken from the NECP Essentials scenario of the European GENeSYS-MOD dataset (Barani et al., 2026; Löffler, Moskalenko, et al., 2026).

3.3.1 Scenario

The NECP Essentials scenario is a predefined scenario within the GENeSYS-MOD framework, representing a pathway consistent with the national energy and climate plans (NECPs) submitted by European member states to the European Commission. It serves as the baseline scenario for both the macro-level European model run and the Swedish sub-model runs, ensuring consistency between the two levels of the vertical integration.

3.3.2 Temporal configuration

The model runs from a base year of 2018 through to 2060, covering the modelling years 2018, 2025, 2030, 2035, 2040, 2045, 2050, 2055, and 2060. Within each year, the model operates at a time slice of every 244th hour, representing seasonal variations. As the vertical integration constraints are applied at the time slice level, the macro-level and sub-model runs use identical temporal resolution.

3.3.3 Emission constraints

A carbon dioxide emission limit is applied across the full model period. The total European emission budget is taken from the NECP Essentials scenario (Barani et al., 2026), with Sweden's share allocated based on population, giving a limit of 739.1301 Mt CO_2, corresponding to 1.62% of the total European budget.

3.3.4 Discount rate and objective

This study used a social discount rate (r) of 5% applied to all technologies and modelling regions. The optimisation objective is to minimise total discounted system cost over the modelling period. The chosen discount rate is normally used for GENeSYS-MOD as the model aims to analyse and forecast a possible system trajectory on a grander societal level and with lower demand for immediate returns in time, justifying a lower discount rate.

3.3.5 Trade configuration

Trade between the Swedish bidding zones is optimised freely by the model subject to capacity constraints. In the vertically integrated runs, trade between the Swedish bidding zones and neighbouring countries is additionally constrained by the coupling constraints described in Section 3.2.2, derived from the macro-level European model solution.

3.3.6 Model limitations

GENeSYS-MOD, like all energy system models, simplifies reality through a set of structural assumptions. It optimises for cost under perfect foresight, treating future costs and constraints as fixed across the entire time horizon; it assumes price-inelastic energy demand; and it operates within a bounded set of technologies and regional definitions. These abstractions mean the model's outputs are not predictive forecasts, but rather internally consistent scenarios for evaluating how technologies and trade configurations interact under specified conditions. In this study, the results are used to explore plausible developmental pathways for Sweden's bidding zones, specifically highlighting how outcomes differ between an isolated and a vertically integrated model configuration.

4

Results

This section presents the results from the two different models, an isolated Swedish model and a vertically integrated one, comparing how the inclusion of cross-border trade affects the optimal energy system configuration. The results are structured around different key insights such as trade, power, hydrogen, heat, transport and emissions. The focus lies in the difference between the two models rather than the accuracy of the results in absolute terms. The complete results from the two Swedish models can be found in the Zenodo repository Rosenberg and Roslund (2026a). From here on, the vertically integrated model will be referred to as the ”integrated” model.

The most immediate difference between the two models is the total system cost. The objective value of the isolated model is EUR 817 820, compared to EUR 797 940 for the integrated model, indicating a more cost-efficient system when cross-border trade is included. A broader picture of how the two models differ in energy production and utilisation is shown in Figure 4.1, with the integrated model showing notably increased production of power and hydrogen as well as greater use of power, biomass and natural gas. The following sections investigate what drives these differences.

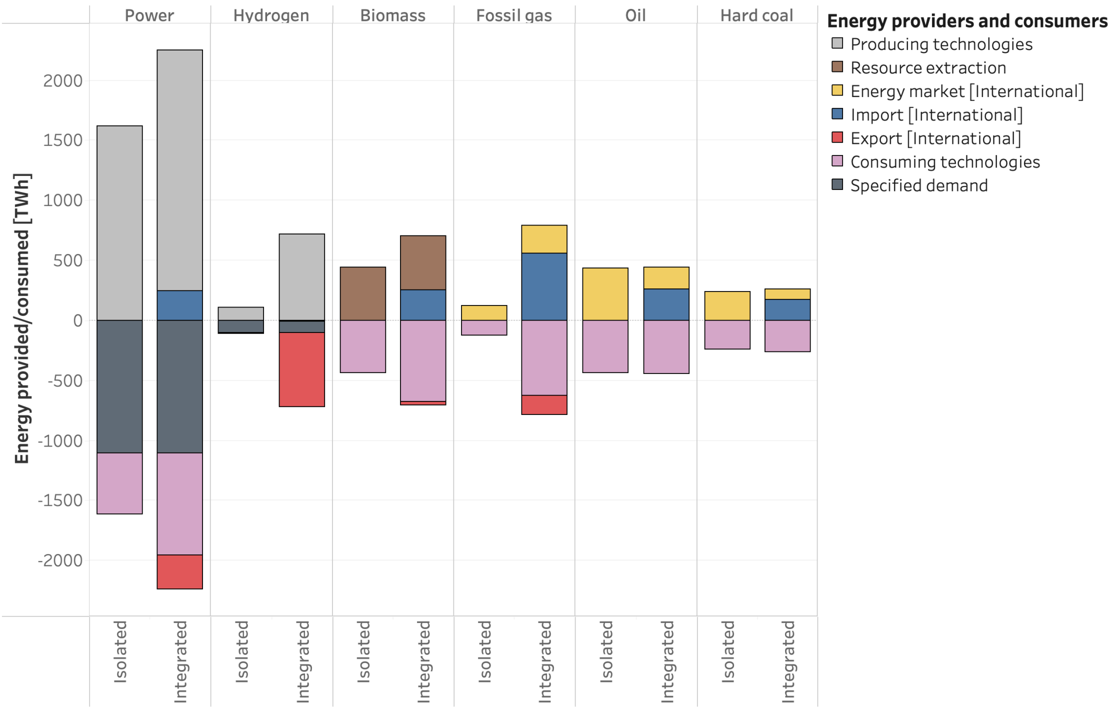

Figure 4.1: Distribution of energy carriers provided and used in Sweden summarised over all model years, comparing the isolated and the integrated models. Positive values represents production of energy carriers by resource extraction, technology activity or imports, either from the global energy market or neighbouring countries. Negative values represent utilisation of energy carriers through either export, technologies or specified demand given as model input. Imports from the ”global energy market” refers to imports from the specific Z_Import technologies as described in Section 2.5.1.2.

4.1 Trade

This section presents the results regarding trade, first highlighting the international trade between Swedish regions and neighbouring countries, which is only applicable for the integrated model. The results presented here are based on hard constraints, see Section 3.2.2. A parallel run with soft constraints yielded near-identical results, with natural gas imports differing by less than 1% and no changes in exports, and is therefore not discussed further here. Later we present the domestic trade within Sweden and compare the different model outputs.

4.1.1 International trade

When investigating the trade between Swedish regions and the neighbouring countries there are a few things which stand out. Studying Figure 4.2 it is evident that hydrogen becomes the most important export commodity in the energy system. SE3 and SE1 together exports 616.83 TWh of hydrogen over the whole model period to Finland, with SE3 accounting for about three quarters of the export. Sweden is also a net exporter of power, although only 35.33 TWh more power is exported than imported, with most of the export being done by SE1 and SE4.

Overall Sweden imports more energy than what it exports. Most prominent is the import of natural gas, observed across all regions with most being imported to SE3 and SE4. Then we also see an import of oil, hard coal and biomass.

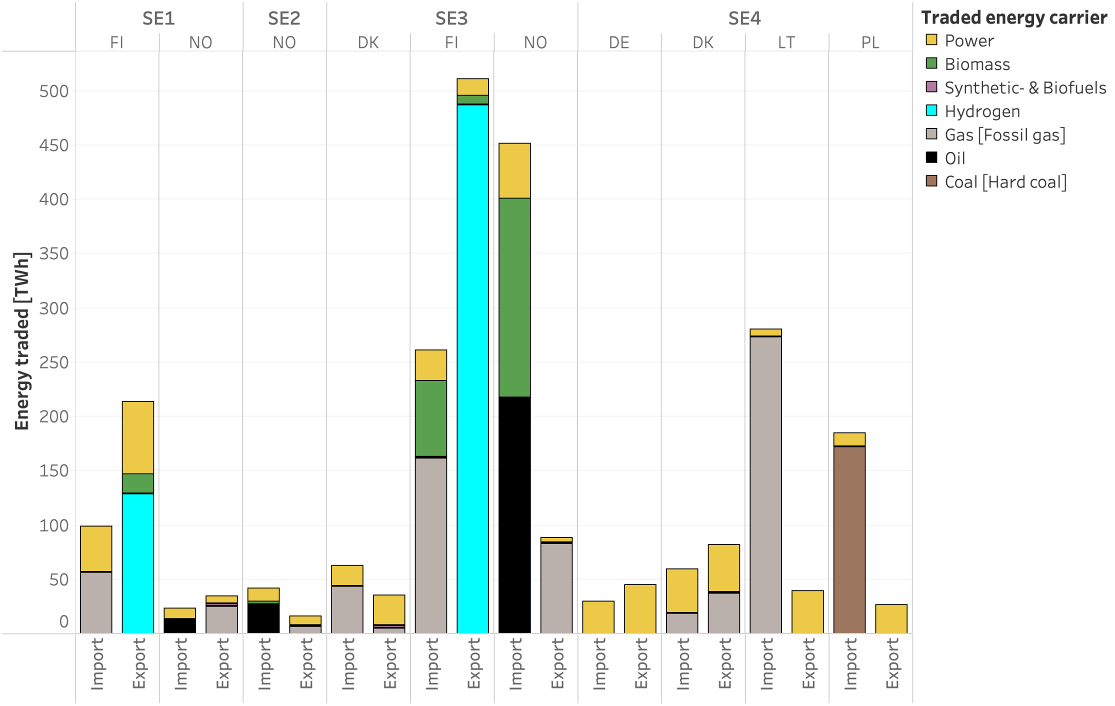

Figure 4.2: Trade between Swedish regions and neighbouring countries in the integrated model. Presented as amount of import/export in TWh of different fuels for all trade routes, summarised over all model years.

As the trade of power and gas is limited by the trade capacity (transmission lines and pipelines) the model had to invest in trade capacities in order to fulfil the exogenous trade constraints. Table 4.1 presents the total trade capacities built in the integrated model between the Swedish bidding zones and neighbouring countries. The largest investments were in hydrogen trade capacity between Sweden and Finland and natural gas trade capacity between multiple regions and countries.

Table 4.1: Total trade capacities in GW built to neighbouring countries in the vertically integrated model.

Region	Fuel	Value [GW]
SE1 - FI	H2	6.8754
SE1 - FI	Natural gas	2.2225
SE1 - FI	Power	1.3954
SE1 - NO	H2	0.0627
SE1 - NO	Natural gas	0.7517
SE2 - NO	H2	0.0385
SE2 - NO	Natural gas	0.5564
SE3 - DK	Natural gas	2.6852
SE3 - DK	Power	0.1190
SE3 - FI	H2	21.1840
SE3 - FI	Natural gas	4.6838
SE3 - NO	H2	0.0324
SE3 - NO	Natural gas	5.7320
SE4 - DE	Natural gas	0.0002
SE4 - DE	Power	0.7710
SE4 - DK	Natural gas	1.1418
SE4 - DK	Power	0.0261
SE4 - LT	Natural gas	5.6223
SE4 - LT	Power	0.0112
SE4 - PL	Natural gas	0.0001
SE4 - PL	Power	0.0584

4.1.2 Domestic trade

In the integrated model we see an overall increase in trade between Swedish regions compared to the isolated model. As seen in Figure 4.3, SE1 and SE2 are primarily exporters in both models while SE3 is primarily an importer. SE4 on the other hand imports more than it exports in the isolated model, while becoming a net exporter in the integrated model. Being the southernmost region and connected to several neighbouring countries, SE4 imports fuels from abroad and exports them northward into SE3, which serves as the main hub for hydrogen export to Finland. The greatest difference in domestic trading patterns lies in the greater flow of natural gas and hydrogen into SE3 in the integrated model, arriving from all other regions. In addition, SE3 exports more power to SE4 in the integrated model.

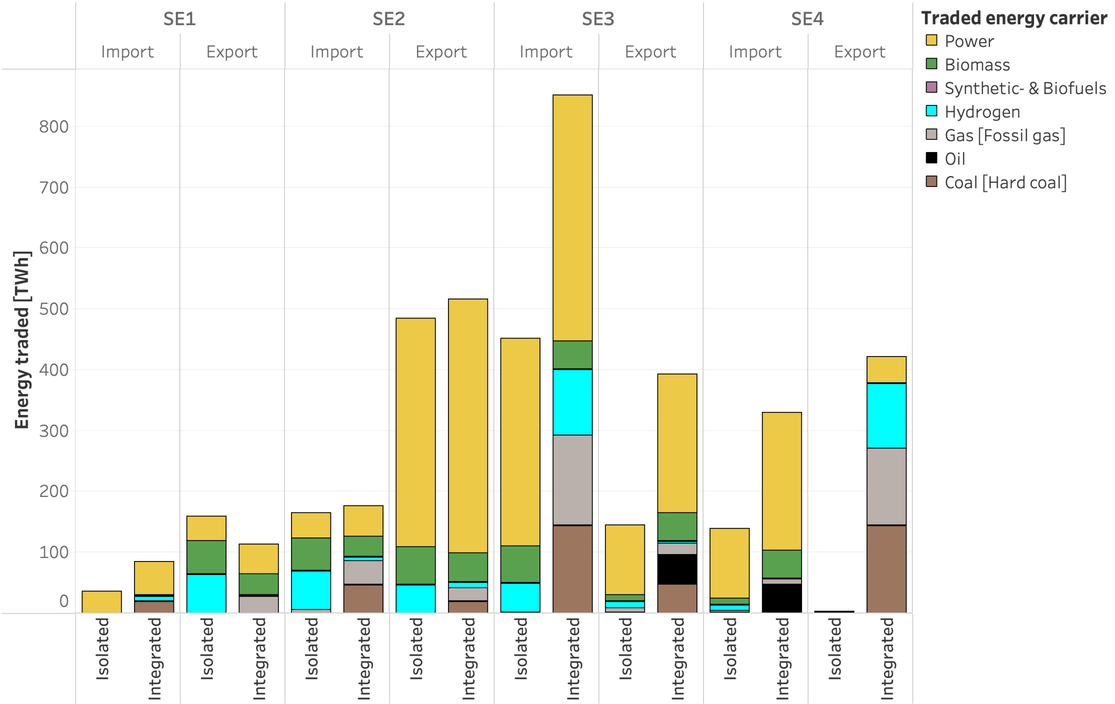

Figure 4.3: Comparison between the models of total domestic trade in Sweden. Presented as total amount of import/export in TWh of different fuels in each region, summarised over all model years.

The domestic trade of power and gases also requires the existence of trade capacities. In Table 4.2 we can see that the same trade capacity expansion occurs in both models for power lines. However, there is a clear difference between the capacities built for gas, both natural gas and hydrogen. The integrated model builds a larger natural gas network with especially a lot of capacity from SE1 to SE2 and SE2 to SE3. We also find a greater trade capacity for hydrogen from SE4 to SE3, though it is noticeably lower from SE2 to SE3 compared to the isolated model.

Table 4.2: Total trade capacities in GW built between Swedish bidding zones.

Trade route	Fuel	Isolated model [GW]	Integrated model [GW]
SE1 - SE2	H2	6.7542	6.7542
SE1 - SE2	Natural gas	0.1184	2.8536
SE1 - SE2	Power	0.7	0.7
SE2 - SE1	H2	6.7542	6.8355
SE2 - SE1	Natural gas	0.0001	0.3059
SE2 - SE1	Power	4.2	4.2
SE2 - SE3	H2	1.1583	-
SE2 - SE3	Natural gas	0.1413	4.1002

Continued on the next page...

Table 4.2: Total domestic trade capacities built (continued)

Region	Fuel	Value [GW]	
SE2 - SE3	Power	2.9	2.9
SE3 - SE2	H2	0.0872	0.2506
SE3 - SE2	Natural gas	1.5532	0.9688
SE3 - SE2	Power	-	-
SE3 - SE4	H2	0.2682	-
SE3 - SE4	Natural gas	-	-
SE3 - SE4	Power	0.8	0.8
SE4 - SE3	H2	-	2.9977
SE4 - SE3	Natural gas	-	1.4739
SE4 - SE3	Power	1.6	1.6

4.2 Power

Here we present the results regarding power in terms of generating technologies and electrification of sectors.

4.2.1 Power generation

When comparing the power production and consumption across the years we can in Figure 4.4 see that both generation and utilisation increases up to 2040 and then stabilises in both models. However, more power is both generated and used in the integrated model in all modelled years. The integrated model shows primarily more power generation from onshore wind, photovoltaics (PV) and thermal plants fuelled with biomass. Meanwhile, the greater use of power is due to more electrolysis activity in the integrated model.

Neither system seems dependent on fossil fuels even though the integrated model consumes slightly more natural gas. While the isolated model is free from natural gas after 2035, the integrated model keeps a small amount of natural gas use up until 2055, although not more than 3.183 TWh per year.

The nuclear activity varies greatly across the years. The sudden drop in nuclear power generation happens in 2030, which is when the existing power plants are expected to be decommissioned. Although both models rebuild their nuclear capacity, the integrated model seems to utilise the technology slightly more with a faster build-out.

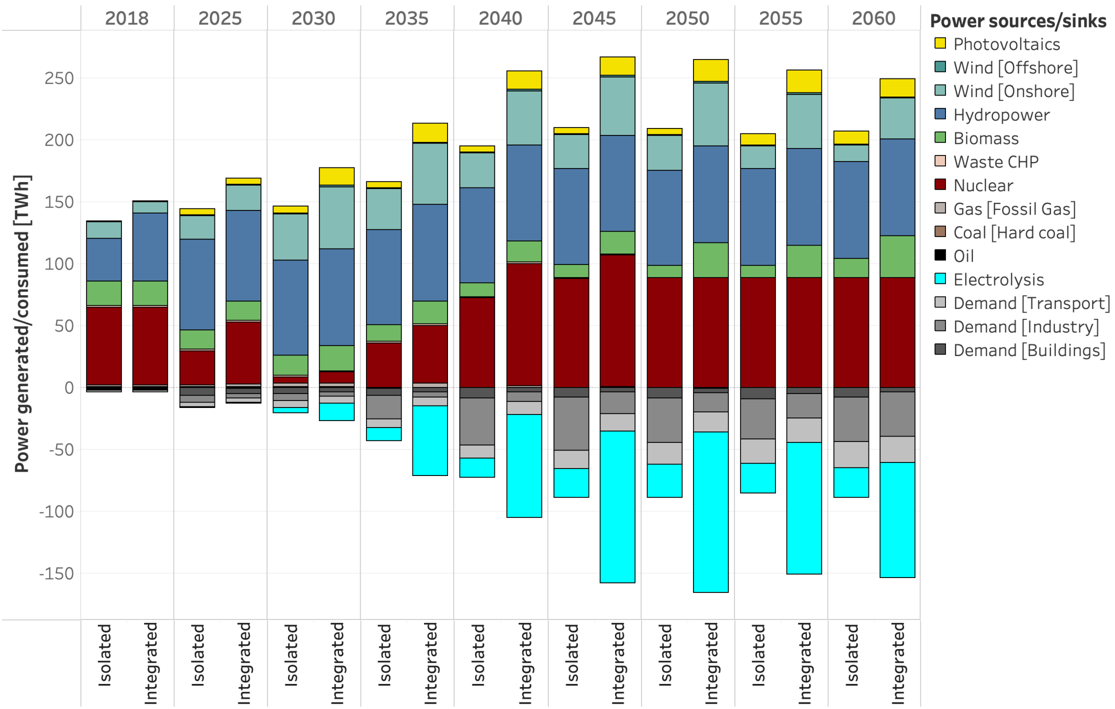

Figure 4.4: Power generation and utilisation, comparing the isolated and the integrated models. Presented as TWh power generated/utilised by different technologies across all modelled years. Values above zero represent power generation while values below zero represent power use.

If we further investigate the difference between the models we find that the greatest difference is found in SE3, see Figure 4.5. In SE1 we see both more nuclear power generation and electrolysis activity in the integrated model, similar to the greater use of onshore wind and electrolysis in SE4. Meanwhile the energy mix barely differs for SE2. In SE3 we see an in general higher generation of renewable and nuclear power in the integrated model, as well as much higher electrolysis activity.

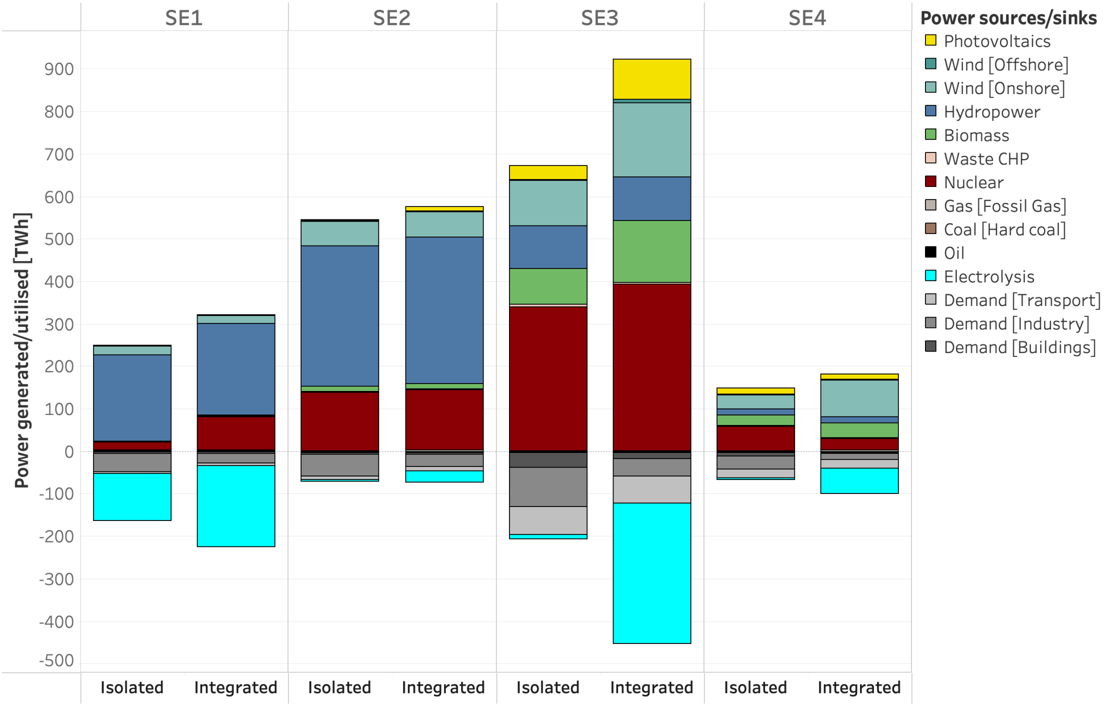

Figure 4.5: Power generation and utilisation, comparing the isolated and the integrated models. Presented as TWh power generated/utilised by different technologies in different regions, summarised across all modelled years. Values above zero represent power generation while values below zero represent power use.

4.2.2 Electrification of sectors

The vertical integration also had an effect on the electrification of the Swedish system. Most noticeable is the difference in industrial electrification rates, as seen in Figure 4.6. In the isolated model industry reaches over 50% electrification in 2040 and 65% in 2045. Meanwhile in the integrated model the industry is still less than 50% in 2055, only to reach 57% in 2060. A similar pattern is found for district heating which also electrifies slower in the integrated model. However, for district heating the difference grows between the models across the years and it never reaches 25% in the integrated model, while the isolated model has an electrification rate of 50% at its peak in 2055. The transport and building sector shows little to no difference between the models.

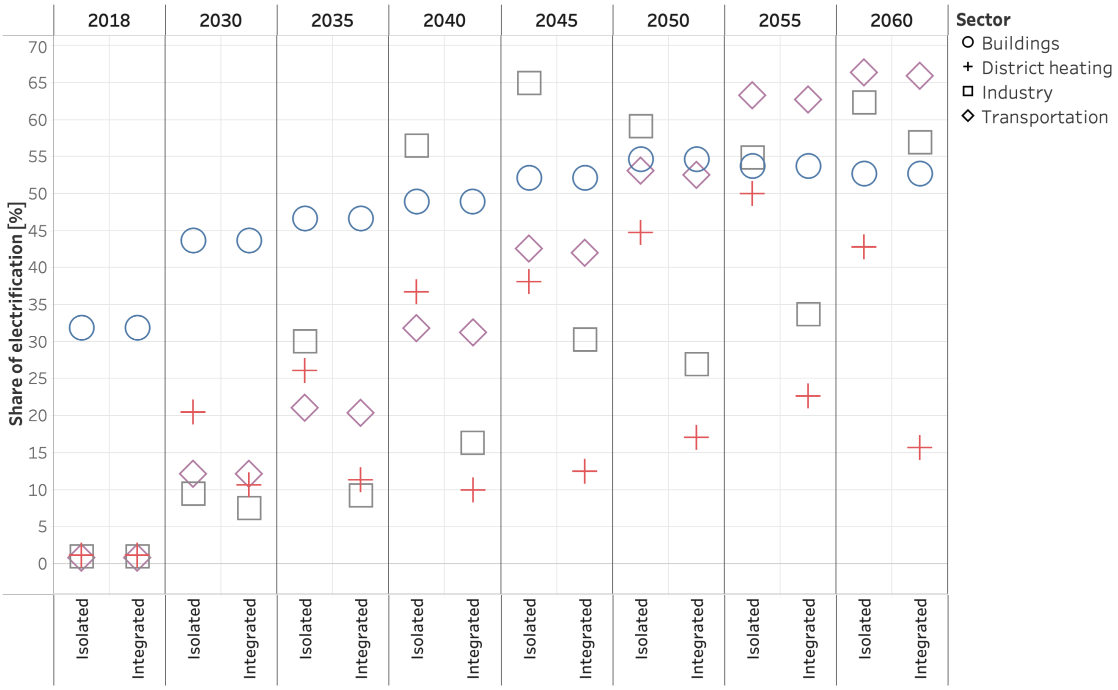

Figure 4.6: Electrification rate shown for each modelled sector across the years, comparing the isolated and the integrated models. Values represent the percentage of total energy use met by electricity for each sector.

4.3 Hydrogen

As already described in Section 4.2.1, we could see that more power was used to produce hydrogen in the integrated model compared to the isolated model. In Figure 4.7, this difference becomes even more apparent. In the isolated model the annual production of hydrogen reaches at most 21.2 TWh in 2050, while for the integrated model it is 148.7 TWh in the same year, and reaches 163.9 TWh in 2060. In the isolated model this production stems almost solely from electrolysis from 2035 and onwards, while in the integrated model we instead see a steady increase in the usage of natural gas. The gas reforming used however is a mix of Steam-Methane Reforming (SMR) and Autothermal Reforming (ATR) combined with Carbon Capture and Storage (CCS), with ATR with CCS becoming the dominant method beyond 2045. From 2035 electrolysis is the primary production method in the integrated model as well, but in 2060 gas reformation is the dominant method once again. Another difference between the models is the greater prevalence of hydrogen storage in the integrated model, reaching its highest level in 2060 with about 18 TWh stored as well as discharged from storage, ten times that of the isolated model.

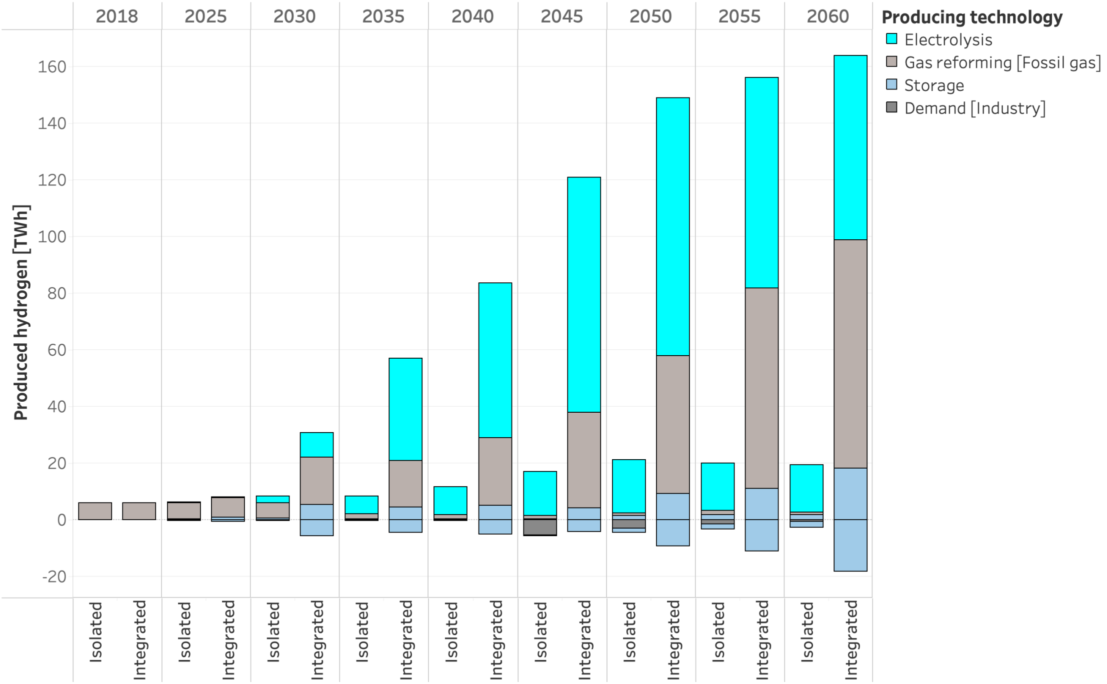

Figure 4.7: Hydrogen production and utilisation across years, comparing the isolated and integrated models. Presented in total amount of TWh hydrogen produced or utilised. Produced hydrogen and storage discharge are shown as positive values, while utilisation and storage intake are shown as negative values.

The distribution of hydrogen production within Sweden also changes between the models, as can be seen in Figure 4.8. In the isolated model the production is concentrated to SE1, with very little production in any other region, especially SE2 and SE4. Meanwhile in the integrated model the production is distributed between multiple regions, with a majority being produced in SE3. However, there is barely any change in the use of hydrogen between the two models, both using only small amounts within industry.

The production method also varies between the regions, with almost only electrolysis being used in SE1 and SE2, while being more evenly split between gas reforming and electrolysis in SE3 and gas reforming being dominant in SE4. In addition, hydrogen storage is concentrated in SE3 and SE4, with negligible storage activity in the other regions.

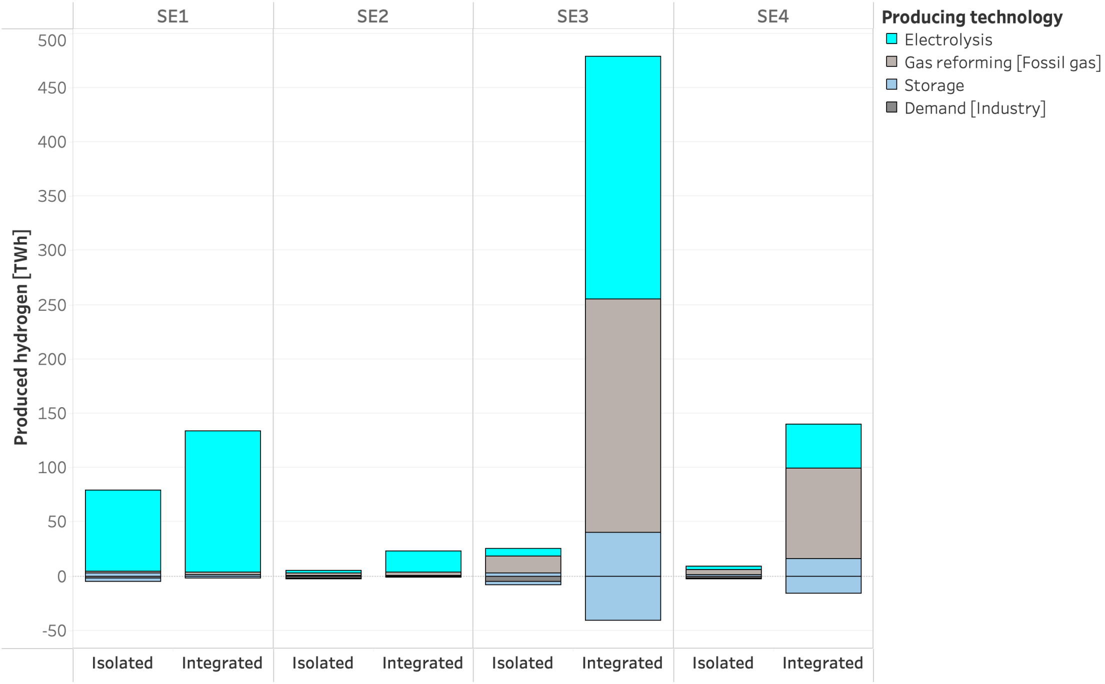

Figure 4.8: Hydrogen production and utilisation across regions, comparing the isolated and integrated models. Presented as the total amount of TWh produced or utilised, summarised over all model years. Produced hydrogen and storage discharge are shown as positive values, while utilisation and storage intake are shown as negative values.

4.4 Heat

This section begins with industrial heat, followed by building heating and district heating.

4.4.1 Industry

As heat is not treated as a tradeable fuel by the model there was no change in the utilisation of heat between the models. However, the technology used for heat generation changed, as seen in Figure 4.9, where the integrated model generates more heat from burning fossil fuels, it especially shows an elevated use of fossil gas. In the isolated model heat from direct electricity becomes the dominant industrial heat source from 2040 and onwards, while this happens first in 2060 in the integrated model. In the isolated model we also find some hydrogen being used for heat, while none is used in the integrated model.

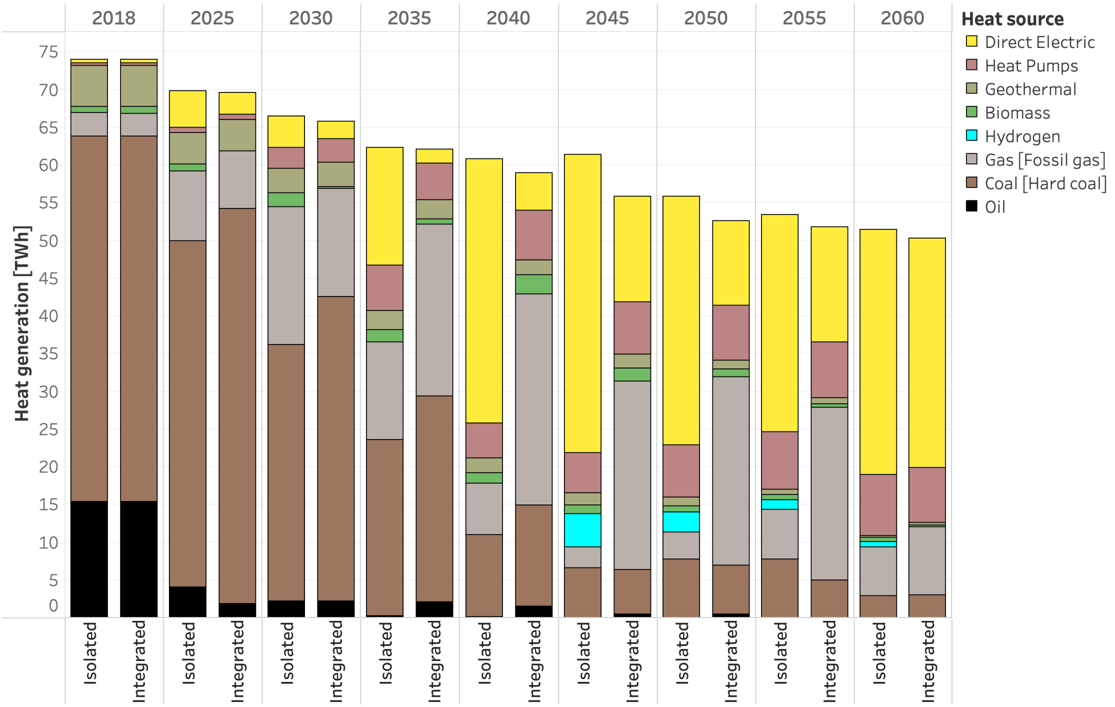

Figure 4.9: Total industrial heat production in TWh by different sources across the years. Comparing the isolated and the integrated models. All temperature levels of industrial heat are included.

4.4.2 Space heating

The same pattern cannot be found for heating of buildings. Figure 4.10 shows that the vertical integration has little to no effect on the source of space heating, with the majority of heat stemming from electric heat-pumps or district heating.

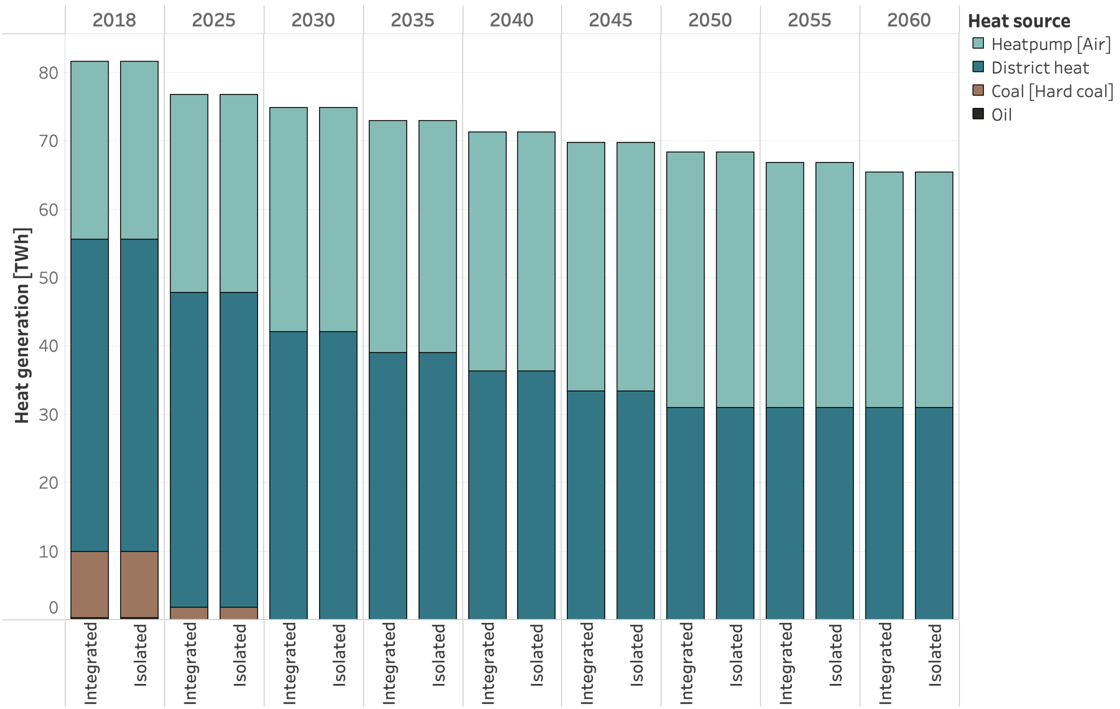

Figure 4.10: Production of heat for buildings in TWh by different sources across the years. Comparing the isolated and integrated models.

4.4.3 District heating

In both models district heat production is dominated by CHP plants fuelled with biomass, with a similar phase out of fossil fuels and waste incineration. In the isolated model more heat is generated from direct electricity and aerial heat pumps, while the integrated model utilises more biomass fired CHP instead.

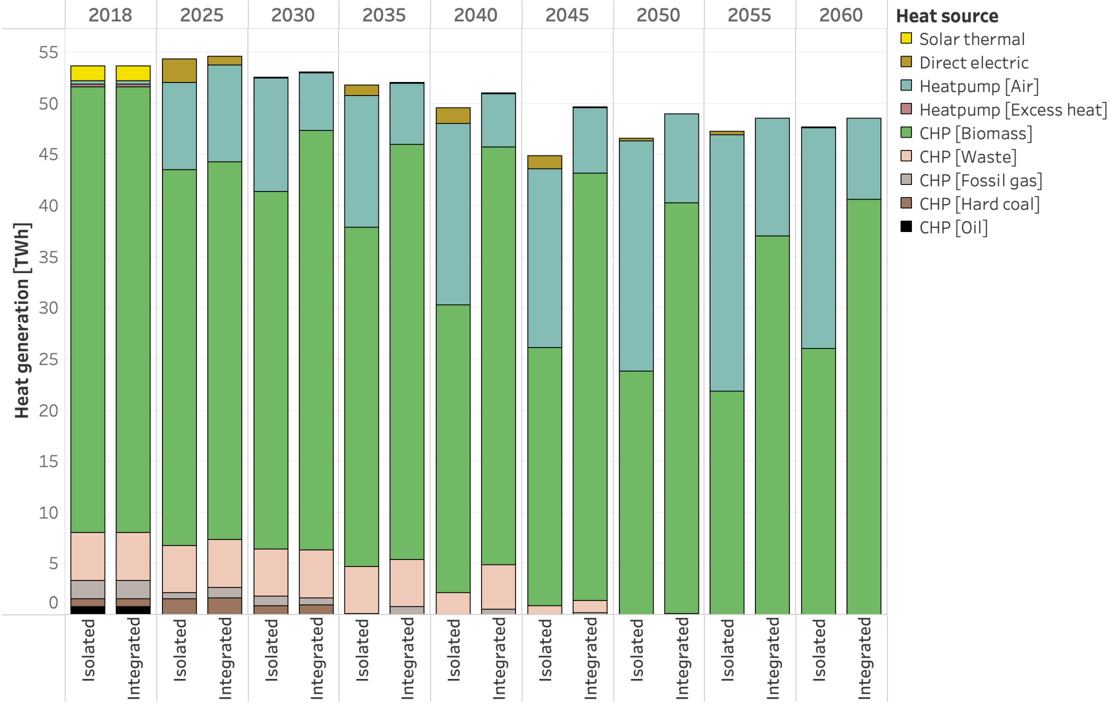

Figure 4.11: District heat production by source across the model years. Comparing the integrated and isolated models.

4.5 Transport

As transport is not traded between regions in GENeSYS-MOD, total mobility production is the same in both models, though differences emerge in the modality and fuel mix used. First, we look at the changes in freight transport and then continue on to passenger transport.

4.5.1 Freight transport

For freight transport we can, in Figure 4.12, see that the distribution between rail, road and ship transport is remains largely the same between the models, with road being the dominant mode of transport. The phase out of conventional propulsion fuels is quite similar between the models with the deployment of battery electric vehicles happening slightly faster in the isolated model.

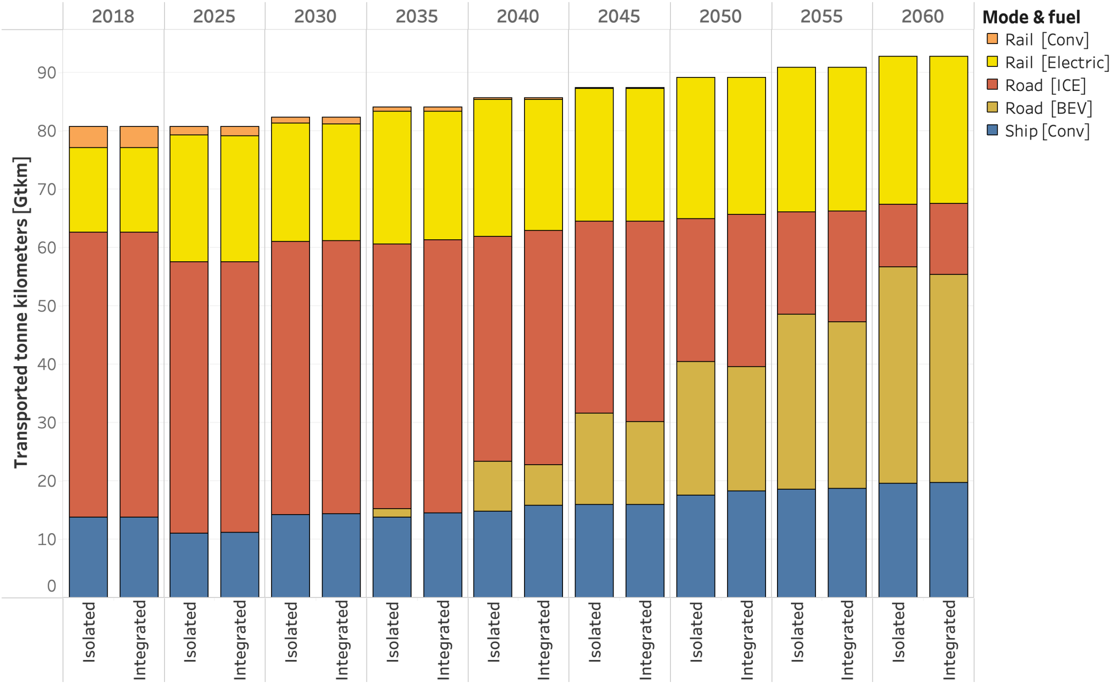

Figure 4.12: Freight transport. Amount of billion tonne-kilometres provided by different modes of transport using different fuels across the years. Comparing the isolated and integrated models.

4.5.2 Passenger transport

Looking at passenger transport in Figure 4.13, there is little change in the distribution between road, rail and air between the models. The most noticeable difference is the higher use of plug-in hybrid electric vehicles in the isolated model between 2040 and 2050, along with a brief introduction of biofuel cars in 2040 that does not persist in subsequent years. This reflects a slightly faster phase-out of conventional road vehicles in the isolated model.

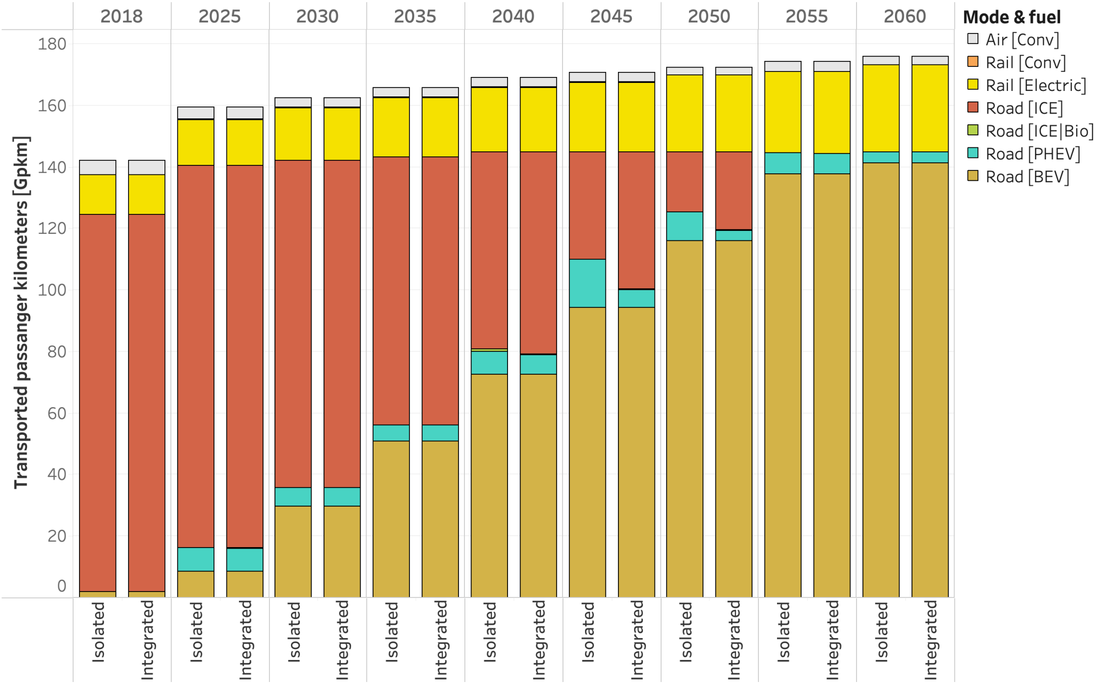

Figure 4.13: Passenger transport. Amount of billion passenger-kilometres provided by different modes of transport using different fuels across the years. Comparing the isolated and integrated models.

4.6 Emissions

The total net emissions are almost identical between the models, with the isolated model producing 2.742 Mt CO_2 more than the integrated model. As seen in Figure 4.14, the overall distribution is quite similar between the two. However, the integrated model shows higher gross emissions, particularly from industry, transformation and the use of natural gas. This is compensated by greater use of CHP plants combined with bioenergy with carbon capture and storage (BECCS), which generates significant negative emissions, ultimately resulting in the integrated model having slightly lower net emissions despite its higher gross emissions.

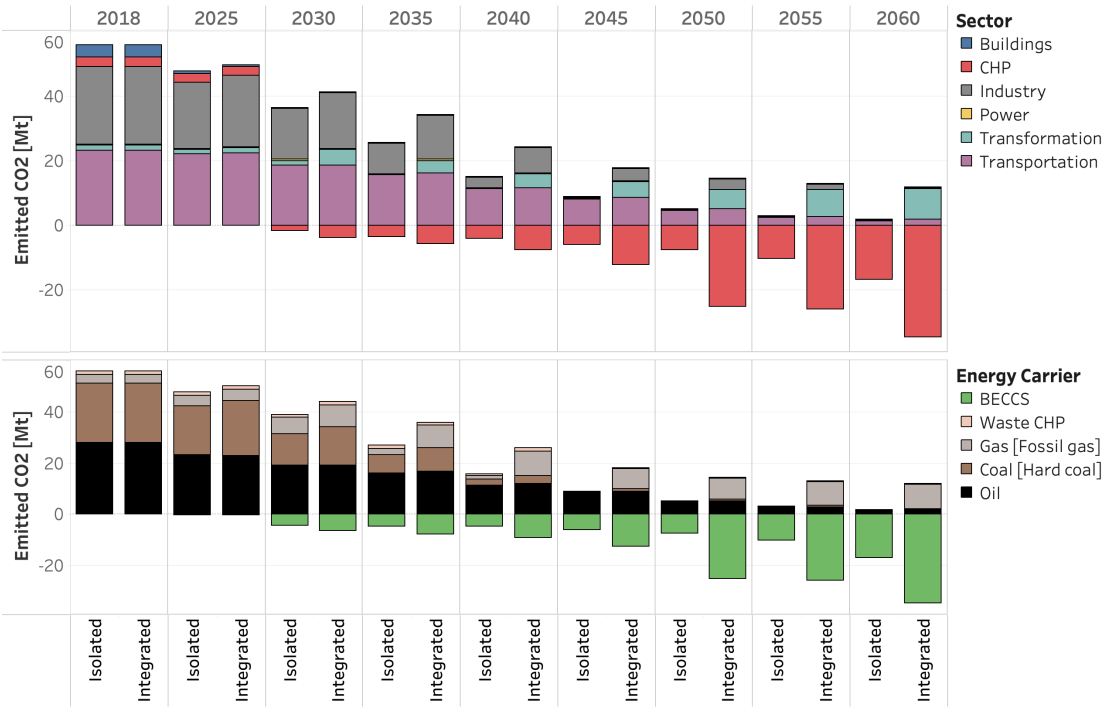

Figure 4.14: Emissions by sector and energy carrier compared between the isolated (left) and the integrated model (right). Upper graph shows the emissions from each sector across the years. Lower graph shows the emissions associated with different energy carriers.

5

Discussion and conclusion

This chapter reflects on the development and outcomes of a vertically integrated ESOM, examining both how cross-border trade can be implemented in national energy models and what effect it has on the resulting system configuration. The discussion begins with methodological reflections on the implementation process, the dataset, and their respective limitations. This is followed by an analysis of how incorporating European trade flows reshapes the Swedish energy system, drawing on the results presented in the previous chapter. The chapter closes with suggestions for future research.

5.1 Methodological reflections

In this project two methods for implementing vertical integration were investigated, though only one yielded usable results. The successful method was the so called separate implementation highlighted in Section 3.2.3, treating the exogenous regions as a separate set, with separate trading equations. The benefit of this solution lies in its simplicity. The framework of GENeSYS-MOD was not significantly altered and the exogenous trade costs were added as an additional cost to the objective value. The imports were treated as a new potential source of fuel and the exports as additional demand. Adding new sets of equations used only for the exogenous trade made the implementation and debugging process simple as the potential errors in development could be narrowed to a separate set of equations. The drawback of this solution is that the exogenous trade becomes less integrated in the general model structure. In future updates of the model regarding trade, or if you are adding more information to the vertical integration, it will have to be done in multiple parts of the framework in order for the exogenous regions to follow the same rules as that of the endogenous regions in the model. The current implementation also includes some additional simplifications which a more integrated implementation possibly could avoid.

For simplicity the exogenous trade capacities are only given once for each combination of endogenous and exogenous region with one possible trade route. That means that the import and export capacities are treated as one and the same, while in reality these may be different. This affects the costs of building trade capacity as building trade capacity for one direction automatically leads to capacity also being built in the other direction as well. If export and import capacities would have been treated differently the model could potentially have found increasing the exogenous trade capacity too costly, resulting in another distribution of trade.

The limitations of treating the exogenous trade in a separate set of equations was recognised early in the project, motivating the attempt at a more integrated tag-based implementation. This approach would have allowed the same equations to be used for both endogenous and exogenous trade, with exogenous regions treated like any other region for trade purposes while being excluded from other equations. In theory this should produce results equivalent to the separate implementation, aside from differences arising from the simplifications made in the latter, while also potentially capturing dependencies between exogenous trade and other model equations that the separate implementation may overlook by design. However, the deeper integration made debugging significantly harder, as any error could stem from incorrectly including or excluding exogenous regions across the full set of model equations. Due to time constraints this could not be fully resolved within the scope of this thesis.

Changing the strictness of the constraints for exogenous import and export had very limited effect on the system. As export was set as a lower bound, the model was still enforced to export the required amounts, leading to no change in outcome. The model was allowed to import less under soft constraints, as import was set as an upper bound, yet this only led to marginally lower imports. This implies that the import volumes set by the European model are close to optimal for the more detailed Swedish model, given the national and international demands on the system. It is also worth noting that the model did not choose to export more than required, despite the potential to invest in cheap wind power while offloading surplus generation through excess export. This behaviour is intuitive, as the model has no broader economic incentive to export beyond what is required, and imports are generally cheaper than domestic capacity investment, meaning the model will naturally import as much as permitted. It is therefore expected that the export lower bound is non-binding while the import upper bound is actively constraining, and this asymmetry should be kept in mind when using European model outputs as boundary conditions for national modelling.

A related question is whether a dataset compiled for an isolated model can be reliably used in an integrated setting. A vertically integrated model places additional demands on the system, and it would not be unreasonable for base year production to be unable to meet both national and international demands simultaneously. In this study the dataset proved compatible in both configurations, but this cannot be assumed in general and warrants further investigation to establish a standard approach for dataset construction across modelling levels.

The construction of natural gas pipeline capacity warrants particular attention. Currently, Sweden's gas pipeline network is limited, connecting primarily Denmark to SE4 and SE4 to SE3. Both models extend this network, but the integrated model builds more than five times the pipeline capacity of the isolated model, driven by the availability of cheap imported natural gas from international trade. For a country with little history of large-scale pipeline infrastructure, such extensive investment, spanning several hundred kilometres from south to north, may seem unrealistic.

This highlights a broader limitation of applying macro-level trade patterns as boundary conditions for a sub-model. A macro-level model operating at lower spatial resolution may find it reasonable to route energy between countries, without accounting for where the consuming technologies are actually located within those countries. In the Swedish case, heavy industry relying on imported gas may be concentrated in the north, while the gas enters through southern trade routes, requiring costly internal transmission that the macro-level model does not capture. This mismatch in spatial resolution can therefore lead the sub-model to make infrastructure investments that appear unrealistic, or incur costs that are not reflected in the macro-level results. It should also be noted that the pipeline costs captured in the model likely underestimate the true infrastructure investment required, as the model only builds capacity between regional connection points without accounting for the internal distribution network needed to deliver gas to consuming technologies within each region. Depending on where demand is concentrated, the real pipeline network required could be substantially longer and more costly than what the model reflects, further reinforcing the concern that the integrated model's gas infrastructure investments may be both unrealistic in scale and incomplete in cost representation. Related to this, the build-out capacity of gas pipelines may need to be adjusted when modelling smaller regions. The current framework allows extensive expansion of gas networks, which may be justified at the European level but could be unreasonably large when applied to sub-regional models.

As of now, only import and export flows between regions in the European model, along with the related capacities and costs, are transferred into the Swedish model. Although trade might be the most important factor to transfer, other results from the European model could also be used to constrain the sub-model. One example is emissions. Currently the emission limit for Sweden is calculated exogenously and provided by the model user, but the Swedish emissions from the European model results could instead be extracted and used as the upper limit for the Swedish model. In this case it would have made little difference, as the Swedish model kept its emissions far below the set limit and the constraint was therefore non-binding. Nonetheless, for other national systems or model configurations where emissions are more tightly constrained, this could be a meaningful addition.

Another factor worth transferring is the use of the global energy market in the macro-level model. In the European model, Sweden accesses certain fuels such as oil and gas through global import technologies, and the same is true for the bidding zones in the Swedish model. However, even with access to natural gas through exogenous trade, the regions in the integrated model continued purchasing additional gas from the global energy market, suggesting that some energy imports may not be fully captured by the vertical integration as currently implemented. It could therefore be of interest to limit how much Sweden can purchase from the global energy market in the sub-model, constraining it to the import volumes used in the European model, in order to achieve a more consistent representation across the two modelling levels.

The implementation of vertical integration in this study only transfers information from a higher spatial level to a lower one. The sub-model is constrained by macro-level conditions, but the macro-level model is not informed by sub-model results, meaning that locally specific dynamics captured in the sub-model have no influence on the broader European system. An iterative process, where the sub-model feeds back into the macro-level model and vice versa, could address this and provide a more complete representation of how national and European energy systems interact. However, such an approach would be considerably more complex and would raise the question of whether multiple national sub-models would need to be developed in parallel to ensure a balanced representation, which would ultimately approach the computational and conceptual challenges of building one fully integrated large-scale model.

The implementation is currently built around the GENeSYS-MOD framework, meaning the tools and scripts developed are not directly transferable to other ESOMs. The underlying conceptualisation, however, is framework-agnostic and could in principle be applied elsewhere. Doing so would be a valuable avenue for future work, as it would help assess the robustness and generalisability of the methodology beyond a single framework. Because the vertically integrated model captures cross-border trade flows that typical national models ignore, it incorporates additional dynamics that can yield new insights. Nonetheless, due to time constraints, no elaborate sensitivity analysis was performed beyond investigating hard and soft constraints. This limits the ability to isolate the exact causalities of specific implementation choices, increasing the uncertainty around whether the forecasts made by the integrated model are definitively more accurate than those of the isolated model.

Ultimately, while the implementation introduces new uncertainties and requires further refinement, the methodology developed successfully addressed the core research questions of this project. Specifically, regarding how vertical integration can be implemented within the GENeSYS-MOD framework, the ”separate implementation” method proved to be an effective solution for transferring boundary conditions and trade flows from higher to lower spatial levels. By treating exogenous regions as a separate set with dedicated trading equations, the model successfully integrated macro-level European trade patterns into the detailed Swedish sub-model without requiring a complete overhaul of the underlying framework. Despite the practical challenges and limitations discussed, these methodological choices demonstrated a viable path forward, showing that linking spatial levels in this way is both feasible and analytically valuable.

5.2 Effects of vertical integration on the Swedish energy system

Incorporating European trade flows into the Swedish model produces a markedly different system configuration despite a relatively modest reduction in total system cost of 2.43%. The most significant driver of this reconfiguration is the demand for Swedish hydrogen exports to Finland, which reshapes power distribution, fuel choices, and sectoral electrification rates across the country. The following paragraphs examine these effects in turn.

The dominant export is hydrogen, with SE3 and SE1 together exporting 616.8 TWh to Finland over the model period. Notably, the model concentrates the majority of this export in SE3 rather than distributing it more evenly between the two regions. This reflects an emergent transmission pattern in which SE1 exports power southward to SE2, which in turn forwards it to SE3, effectively channelling the electricity needed for large-scale electrolysis toward the primary hydrogen export hub.

Beyond hydrogen, remaining exports are modest, consisting primarily of power along with small amounts of natural gas and biomass. Power trade is roughly balanced between import and export, suggesting a limited net effect on the domestic system. The natural gas picture is more nuanced, while Sweden imports considerable volumes, much of it is consumed domestically as feedstock for hydrogen production through gas reforming. Some gas is also exported, which given that Sweden has no domestic gas production, likely represents fuel entering through southern trade routes and passing onward to neighbouring countries. The import of oil and coal follows a simpler pattern, substituting purchases that the isolated model sourced from the global energy market rather than increasing total consumption of those fuels.

The increase in hydrogen production is substantial, particularly in SE3 but also noticeable in SE1 and SE4, yet domestic consumption of hydrogen remains negligible, and is limited to small amounts used for industrial heat generation. The hydrogen produced in Sweden is therefore destined almost entirely for export to Finland. This export demand has cascading effects on the broader power system. In the integrated model, 479.2 TWh more power is directed toward hydrogen production compared to the isolated model, while total power generation increases by only 385.9 TWh. The resulting discrepancy of 93.3 TWh must be drawn from other power uses within the system. The most likely and significant source is the industrial sector, where electrification rates are considerably lower in the integrated model. This suggests that Sweden's role as a large-scale hydrogen exporter comes with a systemic trade-off: the power balance is maintained partly by slowing the electrification of domestic industry.

The slower industrial electrification in the integrated model is therefore driven by two reinforcing factors. First, as established above, a greater share of available power is redirected toward hydrogen production, leaving less for industrial electrification. Second, the abundant supply of imported natural gas provides a cost-effective alternative to electric heating, reducing the incentive to electrify in the first place. Together these create a compounding effect where industry faces both reduced access to power and a cheaper fossil fuel substitute, naturally pushing the model toward gas-fired technologies over electric alternatives. The transport sector, by contrast, shows little difference between the two models. Unlike industrial heating, transport technologies have no equivalent gas substitution pathway. The available options are electric, hydrogen-based, or liquid fuel dependent which leaves the sector largely unaffected by the greater gas availability, highlighting how the effects of cross-border trade are not uniform but depend heavily on the fuel flexibility each sector has at its disposal.

The greater availability of natural gas in the integrated model does not simply reflect the volume of exogenous imports, the model also purchases additional gas from the global energy market beyond what cross-border trade provides. This is consistent with path dependency: once the model has invested in gas-consuming technologies, it becomes more efficient to utilise them fully than to switch to alternatives, even if doing so generates additional emissions and associated costs. This self-reinforcing dynamic helps explain why natural gas use in the integrated model extends further into the model period than in the isolated model, and why the two systems diverge more over time despite starting from similar configurations.

Despite the greater reliance on fossil fuels, net emissions in the integrated model increase by only around 2% compared to the isolated model, with no significant change found in the building, transport or power sectors. The increase is concentrated in industry and hydrogen production, both driven by natural gas consumption. However, the emissions profile of the two models differs more than the net figures suggest. The integrated model generates substantially higher gross emissions, offset by considerably greater deployment of CCS and BECCS. ATR-based hydrogen production captures point-source emissions directly, while BECCS compensates for emissions from industrial heat generation. This compensation mechanism keeps net emissions comparable between the models, but it comes at the cost of a much greater dependency on carbon capture technologies. The integrated system is therefore more sensitive to uncertainties in CCS development and cost trajectories than the isolated model, a risk that the net emissions figure alone does not reveal.

It is evident that the exogenous trade has changed the configuration of the Swedish energy system. Most important is the demand for Swedish hydrogen in Finland. This export reshapes the distribution of power in the system, resulting in a greater need for fossil fuels, primarily provided by the imports from exogenous trade. Although we cannot say whether this new system configuration is more accurate, it is clear that adding the information about the supply and demand in other regions outside of Sweden changes the landscape in which the system takes form. It is worth noting that enforcing exogenous demand constraints may increase the cost of the national system, since the macro-level optimal solution does not necessarily align with what is optimal for any individual sub-system. A more expensive outcome for one region can be justified if it enables greater savings elsewhere, making the overall system more efficient. However, in this case we found that the Swedish system benefitted from European energy trading, resulting in a lower total system cost.

Taken together, these results demonstrate that incorporating European trade flows does not simply add a layer of complexity to the Swedish energy system, it fundamentally reshapes it. The demand for hydrogen exports to Finland emerges as the single most consequential driver, cascading through the power system, slowing industrial electrification, increasing fossil fuel dependency, and deepening reliance on carbon capture technologies. These are not marginal adjustments but structural changes that an isolated national model would not capture. It is also worth acknowledging that enforcing macro-level trade constraints does not guarantee a better outcome for any individual sub-system, as a nationally suboptimal configuration may be justified if it enables greater efficiency at the European level. In this case Sweden happens to benefit, with total system costs falling by 2.43%, but this cannot be assumed in general. More fundamentally, whether a lower-cost configuration that increases fossil dependency and slows decarbonisation aligns with national policy goals is a question the model alone cannot answer, and one that points directly to the limitations and opportunities explored in the following section.

5.3 Future research

The results of this study open several directions for future research, spanning methodological refinements, broader modelling ambitions, and questions of policy relevance. These are discussed in order of increasing scope.

The most immediate avenue concerns refining the vertical integration methodology itself. One practical limitation identified in this study is that the build-out capacity of gas pipelines may need to be scaled when applying the framework to sub-regional models. Constraints that are reasonable at the European level can produce infrastructure investments of unrealistic scale when transferred to a national or sub-national context, as demonstrated by the extensive pipeline network built in the integrated model. Establishing guidelines for how capacity constraints should be adjusted across spatial levels would make the methodology more robust and its outputs more credible. Related to this, the question of how to standardise datasets used across both isolated and integrated configurations warrants further investigation. In this study the dataset proved compatible in both settings, but this cannot be assumed in general, as a dataset optimised for an isolated model may not adequately represent the additional demands placed on the system in an integrated context. Developing a standard approach for dataset construction and validation across modelling levels would be a valuable practical contribution. Further refinements could also include transferring additional outputs from the macro-level model to the sub-model beyond trade flows, such as national emission limits derived from European model results or optimal capacity allocations that the sub-model could then distribute spatially. Each addition would bring the two modelling levels into closer alignment, though the trade-off between macro-level consistency and sub-model flexibility would need to be carefully considered.

A second direction concerns moving from one-way to bidirectional integration. While this study transfers information exclusively downward from macro to sub-model level, an iterative exchange where sub-model results also inform the macro-level model could capture a richer set of interaction dynamics across system scales. Pursuing this would likely require developing multiple national sub-models in parallel to ensure balanced representation, a substantial undertaking, but one that would significantly advance the field. Separately, testing the underlying conceptualisation in a different modelling framework would help establish how robust and generalisable the methodology is beyond GENeSYS-MOD, and would be a natural next step for broadening its applicability.

The third and perhaps most consequential direction concerns the policy relevance of vertically integrated models. The results of this study illustrate a tension that deserves closer examination: the configuration that minimises total system cost from a European perspective is not necessarily aligned with national policy goals. In the Swedish case, the integrated model produces a system with greater fossil fuel dependency, slower industrial decarbonisation, and deeper reliance on carbon capture technologies, all in exchange for a modest reduction in total system cost and a significant role as a hydrogen exporter. Whether this trade-off is acceptable depends entirely on the policy lens applied. From a European perspective it may be efficient; from a national perspective, particularly given Sweden's target of net-zero emissions by 2045 (Naturvårdsverket, 2025b), it may be counterproductive. Future research should investigate this tension more systematically, exploring under what conditions vertical integration produces nationally suboptimal configurations and how policy makers should interpret and respond to such findings. There is also a broader question of whether models showing fossil dependency to be cost-effective risk providing justification for delaying climate action, and how the communication of such results should be handled responsibly. Ultimately, vertical integration offers a more complete picture of how national energy systems are shaped by their international context, but translating that picture into actionable national policy guidance remains an open and important challenge.

The need for more representative and insightful ESOMs is becoming increasingly important as policy makers and investors navigate the transition to a sustainable and robust energy system. Understanding the effect of energy trade on local energy systems, and treating domestic systems as part of a broader international landscape, is key to developing models that better capture the sensitivities and dynamics of real-world energy decisions. Further research is needed to deepen this understanding. On the vertical integration side, it would be valuable to investigate additional parameters worth including, such as CO_2 emission limits. Furthermore, exploring how information can be passed upward from local to regional models, and iteratively exchange information between levels, could help capture a richer set of interaction dynamics across system scales.

Another way to further extend macro-level constraints on the sub-model would be to allow the macro-level model to make national decisions beyond trade flows. The result from the macro-level model also includes the optimal national capacities, considering the macro-level perspective. These capacities could also be forwarded to the sub-model, becoming constraints for max capacities in the sub-model. In the case of Europe and Sweden this could be that the European model for example determines the optimal capacity of wind power for Sweden. The Swedish model could then be constraint to not build more than this, but instead get to allocate the capacity across the country, finding the optimal placement of capacities. This would lead to a further integration between the models. However; this could also potentially lead to less optimal national configurations. As the national model takes more detailed information into account, it may be able to build a more cost effective system with less continental constraints. Investigating this topic further should be of interest for future research, to analyse what differences in system configurations can be found when the sub-model is given more or less influence from the macro-level model.

5.4 Conclusion

This study demonstrated that vertical integration can be effectively implemented within the GENeSYS-MOD framework by treating exogenous regions as a separate set with dedicated trading equations, successfully transferring macro-level trade flows as boundary conditions for a national sub-model without requiring fundamental changes to the framework.

The sub-model also exposed an important limitation of applying macro-level trade patterns at national resolution: infrastructure investments that appear feasible at the European scale can be wholly impractical domestically. This points to the need for investigating how capacity build-out constraints across spatial levels should be addressed.

On the system level, vertical integration fundamentally reshapes Sweden's optimal energy configuration. This change was found both using soft and hard constraints for the international trade. Hydrogen export demand to Finland cascades through the power system, slowing industrial electrification and increasing fossil fuel dependency, showing effects invisible to an isolated national model. Although net emissions remain comparable between the models, this masks a substantially greater reliance on CCS in the integrated model, introducing sensitivities that aggregate figures do not reveal.

It is of interest for future research to target the possibility and value of transferring more information between the macro-level model and the sub-model. In addition, the reliability of using one dataset for both an isolated and vertically integrated setting, should be further investigated.

Most broadly, this study surfaces a tension between European and national optimality that vertically integrated models are well positioned to identify. A configuration that is efficient from a continental perspective may conflict with national decarbonisation commitments. Understanding when and how these objectives diverge is a consequential direction for future research.

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A

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B

Supplementary data tables

This appendix details which counties and municipalities were assigned to each bidding zone, and presents the splits used to allocate national Swedish data to the bidding zone level.

B.1 Swedish bidding zones divided into NUTS-3 (counties) and municipalities

Table B.1 shows how we divided the Swedish bidding zones into the smaller regions: NUTS-3 (counties) and municipalities. This was done to enable aggregation of higher-resolution data to the bidding zone level. The bidding zone borders are based on the interactive map produced in collaboration between Internaut AB and Svenska Kraftnät (the Swedish transmission system operator) (Internaut AB, n.d.). Most municipalities lie completely within a single bidding zone, while some are on the border between bidding zones. In these cases, the municipal seat was used as the determining criterion, and the municipality was assigned to the bidding zone in which it is located. Similarly, most counties lie entirely within one bidding zone, with a few exceptions. As the municipalities had already been assigned to bidding zones, counties spanning multiple zones were split using the population share of their constituent municipalities.

Table B.1: Swedish bidding zoned divided into NUTS-3 (counties) and municipalities

Bidding zone	NUTS-3	Municipalities
SE1	Norrbottens län, Västerbottens län (29.50%)	Arjeplog, Arvidsjaur, Boden, Gällivare, Haparanda, Jokkmokk, Kalix, Kiruna, Luleå, Malå, Norsjö, Pajala, Piteå, Skellefteå, Älvsbyn, Överkalix, Övertorneå
SE2	Gävleborgs län (47.56%), Jämtlands län, Västerbottens län (70.50%), Västernorrlands län	Berg, Bjurholm, Bollnäs, Bräcke, Dorotea, Hudiksvall, Härjedalen, Härnösand, Kramfors, Krokom, Ljusdal, Lycksele, Nordanstig, Nordmaling, Ockelbo, Ovanåker, Ragunda, Robertsfors, Sollefteå, Sorsele, Storuman, Strömsund, Sundsvall, Söderhamn, Timrå, Umeå, Vilhelmina, Vindeln, Vännäs, Ånge, Åre, Åsele, Örnsköldsvik, Östersund

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Table B.1: Swedish bidding zones (continued)

Bidding zone	NUTS-3	Municipalities
SE3	Dalarnas län, Gävleborgs län (52.44%), Gotlands län, Hallands län (44.63%), Jönköpings län (87.75%), Kalmar län (27.30%), Stockholms län, Södermanlands län, Uppsala län, Värmlands län, Västmanlands län, Västra Götalands län, Örebro län, Östergötlands län	Ale, Alingsås, Aneby, Arboga, Arvika, Askersund, Avesta, Bengtsfors, Bollebygd, Borlänge, Borås, Botkyrka, Boxholm, Dals-Ed, Danderyd, Degerfors, Eda, Ekerö, Eksjö, Enköping, Eskilstuna, Essunga, Fagersta, Falköping, Falun, Filipstad, Finspång, Flen, Forshaga, Färgelanda, Gagnef, Gislaved, Gnesta, Gotland, Grums, Grästorp, Gullspång, Gävle, Göteborg, Götene, Habo, Hagfors, Hallsberg, Hallstahammar, Hammarö, Haninge, Heby, Hedemora, Herrljunga, Hjo, Hofors, Huddinge, Hultsfred, Håbo, Hällefors, Härryda, Järfälla, Jönköping, Karlsborg, Karlskoga, Karlstad, Katrineholm, Kil, Kinda, Knivsta, Kristinehamn, Kumla, Kungsbacka, Kungsör, Kungälv, Köping, Laxå, Lekeberg, Leksand, Lerum, Lidingö, Lidköping, Lilla Edet, Lindesberg, Linköping, Ljusnarsberg, Ludvika, Lysekil, Malung-Sälen, Mariestad, Mark, Mellerud, Mjölby, Mora, Motala, Mullsjö, Munkedal, Munkfors, Mölndal, Nacka, Nora, Norberg, Norrköping, Norrtälje, Nykvarn, Nyköping, Nynäshamn, Nässjö, Orsa, Orust, Oxelösund, Partille, Rättvik, Sala, Salem, Sandviken, Sigtuna, Skara, Skinnskatteberg, Skövde, Smedjebacken, Sollentuna, Solna, Sotenäs, Stenungsund, Stockholm, Storfors, Strängnäs, Strömstad, Sundbyberg, Sunne, Surahammar, Svenljunga, Säffle, Säter, Sävsjö, Söderköping, Södertälje, Tanum, Tibro, Tidaholm, Tierp, Tjörn, Torsby, Tranemo, Tranås, Trollhättan, Trosa, Tyresö, Täby, Töreboda, Uddevalla, Ulricehamn, Upplands-Bro, Upplands Väsby, Uppsala, Vadstena, Vaggeryd, Valdemarsvik, Vallentuna, Vansbro, Vara, Varberg, Vaxholm, Vetlanda, Vimmerby, Vingåker, Vårgårda, Vänersborg, Värmdö, Västervik, Västerås, Ydre, Åmål, Årjäng, Åtvidaberg, Älvdalen, Älvkarleby, Öckerö, Ödeshög, Örebro, Österåker, Östhammar
SE4	Blekinge län, Hallands län (55.37%), Jönköpings län (12.25%), Kalmar län (72.70%), Kronobergs län, Skåne län	Alvesta, Bjuv, Borgholm, Bromölla, Burlöv, Båstad, Emmaboda, Eslöv, Falkenberg, Gnosjö, Halmstad, Helsingborg, Hylte, Hässleholm, Höganäs, Högsby, Hörby, Höör, Kalmar, Karlshamn, Karlskrona, Klippan, Kristianstad, Kävlinge, Laholm, Landskrona, Lessebo, Ljungby, Lomma, Lund, Malmö, Markaryd, Mönsterås, Mörbylånga, Nybro, Olofström, Osby, Oskarshamn, Perstorp, Ronneby, Simrishamn, Sjöbo, Skurup, Staffanstorp, Svalöv, Svedala, Sölvesborg, Tingsryd, Tomelilla, Torsås, Trelleborg, Uppvidinge, Vellinge, Värnamo, Växjö, Ystad, Åstorp, Älmhult, Ängelholm, Örkelljunga, Östra Göinge

B.2 Disaggregation splits

Depending on the data being disaggregated, different splits were constructed using different datasets and assumptions. In total, 12 splits were developed, including a Europe-to-Sweden split used to allocate the European CO_2 cap to Sweden's share, based on population.

The remaining splits are used to disaggregate national Swedish data into bidding zones (see Table B.2): "Population" (based on municipal populations per bidding zone, see Table B.1), "Area" (calculated from GeoJSON files retrieved from Svenska Kraftnät (2025)),

”Coastline” (based on municipal coastline lengths in 2000 (SCB, 2002)), ”Industry” (based on employment in SNI2007 sectors B and C, extraction and manufacturing, in 2019 (SCB, 2022a, 2022b), ”HHI” (High Heat Industry; based on the assumption that SE1 and SE3 account for the majority of high-temperature industrial heat demand, with smaller shares in SE2 and SE4), ”Power” (based on electricity consumption by bidding zone in 2021 (SCB, 2026)), ”Registered cars” (based on registered vehicles per municipality (Transport Analysis, 2019a)), ”HB” (Heat Buildings; based on total heat production excluding district heating, covering non-residential premises, apartment buildings, single-family houses, and second homes (Swedish Energy Agency, 2024, 2025a), ”DH” (District Heating; based on total district heating consumption in non-residential premises, apartment buildings, and single-family houses (Swedish Energy Agency, 2025b, 2025c, 2025e), ”Freight” (based on the raw ton-kilometer data used for ModalSplitByFuel, see C.7), and ”PSNG” (based on the raw passenger-kilometer data used for ModalSplitByFuel, see C.7).

Table B.2: Splits for disaggregation

Split name	**SE1**	**SE2**	**SE3**	**SE4**
Population	3.12%	6.62%	69.44%	20.81%
Area	26.37%	31.90%	33.16%	8.58%
Coastline	15.12%	23.89%	42.91%	18.08%
Industry	10.70%	19.67%	52.68%	16.94%
HHI	48.00%	1.00%	48.00%	3.00%
Power	7.49%	12.03%	62.61%	17.87%
Registered cars	3.81%	7.78%	66.74%	21.66%
HB	3.93%	8.64%	64.07%	23.35%
DH	5.14%	8.29%	69.13%	17.44%
Freight	11.27%	14.82%	54.25%	19.67%
PSNG	3.72%	6.91%	68.38%	20.98%

C

Detailed descriptions and methods for region specific parameters

This appendix provides a detailed description of the 21 region-specific parameters that are important when introducing a new region, along with how the values for some of these parameters were determined. All values described and calculated in this section are, where applicable, consistent with the NECP Essentials scenario of the GENeSYS-MOD dataset (Löffler, Moskalenko, et al., 2026), one of four scenarios derived from (Barani et al., 2026). Table C.1 gives an overview of all 21 parameters.

Table C.1: Overview of region specific parameters

GENeSYS-MOD parameter	Description	Unit
Par_AnnualExogenousEmission	Describes emissions not otherwise captured by the model that should still be accounted for, such as those from agriculture and cement production.	Megatonnes
Par_AvailabilityFactor	Expressed as a fraction, caps the maximum amount of time a technology may run over the course of a year. Often used to simulate planned outages such as maintenance, but it does not account for intermittent energy production, that is handled by other factors. Can also be used to "turn off" technologies by setting the availability to zero. When outages occur is determined by the model during the run.	Fraction
Par_CommissionedTradeCapacity	Represents already planned and commissioned trade capacity. Built by the model at the same cost as any other capacity. Can also be used to simulate planned policy implementations or other committed capacity additions.	GW
Par_DistrictHeatDemand	Accounts for the district heating demand in the region, including both building heating and industrial process heat below 100° Celsius.	PJ
Par_DistrictHeatSplit	Splits Par_DistrictHeatDemand into two fractions, buildings and industry, to distribute the demand.	Fraction
Par_GrowthRateTradeCapacity	Based on the previous year's total capacity, determines the maximum rate at which trade capacity can grow between two regions each year, thereby limiting how much new capacity can be added annually.	Fraction
Par_ModalSplitByFuel	Defines how passenger and freight transport are split between different modal types (technologies), giving the minimum share of each. Freight transport is divided into road, rail and ship, with each mode further split between conventional (fossil) and renewable fuels. Future years are typically assigned lower shares, serving as a lower bound and giving the model flexibility to allocate remaining shares as needed.	Fraction
Par_ModelPeriodActivityMaxLimit	Represents the maximum potential of a resource in the region, i.e. the reserve that can potentially be accessed. Applicable to finite resource-dependent technologies such as R_Coal_Hardcoal or R_Gas.	PJ
Par_ModelPeriodEmissionLimit	Sets a maximum limit on total emissions across the whole modelled area.	Megatonnes

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Table C.1: Overview of region specific parameters (continued)

GENeSYS-MOD parameter	Description	Unit
Par_RegionalBaseYearProduction	Uses existing capacities to describe how much each technology in each region must produce in the base year in order to meet power and heat demands.	PJ
Par_RegionalCCSLimit	Sets the limit for how much CO_2 a region can store using carbon capture and storage technologies over the whole model period.	Megatonnes
Par_REMinProductionTarget	Defines the minimum amount of energy that must come from renewable sources in order to meet established targets.	PJ
Par_ResidualCapacity	Represents the existing capacity of the region prior to the model base year, accounting for technology lifespans and any planned decommissions.	GW
Par_ResidualStorageCapacity	Accounts for stored capacities available at the start of the base year, such as pumped hydro storage.	GW
Par_SpecifiedAnnualDemand	Specifies the annual demand for each region from the base year to the end of the model period, covering electricity, heat, and mobility. Future years are typically determined by scenario assumptions, while the base year is usually sourced from statistical data.	PJ
Par_TotalAnnualMaxActivity	Represents the maximum biomass availability each year in each region.	PJ
Par_TotalAnnualMaxCapacity	Defines the maximum capacity that can be built in a region. Can for example be used to set an upper limit for available land for onshore wind or as a threshold reflecting a political decision.	GW
Par_TotalAnnualMinCapacity	Defines the minimum total capacity each year. Can be specified to meet requirements for commissioned capacity or policy plans.	GW
Par_TradeCapacity	Describes the total trade capacity between two regions in a specific year and for a specific fuel. Gas is traded in PJ while power is traded in GW.	GW for power, PJ for gas
Par_TradeCapacityGrowthCosts	Defines the cost of expanding trade capacity between two regions.	M€/GW for power, M€/PJ for gas
Par_TradeRoute	States the distance between adjacent regions in the model, defined as the distance between the centre points of the regions.	km

C.1 Par_AnnualExogenousEmission

For this parameter the value for Sweden, from the European dataset, was used (Löffler et al., 2025b). The disaggregation was done using the industry split from Table B.2.

C.2 Par_AvailabilityFactor

All bidding zones were assigned the same availability factors as Sweden in the European dataset of GENeSYS-MOD (Löffler et al., 2025b).

C.3 Par_CommissionedTradeCapacity

The commissioned trade capacities between Swedish bidding zones were collected from the government assignment *Mål för ökning av överföringskapaciteten mellan Sveriges elområden* [Targets for increasing transmission capacity between Sweden's bidding zones] (Svenska Kraftnät, 2024) and known values of 2025 from the Nordic Unavailability Collection System (NUCS) and their compilation of maximum net transfer capabilities (NUCS, 2024), which also covered trade capacities between Swedish bidding zones and neighbouring countries. Other international trade capacities were gathered from the the Ten-Year Network Development Plan (TYNDP) 2024 and Annex D1 regarding implementation guidelines hydrogen projects from the European Network of Transmission System Operators for Gas (ENTSOG) (ENTSO-G, 2025).

C.3.1 Par_CommissionedExoTradeCap

Also for the exogenous trade was the information about planned transmission line construction gathered from Svenska Kraftnät (2024) and NUCS (2024), while the information on planned pipe line extensions were collected from ENTSO-G (2025).

C.4 Par_DistrictHeatDemand

This parameter requires the district heat demand for each bidding zone: SE1, SE2, SE3, and SE4, for each modelling year: 2018 (base year), 2025, 2030, 2035, 2040, 2045, 2050, 2055, and 2060.

Municipal district heat production data were obtained from Statistics Sweden's *Fjärrvärmeproduktion och bränsleanvändning (MWh), efter län och kommun, produktionssätt samt bränsletyp. År 2009 - 2023* [District heat production and fuel use (MWh), by county and municipality, production type and fuel type. Year 2009 – 2023)] (Statistics Sweden (SCB), 2025b). Using Table B.1, municipal values were aggregated to the corresponding bidding zones, yielding a total production of 58 350 GWh, which compared to the national figure of 58 424 GWh is a difference of approximately 0.13%.

Transportation losses to delivery points for 2018 were estimated at 7 100 GWh, equivalent to roughly 12% of total production (Statistics Sweden (SCB), 2025a). This percentage was applied to the bidding zone production values to estimate total deliveries per region. Total use of district heating was then derived from *Fjärrvärme (GWh)* [District Heating (GWh)] (Statistics Sweden (SCB), 2025a), where total deliveries compared to total use yielded a ratio of approximately 99.2%, which was applied to the aggregated bidding zone data. The total use differed by around 0.18% and the final value was then converted to petajoules (PJ), giving the following base year results:

$$
\begin{aligned}
\text{SE1:} &\quad 9.4060\ \text{[PJ]},\\
\text{SE2:} &\quad 15.1880\ \text{[PJ]},\\
\text{SE3:} &\quad 126.5751\ \text{[PJ]},\\
\text{SE4:} &\quad 31.9321\ \text{[PJ]}.
\end{aligned}
$$

For subsequent modelling years, the same forecast used for Sweden in the European GENeSYS-MOD dataset was applied to each bidding zone by scaling values according to the fractional change between years.

C.5 Par_DistrictHeatSplit

The district heat split was determined using data from the Swedish Energy Agency on district heat consumption in non-residential premises (Swedish Energy Agency, 2025c), single-family houses (Swedish Energy Agency, 2025e), and apartment buildings (Swedish Energy Agency, 2025b), which together represent district heat use in buildings at the county level. These data were aggregated to the bidding zone level according to Table B.1 and expressed as a fraction of total district heat use. The remaining share of district heat demand was assumed to be consumed by industry. The splits for the base year are summarised below:

SE1: buildings = 71.11%, industry = 28.89%.
SE2: buildings = 80.84%, industry = 19.16%.
SE3: buildings = 90.60%, industry = 9.40%.
SE4: buildings = 95.58%, industry = 4.42%.

For subsequent modelling years, the same forecast used for Sweden in the European GENeSYS-MOD dataset was applied to each bidding zone by scaling values according to the fractional change between years.

C.6 Par_GrowthRateTradeCapacity

The maximum trade capacity growth rate was assumed to be the same across all bidding zones and fuels, adopting the value used for Sweden in the established European dataset (Löffler et al., 2025b).

C.6.1 Par_GrowthRateExoTradeCapacity

For the exogenous trade the maximum trade capacity growth rate was collected from Löffler et al. (2025b), making the same assumptions.

C.7 Par_ModalSplitByFuel

This parameter defines the modal split of transport demand across each bidding zone, covering both freight and passenger transport. Freight is divided into road, rail, and ship, while passenger transport is divided into road, rail, and air. Each mode is further split by fuel type (conventional or renewable), giving for example the share of freight transported by road using renewable fuels.

C.7.1 Freight transport

The modal split by fuel for freight transport, divided into road, rail, and ship, was determined using total million tonne-kilometres. Road transport was determined using data on million tonne-kilometres for domestic freight with Swedish lorries between counties in 2018 (Transport Analysis, 2019c). As the data were at the county level, these had to be aggregated to the bidding zone level. For some routes, all freight remained within a single bidding zone, while most routes crossed multiple zones. In the latter case, routes were divided by identifying major cities in each county and determining the most likely road corridor to the destination, establishing a bidding zone split for each route. The resulting total tonne-kilometres per region are:

SE1: 1,883.82 [Gtkm].
SE2: 4,752.83 [Gtkm].
SE3: 22,300.32 [Gtkm].
SE4: 6,895.68 [Gtkm].

Maritime transport was estimated in a similar way, using data on domestic shipping of goods, crude petroleum, and petroleum products between coastal areas (Transport Analysis, 2019d). Distances were estimated based on routes between major ports, with bidding zone boundaries defined at points where routes cross between zones. The resulting total tonne-kilometres per region are:

SE1: 382.69 [Gtkm].
SE2: 992.40 [Gtkm].
SE3: 3,758.26 [Gtkm].
SE4: 4,206.32 [Gtkm].

Regional data for rail freight are more limited. Instead, national data for total tonne-kilometres, including and excluding the Iron Ore Line (Transport Analysis, 2019b), were used, with the following assumed distribution across bidding zones:

SE1: 15% of total (excl. the Iron Ore Line) + the Iron Ore Line.
SE2: 25% of total (excl. the Iron Ore Line).
SE3: 45% of total (excl. the Iron Ore Line).
SE4: 15% of total (excl. the Iron Ore Line).

These shares were estimated based on the industrial composition of each zone and the availability of alternative transport modes. SE1 has limited general rail freight beyond the Iron Ore Line itself. SE2 hosts significant heavy industries, primarily timber, steel, and paper, with strong rail utilisation. SE3, being the largest zone with long internal distances and diverse industries, carries the largest share of rail freight, consistent with its dominance in other energy and transport patterns. SE4 has shorter distances and relies more heavily on road transport, with some rail activity primarily oriented towards exports. The resulting rail freight tonne-kilometres per region are:

SE1: 3,868.70 [Gtkm].
SE2: 2,789.50 [Gtkm].
SE3: 5,021.10 [Gtkm].
SE4: 1,673.70 [Gtkm].

Both road and maritime transport were assumed to be entirely conventional fuel-driven in 2018, consistent with the data used in the European model (Moskalenko, Löffler, et al., 2026a). For rail, 80% was assumed to be renewable and 20% conventional, also consistent with the European model. The resulting modal split by fuel for each bidding zone is summarised in Table C.2.

Table C.2: Modal type split by fuel and bidding zone, freight.

Bidding zone	**Road [%]**	**Rail [%]**	**Ship [%]**
SE1	30.70 (30.70 CONV)	63.05 (50.44 RE, 12.61 CONV)	6.23 (6.23 CONV)
SE2	55.68 (55.68 CONV)	32.68 (26.14 RE, 6.54 CONV)	11.62 (11.62 CONV)
SE3	71.75 (71.75 CONV)	16.15 (12.92 RE, 3.23 CONV)	12.09 (12.09 CONV)
SE4	53.97 (53.97 CONV)	13.10 (2.62 RE, 10.48 CONV)	32.92 (32.92 CONV)

For subsequent modelling years, the same forecast used for Sweden in the European GENeSYS-MOD dataset (Löffler, Moskalenko, et al., 2026) was applied to each bidding zone by scaling values according to the fractional change between years.

C.7.2 Passenger transport

The passenger transport modal split across road, rail, and air was determined using passenger-kilometres. Road transport combines private car travel and public road transport. Car travel was estimated using registered cars at the end of 2018 (Transport Analysis, 2018a), from which a fuel split between conventional and renewable was also derived, electric and plug-in hybrid vehicles were classified as renewable while all other were classified as conventional. Passenger-kilometres were calculated by multiplying the number of registered cars by an average occupancy of 1.4 passengers and by the average kilometres driven per car in each region (Transport Analysis, 2018b). Municipal data were aggregated to the bidding zone level according to Table B.1, giving:

SE1: 2,999.78 [Gpkm].
SE2: 6,178.02 [Gpkm].
SE3: 55,291.92 [Gpkm].
SE4: 17,661.07 [Gpkm].

Bus transport was sourced from regional public transport data (Transport Analysis, 2018c) and aggregated from county to bidding zone level according to Table B.1, giving:

SE1: 256.62 [Gpkm].
SE2: 418.30 [Gpkm].
SE3: 5,454.21 [Gpkm].
SE4: 1,162.05 [Gpkm].

Combining car and bus transport gives the total road passenger-kilometres per bidding zone:

SE1: 3, 256.40 [Gpkm].
SE2: 6, 596.32 [Gpkm].
SE3: 60, 746.13 [Gpkm].
SE4: 18, 823.12 [Gpkm].

Rail transport, encompassing trains, metros, and trams, was derived from the same public transport dataset (Transport Analysis, 2018c), where all non-bus public transport was assumed to be rail (i.e. TOTAL - BUS = RAIL). Aggregated from county to bidding zone level according to Table B.1, this gives:

SE1: 36.75 [Gpkm].
SE2: 140.69 [Gpkm].
SE3: 6, 911.36 [Gpkm].
SE4: 2, 268.51 [Gpkm].

Inland air transport was estimated using passenger statistics from Swedavia-owned airports (Swedavia, 2019). All inland flights outside Stockholm were assumed to fly to Stockholm, while distances from Stockholm were averaged across destinations. As the passenger statistics include both departures and arrivals, passenger-kilometres were calculated as the number of passengers multiplied by the estimated distance, divided by two. The airports included, their estimated distances to or from Stockholm, and their corresponding bidding zones are listed below:

Table C.3: Airports included in inland air transport estimation

Airport	Distance to/from Stockholm [km]	Bidding zone
Bromma Stockholm	500	SE3
Göteborg Landvetter	400	SE3
Kiruna	900	SE1
Luleå	700	SE1
Malmö	500	SE4
Ronneby	400	SE4
Stockholm Arlanda	500	SE3
Umeå	470	SE2
Visby	200	SE3
Åre Östersund	430	SE2

Applying the methodology described above, the resulting inland air passenger-kilometres per bidding zone are:

$$\begin{aligned}\text{SE1:} &\quad 511.05 \text{ [Gpkm]}.\\ \text{SE2:} &\quad 325.98 \text{ [Gpkm]}.\\ \text{SE3:} &\quad 2,196.46 \text{ [Gpkm]}.\\ \text{SE4:} &\quad 336.84 \text{ [Gpkm]}.\end{aligned}$$

All rail passenger transport was assumed to be renewable, and all air transport conventional. The fuel split for cars follows the registered vehicle data described above, while buses were assigned a national renewable share of 1.65%, derived from the same source but applied uniformly across all regions. The resulting modal split by fuel for passenger transport is presented in Table C.4.

Table C.4: Modal type split by fuel and bidding zone, passenger

Bidding zone	Road [%]	Rail [%]	Air [%]
SE1	85.60 (85.16 CONV, 0.44 RE)	0.97 (0.97 RE)	13.43 (13.43 CONV)
SE2	93.39 (92.78 CONV, 0.61 RE)	1.99 (1.99 RE)	4.62 (4.62 CONV)
SE3	86.96 (85.56 CONV, 1.40 RE)	9.89 (9.89 RE)	3.14 (3.14 CONV)
SE4	87.84 (86.88 CONV, 0.96 RE)	10.59 (10.59 RE)	1.57 (1.57 CONV)

For subsequent modelling years, the same forecast used for Sweden in the European GENeSYS-MOD dataset was applied to each bidding zone by scaling values according to the fractional change between years.

C.8 Par_ModelPeriodActivityMaxLimit

All bidding zones were assigned the same model period activity max limits as Sweden in the European dataset of GENeSYS-MOD (Löffler et al., 2025b).

C.9 Par_ModelPeriodEmissionLimit

The emission limit is given for the entire model, limiting the total sum of emissions across the model years and regions. The value from the European model was used and Sweden's appointed share was calculated based on population, which gave Sweden a limit of 739.1301 Mt CO_2, corresponding to 1.62% of the total European emissions in the NECP Essentials scenario (Löffler et al., 2025b).

C.10 Par_RegionalBaseYearProduction

National data for Sweden from the European GENeSYS-MOD dataset was used as the basis for the regional base year production values. This data draws on partner feedback, literature on the Swedish energy system, the European Network of Transmission System Operators' (ENTSO-E) Ten Year Network Development Plan (TYNDP), and data from the European Commission (Löffler et al., 2025b). The national values were then disaggregated into the four bidding zones using different splits depending on the technology.

All Heat_Buildings technologies were distributed using the Build split, while Heat_Low_Industrial, Heat_MediumLow_Industrial, and Heat_MediumHigh_Industrial technologies were distributed using the Industry split. Heat_High_Industrial technologies were distributed using the HHI split. For Heat_District, CHP technologies were distributed according to residual capacities (see C.13), while heat pump technologies were distributed using the District Heating split from C.5. Power-producing technologies were distributed using the Power split, with the exception of nuclear, which was allocated according to residual capacity (see C.13). All values were subsequently refined through model calibration to ensure consistency with known residual capacities.

C.11 Par_RegionalCCSLimit

The regional CCS limit was collected from a report by the Geological Survey of Sweden accounting for the storage potential of CCS within Sweden and neighbouring countries. They state all the CCS storage potential can be found in SE3, 1724 Mt, and SE4, 1674 Mt (Møl Mortensen & Sopher, 2021).

C.12 Par_REMinProductionTarget

All bidding zones were assigned the same minimal production target for renewable energy as Sweden in the European dataset of GENeSYS-MOD (Löffler et al., 2025b).

C.13 Par_ResidualCapacity

This section describes the assumptions and methods used to determine the residual capacities of each modelled technology. As this parameter represents the existing capacity of each technology in the Swedish bidding zones at the model base year, the sources and assumptions vary by technology. For some technologies, particularly regarding heat and transport, residual capacities were difficult to source directly and were instead determined through a calibration run in which the model was allowed to freely build the necessary capacity for the base year.

C.13.1 CHP and other thermal power plants not including nuclear

Residual capacities for conventional power plants and combined heat and power (CHP) plants were compiled simultaneously. Installed capacity values were sourced from Statistics Sweden (SCB, 2025a), which provides installed capacity for all conventional power plants, excluding nuclear, in each Swedish bidding zone. As this dataset does not distinguish between CHP and other power plants, nor between fuel types, electricity production data from Statistics Sweden (SCB, 2025b) was used as a proxy to determine these splits.

The electricity production dataset (SCB, 2025b) provides production by municipality and county, differentiating CHP plants from other thermal power plants. Nuclear power, however, is grouped with other thermal power plants in this dataset; municipalities containing nuclear power plants were therefore excluded from these calculations.

The share of total installed conventional capacity belonging to CHP versus non-CHP plants was determined using each type's share of total electricity production in each bidding zone. Equation C.1 shows an example for CHP plants in SE1, where C_{SE1} is the total installed conventional capacity in SE1, $E_{CHP_{SE1}}$ is the electricity produced by CHP plants in SE1, E_{SE1} is the total electricity produced by conventional power plants in SE1, and $C_{CHP_{SE1}}$ is the resulting installed CHP capacity in SE1.

$$C_{SE1} \cdot \frac{E_{CHP_{SE1}}}{\sum E_{SE1}} = C_{CHP_{SE1}} \tag{C.1}$$

Once CHP and non-CHP capacities were established, each was further divided by fuel type using each fuel's share of total consumption within the respective plant category. Equation C.2 shows an example for liquid fossil fuel-fired CHP plants in SE1, where $C_{CHP_{SE1}}$ is the installed CHP capacity in SE1, $E_{CHP_{liq_{fossil}}SE1}$ is the fossil liquid fuel consumed by CHP plants in SE1, $E_{CHP_{fuel}SE1}$ is the total fuel consumption by CHP plants in SE1, and $C_{CHP_{liq_{fossil}}SE1}$ is the calculated installed capacity of CHP plants in SE1 consuming fossil liquid fuels.

$$C_{CHP_{SE1}} \cdot \frac{E_{CHP_{liq_{fossil}}SE1}}{\sum E_{CHP_{fuel}SE1}} = C_{CHP_{liq_{fossil}}SE1} \tag{C.2}$$

The resulting capacities were then mapped to the technologies used in the model, as shown in Table C.5. For most technologies this was straightforward; for example, CHP plants using liquid fossil fuels were mapped to *CHP_Oil*. However, further assumptions were required for plants using biofuels or gas, and for CHP plants using waste or coal.

Table C.5: Categorisation of thermal power plant capacity

GENeSYS-MOD technology	Statistics Sweden category
CHP_Biomass_Solid	CHP using solid renewable fuel + CHP using liquid renewable fuel
CHP_Coal_Hardcoal	CHP using solid fossil fuel × (1 - share of waste)
CHP_Gas_CCGT_Biogas	CHP using gaseous renewable fuel
CHP_Gas_CCGT_Natural	CHP using gaseous fossil fuel
CHP_Oil	CHP using liquid fossil fuel
CHP_WasteToEnergy	CHP using solid fossil fuel × share of waste
P_Biomass	non-CHP using solid renewable fuel + non-CHP using liquid renewable fuel
P_Coal_Hardcoal	non-CHP using solid fossil fuel
P_Gas_CCGT	based on Genrup and Thern (2021)
P_Gas_OCGT	based on Genrup and Thern (2021)
P_Oil	non-CHP using liquid fossil fuel

For biofuel-fired plants, CHP plants using gaseous biofuels were mapped to *CHP_Gas_CCGT_Biogas*, while those using solid or liquid biofuels were combined into *CHP_Biomass_Solid*. Non-CHP plants using any form of biomass were summed into *P_Biomass*.

As Statistics Sweden (SCB, 2025b) does not distinguish waste-fired plants from other solid fossil fuel plants, waste was assumed to be reported under solid fossil fuels. Assumptions were therefore made for the share of solid fossil fuel capacity attributable to hard coal versus waste in each bidding zone, summarised in Table C.6. SE1, characterised by heavy industry requiring high temperatures and a sparse population, was assumed to have 90% hard coal and 10% waste. SE2, with comparatively little heavy industry, was assumed to be predominantly waste-fired, with 5% attributed to peat combustion. SE3 and SE4, both being more densely populated while still hosting some heavy industry, were each assumed to have 90% waste and 10% hard coal.

Table C.6: Share of waste and hard coal amongst solid fossil fuel fired CHP plants

Bidding zone	Share of waste [%]	Share of hard coal [%]
SE1	10	90
SE2	95	5
SE3	90	10
SE4	90	10

Statistics Sweden (SCB, 2025b) records no gas consumption in non-CHP power plants between 2018 and 2023, likely because gas turbines in Sweden operate primarily as reserve capacity and may therefore show no production during this period. Installed capacities for gas power plants were consequently sourced separately from (Genrup & Thern, 2021).

For subsequent modelling years, each technology's rate of decline was taken from the corresponding Swedish values in the European GENeSYS-MOD dataset (Moskalenko, Löffler, et al., 2026b) and applied to each bidding zone by scaling values according to the fractional change between years.

C.13.2 P_PV_Utility_Avg

Installed solar PV capacity data were collected from the Swedish Energy Agency's statistical database (Energimyndigheten, 2026) at the regional and municipal level for 2018 through 2024, with the 2024 value assumed to also represent 2025. Data were aggregated to the bidding zone level according to Table B.1.

Given the negligible installed capacity prior to 2016, all residual capacity was assumed to have been built from 2016 onwards. For each subsequent year, the increment in total installed capacity was assumed to represent new capacity built in that year. An operational lifetime of 25 years was assumed, consistent with the value used GENeSYS-MOD's European model (Moskalenko, Backe, et al., 2026). Combining the assumed build year and operational lifetime, the decommissioning year for each increment was determined, enabling a forecast of remaining residual capacity for each modelling year from 2025 onwards.

C.13.3 P_Nuclear

Based on Swedish Radiation Safety Authority (2026), eight nuclear reactors were active in Sweden in 2018, all located within SE3. Installed capacities were sourced from the ENTSO-E Transparency Platform (ENTSO-E, 2026). Decommissioning dates were assumed based on statements from the reactor operators: Ringhals 3 and 4 are assumed to be decommissioned by 2045 (Vattenfall, 2026b), Forsmark 1, 2, and 3 by 2050 (Vattenfall, 2026a), and Oskarshamn 3 likewise by 2050 (OKG, 2023).

C.13.4 P_Hydro

Hydropower in Sweden, and in the model, is divided into reservoir hydropower and run-of-river (RoR) hydropower. Residual capacities for each bidding zone were sourced from Statistics Sweden (SCB, 2025a), which provides total installed hydropower capacity. Sweden has approximately 1,800 hydropower facilities, many of which are small installations (SwAM, 2019). However, the 200 largest plants provide around 93% of total hydropower production and were assumed to be reservoir hydropower, while the remaining 7% was assumed to be RoR. This split was applied uniformly across all bidding zones.

C.13.5 P_Wind

Wind power can be divided in several ways; in the European GENeSYS-MOD dataset, Sweden's wind power is split between onshore average and offshore transitional. Total installed wind capacity per bidding zone was sourced from Statistics Sweden (SCB, 2025a). The split between onshore and offshore was determined from the Swedish Energy Agency data on installed wind power (Swedish Energy Agency, 2025d), giving 97.22% onshore and 2.78% offshore, mapped to P_Wind_Onshore_Avg and P_Wind_Offshore_Transitional respectively. This split was applied uniformly across all bidding zones.

C.14 Par_ResidualStorageCapacity

No residual storage capacity was found during data collection.

C.15 Par_SpecifiedAnnualDemand

The specified annual demand was disaggregated into the four Swedish bidding zones using the splits summarised in Table B.2. Unless stated otherwise, the underlying national values were taken from the European GENeSYS-MOD dataset (Löffler, Moskalenko, et al., 2026) and are based on the NECP Essentials scenario.

Heat_Buildings and Power are exceptions to the European dataset, where known values for 2018 and 2025, sources as in C.13, were used as the basis, with remaining years filled in according to the expected rate of change from the European model. Heat_Low_Industrial, Heat_MediumLow_Industrial, and Heat_MediumHigh_Industrial were all distributed using the Industry split, while Heat_High_Industrial was distributed using the HHI split. Mobility_Passenger was distributed using the Registered Cars split, and Mobility_Freight using the Freight split. H2 demand was distributed using the Industry split, reflecting the assumption that industrial processes account for the majority of hydrogen demand in each region.

C.16 Par_TotalAnnualMaxActivity

Swedish value from the European model (Löffler, Moskalenko, et al., 2026) disaggregated between bidding zones based on area, except for residues and cardboard which was based on population, both splits can be found in Table B.2.

C.17 Par_TotalAnnualMaxCapacity

Swedish value from the European model (Löffler, Moskalenko, et al., 2026) disaggregated between bidding zones based on land area, except for off-shore wind which used length of coastline and hydropower which was limited to the size of residual capacities. The area and coastline splits can be found in Table B.2.

C.18 Par_TotalAnnualMinCapacity

Swedish value from the European model (Löffler, Moskalenko, et al., 2026) disaggregated between bidding zones based on residual capacity distribution, except for Li-ion batteries which used new data from a report on battery energy storage projects in Sweden (Solarplaza, 2025).

C.19 Par_TradeCapacity

Electricity trade capacity between the Swedish regions and the neighbouring countries was decided by the Nordic Unavailability Collection System (NUCS) and their compilation of maximum net transfer capabilities (NUCS, 2024) for the year 2018. Gas trade capacities were determined by Table 11 in the report *Sweden's electricity and natural gas market 2023* [Sveriges el- och naturgasmarknad 2023] (Swedish Energy Market Inspecorate, 2024).

C.19.1 Par_ResidualExoTradeCapacity

The trade capacity between Swedish regions and the neighbouring countries were also collected from NUCS (2024) for power and Swedish Energy Market Inspecorate (2024) for gas.

C.20 Par_TradeCapacityGrowthCosts

All trade capacity growth costs are the same as Sweden's values towards other neighbouring countries in the European dataset of GENeSYS-MOD (Löffler et al., 2025b).

C.20.1 Par_ExoTradeCapacityGrowthCosts

Consistent with the approach described above, the capacity growth costs for international trade are assumed to be identical to those for domestic trade, based on European dataset of GENeSYS-MOD (Löffler et al., 2025b).

C.21 Par_TradeRoute

Trade route distances between regions were determined as straight-line distances between representative central points in each region, measured using distance.to. The selected centre points for the Swedish bidding zones were Gällivare (SE1), Strömsund (SE2), Örebro (SE3), and Älmhult (SE4).

C.21.1 Par_ExogenousTradeRoute

In addition to the routes between the Swedish bidding zones, trade routes were also established between the Swedish bidding zones and the neighbouring countries represented in the European model. The centre points used for these international connections are summarised in Table C.7.

Table C.7: International trade route centre points

Bidding zone	Country	Centre point
SE1	Finland	Sodankylä
SE1	Norway	Fauske
SE2	Norway	Trondheim

Continued on next page...

Table C.7: International trade route centre points (continued)

Bidding zone	Country	Centre point
SE3	Denmark	Viborg
SE3	Finland	Tampere
SE3	Norway	Gol
SE4	Germany	Göttingen
SE4	Denmark	Slagelse
SE4	Lithuania	Kėdainiai
SE4	Poland	Płock

D

Declaration of AI usage

During this thesis, the authors utilised large language models (LLMs) strictly as assistive tools to refine presentation, formatting, and technical implementation. Google Gemini 3.1 Pro and 3.5 flash was employed to assist with text revision, document layout, LaTeX-formatting, and minor coding and debugging tasks during the development of supplementary Python scripts. Additionally, Claude Sonnet 4.6 was used exclusively to revise and polish individual, pre-written text segments. The authors confirm that no AI tools were used to draft original academic content or generate core ideas. Full responsibility for the final content, analysis, and conclusions rests entirely with the human authors.

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