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Long-Term Provision of Ancillary Services for the Electricity System Using District Heating Technologies – Modeling Study for the Case of Sweden

Karl Vilén * [a], Parvathy Sobha [b], Akram Sandvall [c], Dmytro Romanchenko [d]

[a]*Swedish Environmental Research Institute (IVL), Aschebergsgatan 44, 41133, Gothenburg, Sweden*
[b]*Swedish Environmental Research Institute (IVL), Valhallavägen 81, 11428, Stockholm, Sweden*
[c]*Svenska Kraftnät (Svk), Gamlestads Torg 5, 41512, Gothenburg, Sweden*
[d]*CIT Renergy, Sven Hultins Plats 1, 41258, Gothenburg, Sweden*

ABSTRACT

The electricity sector is a key sector in the full energy system and is therefore crucial to. consider in the transformation into a fossil-free energy system. Several ancillary services (AS) which operate at short-term scales, i.e., seconds up to multiple minutes, are implemented by the grid operators to balance the electricity system. District heating technologies, such as heat pumps (HPs) and combined heat and power (CHP), could potentially provide AS for the electricity system, thus improving the cost-efficiency of future energy systems.

A long-term modeling approach using the TIMES framework is used in this study to analyze how the Swedish energy system can develop cost-efficiently when demands for energy and AS shall be fulfilled in several developed cases. The results are compared to cases without AS.

The results show that DH technologies can cost-efficiently provide AS, mainly for the slowest upwards service, mFRR+. DH HPs and biomass CHP plants cover over half of the mFRR+ demand in the winter in southern Sweden, highlighting DH's potential as a flexible resource. The results further show that new investments in DH technologies are attributed to energy demands, not AS provision, thereby indicating that AS provision does not incentivize new investments into DH technologies.

Keywords

Combined heat and power;
Heat pumps;
Batteries;
Energy system optimization;
TIMES model;

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1. Introduction

The global energy transition is driven by the need to mitigate climate change and meet the commitments of the Paris Agreement. Achieving these commitments requires rapid decarbonization of energy systems, with renewable energy playing a central role. In Europe, the

* Corresponding author – e-mail: karl.vilen@ivl.se

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share of renewables in gross final energy consumption is targeted to reach 42.5% by 2030, with ambitions to go beyond 45% under the REPowerEU plan [1]. The Nordic countries are at the forefront of this transition. For instance, in 2024, over 50% of the primary energy consumption of Sweden stems from renewable sources, while it for Denmark and Finland was around 40% [2]. Further, nearly 90% of the electricity production in Denmark stemmed from renewable energy sources, while Sweden and Finland obtained about 70% and 55% respectively [3].

While these developments are essential to meet climate targets, they also introduce challenges for electricity systems. The variability and limited predictability of wind and solar power significantly affect system dynamics. The reduction in inertia, combined with the limited reactive power capability of inverter based resources, leads to faster and larger frequency deviations, shorter response times to disturbances, and a greater need for balancing actions [4,5]. Hence, to preserve stability under high shares of intermittent generation, transmission system operators (TSOs) rely on a set of ancillary services (AS) [6], functions that support frequency control, voltage regulation, and system restoration beyond the basic supply of electricity.

In response to new system conditions, the Nordic TSOs have strengthened and modernized their frequency toolbox across timescales. This now includes a coordinated set of frequency control products: fast frequency reserve (FFR); frequency containment reserves for normal operation and disturbances (FCR-N, FCR-D); automatic frequency restoration reserve (aFRR); and manual frequency restoration reserve (mFRR) [7,8].

The provision of AS in the electricity sector can be expanded and diversified by unlocking flexibility from coupled sectors [9]. District heating (DH) is particularly relevant in the Nordic context, where it supplies a substantial share of the heat demand. DH systems utilize multiple technologies, i.e. combined heat and power (CHP), electric boilers (EBs), large scale heat pumps (HPs), and thermal energy storage (TES), enabling temporal decoupling between heat demand and generation.

There are pilot projects and applied studies in the Nordic power systems, spanning diverse models, scopes, and time resolutions, offering lessons on DH and power-to-heat participation in frequency services. For instance, [10] applies a perfect foresight, static hourly cost optimization (run separately for 2017-2019) to co-optimize a block scale DH+HP system in Finland and finds that the full value is only realized when both FCR-N and open DH participation for third parties are enabled. Drawing on literature review and evidence from a pilot DH subnetwork in Copenhagen, [11] concludes that large DH HPs can meet FCR-N and satisfy aFRR/mFRR response times, generally missing FCR-D's ultra-fast ramps and residential HPs require aggregation and often extra storage to be usefully flexible. Furthermore, using a two stage deterministic EnergyPRO model (hourly day-ahead + 15-min balancing) of connected DH networks in Helsinki, [12] finds that HPs profit most in FCR-D up while the EB profits most in FCR-D downregulation; FCR-N offers limited margins. These studies indicate strong potential for DH and power-to-heat to supply frequency services but also highlight priority areas for further Nordic work such as co-optimization with heat supply, activation/ramping requirements, aggregation and storage sizing, zonal deliverability, and sensitivity to power/ETS prices and market rules.

Focus on district heating flexibility, with limited attention to ancillary services

Most studies assess DH as a flexibility resource for planning and energy balancing, with only limited attention to explicit AS provision. For instance, [13] soft links a city level DH planning model with a dynamic flexibility model that shifts network water temperature, letting DH act as short term storage for day-ahead energy balancing. [14] develops a national scale method to map and cluster DH network investment costs for use in sector coupled optimization, stressing that DH competitiveness hinges on flexibility via TES and sector coupling. [15] finds that power-to-heat solutions in DH systems can increase system flexibility in a short time period that considers hours to weeks, but also in a longer periods that accounts for the significant inter annual variability in hydropower supply in the north European power system. Further, [16] proposes a strategic investment scheme for a DH system participating in both electricity and reserve markets, enabling enhanced investment decisions for the installation of CHP plants, HPs, and TES. [17] proposes an alternative control strategy for combustion based DH systems allowing the pumping system to operate as a flexible load for a case study municipality considering participation in a local flexibility market and in a demand response program.

[18] analyzes how national policies and grid tariff designs shape the business case for flexible DH portfolios, finding that TES is a consistent cost reducer, while capacity-based electricity tariffs suppress EB flexibility relative to energy or time-of-use tariffs. Although flexibility and AS are linked, [13–18] do not explicitly consider AS.

Shortcomings of current ancillary service models

Studies at the plant level [19] and at DH system level [20,21], together with high resolution operational control work, demonstrate the technical feasibility of providing AS [22]. However, these studies overlook market competition, network and zonal deliverability constraints and endogenous capacity expansion feedback. These gap limit the extent to which their findings can inform policy or system scale conclusions. [23] expands the analysis to national scale but remains an operational simulation without long term planning. The study treats the system largely as a single node, thus overlooking locational reserve procurement and how reserve requirements shape long run investments. Also, in most case studies, AS assessments have been limited to one or a few products, typically FCR (normal or disturbance) [20] or aFRR [21], while only a handful extend to mFRR participation or multi analyses which considers FCR, aFRR, and mFRR [19]. Although [19–23] consider AS, these studies do not consider long term planning of investment decisions in in new DH technologies and their consequential role in the full energy system.

Focused on individual DH technologies

Many studies focus on individual technologies, leaving the system level co-optimization of heterogeneous DH portfolios across energy and ancillary markets comparatively underexplored. For example, [24] focusses on CHP plants as AS providers and finds that co-optimizing day-ahead and frequency regulation participation can raise CHP profits. The review study [25] showed that including one or more energy storages benefits the distribution system operators and the prosumers, from both technical and economic perspectives. [10] finds that realizing the full value of a hybrid heating system (centralized DH + decentralized HPs) requires enabling building side HPs to participate in AS markets and compensating them for heat fed into the open DH network. [26] identified that supply primary frequency regulation for the grid is the best suited control structure of the HP. Furthermore, [27] finds that for a HP based system, the operation according to AS regulation request resulted in higher exergy destruction and higher overall system cost.

Contribution of this paper

Previous studies have assessed ancillary services, yet gaps remain. There is a lack of studies which investigate the long-term development of energy systems while simultaneously considering the development of supply and demand of AS. This paper addresses the identified gaps by using a long-term techno-economic energy system model which considers several types of AS simultaneously and together in several regions. The full energy system is considered in this paper while having a focus on assessing the role on how the DH sector can provide frequency related AS in a cost-efficient energy system.

This study adopts a system level optimization framework including DH flexibility and AS requirements to reflect the system realities and the evolving AS products. The Swedish energy system with all electricity bidding zones (SE1-SE4) is applied as a case study and is represented through the TIMES-SE model which captures long term (up to year 2050) dynamics, price zone details, transmission constraints, cross border interactions, and joint optimization of production and demand of energy, as well as investment decisions.

2. Background of Ancillary Services in Nordic Countries

The Nordic synchronous area (Sweden, Norway, Finland and eastern Denmark) is jointly operated by the four TSOs, Svenska kraftnät (Svk), Statnett, Fingrid and Energinet with coordinated balancing and harmonized AS [7,8]:

- Fast Frequency Reserve (FFR)
- Frequency Containment Reserves normal/ disturbance (FCR-N/FCR-D)
- Automatic Frequency Restoration Reserve (aFRR)
- Manual Frequency Restoration Reserve (mFRR).

There are associated markets for each AS on which the TSOs procure sufficient capacities. Actors which want to provide AS need to prequalify their technologies and be associated with a Balancing Service Provider (BSP), or be BSPs themselves [28]. The actors then provide bids for each AS on their associated markets. Since 2024, all markets utilizes marginal pricing [7] which decreases the use of price setting strategies from the providers [28]. The bids are secret and which technologies that are activated for each AS are not published.

The areas' day-ahead market switched from net transfer capacity (NTC) to flow based market coupling in late 2024. This has improved the use of cross zonal capacity and reshaping price formation and congestion management across Nordic bidding zones [29]. Furthermore, the Nordic mFRR Energy Activation Market (EAM) is being rolled out with 15-minute activation resolution, aligning balancing operations with finer market granularity from early 2025 [30,31]. These institutional changes increase the value of fast and controllable flexibility and make the geographic location of flexibility providers more consequential for system operation.

Sweden has a north-south transfer corridor with surplus generation in the hydro dominated north, demand concentrations and nuclear reactors in the south, and connections to continental Europe and the Baltics [32]. The combination of internal north-south bottlenecks and strategic cross border links means its flexibility affects both Nordic and cross zonal frequency quality, making Sweden a particularly relevant case for assessing AS provisions.

3. Method, Model and System

Long-term energy system modeling enables investigation into how an existing system can develop over time when existing technologies are dismantled and new technologies can be added when energy and AS demands shall be fulfilled. The developed model developed in this study is presented first in this section, which includes an overview of the model, geographical scope, and time horizon investigated. This is followed by a detailed description on how AS are implemented in the model.

3.1 Model

The role of the DH sector in providing AS for the electricity system is examined by using the TIMES (The Integrated MARKAL-EFOM System) energy system modeling framework. TIMES is a well-used bottom-up optimization modeling framework used in more than 50 countries for investigating energy systems over long periods, i.e. decades. TIMES-SE (TIMES Sweden) [33], developed by Energy Modelling Lab (EML) is used and further developed within this study. The TIMES-SE model is briefed below.

TIMES-SE is a multi-regional energy system optimization model based on linear programming, covering the entire Swedish energy system. The model is based on macro-economic drivers and identifies the least cost combination of technologies to meet future energy demand, subject to user-defined constraints (e.g., emission targets), over both medium- and long-term time horizons. The model structure consists of three main parts: primary energy supply, conversion sectors, and end-use sectors.

Primary energy supply represents the import, export, and domestic extraction of primary energy commodities. Each energy commodity is associated with specific emission factors, allowing the model to track emissions from fuel combustion and other processes across all sectors. These include fossil fuels, biomass, waste resources, and other raw energy carriers. The model can trade these commodities between areas, enabling detailed analysis of energy flows and areal interactions within Sweden.

Conversion technologies transform primary commodities into secondary energy carriers such as electricity, DH, and refined fuels. This component includes the power plants, DH production plants, refineries, and other transformation processes. Transmission constraints and areal bidding-zone representation allow the model to capture electricity flows, congestion, and cross-border interactions.

End-use sectors incorporate the major sectors of the Swedish economy: industry, residential, commercial, transport, agriculture, waste, water, and land use. End-use technologies in each sector consume secondary energy carriers to deliver energy services. This integrated structure ensures internal consistency of energy balances and enables the identification of synergies between sectors, such as sector coupling between electricity, heating, and transport.

A schematic description of the TIMES-SE model is presented in Figure 1.

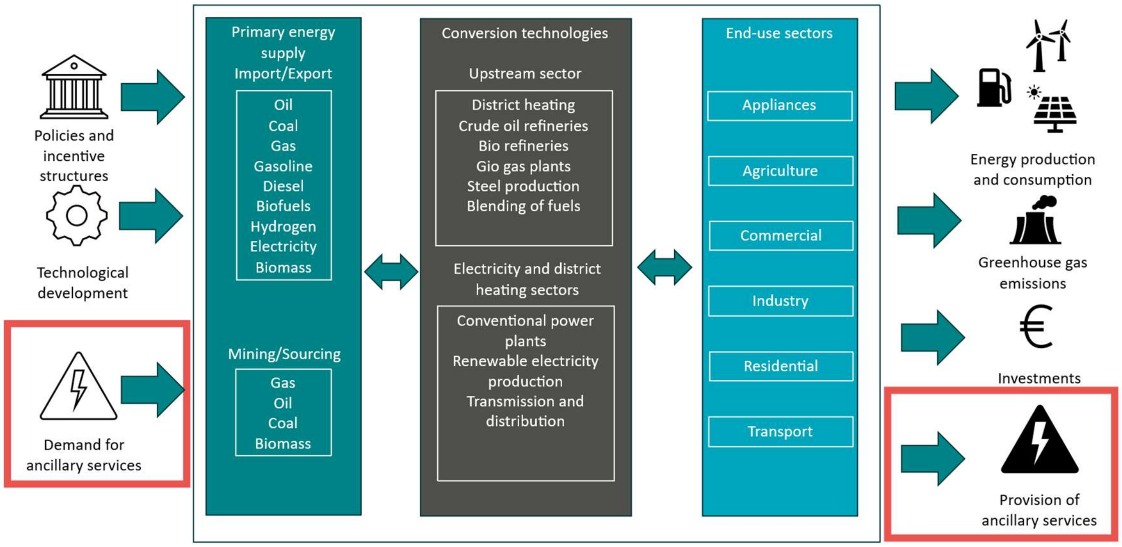

Figure 1: Schematic description of the TIMES-SE model, with the addition of ancillary services (red boxes) which have been added in this study.

3.1.1 Time Horizon and resolution

The model's time horizon is in this study set to 2050 and the model uses perfect foresight. Each modeled year is divided into 56 times slices which are chosen to represent different seasons and situations in the power system. Some slices represent situations where the system is not strained, while others represent, for example, situations with high electricity consumption and low production from photovoltaics and wind power. The amount of time slices is chosen to balance the need to be able to analyze differences in the production and demand of energy at different periods, while at the same time requiring that the model is solved in reasonable time due to the higher computational power required for solving models with a very high time resolution. All time slices are not equal in length and can therefore reflect period which happens for very few hours during the year, such as peak periods. This allows the model to analyze how the energy and AS demand shall be met during these peak periods.

The model is required to fulfill the need for all AS during all times slices, meaning that there must always be sufficient upwards and downwards regulation available. Trading in the intraday market for electricity is not implemented due to the perfect foresight of the model as the intraday market is enabling need for adjusting the electricity production arising due to circumstances which can only be known very close to the actual deliverance of electricity, such as exact weather conditions.

3.1.2 Geography

The modeled are in TIMES-SE, Sweden, is divided into four areas, which correspond to the NordPool price areas SE1-SE4. Each price area has different demands of AS which need to be fulfilled with the technologies present in respective areas. Further, each area has its separate supply plants and demands, but exchange of energy carriers within the four areas and to/from the "outside world" is also allowed in the model. Electricity between the areas can be traded via the transmission lines, as well as import/export of electricity from/to the surrounding countries is possible. Buildings and their heat demands are further divided into urban areas, suburbs, and rural areas for a better representation of DH areas and their respective bottlenecks. Technologies which can provide AS are assumed to be connected to the transmission grid within their respective price areas and are therefore not affected by bottlenecks within price areas.

3.1.3 Technologies

In the chosen base year, 2022, the existing generation, transmission, and storage capacities as well as energy demands in Sweden are represented in the model and are mapped and calibrated based on statistical information. Under the modelled time horizon, the existing capacities are phased out (depending on their lifetime) and need to be replaced by new technologies to keep satisfying the energy demands of the modeled areas. Techno-economic parameters of the technologies available for investments are primarily based on the Danish Energy Agency's technology catalogues and supplemented with other sources. This gives the model the opportunity to make investments in many technological alternatives at different years.

The main model development contribution of this paper is the addition of the AS package to the TIMES-SE. Corresponding data for the technologies in the energy system are collected, with a focus on the DH sector. The implementation of the AS is described in the following Section.

3.2 Ancillary Services

In the model, the balance of energy supply and demand must be met. Additionally, introduced in this study, is the balance between demand for and supply of AS that enables the system operator (SO) to deal with short term system imbalances. The operating reserve can be defined as the generating capacity available to the SO within a short time interval, to meet the demand in case of a disruption in energy supply [34]. The control reserve is classified both based on the time of activation and the upward (positive, "+") or downward (negative, "-") regulation. Positive reserve occurs when there is a shortage of supply, meaning that additional units need to be brought online, storage devices discharged, or demand units reduce their consumption. Negative reserve occurs when there is an excess of supply [34].

3.2.1 Model implementation of ancillary services

The TIMES modeling framework added an AS modeling package in version 4.4, see [34] for a more detailed description. The AS are treated as commodities with exogenously provided demands in the model.

In the model, four types of AS are included: FCR-D, FCR-N, aFRR and mFRR, each of which has upward (+) and downward (-) regulations. The corresponding activation times and endurance time for each AS is presented in the supplementary material.

3.2.2 Demand for ancillary services

Currently, in the Nordic region, the designed demand for FCR-D+ is based on the capacity of the largest Swedish nuclear reactors, Oskarshamn 3, i.e., 1450 MW. The need for FCR-D- is based on the fault in one of the international subsea cables of North Sea Link (between Norway and the United Kingdom) or Nordlink (between Norway and Germany), i.e., 1400 MW [7]. The demand for FCR-N is based on historic imbalances in the Nordic synchronous area [7]. All FCR services are provided at national level. The demands for FCR services are therefore implemented in TIMES-SE to be met on a national level.

For the aFRR service, the current total Nordic demand is 300-400 MW, of which 105-140 MW belongs to Sweden. The demand is estimated to increase significantly in the future, although with high uncertainties. The dimensioning is based on historic frequency quality in the Nordic synchronous area [7]. The maximum mFRR demands in 2024 were 630/750 MW for upward/downward regulation respectively. The dimensioning is based on the need to manage the largest failure scenario and continuous normal imbalances [7].

The total procurement for aFRR/mFRR are done separately for the four electricity areas in Sweden. The demand for aFRR and mFRR are therefore implemented in TIMES-SE to be met within each electricity price area.

3.2.2 Provision of ancillary services

All types of technologies which can provide AS can do so in proportion to their installed capacity, current output, and ramping rate. Technologies which provide AS does so by allocating a certain amount of capacity to provide AS, and this allocated capacity cannot therefore be used to provide other forms of energy. There is no extra cost applied for providing AS in the model, but the allocation of capacity for providing AS creates an alternative cost as other technologies has to be used instead for energy production.

Direct electricity storage, such as batteries, uses a slightly different approach where the state of charge is also affecting the ability to provide AS. A detailed description of the implementation of provision of ancillary services is presented below, and more detailed in the supplementary material.

How much a certain technology can provide a certain upwards AS, a ($a \epsilon aUP$, where aUP is the set of all upwards AS), at time, t, is determined by the following equation:

$$P_{max,a,t} = (c - g_t) \cdot \frac{r}{60} \cdot \tau_a \quad (1)$$

Where:

$P_{max,a,t}$ (MW) is the maximum provision of upwards AS a (MW) at time t

c is the installed electrical capacity (MW)

g_t is the electricity generation (MW) at time t

r is the hourly ramping rate (%/hour)

τ_a is the activation time for AS a (minutes)

While for the following equation determines the maximum capacity for provision of downwards AS a ($a \epsilon aDO$, where aDO is the set of all downwards AS):

$$P_{max,a,t} = (g_t - c_{min}) \cdot \frac{r}{60} \cdot \tau_a \qquad (2)$$

Where c_{min} is the minimum output.

For all types of ancillary services that the provision is equal to or lower than the maximum provision for that specific type:

$$\forall a \in (aUP \cup aDO): P_{a,t} \leq P_{max,a,t} \qquad (3)$$

Where $P_{a,t}$ (MW) is the provision of AS a at time t.

Further, the different types of reserves provided by a certain technology cannot overlap. All technologies therefore need to fulfill the following equation for upwards regulation:

$$\sum_{a \epsilon aUP} P_{a,t} \leq (c - g_t) \qquad (4)$$

Similarity, the following equation must hold for downwards regulation:

$$\sum_{a \epsilon aDO} P_{a,t} \leq (g_t - c_{min}) \qquad (5)$$

The setup of the equations presented above is summarized in Figure 2.

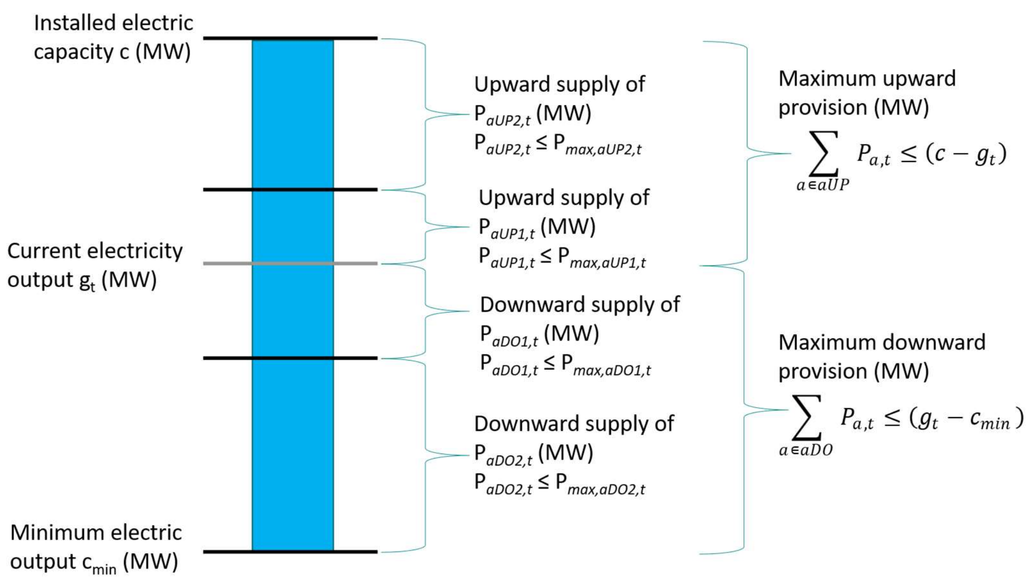

Figure 2: Setup on how a specific technology can provide several ancillary services, ({aUP1, aUP2} ∊ aUP and {aDO1, aDO2} ∊ aDO), at time t

In this study, the ramping rates are different across CHP plant types as the turbine design determines how fast each plant can regulate its electricity production. Since the heat demand is much higher during winter compared to summer, many CHP plants are not active during the summer months [35]. For this reason, the ability for CHP plants to provide AS in the model during summertime is decreased drastically by 90%.

Nuclear reactors have the technical possibilities to regulate their electricity output. However, the reactors active in Sweden seldom do so in a fast manner resulting in slower ramping rates compared to other condensing type turbines included in TIMES-SE model.

Intermittent electricity producers can use curtailment to regulate downward, and some wind power and solar power installed in Sweden as of today have been pre-qualified to provide AS. For this reason, these technologies can only provide downward regulations.

For electric storage, in the form of batteries and flywheels, the state of charge is used together with the duration of the specific AS as the storage needs to be charged/discharged enough to have sufficient energy stored/storage available to be able to provide downward and upward regulations respectively.

The potential for industrial electricity consumers to reduce their electricity consumption to provide AS is not considered in this study.

4. Data and cases

In this chapter is the data used in the model presented. This includes the data for each of the sensitivity cases as well as for parameters related to the demand and provision of AS.

4.1 Overview and energy system

As described in chapter 3.1, the modeled system consists of subsectors, such as electricity, heating, industry, and transport. Hence the model can determine how to meet all defined demands at the lowest total system cost by optimizing all sectors simultaneously. In all investigated sensitivity cases are the carbon emissions from the full energy system required to decline each year, eventually attaining carbon neutrality by 2045.
Since this study focuses on the provision and demand for AS for the electricity system, the remainder of this chapter focuses on aspects relevant to these.

4.2 Sensitivity cases

Eight sensitivity cases are assessed as there are many uncertainties on for the future energy system could develop. The modeled cases are described in Table 1**Fejl! Henvisningskilde ikke fundet.**. Two cases do not have the requirement to fulfill the AS demands, which are required in the remaining six. The cases are chosen to assess uncertainties in energy system pathways such as industrial electrification, nuclear power production and biomass prices. A detailed description of each case is presented in the supplementary material.

Table 1 Sensitivity case description. A more detailed description of each case can be found in the supplementary material.

	Case name	Difference from base case
No requirement to fulfill ancillary services (NO)	NO Base	-
	NO IncElc	Increased electricity demand of approximately 16.7/33.4/50.1/66.9 TWh annually
Demand for ancillary services must be fulfilled (AS)	AS Base	-
	AS IncElc	Similar electricity demand increases as in No IncElc case.
	AS HighBio	Costs of wood pellets, wood chips and wood waste increased by 50% for all years compared to the other cases
	AS LowHyd	Reduced hydro power availability for ancillary service provision from 2595 MW to 2107 MW in SE3, and from 347 MW to 152 MW in SE4.
	AS NewNuc	Predefined minimum size of nuclear fleet in SE3: 2500/5000/7500 MW_e in 2035/2040/2045 respectively
	AS NoNuc	No investments in new nuclear.

4.3 Demand of ancillary services

Table 2 shows the implemented demands, activation times and required endurances for each type of AS in Sweden, based on [7,36]. The activation time of all AS services are presented in the supplementary material. The requirement to activate 50% of the FCR-D within 5 seconds (see supplementary material), is linearly interpolated as 100% activation within 10 seconds in the model. This way of representation is due to the use of linear programming in the model.

Table 2 Allocation of ancillary service demands in the electricity areas of SE1-SE4 from 2025 onwards, based on [7,36]. Note that the values for all ancillary services, except FCR-D upward and FCR-N, are higher than the historic values presented in [7] indicating that Svenska kraftnät estimates an increased demand for ancillary services compared to past years.

Ancillary service	Upward demand SE1 / SE2 / SE3 / SE4	Downward demand SE1 / SE2 / SE3 / SE4	Activation time / endurance

FCR-D (MW)	567 (national)	547 (national)	10s / 20m
FCR-N (MW)	235 (national)	235 (national)	3m / 1h
aFRR (MW)	65 / 62 / 79 / 93	68 / 68 / 93 / 92	5m / 1h
mFRR (MW)	190 / 238 / 476 / 595	539 / 337 / 162 / 162	15m / 1h

4.4 Supply of ancillary services

The Swedish electricity supply units and capacities from 2022 is used as the baseline, to which new supply units can be added in subsequent years. The installed capacities which can supply AS are presented in the supplementary material.

The ramping rates of the different technologies are shown in

Table 3. It is assumed that existing power plants and future plants have the same ramping rates.

Not all CHP plants in the model are available to provide AS. This stems from both that technical limitations, but also that regulatory and lack och competence hinder the provision of AS [37,38].

Today, around 400 MW of CHP are prequalified to provide mFRR [37]. Apart from that capacity, there is also a combined capacity of 1060 MW in CHP plants where the owners are interested in providing mFRR, and up to 380 MW capacity for CHP plants to provide other sorts of flexibility. This sums up to 1840 MW, which is close to how much mFRR the available non-waste fueled CHP plants in the model can provide in 2022 (around 2080 MW mFRR). For this reason, it is assumed that waste fueled CHP plants cannot provide AS as these kinds of CHP plants typically operate at full capacity as waste treatment and waste to energy utilization are their primary function.

Table 3 Ancillary service technical parameters for technologies which can provide ancillary services.

	Ramping rate, minutes to full power	Reference
CHP gas turbine, gas engine, combined cycle	3.33	[39]
CHP other	25	[39]
Thermal electric plants, except nuclear	25	[39]
Hydro power	5.82	[40]
Nuclear power	230	[40]
District heating electric boilers	0.5	[39]
District heating heat pumps	6	[39]
Electric batteries and flywheels	<1 second	[41]
Wind power	4.3% of installed power available for FCR-D- 8.2% of installed power available for mFRR-	[40]
Solar power	1.3% of installed power available for FCR-D-	[40]

5. Results

The results from the modeled cases are presented in this section. The results for domestic electricity and DH production and capacities are presented on national levels. Electricity production covers both domestic demand and exports but not imports.

The results for the provision of the fastest (FCR-D) and slowest (mFRR) AS are presented, but in different areas. This is done as most of the CHP pre-qualified for AS provision qualified for mFRR, but some also for FCR-D [7]. The provision of FCR-D is presented on national level, while mFRR is presented for SE4. This is done as the demand for FCR-D needs to be fulfilled on a national level, while for mFRR, each area needs to fulfil their respective demands. The results for mFRR provision in SE4 are chosen to be presented since SE4 is the area with the highest demand for mFRR+, and with the lowest availability of hydro power.

All AS are presented for two specific time slices. The summertime slice represents a time slice in summer with low electricity demand and high availability of wind and solar power. The wintertime slice represents a time slice in winter with high electricity demand and low wind and solar power availability. The summer and wintertime slices thereby represent two slices where the strain on the electricity system is the lowest, respectively the highest.

5.1 Electricity supply

In this section are the production of electricity and installed electricity capacity throughout the modeled period presented.

5.1.1 Electricity production

In general, the electricity production in 2022 and 2030 is similar between the cases, see Figure 3. The main exception is that in the HighBio case, there is no electricity production from bio CHP, which consequently has an annual lower production of about 15 TWh in 2030, as the fuel cost is too high for it to be economical. Also, there are no significant changes in the electricity production depending on whether AS are required or not. In 2040, there are differences in the results between the cases, but there are no significant changes in the production pattern if AS are required. The general trend of increased production from 2022 to 2030 and between 2030 and 2040 is mainly due to increases (NewNuc) and decreases (NoNuc) in exports, increased domestic demand (IncElc) but also some increases in the electricity use in industrial processes, as well as some electrification for heat production using HPs.

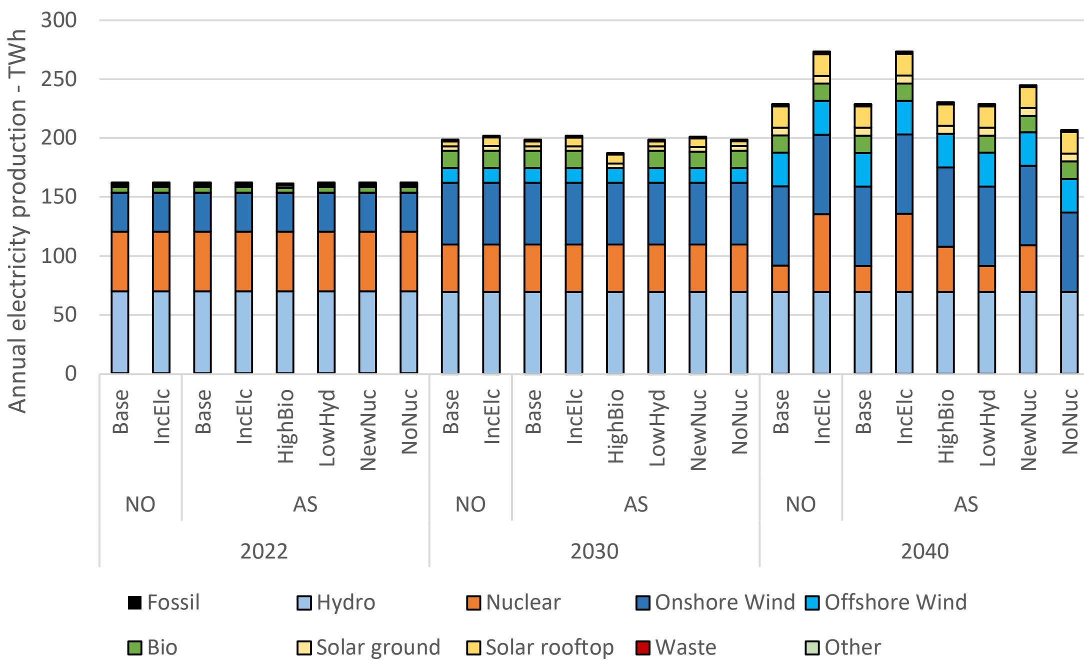

Figure 3: Modeling results for annual electricity production in Sweden depending on fuel type. Note that all technologies described in the legend produce some electricity at some point, but some produce very little compared to the other technologies.

5.1.2 Electricity capacity

In all cases, there is an expansion of the electricity production capacity, see Figure 4. Both onshore and offshore wind are expanded, as well as solar power on ground and on rooftops. The main difference is that there is no expansion of the bio CHP in the HighBio case. see Figure 5. The higher gas power capacity is always built in SE4 to help cover the demand for mFRR+, see There is also a difference in the nuclear capacity between the cases. But a higher nuclear capacity does not significantly correspond to a lower capacity of other production technologies.

In 2030, there is a low difference in the gas power capacity between the cases, except for the LowHyd case, chapter 5.3.3.

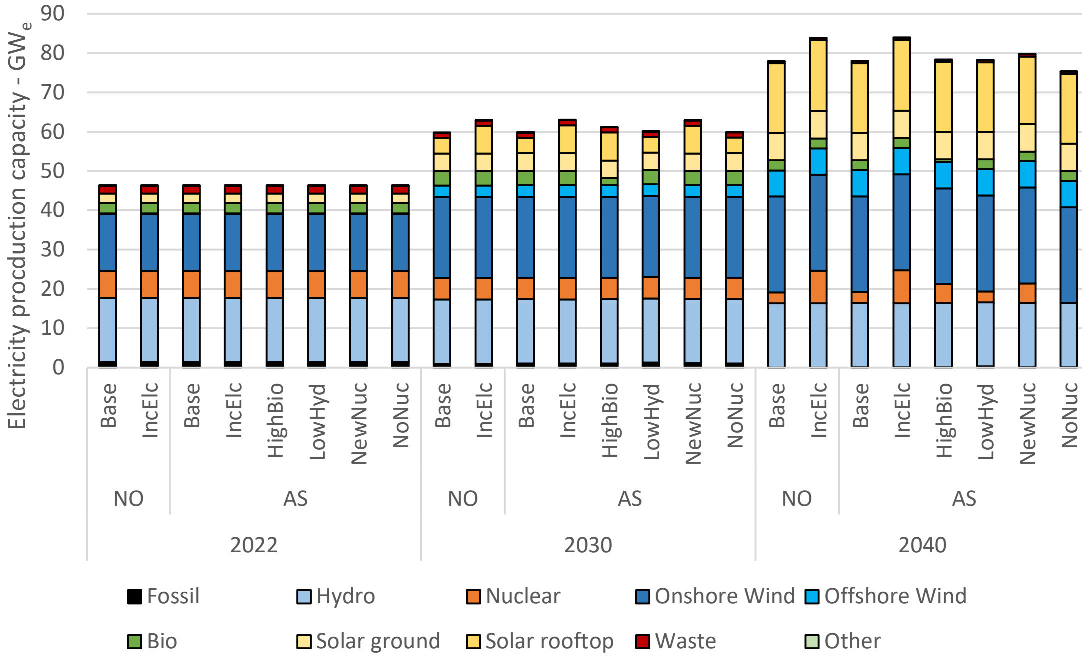

Figure 4: Modeling results for electricity production capacity in Sweden depending on fuel type. Note that all technologies described in the legend are present in the system, but some have very small capacities compared to the other technologies.

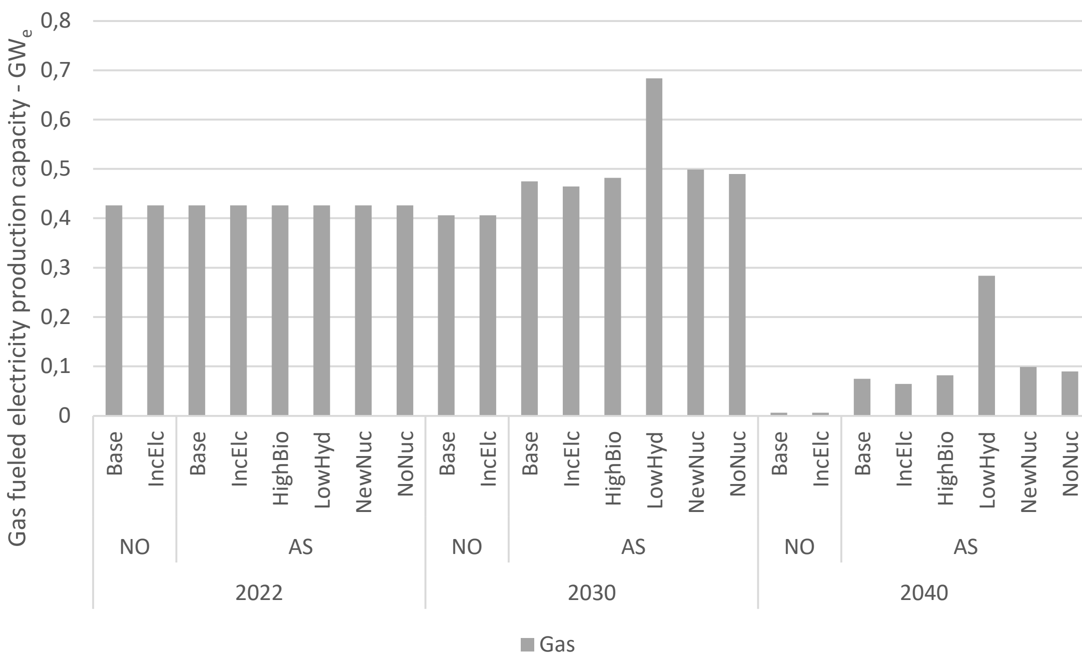

Figure 5: Modeling results for electricity production capacity from gas fueled technologies in all areas.

5.2 District heating production

The results for DH production are shown in Figure 6. 2030, although a slight increase, 8%, in the use of DH HPs is present in the NewNuc compared to the other cases, except HighBio.

In 2030, for the HighBio case, the use of bio CHP has been phased out completely, and DH HP is the dominant technology. The other cases are similar to each other in In 2040, the results are similar to the 2030 results in that no CHP is utilized in the HighBio case and that a slight increase of DH HPs is present in the NewNuc case compared to the other cases. A slightly lower use of DH is seen in the IncElc and NewNuc cases, stemming from a higher use of heating solutions which are not connected to DH.

Addition of the AS requirements to the model does not show significant impacts on the long-term cost-optimal energy system development, i.e., the optimized electricity and heat generation capacity mixes do not differ between the cases with and without AS requirements.

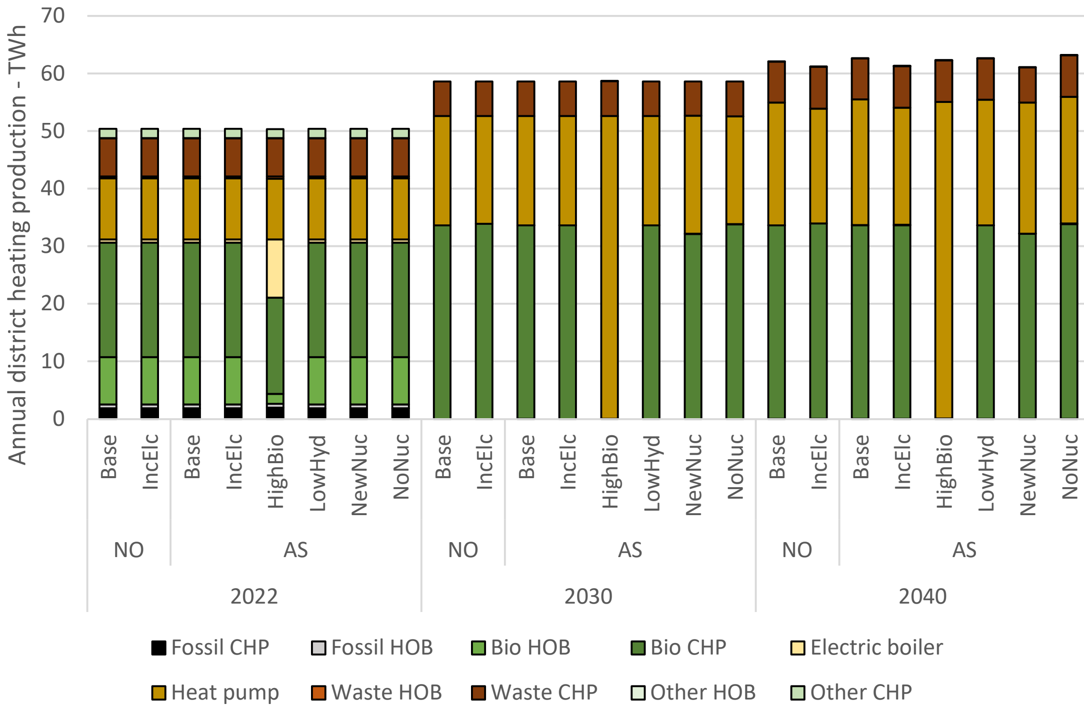

Figure 6: Modeling results for annual district heating production in Sweden.

5.3 District heating production

In this section is the provision of the different AS throughout the modeled period presented.

5.3.1 FCR-D- and mFRR-

There is an abundance of technologies available which can provide FCR-D- and mFRR- in all cases for all seasons, meaning that the availability is so high that the supply is higher than the demand. This stems from that electricity producing technologies can only provide downwards AS when they are producing electricity, and DH HPs can provide upwards AS when they are not running at full power. For more details on these AS, see the supplementary materials.

5.3.2 FCR-D+

Although several technologies are available for the provision of FCR-D+, the two dominating technologies are hydro power and batteries, see Figure 7. Some use of DH HPs can be seen in the results, most noticeable in the HighBio case, as well. The significantly higher contribution from DH HPs in the HighBio case stems from the fact that the production capacity is much higher in that case, and the ramping rate of DH HPs is much faster compared to the bio CHPs.

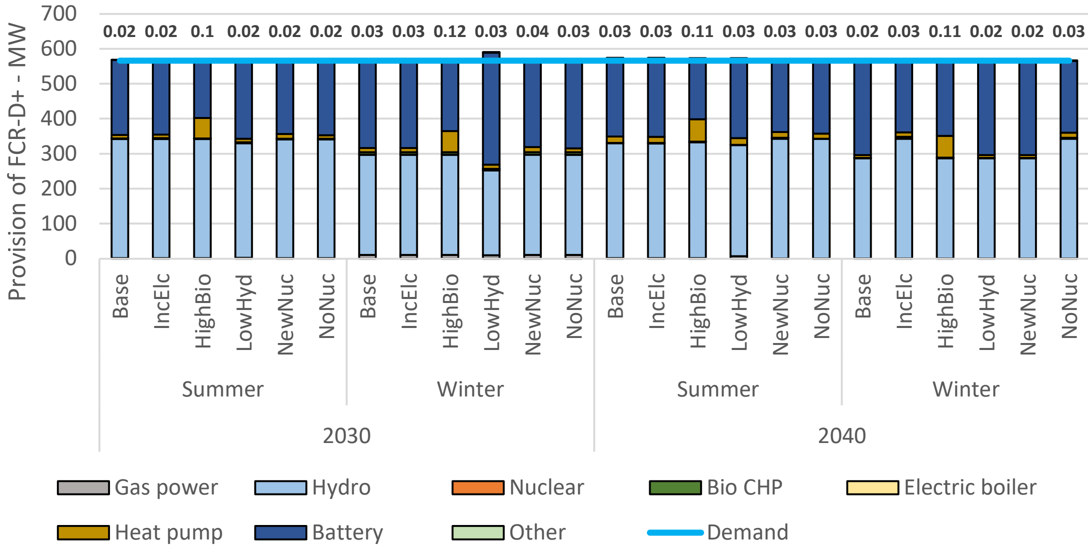

Figure 7: Modeling results for provision of FCR-D+ for Sweden. The numbers above the graphs indicate the share of the provision which stems from DH technologies.

5.3.3 mFRR+

In Figure 8, the mFRR+ in SE4 is presented. As can be seen in the figure, the demand for mFRR+ is covered by different technologies depending on the season. Overall, DH technologies provide a much higher share of the total provision of mFRR+ compared to FCR-D+. This stems from the slower activation time for mFRR+ compared to FCR-D+. The results reflect that most of the CHP pre-qualified for AS provision is qualified for mFRR [7].

During summer, when there is limited ability of biomass CHP to provide AS, other technologies cover the mFRR+ demand during that season instead. Hydro power and HPs cover a large part of the demand in both 2030 and 2040. Although in the LowHyd case, the lower provision from hydro power is instead covered by gas power, which can utilize both biogas and natural gas due to the low investment cost of gas power. The contribution from DH technologies is almost the same for all cases, between 36-39%. In 2040, the nuclear power which is built in SE4 also covers some of the mFRR+ demand. A bit of the mFRR+ demand is also covered by batteries in cases where no nuclear power is built in SE4 (NewNuc and NoNuc). The overall contribution from DH technologies is higher (39-41%) in these two cases compared to the cases where new nuclear power is built (31-32%).

During winter in 2030, all cases show a domination of mainly DH HPs and bio CHP, which cover 67-70% of the demand in all cases except LowHyd. In the LowHyd case, the gas power contribution is significantly higher compared to the other cases and the DH contribution is somewhat lower compared to the other cases (58%). There is almost no difference in the contribution from DH technologies between the cases in winter in 2040, which cover 52-53% of the demand, but the proportion of DH HPs is higher in 2040 compared to 2030 since the capacity for bio CHP is lower in 2040 compared to 2030. The lower use of batteries in the LowHyd case compared to the other cases stems from the lower ability for hydro to provide AS, making it cheaper to invest in new gas power to provide slower AS and prioritize batteries for faster AS.

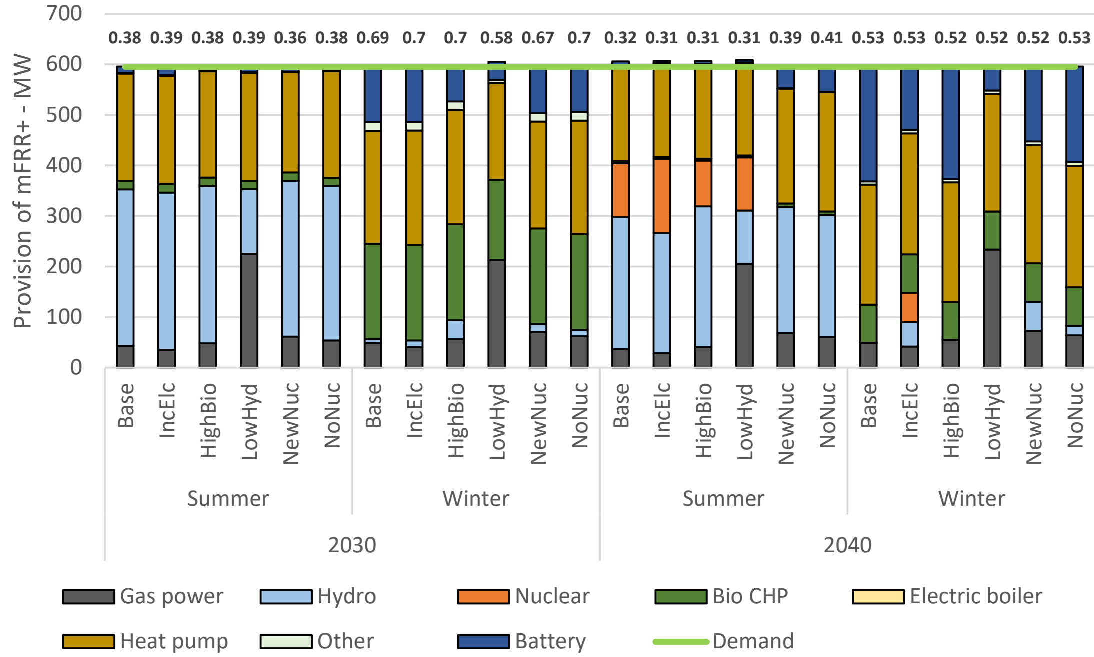

Figure 8: Modeling results for provision of mFRR+ for SE4. The numbers above the graphs indicate the share of the provision which stems from DH technologies.

6. Analysis and discussion

The modeling results show that electricity and DH production, in terms of both capacity and annual output, remain largely unaffected by the introduction of AS constraints. This indicates that investments decisions and dispatch of different power technologies within the energy system are only marginally influenced by the requirement to provide ancillary services. These results thereby contribute to understanding the role of DH in the future in a sector coupled energy system with requirements to fulfill AS in the electricity system. This is important to consider as previous studies have shown that it can be economical for DH technologies to provide AS but have not been focused on long term planning of sector coupled energy systems.

An important exception is seen in the LowHyd case with significant investments in new gas power in the area (SE4) lacking other technologies which can provide AS. These gas power units are built as reserves to cover the slower AS demands rather than covering electricity demand under normal operation. This result indicates that the main investments in new, non-gas fired, power plants are primarily made to cover the electricity and DH demands and are not affected by the AS requirements. If these technologies are not sufficient to cover the AS demands, the cheapest option for the system is to make investments in gas power plants, due to the fast ramping and low investment cost of this technology, which are only providing upwards AS but not actually producing electricity. This contrasts with the option to change production patterns by investing in more or larger plants which are then used to cover both the electricity and DH demands, as well as the AS demands.

Important to note is that the modeled cases in this study use exogenous forecasts for future demands of AS. An opportunity for future studies would be to implement how the demand for AS can be calculated endogenously within the model. The demands for the different AS are calculated depending on AS type [7], such as size of largest production unit for FCR-D, and historic imbalances for mFRR. Endogenous calculations would therefore require considering how different types of technologies contribute to the demands of the different types of AS. But as the results indicate, if the demand for AS would be even higher than what has been investigated in this study, it would be more cost efficient to build peak power compared to building larger electricity and DH production facilities.

The results further indicate that there is an abundance of downwards regulation for AS. This is largely due to the modeling results that wind power is a cost-efficient technology to cover large parts of the electricity demand as well as that the available hydro is also used to cover large parts of the electricity and AS demands. Some electricity consuming technologies in the form of DH EBs and DH HPs can also be seen in the results, but as the total provision of AS is higher than the demand, the DH technologies are not decreasing the system cost by providing the downward regulation. This indicates that companies could possibly not expect any additional revenue by qualifying their technologies for downward regulation. Revenues for already qualified technologies could also be at risk.

For DH companies, the results indicate that contributing to the AS market could result in additional income, mainly mFRR in areas where there is a low amount of hydro power available. This reflects that most of the pre-qualified capacity for AS provision from CHP plants is qualified for mFRR [7]. But as DH companies often have the local heating as their primary purpose, it is of crucial importance to make sure that the company can fulfill its obligations to its heating customers if it also contributes to the electricity system. Further, there are opportunities for DH companies to be active in the intraday market for electricity, which can also provide additional income. Being active in the intraday market as well as providing AS can however compete against each other as providing AS means that some production capacity must be reserved for AS provision and is therefore not available for use on the day-ahead market, or the intraday market. It thereby comes with potential resource and organizational challenges for the DH companies to be able to be active on several markets at the same time [38]. Although DH companies may find opportunities also in the faster markets, the results indicate that other solutions, such as batteries, could be a more cost-efficient technology to provide fast AS.

How much capacity that is prequalified for AS provision in the Swedish system is publicly available, but the actual provision of AS is not. The model results are therefore not calibrated to try and mimic the provision in the current Swedish system but uses techno-economical assessment to evaluate how AS can be provided in future systems. The results do reflect that the DH companies that are active on the AS markets are mainly active in mFRR provision [28], thereby strengthening that the results of this study reflect how AS can be provided in a future Swedish energy system.

Further, bio CHP is dependent on the availability of sufficient sustainable biomass at affordable price. As seen in the HighBio case, an increase in the prices of biomass can make bio CHP uneconomical. Future market prices for biomass are hard to predict and can rise rapidly due to outside factors. As an example, the price increased significantly in Sweden after the Russian invasion of Ukraine and was as of the beginning of 2025 almost double as of the beginning of 2022. There is also an expectation that more industries will start using residue products from forestry, which could therefore increase the competition for cheap biomass products and consequently increase market prices. As many DH systems in Sweden of today utilize biomass as the primary energy source, it can also be economical and organizational challenges for DH companies to switch their respective DH system into systems which do not rely on combustion of biomass to stay economically competitive.

7. Conclusions

In this study, an optimizing energy system model was expanded by integration of the need to provide ancillary services to the electricity system.

The results show that DH is economical in future energy systems with a mix of HPs and bio CHP, but the technology choice and sizing of DH plants is not affected by the requirements to fulfill the need for AS in the electricity sector as they are built to cover the demand for DH. But the results show that DH technologies do contribute to the provision of AS services, as they mainly cover a significant part of the slower AS (i.e., mFRR+).

However, there are some changes in the investment in new non-DH technologies in the energy system with the requirement to fulfill AS. Batteries are economical for the system to provide AS for the faster upwards regulation service. Additional gas power plants are economical to have in reserve for slower AS if the other technologies are not sufficient to cover the AS demands due to the low investment cost of gas power.

But potential for additional revenues could be viable by providing upwards regulation. In the case of heating companies, both HPs and CHP plants are viable options. But it is important for each specific company to investigate their specific technological, economical and organizational opportunities and challenges to start providing services which they have not provided previously.

The results also show that there is an overabundance of downwards regulation, meaning that companies which have not yet qualified their technologies for downwards regulation could probably not expect additional profits by providing these services. Also, the revenues from already qualified technologies could be at risk.

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