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## Centralisation of power and decentralisation of production

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### Abstract:

The future of energy is largely anticipated to be decentralised. Recent developments in renewable energy have driven this trend of decentralisation in terms of distributed generation and democratisation of power. However, these trends have started to slow, sowing doubt as to the degree of decentralisation in future energy systems. This study analyses the last ten years of the installed electricity mix in Sweden and the ownership thereof. Furthermore, an outlook thereto is provided by reviewing trends driving both increased centralisation and decentralisation. Findings show that renewable energy development is increasingly of a centralised form, and the ownership of distributed generation is slowly consolidating. These findings confirm the suspicion that the future is not inherently as decentralised as once anticipated. Implications thereof emphasise how centralised and decentralised infrastructure co-evolve. Further development in policy is required to price in the positive externalities of decentralised infrastructure and thus support neutral development.

**Keywords:** Energy futures; centralisation; decentralisation; electricity generation; grid development; systemic innovation; trend analysis; small-scale; distributed generation.

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## 1 Introduction

That we are heading towards a more decentralised system is a common narrative across media, policy pro memoria, and research articles, and has become regarded as a certainty of future energy systems (Wu et al., 2021). Following the techno-economic improvements and rising environmental concerns of the 21<sup>st</sup> century, the integration of renewable energy has flourished. This development of renewable energy brought with it a wave of small-

scale development, prosumerism, and decentralisation of power generation, by leveraging the lower costs, shorter lead times, and direct benefits of such investments (Di Silvestre, 2018; Önnared & Bravic, 2024).

These are features which have made decentralised renewables quicker to the fore, whilst centralised infrastructure has fallen behind due to requiring immense investments along with long lead-times, and legislative hindrances. Nowadays, however, slow-moving centralised infrastructure has begun to catch up and is itself now standing before a large-scale expansion. In light of artificial intelligence, deep decarbonisation through electrification, and green hydrogen – the demand for electricity is projected to increase dramatically (see e.g., Sweden Energy Agency, 2025; IEA, 2025). To meet this demand, nuclear power has experienced a renaissance, and massive offshore wind farms and energy islands are being developed throughout Europe. Concurrently, grid infrastructure stands before enormous development both within and between European countries (European Commission, 2023), moving us from a time of maintenance and management to expansion.

To support this change in direction, the Swedish Government is going through a suite of policy changes to pave the way for nuclear power and shortening lead-times for grid expansion. Including reforming several energy political targets, procuring government backed loans, and providing price guarantees (CfD) to persuade investors. Meanwhile, the incentives for more distributed power generation have been receding, and the profitability of investments is further diminishing due to an excess of renewable electricity production - indicating a turn in the extent of how decentralised the future of energy will be. Therefore, this study sets out to survey the development of electricity grids and lays forth potential avenues for its continuation by assessing different trends of centralisation and decentralisation – addressing the following research question:

*RQ: How have the trends of centralisation and decentralisation developed the last ten years and what are the future uncertainties thereof in Sweden?*

Homing in on Sweden, this paper describes how electricity systems have emerged, and the interplay between the trends of centralisation and decentralisation of energy infrastructure. Sweden serves as a prudent case for this enquiry, as its energy system can be described as both centralised in terms of a strong central government and state agencies, and decentralised given the responsibilities handed over on regional and municipal levels (Maliszewska-Nienartowicz & Stefanski, 2024). This study contributes with an outlook on possible futures given their continued interplay and critical position in an increasingly electrified future and how decentralised the future can come to be. In doing so, this study contributes to the operationalisation of energy system centralisation and decentralisation.

The following chapter provides a brief literature review presenting core concepts. Followed by a historical account of the development of modern electricity grids. In chapter 3 Methodology, data collection and the trend analysis is described. Followed by an account of the resulting trends analysis, and a discussion of how they may continue. To conclude, a set of strategic-, and policy implications, as well as avenues for further research are provided.

### *Literature review*

To begin, we must first establish a few terms and concepts. This chapter puts forth definitions of centralisation and decentralisation in the context of energy systems; and briefly discusses the distinction between electrical and institutional power as reflected by these trends.

### *Centralisation & decentralisation*

What is decentralised contra centralised depends much upon one's frame of reference. From a national perspective, district heating networks can be viewed as a decentralised form of heating; whereas from a household-level, district heating represents a centralised heating system. Table 1 present more examples thereof.

**Table 1.** Examples of centralised and decentralised systems from different perspectives.

Level	Centralised solution	Decentralised equivalent
Household	Hot-water radiator and boiler. Fireplace.	Multiple heat pumps. Candles.
District	District heating with CHP-plant. CHP-plant, solar farms, smaller wind farms, connected to the Distribution System Operator (DSO).	District heating with waste heat capture Prosuming residents and industries.
National	Offshore wind, hydropower dams, coal-, oil-, gas-, and nuclear power plants.	CHPs, solar, onshore wind, and run-of-the-river hydropower.
International	Energy independence	Interconnectors.

Source: Authors.

Whilst these concepts are relative, in the context of energy system research and practice, which commonly takes a national perspective, common positions can be found and explicit demarcations drawn (Ackermann, Andersson, & Söder, 2001).

The centralised system is comprised of large-scale power production and energy intensive consumers, connected through a high-voltage transmission grid (Dokk Smith et al., 2022). Typically, to be connected to the transmission grid, the customer should be of a magnitude greater than 100MW (Holmberg & Tangerås, 2023, p. 6). 100MW is also the threshold for reporting power production to the ENTSO-e, and an upper bound for defining decentralised production (Ackermann, Andersson, & Söder, 2001).

A decentralised system is achieved through the positioning of energy generation and conversion in relatively close proximity to its end users (Carmon et al., 2025). A decentralised system is thereby commonly found and defined as connected to the distribution grid, or below - operating at local levels (Ackermann, Andersson, & Söder, 2001).

It is difficult to draw a line between centralised and decentralised transmission systems based solely on voltage levels, rather, it is more prudent to use the legal and public classifications thereof instead (Ackermann, Andersson, & Söder, 2001). In the European context there are two distinct levels to electricity grids, namely distribution and transmission. Whereas in Sweden, however, there are the three levels of national, regional, and local that emerge as distinct levels (Maliszewska-Nienartowicz & Stefanski, 2024), however, for all intents and purposes, the regional and local comprise the Distribution System Operator (DSO) level as seen in other countries.

### *Electrical and institutional power*

In the context of energy, power refers not only to electrical power, but also political, financial and administrative power. Whilst electrical power production is becoming more decentralised in how it is distributed, political power can remain largely centralised (Carmon et al., 2025; Dokk Smith et al., 2022). Ahlqvist, Holmberg, & Tangerås (2022) provides further distinguishing between centralised and decentralised electricity markets. In this light decentralisation becomes synonymous with liberalisation and privatisation (Wilson, 2002). Following this liberalisation during the 90s, the ownership of electricity production started to decentralise. However, already in 2005, the ownership of electricity production was well concentrated to three companies, where Vattenfall was by far the largest owner followed by E.ON (at the time “Sydkraft”) and Fortum, the fourth largest had a market share of 3% (Nilsson, 2005). According to Nilsson (2005) ownership was concentrated to such an extent that any more concentration would be “welfare decreasing”. Since then, however, distributed generation in the form of wind and solar have developed immensely. Something which Carmon et al. (2025) argue should inevitably leads to the distribution of control, ownership, and responsibility amongst its local stakeholders. Despite which, we are seeing tendencies towards greater market concentration and the accompanying inefficient market behaviour and decreasing customer satisfaction (Holmberg & Tangerås, 2023; SKI, 2025).

## **2 The past**

This chapter provides a background on the development of the electrical grid. Starting with its grassroots beginnings, to the large-scale electrification of the 60s, and up to present day.

Historically, changes of energy systems were slow, from biomass such as firewood, food and human work; to the domestication of animals; and then the utilization of energy through water- and windmills. The more modern systems began to emerge during the 18-hundreds. Towards the end of the 1930s, there were an excess of 3500 electricity distribution companies in Sweden (Heden, 2012). Most of which were grassroots movements, organising local actors and skills in unison to create local grids. Capacity was limited and the customers few, ownership structures were predominantly economic cooperations, the others were larger industrial companies who procured their own electricity whilst also distributing to its community. In the cities, steam driven power generators were built, powered by coal, peat, and oil, largely owned by their municipalities (Heden, 2012). On the countryside, many small hydropower plants, established around communities and industries with sufficient demand and of course, the natural resources

(Wangel, 2015). Gradually these local electricity systems were connected into larger grids eventually spanning regions, countries and continents – now described as the biggest machine in the world (Baird, 2021). As demand grew, more hydropower was exploited in the northern parts of Sweden, supplying the south through transmission grids enabled by the higher voltage alternating current cables. Investments in both power generation and the accompanying transmission was costly, which led to coalitions sharing the cost and risk (Wangel, 2015).

Thereafter came the large-scale development of nuclear power. The biggest expansion of the Swedish electricity system was from the 1950s to the 1980s when the last nuclear power plant was inaugurated (Wangel, 2015). The development of the transmission grid subsequently followed and continued to increase following increased international trade (Wangel, 2015). Meanwhile, the economies of scale of these large-scale power production facilities made it infeasible to continue to operate local power production, thus leading to the ceasing of production (Wangel, 2015).

### **3 Methodology**

This study surveys the trends of centralisation and decentralisation in electricity infrastructure. Combining a quantitative analysis of statistical data on electricity production and ownership, and a qualitative analysis of outlooks, projections, and projects in the pipeline to gauge their emerging trajectories. To validate the interpretation of data, 3 unstructured interviews were conducted with data owners and DSO actors.

#### *Data*

Publicly available data from the Swedish Energy Market Inspectorate (Ei), ENTSO-e, SCB, and Swedish Energy Agency is used. Additional data was acquired from Green Power Sweden. Ei provides insight into the total number of feed-in connection points at the different grid levels and includes, how many thereof are small-scale, and how much electricity is fed into the grid in total from these sources. Data from ENTSO-e shows total installed capacity and units greater than 100MW, and aggregate data from all production units equal or greater than 1MW. Swedish Energy Agency provides data on number of units of solar power and wind power delineated between land and sea. Finally, Green Power Sweden, an interest group for renewable energy, procured ownership data amongst its member organisations which represents approximately a third of total capacity. Ownership data for 2020-2021 were either missing or excluded due to quality discrepancies.

In some instances, the data had to be scrubbed for double reporting during e.g., such acquisitions, and miss-reported figures that show as clear outliers. Other aspects such as legislative changes have affected organizational forms and reporting necessities which affects the reporting of data.

#### *Analysis*

The historical trend of decentralisation is thereafter calculated as the fraction of decentralised production of the Total Grand Capacity ( $T_{gc}$ ), as seen in equation 1. Total

Centralised capacity is defined as units above 100MW ( $T_c$ ) which is subtracted from the total, giving us the remaining production as small-scale, defined as decentralised. The 100MW threshold reflects both ENTSO-e reporting practices and established literature, rather than a normative claim about decentralisation per se.

$$D_c = \frac{T_{gc} - T_c}{T_{gc}}$$

Concerning ownership, the data was aggregated such that the scale of the owner was delineated in a similar manner as that of individual plants. Entities with total owned capacity above 100MW were classified as centralised, whereas smaller shares were deemed small-scale and thus decentralised. In the event of co-ownership, the share of ownership was attributed the corresponding share of production capacity.

To look forward, however, a more qualitative enquiry is required. To do so, we undertook an extensive scanning exercise, focusing on input from industry and industry associations, media, meetings and conferences, and grey literature (Hines et al., 2019). This included amongst other things: reports, statistics, and forecasts from industry associations; short-term forecasts and long-term scenarios of public agencies; and industry conference and seminar participation.

### *Limitations*

A limitation within this work is that we make no attempts to weigh aspects such as grid level, capacity, and governance against each other, further research could work to establish a composite indicator, building upon this operationalisation.

The effective capacity of many renewable technologies is only a fraction of the installed capacity. Therefore, the  $T_{gc}$  can appear inflated. The alternative would be to look at generated electricity. However, this is hindered by a lack of granular data and behind the meter consumption.

Ownership data is not representative of the entire electricity mix. However, considering how renewable the Swedish electricity system is and how centralised the remaining capacity is, it gives us a strong indication of the trend.

Furthermore, there are small units which are not reported, off-grid solutions, and energy communities are not found in the data. By taking a top-down approach to this question, centralised systems are inevitably favoured since we adhere to centralised reporting schemes. A bottom-up approach which instead attempts to capture the small-scale, decentralised production and ownership thereof, could provide a clearer picture thereto, however, cumbersome.

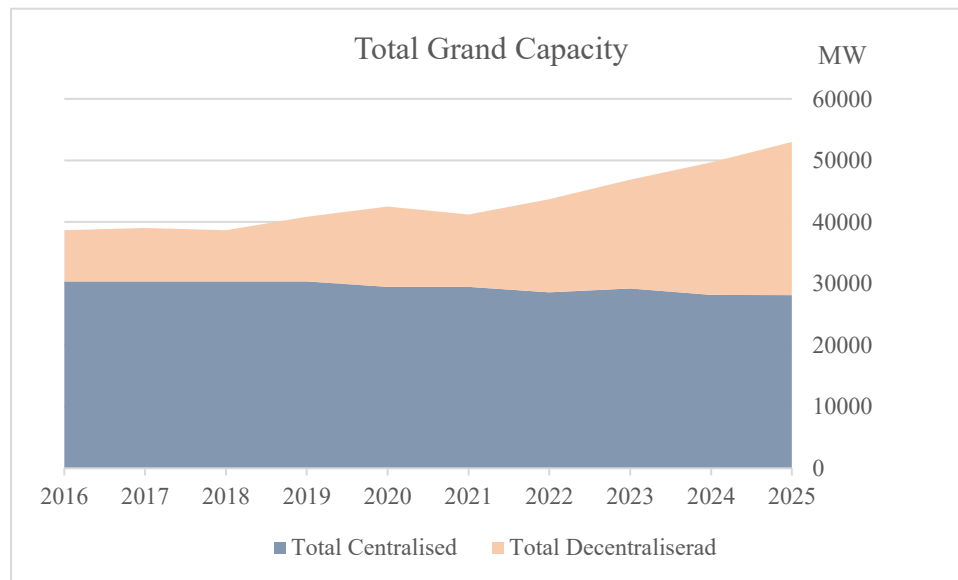
## **4 The present state**

This chapter presents the results as pertaining to the recent development of centralised and decentralised infrastructure, and how the ownership thereof has evolved.

### *Installed production capacity*

Installed decentralised capacity took off noticeably in 2019, and between 2019 and 2024, the number of feed-in subscriptions have increased from an approximate 40 000 to 300 000 nationally. Most of which are so-called micro producers (maximum 43,5kW). In total, installed capacity of generation below 100MW in size has increased threefold over the last ten years. Whereas large-scale capacity decreased by approximately 0,72% per year over the last ten years. This can be explained through the shutdown of 4 out of 10 nuclear reactors during the period of study. This should show a more significant drop in centralised capacity; however, this drop has been offset by an increase in centralised wind capacity.

For wind power, there are 46 onshore parks exceeding 100MW, making up half of the total wind power capacity, notably, however, 3 parks lie just below the threshold at 98MW. Offshore wind parks remain few, in total there are 75 turbines, 48 of which are concentrated in the largest park, which has an installed capacity of 110MW (Vattenfall, n.d.), the closest runner up is the Kårehamn windfarm with a capacity of 48MW. Hydropower has an installed capacity of 16,400MW, of which 54% is from capacity above 100MW, spread across 40 units. Three CHP units over 100MW are reported with a combined capacity of 614MW.



*Figure 1. Total Grand Capacity of Sweden. Source: Entso-e*

Amongst the historical data set, no solar power reaches the scale of what we define as centralised production. The largest park in operation reported 91,3MW<sup>1</sup> in installed capacity, with the closest runner up at approximately 64MW, put into operation earlier the same year. If this trend continues, we can expect solar parks exceeding 100MW in the future. Installations of roof-top solar, however, have started to slow. This is in part due to the removal of a tax reduction incentivising installations; and in part due to diminishing

<sup>1</sup> Some sources report this park as 100MW, the value used is drawn from ENTSO-e reporting for consistency.

returns on investments, exacerbated by the removal of tax reduction on sold electricity from micro-producers.

### *Ownership of production capacity*

Since the concentrated market situation in 2005, there has been a significant diffusion of ownership and decentralisation in terms of production. However, in more recent times, we see that despite a tremendous increase in decentralised production capacity, the ownership thereof has not followed the same trajectory. Figure 2 depicts the share of ownership across solar and wind power capacity in Sweden. Remaining rather constant the last ten years, showing only a notable and potentially altering trajectory just the last year. This means, that despite an increase in decentralised production, ownership thereof has concentrated, and the rate thereof is now increasing.

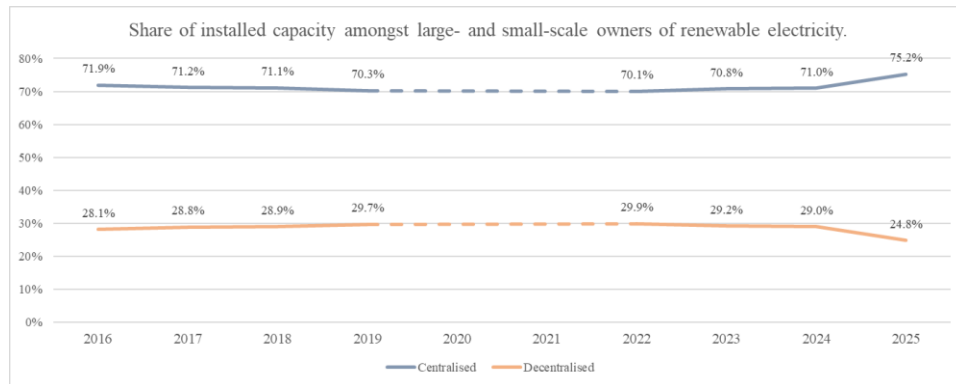


Figure 2. Distribution of ownership of power production. Source: Green Power Sweden.

This observation can be explained through a few mechanisms. For one, there has been a slow, yet steady consolidation of energy companies (see e.g., Wasilewska et al., 2022), most of which are small and locally or municipally owned. Most of the consolidation is done by the three largest DSOs, and whilst customer satisfaction is decreasing across the board for energy companies, the greatest dissatisfaction can be observed with these three (SKI, 2025). To gauge the general ownership of electricity production, Swedenergy reported numbers for 2020 across their members (representing 77% of total capacity, with the remaining largely comprised of smaller owners), stating that the Swedish state owned 41% of capacity, foreign national equivalents combined owned 36%, municipalities 13%, and other actors 10%, showing how rather centralised ownership of capacity is (Swedenergy, 2023).

Secondly, previously small-scale actors may have grown to become considered large-scale according to our definition by growing their portfolio of electricity production. Meanwhile, as currently operating decentralised solutions approaching their end-of-life, introduces further uncertainties in terms of restoration and reinvestment (Sandoff & Williamsson, 2020).

Lastly, since this dataset represents only renewable energy, this can also be attributed to the large-scale development of wind power which has offset the loss of nuclear power capacity. To complement this view, we can also state that ownership of CHP capacity is

largely decentralised. Meanwhile, however, 95% of hydropower capacity can be classified as centralised ownership.

## 5 Outlook

The last few years have shown an excess of distributed renewable power capacity being installed, evenly split between small- and large-scale actors. Whether these trends continue, however, is not as certain and unveils several avenues of potential development.

In terms of installed power capacity, we see tendencies towards large-scale infrastructures such as nuclear power, large-scale offshore wind parks, however, both riddled with uncertainty. Meanwhile, the expansion of decentralised capacity is starting to slow down, and with approaching re-investment needs, future capacity could stagnate at levels lower than previously anticipated. Meanwhile, a slew of ancillary trends is pushing the decentralisation and centralisation of energy infrastructure, as presented in Table 2, providing an account of broader trends. The chapter then continues with a more detailed outlook of the continued development of solar-, wind-, hydro-, combined heat and power, and nuclear power.

**Table 2.** Trends.

Trend	Centralised development	Decentralised development
Storage	Reopening of pumped-hydro storage. Increasing installations of grid sized batteries.	Growing share of home batteries installation, and increased penetration of EVs and growing potential for EVs with V2G.
Hydrogen	Emerging demand for green hydrogen and ammonia is pushing for the buildout of national transmission capacity and centralised power production.	Electrolysers can be placed proximity to e.g., wind parks and thereby alleviate grid congestion through pipelines and balancing through flexibility. Hydrogen production at the local level can be coupled with district heating networks such that some of their inefficiencies are recouped through waste heat capture.
Balancing	Previous balancing responsible actors attempt to retain their position and delaying legislation which otherwise would support greater competition.	New formal roles (the BSP), allowing for more emerging actors in the balancing markets. Increasing amount of registered and active BRPs and BSPs.
Grid expansion	Immense congestion revenues are being fed into centralised transmission capacity.	Local grids are, likewise, undergoing significant development. Local flexibility markets are emerging. Some energy communities build internal grids.
Protection of interests	The oligopoly does their best to maintain their revenue streams by maintaining barriers for new market entrants. Large firms use their lobbying resources to promote their agenda and protect their respective interests.	The evolution of niche actors, such as aggregators focusing on aggregating home batteries for energy optimisation, or steering equipment for house heating.
Professionalisation	Consolidation of firms. Growth which surpasses definition of small-scale. Growing complexity in markets, leads to the need for dedicated knowledge.	Smaller actors are growing in size, larger parks and portfolios whilst remaining small-scale and decentralised. Actors specialise in offering decentralised solutions to end user that are custom made.

Energy-as-a-Service	Concentrates the ownership of production.	Supports the development decentralised production. Creates platforms for aggregation which can compete with incumbents.
Resilience	Focus on security, defence, and geopolitical situations is driving centralised efforts to bolster energy resilience.	Efforts made on local levels to build out preparedness, island mode capacities, emergency inverters, etc.

Source: Authors.

### *Solar power*

The pace of new solar installations grew until 2023, then the number of installations fell with 62% 2024 and another drop with 39% for 2025 (Svensk Solenergi, 2025). This collapse can partly be explained through the increased cannibalisation of profitability within solar- and wind power, in combination with slow legislative changes and populist incentives which became unsustainable for the renewable industry. The first time Sweden encountered negative day-ahead prices was on the 12 of November 2022, However, this has increased rapidly, during 2025 Swedens four electric bidding areas had negative prices during 3.9-7.8% of all hours of the year (for a comparison Germany had 6.5% of the hours with negative pricing). At the same time the subsidies benefiting wind and solar installations have diminished. E.g., beginning of 2026, the tax reduction micro producers were abolished. In turn, lowering the interest for new installations of solar power, but at the same time increasing the interest in adding home batteries to existing solar power installations to increase profitability, a development which can in the future support the continued development of so-called hybrid parks.

There are not only economic incentives, however. Recent pressures to bolster resilience drives further investments in solar panels combined with emergency inverters and storage solutions, creating back-up systems. Similarly, this is a driver for decentralisation on a distribution network level. In preparation for crisis, the ability for local grids to operate independently of the transmission grid are being explored.

### *Wind power*

Looking at the other big driver for decentralisation of electricity production; wind, there is an even greater stagnation in development. In the period 2025-2027, half of parks taken into operation or under construction can be considered decentralised, accounting for only 20% of newly installed capacity. Past 2027, no new development is currently anticipated as current investments have come to a full stop (Johansson, 2026). Many established wind production companies are making great losses and seeing increased cost, partly because of cannibalisation, but also from increase imbalance cost since Sweden transitioned to imbalance settlement period (ISP) of 15 min and flow-based capacity calculation.

The permitting environment for onshore wind power in Sweden has meanwhile deteriorated, while 48 % of permit applications were approved over the full period of 2014-2025, approval rates declined sharply to 6 % in 2024 and 17 % in 2025. Municipal vetoes are the dominant objections, accounting for 13 out of 15 unsuccessful applications in 2025 (Westander & Kaufmann, 2026). Meanwhile, the Swedish government rejected thirteen out of fourteen proposals for offshore wind power development, all of which were greater

than 1,000MW in capacity, citing military security concerns (Government Offices of Sweden, 2024). The approved, a 1,400MW park, is planned to be taken into operation early 2030s.

Meanwhile, however, onshore wind power is expected to meet the rise on electricity demand in the short- to medium term, showing the discrepancy between modelled scenarios and unfolding reality (see e.g., Johnsson et al., 2025; Swedish Energy Agency, 2025). This asymmetrical development of onshore and offshore wind power will further skew development towards greater centralisation.

### *Hydropower*

The large share of hydropower in the Nordic energy mix provides a centralised backbone of the system through large-scale facilities, as well as a decentralised resource through the vast number of distributed generators.

The future of hydropower in Sweden is considered quite certain. In the national long-term energy scenarios, the four different scenarios see no variations in term of hydropower capacity, with all increasing approximately 2GW through capacity increases and efficiency improvements of current large-scale facilities (Swedish Energy Agency, 2025). However, underlying the assumption of continued or evenly increasing hydropower capacity, is a changing composition between the large- and small-scale. For instance, an ongoing and highly debated hydropower permit review, however, is inflicting some uncertainty. Which may inflict unevenly on large- contra small-scale hydropower plants.

Overall, there are only few hydropower developments, across both small- and large-scale facilities, and there appears to be a continued loss of decentralised capacity. There is, however, also a moderate loss from the capacity of some large-scale units, however, this deficit is made up by investments in capacity increasing measures, and an increase in precipitation which increases the total energy produced over a year. There lies greater uncertainty as to the future of decentralised hydropower, whether they persist or continue to phase out as they reach their ends-of-life. Both centralised and decentralised hydropower has the technical potential for capacity and efficiency improvements, however, the lack of profitability and capital intensity of such investments make them rather unlikely (Sandoff & Williamsson, 2020). The more likely development is status quo for centralised hydropower, accompanied by a steady decommissioning of decentralised hydropower plants, possibly complemented by a few capacity increasing measures.

### *Combined heat and power*

Combined heat and power (CHP) plants have been a staple of decentralised infrastructure in Sweden for some time now. Connected to local grids, CHPs provide plannable baseload production, oftentimes using local forest residue products or household waste as feed-in fuels. This capacity was built up over a long period, replacing direct electric heating and oil-fired boilers (Dzebo & Nykvist, 2017). It should be noted, however, that the primary business of these facilities is heat, and electricity production is an extra service (AFRY, 2025).

Nowadays, however, due to rising competition from other heating solutions such as heat pumps and geothermal, rise of negative prices, and removal of the electricity certificate system - an expansion of district heating and subsequent power production from CHP-plants is therefore currently seen as unlikely. Concurrently, much of this infrastructure, built out in the past century, is approaching their end-of-life in terms of both networks and plants – which has their owners contemplating alternative solutions (AFRY, 2025).

Nevertheless, with 90% of the multi-family housing in Sweden being connected to district heating its position remains secure for the foreseeable future. However, with diminishing heat demand, there is also less potential to generate electricity (Swedish Energy Agency, 2025; AFRY, 2025). Potential for capacity improvements can be found in heating plants, which lack power producing capabilities (AFRY, 2025; see e.g., Carpe Futurum).

Despite already considered a decentralised resource, district heating systems are becoming more decentralised, increasing in the utilisation of waste heat and heat pumps (Swedish Energy Agency, 2025). In Swedish Energy Agency's 2050 scenarios, electricity production remains stable from CHPs until 2030, from where it starts to decline. Two scenarios see some of this capacity being replaced with Small Modular Reactors (SMR) which could become another source of competition in the heating market, if allowed, and subsequently affect electricity capacity of CHPs in the future.

### *Nuclear power*

Currently operating nuclear power plants could continue to operate until 2045 without lifetime extensions. This planned decommissioning, however, has been upheaved, and currently operating power plants are seeking to prolong their life, and legislation has opened for new nuclear power plants, at both old and new sites.

Nuclear power capacity is expected to remain in the foreseeable future and possibly increase further along if new investment steps are taken alongside continued political support, and in doing so driving further centralisation. Whilst no nuclear power is categorised as decentralised herein – SMRs in the upwards of ~500MW are potentially entering the mix, allowing for more decentralised nuclear power (WSP, 2022; Krayem & Thorin, 2024). Weaker signals of decentralisation of nuclear power includes so-called micro reactors with off-grid application such as nuclear submarines, ships, or even space applications (Morones-García & François, 2024).

## **6 Conclusions**

The future of energy is not necessarily as decentralised as once anticipated. Decentralisation was merely the low hanging fruit of the energy transition. The future of energy is rather paradoxically becoming more centralised and decentralised at the same time, requiring a balancing of centralised and decentralised infrastructure (see also, Funcke & Bauknecht, 2016; Maliszewska-Nienartowicz & Stefanski, 2024). Renewable developments are growing in size but are yet to achieve the grandeur of centralised infrastructure. Meanwhile, ownership of installed capacity is growing in the hands of large

actors, outpacing the slowing development of small-scale infrastructure; and the continued political power of incumbents shows that decentralised production does not necessarily lead to the decentralisation of power.

Historical changes of our energy systems may be slow, but they show a cyclical trend back and forth between developing centralised and decentralised systems (Schewe, 2006). However, the trends of centralisation and decentralisation are not a pendulum back and forth on a spectrum. It is rather a process of co-evolution, building upon prior infrastructure. The trends of centralisation and decentralisation are typically viewed as a proportion, supporting the claim that the system is decentralising. However, this observation overlooks the fact that centralised infrastructure has retained its absolute position, power, and now is expected to grow. To say that the future is decentralised, is thus an inaccuracy. Nevertheless, there are many uncertainties – not the least in decentralised infrastructure. Onshore wind power developments have stagnated, solar power development is slowing down, and CHP has an uncertain future. Meanwhile, offshore wind has great potential but remains limited, nuclear power is experiencing a renaissance, and hydropower continues to prevail, however, with a questionable balance between the large- and small-scale. The outlook provided in this study is largely contingent on political decisions which significantly affect the future of centralisation and decentralisation - and is thus a major source uncertainty.

### *Strategic implications*

The co-evolution of centralised and decentralised energy infrastructure challenges the assumption that energy transition is a zero-sum process, in which decentralised energy resources and production displaces large, centralised units. Strategic decision-making should hence account for the simultaneous expansion of both infrastructures, rather than seeing their pathways as mutually exclusive.

However, the growing concentration of ownership in renewable capacity suggest that competitive dynamics increasingly resembles that of the traditional energy sector. Emerging solutions and enterprises are lacking the disruptive potential of decentralisation when they are forced to compete with the structural reality that large actors continue to maintain, whilst also consolidating their positions.

### *Policy implications*

Politics and policy have significant implications on the development of the balance between centralised and decentralised infrastructure, and so too then, does this study bear implications for policy.

Firstly, the finding that centralised infrastructure retains, and expands(!), its position challenges the narrative of decentralisation as an energy transition. The second implication concerns the valuation of system levels benefits. As the energy system grows in both centralised and decentralised directions simultaneously, the contributions of distributed resources are far from captured by current market mechanisms (see also, AFRY, 2025). Benefits such as taking care of waste processes, local production, stability and balancing create positive externalities. Neutrally pricing these externalities across both centralised

and decentralised infrastructures would support a more balanced co-evolution of the two modes.

Furthermore, to aggregate these benefits, future subsidies and investments should holistically address investments to capture their synergies. Electric vehicles combined with smart chargers can allow for vehicle-to-grid solutions, benefitting both the decarbonisation of transportation and the balancing of the grid; solar instalments coupled with emergency inverters supports island mode operation lowering emissions and aiding resilience; and heat pumps together with Internet-of-Things capabilities creates efficiency improvements in both energy and power use. Thereby future proofing the investments made today.

Lastly, the Swedish context illustrates how regulatory and permitting frameworks can become structural bottlenecks. The rejection of offshore wind projects in the Baltic Sea exemplifies how policy decisions shape the centralisation-decentralisation balance in ways that the market mechanisms cannot explain. Policymakers should therefore be attentive to how such decisions interact with broader system design objectives and not fall victim to centralised tunnel vision (Önnered et al., 2025).

#### *Future research directions*

The delineation between centralised and decentralised infrastructure as applied in this study, serves as a rather crude measure. Further work should be diverted to developing a more nuanced categorisation of the two. Such a continued operationalisation should consider varying national contexts and scale of energy infrastructure in different regions; transmission- and distribution capacity; and the proximity to consumption of proportionate scale. Further consideration should also be given to the development of storage capacity and flexibility to view at which levels of electricity grids these emerge and how control thereof is exercised.

Secondly, finding data on newly added capacity is easier to follow than those which decommission. With forthcoming reinvestment needs across all subsequent forms of electricity production, monitoring the development of decommissioning and rate of reinvestment becomes important in understanding the greater picture of power capacity.

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## References

- Ackermann, T., Andersson, G., & Söder, L. (2001). Distributed generation: A definition. *Electric Power Systems Research*, 57(3), 195–204. [https://doi.org/10.1016/S0378-7796\(01\)00101-8](https://doi.org/10.1016/S0378-7796(01)00101-8)
- AFRY. (2025). Potential för ökad eleffekt och beredskap från Sveriges fjärr- och kraftvärme. Available at: <https://via.tt.se/files/3038139/4118276/247008/sv>
- Ahlqvist, V., Holmberg, P., & Tangerås, T. (2022). A survey comparing centralized and decentralized electricity markets. *Energy Strategy Reviews*, 40. <https://doi.org/10.1016/j.esr.2022.100812>
- Baird, W., H. (2021). Measuring the balance of the world's largest machine. *Am. J. Phys.* 1 December 2021; 89 (12): 1086–1093. <https://doi.org/10.1119/10.0005989>
- Carmon, O., Teschner, N., Zemah-Shamir, S., & Parag, Y. (2025). Evaluating energy security in decentralized systems: Review and new index. *Energy Strategy Reviews*, 60(June), 101754. <https://doi.org/10.1016/j.esr.2025.101754>
- Di Silvestre, M. L., Favuzza, S., Riva Sanseverino, E., & Zizzo, G. (2018). How Decarbonization, Digitalization and Decentralization are changing key power infrastructures. *Renewable and Sustainable Energy Reviews*, 93(May), 483–498. <https://doi.org/10.1016/j.rser.2018.05.068>
- Dokk Smith, I., Kirkegaard, J. K., & Szulecki, K. (2023). A functional approach to decentralization in the electricity sector: learning from community choice aggregation in California. *Journal of Environmental Planning and Management*, 66(6), 1305–1335. <https://doi.org/10.1080/09640568.2022.2027233>
- Dzebo, A., & Nykvist, B. (2017). A new regime and then what? Cracks and tensions in the socio-technical regime of the Swedish heat energy system. *Energy Research & Social Science*, 29(May 2016), 113–122. <https://doi.org/10.1016/j.erss.2017.05.018>
- European Commission. (2023). Grids, the missing link - An EU Action Plan for Grids. Available at: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2023%3A757%3AFIN&qid=1701167355682>
- Funcke, S., & Bauknecht, D. (2016). Typology of centralised and decentralised visions for electricity infrastructure. *Utilities Policy*, 40, 67–74. <https://doi.org/10.1016/j.jup.2016.03.005>
- Government Offices of Sweden. (2024). Avslag på 13 havsbaserade vindkraftparker i Östersjön. Press release. Available at: <https://www.regeringen.se/pressmeddelanden/2024/11/avslag-pa-13-havsbaserade-vindkraftparker-i-ostersjon/>
- Heden, H. (2012). Energimarknadsinspektionen – En sekellång historia. Available at: <https://ei.se/download/18.7353d1b51757f917add78563/1605777386573/Energimarknadsinspektionen-en-sekell%C3%A5ng-historia-bok.pdf>
- Hines, P., Hiu Yu, L., Guy, R. H., Brand, A., & Papaluca-Amati, M. (2019). Scanning the horizon: A systematic literature review of methodologies. *BMJ Open*, 9(5), 1–9. <https://doi.org/10.1136/bmjopen-2018-026764>

Holmberg, P., & Tangerås, T., P. (2023). Den svenska elmarknaden – idag och i framtiden. Available at: [https://www.riksbank.se/globalassets/media/rapporter/pov/artiklar/svenska/2023/230512/2023\\_1-den-svenska-elmarknaden--idag-och-i-framtiden.pdf](https://www.riksbank.se/globalassets/media/rapporter/pov/artiklar/svenska/2023/230512/2023_1-den-svenska-elmarknaden--idag-och-i-framtiden.pdf)

Holmberg, P., & Tangerås, T., P. (2023). *En teknikneutral elmarknadsdesign – med en effektiv elmarknad och nättarifstruktur*. Available at: [https://www.riksbank.se/globalassets/media/rapporter/pov/artiklar/svenska/2023/230512/2023\\_1-den-svenska-elmarknaden--idag-och-i-framtiden.pdf](https://www.riksbank.se/globalassets/media/rapporter/pov/artiklar/svenska/2023/230512/2023_1-den-svenska-elmarknaden--idag-och-i-framtiden.pdf)

IEA. (2025). World Energy Outlook 2025. International Energy Agency, Paris. Available at: <https://www.iea.org/reports/world-energy-outlook-2025>

Johansson, A. (2026). Kvartalsstatistik Green Power Sweden. Available at: <https://greenpowersweden.se/statistik/statistik-och-prognos-fjarde-kvartalet-2025/>

Johnsson, F., Göransson, L., Chen, P., Öberg, S., et al. (2025). Så får industrin tillräckligt med el till 2035. Available at: <https://energiforsk.se/media/gygf3zer/2025-1033-sa-far-industrin-tillrackligt-med-el-till-2035-slutrapport.pdf>

Krayem, A., & Thorin, E. (2024). Sustainability assessment of Sweden's nuclear power: implications of the new expansion plans. *Environment, Development and Sustainability*. <https://doi.org/10.1007/s10668-024-05219-8>

Maliszewska-Nienartowicz, J., & Stefański, O. (2024). Decentralisation versus centralisation in Swedish energy policy: the main challenges and drivers for the energy transition at the regional and local levels. *Energy Policy*, 188(March). <https://doi.org/10.1016/j.enpol.2024.114105>

Nilsson, M. (2005). Electric power oligopoly and suspicious minds - A critique of a recently approved merger. *Energy Policy*, 33(15), 2023–2036. <https://doi.org/10.1016/j.enpol.2004.03.024>

Sandoff, A., & Williamsson, J. (2020). Investeringar i förnybar kraftproduktion -Aff ärmässiga drivkrafter och samhällsliga ansvarsperspektiv. Available at: [https://www.nepp.se/pdf/Drivkrafter\\_ansvar\\_investeringar.pdf](https://www.nepp.se/pdf/Drivkrafter_ansvar_investeringar.pdf)

Schewe, P.F. (2006). The grid: a journey through the heart of our electrified world. Washington, D.C.: J. Henry Press.

SKI. (2025). Kundnöjdheten i energibranschen närmar sig kritiskt låga nivåer. Svensk Kvalitetsindex. Available at: <https://www.kvalitetsindex.se/wp-content/uploads/2025/11/ski-energi-2025.pdf>

Svensk Solenergi. (2025). Grönt avdrag. Available at: <https://svensksolenergi.se/statistik/gront-avdrag-ny/>

Svensksolenergi. (2025). Grönt avdrag. Available at: <https://svensksolenergi.se/statistik/gront-avdrag-ny/>

Sweden Energy Agency. 2025. Scenarier över Sveriges energisystem: Vägar till ett energisystem med nettonollutsläpp 2050. 978-91-7993-230-5. Available at: <https://energimyndigheten.a-w2m.se/Arkitektkopia/ViewTemplate?tid=1173312576a844f5a08e2c4a2005ccfb>

- Swedenergy. (2023). Vem äger elproduktionen? Available at: <https://www.energiforetagen.se/energifakta/elsystemet/produktion/vem-ager-elproduktionen/>
- Vattenfall. (n.d.). Lillgrund. Available at: <https://powerplants.vattenfall.com/sv/lillgrund/>
- Wangel, J. (2015). *Developing Sweden's transmission grid: what are the drivers and barriers?*
- Wasilewska, N., Wasilewski, M., Zabolotnyy, S., & Osiichuk, D. (2022). The Impact of M & As on the Competitive Positioning of European Energy Firms and Market Power Concentration. *Energies*, 15(8798). <https://doi.org/https://doi.org/10.3390/en15238798>
- Westander, H., & Kaufmann, W. (2026). Statistik om landbaserad vindkraft 2014-2025: Samråd, ansökningar, beslut, avslagsanledningar. Available at: <https://greenpowersweden.se/wp-content/uploads/2026/03/Tillstand-landbaserad-vindkraft-2014-2025-slutversion-2026-02-23.pdf>
- Wilson, R. (2002). Architecture of Power Markets. *Econometrica*, 70(4), 1299–1340. <http://www.jstor.org/stable/3082000>
- WSP. (2022). Små modulära reaktorer – En framtidsprognos för industri och samhälle. Available at: <https://www.wsp.com/sv-se/insikter/sma-modulara-reaktorer>
- Wu, T., Xu, D. L., & Yang, J. B. (2021). Decentralised energy and its performance assessment models. *Frontiers of Engineering Management*, 8(2), 183–198. <https://doi.org/10.1007/s42524-020-0148-7>
- Önnered, S., & Bravić, I. (2024). Systemic Innovation in the European Energy Sector: A Collective Outlook. *Journal of Innovation Management*, (PG-). [https://doi.org/10.24840/2183-0606\\_012.002\\_0003](https://doi.org/10.24840/2183-0606_012.002_0003)
- Önnered, S., Johansson, P. E., Stefan, I., & Fundin, A. (2025). Emerging threats to energy security - a Delphi study. *Energy Policy*, 206(June). <https://doi.org/10.1016/j.enpol.2025.114735>