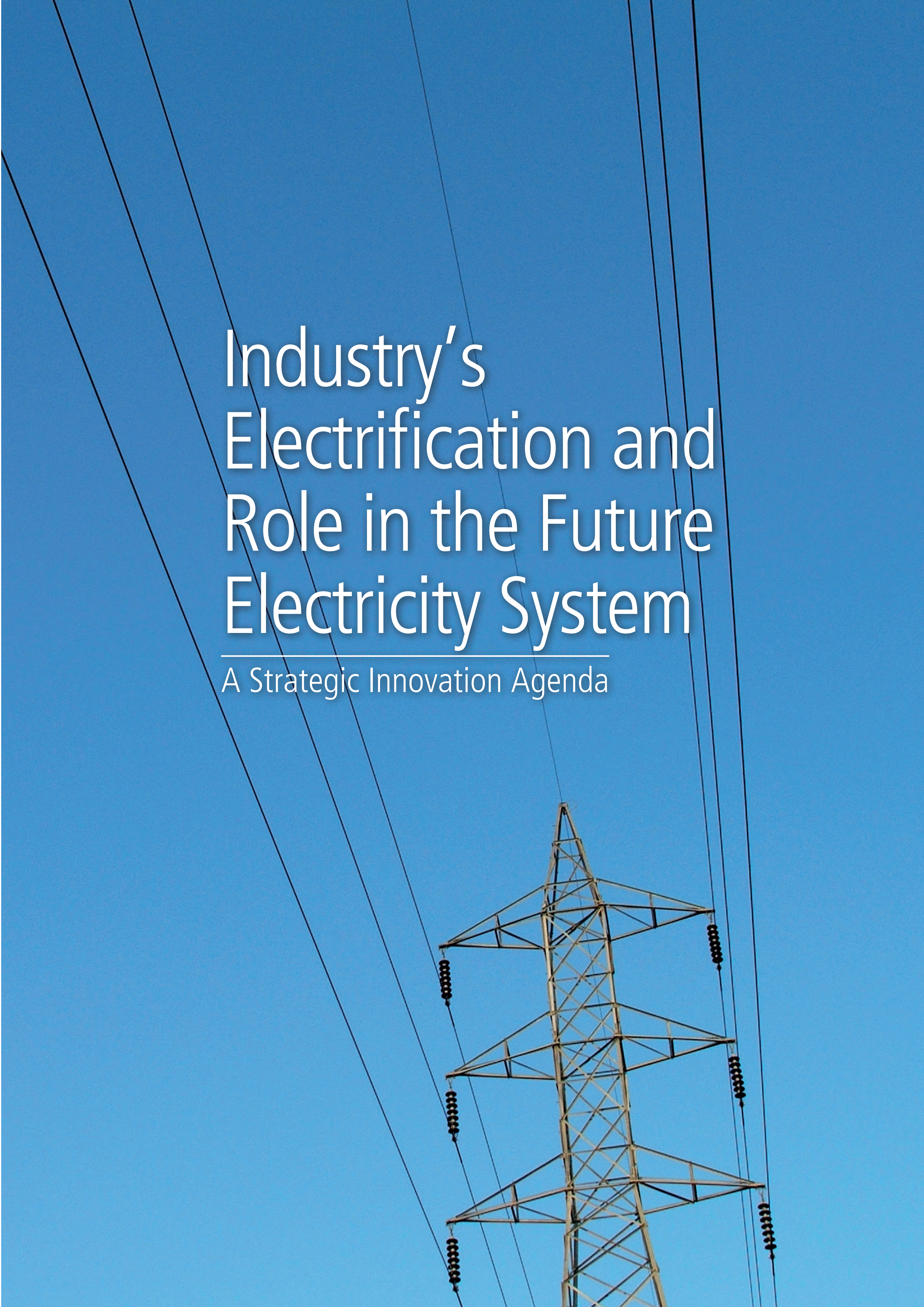
Industry’s Electrification and Role in the Future Electricity System

A Strategic Innovation Agenda



This agenda was produced in collaboration by SP Technical Research Institute of Sweden and Chalmers University of Technology.

Contributing Authors

SP
Magnus Brolin
Jesse Fahnestock

Chalmers
Johan Rootzén

More than 20 organizations from industry, research, and the public sector contributed to the Agenda through participation in workshops, interviews, and review of this document.

Strategic Innovation Agenda

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The program seeks to advance Sweden’s international competitiveness and sustainable solutions to global societal challenges.

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Executive Summary

Trends visible today suggest that a transformation of industrial firms' use of electricity, and a change in their role in the electricity system, could take place as a part of a long-term transition towards a low-carbon Swedish economy. The shape of these changes remains highly uncertain, but electrification, flexible electricity use, and emerging roles in the electricity system for industrial consumers are interdependent developments and should be investigated from a holistic perspective where possible.

Swedish industry is relatively energy intensive, and has stood for roughly 37% of the country's electricity use for a decade. The Swedish Energy Agency's *Vivace* scenario suggests that this share could expand, despite improved efficiency, to 49% by 2050. The increased use of electricity to reduce greenhouse gas emissions and take advantage of market conditions would play out differently in different sectors, and depending on the development of different technologies. However large-scale opportunities may exist in the long-term, such as using electrolysis to produce hydrogen for replacing coke in the iron and steel industry and as a feedstock in the petrochemical industry.

Smaller-scale but still important options for electrification include electric/hybrid boilers in the pulp and paper industry and a variety of electro-thermal technologies for heating and drying.

Increased use of electricity in industry is likely to go hand-in-hand with increasingly *flexible* use of electricity. In some cases, such as the production of hydrogen or process media, this flexibility will be in-built since the storable energy carriers create new production planning options. In other cases, new approaches to planning, process design, and the use of automation may allow firms to match electricity use to favourable market conditions.

The expected high penetration of intermittent renewable electricity in the power system may create incentives for this flexibility. These incentives should appear on the wholesale market, in the form of high- and low-price periods. They may also appear via new capacity markets, or through markets for new system services needed to support stability in both transmission and distribution networks. The frameworks and regulations needed to create these markets are not yet in place, and firms will also need to develop technical and management capabilities to take advantage of them.

Priorities for research

While the overall transition in this direction is likely to take several decades, this agenda identifies priorities for research and innovation action in the short- to medium-term. These include:

- Improve data on electricity use in industry
- Study the economic and CO2 effects of electrification options
- Study the technical and economic potential for flexibility in industrial electricity use
- Use existing Strategic Innovation Programmes to develop flexible technologies related to electricity use
- Develop new financing and programming channels for overcoming silo effects
- Continue evaluation of policy options including Impact Assessment
- Develop platforms for data sharing and collaboration
- Support a wide range of large-scale, long-term demonstration projects related to industrial electricity use

Purpose of the Agenda

The purpose of this Strategic Innovation Agenda is to explore a potential new role for Swedish industry in a changing electricity system. Specifically the Agenda and its contributors are interested in changes in policy, technology, and markets that could result in an increasing role for electricity in industrial processes and a more dynamic role for industrial companies on the electricity market.

The changes in question remain uncertain, both in terms of what they will entail and when and how they will emerge. For this reason the Agenda takes the perspective of a hypothetical future scenario, and focuses on the transition from today's situation to that scenario, with a special interest in the drivers of and barriers to innovation along that pathway.

A major purpose of a Strategic Innovation Agenda is to bring together actors with different perspectives, identify common ground and generate momentum around important innovations. The IndEEl agenda is about systems innovation, and the actors involved in the system naturally approach the Agenda with different and sometimes competing perspectives. The purpose of this process was not to resolve these differences but to document them and to explore their implications. As such this report takes an actor-centric perspective, placing the focus on how the roles of industrial firms, power companies, entrepreneurs and consultants, regulatory authorities and research institutions may change and impact one another. The relevant technologies, policies, and markets are presented in the context of this dynamic between the actors.

The Agenda does not pass judgment on whether this future scenario is more desirable or beneficial than any other outcome. The proposition is that this scenario is one plausible outcome of other changes underway in society, particularly the interlocking efforts to combat climate change, increase the use of renewable energy, and retain and enhance industrial competitiveness in a globalised world.

A system in transition: Multiple interacting trends

Why is it relevant to consider a scenario where industry's use of electricity and role on the electricity market has fundamentally changed? Today we see multiple interlocking trends which suggest that such a transformation could take place in the longer-term.

Sustainability goals: CO2, Renewables, and Energy Efficiency

The European Union's energy and climate strategies put an emphasis on three goals to promote long-term sustainability: reduction in greenhouse gas emissions, an increased role for renewable sources of energy, and increased energy efficiency. These goals are reflected in the Swedish government's own goals, including but not limited to:

- The recently adopted emission-reduction goals for 2030 (63% vs. 1990) and 2040 (75%), covering emissions outside the EU Emissions Trading System,[1] and the five-party agreement to reach zero net emissions by 2045.[2]
- The government's long-term goal of 100% renewable energy, and the five-party agreement's goal of achieving 100% renewable electricity production by 2040.
- The existing goal of reducing energy intensity in the whole economy by 20% (vs. 2008) by 2020,[3] and the commitment to adopt a 2030 goal during 2017.[4]

Industry generates 27% of Sweden's domestic emissions of greenhouse gases,[5] 38% of its energy consumption, and 20% of the country's fossil energy consumption.[6] In terms of policy, industry's direct greenhouse gas emissions are covered by the EU ETS. The Swedish government has articulated its support for a tightening of the EU ETS in future periods, as well as for the reform of the Energy Taxation Directive to allow greater national freedom to use taxes to drive emission reductions.

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[1] http://www.regeringen.se/artiklar/2016/06/miljomalsberedningen-foreslar-nya-utslappsmal-och-en-klimatstrategi/

[2] http://www.regeringen.se/contentassets/b88f0d28eb0e48e39eb4411de2aabe76/energioverenskommelse-20160610.pdf

[3] http://www.regeringen.se/regeringens-politik/energi/energieffektivisering/mal-for-energieffektivisering/

[4] http://www.regeringen.se/contentassets/b88f0d28eb0e48e39eb4411de2aabe76/energioverenskommelse-20160610.pdf

[5] http://www.naturvardsverket.se/Sa-mar-miljon/Statistik-A-O/Vaxthusgaser--nationella-utslapp/

[6] Energimyndigheten, *Energiläget 2015*, https://www.energimyndigheten.se/contentassets/50a0c7046ce54aa88e0151796950ba0a/energilaget-2015_webb.pdf

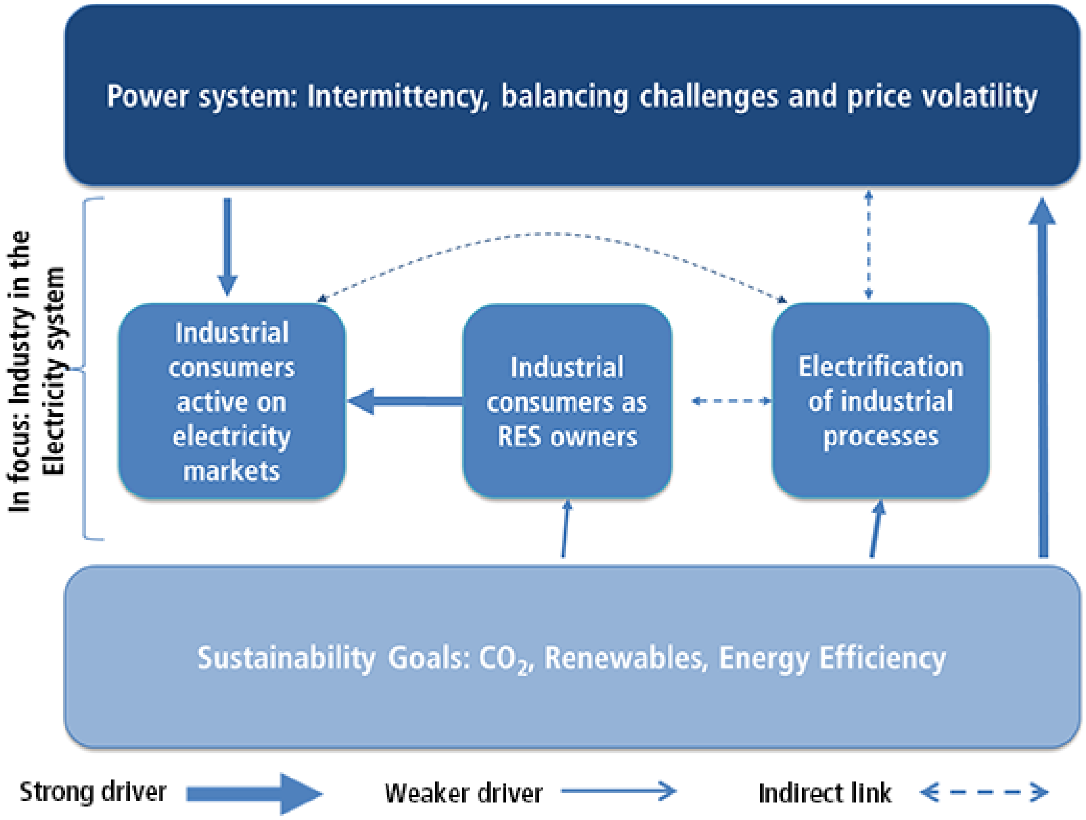

Figure 1 Potential drivers of changes in how industry relates to electricity

The requirement to reduce emissions and fossil fuel use can be met in many ways -- through improved efficiency, switching between fuels, and through electrification of processes. An increased use of electricity, along with incentives and market structures that make distributed ownership of electricity generation by consumers more attractive, could also lead to an increased ownership of renewable electricity systems (RES) by industrial companies.

A changing power system and demand for a new role

The more powerful trend is one that impacts industry indirectly: the increased role of renewable generation in the broader power system. The intermittency of these sources, and the related balancing challenges and price volatility that it is likely to entail, may create a market situation where a new, more dynamic role for industrial consumers in the electricity system is both in demand by the system operator and economically attractive for industry. Should this arise, it is likely to have a reinforcing effect on the other trends -- increasing interest in industrial ownership of RES and electrification of processes.

Scenario 2050: “Vivace+”

To consider how these driving forces might play out, the Agenda takes its starting point in a contextual scenario for Sweden that illustrates the broader future for the Swedish economy and industry with a special focus on sustainability.

In April 2016, the Swedish Energy Agency released *Fyra Framtider* (Four Futures), a look at different plausible, alternative futures for the Swedish economy and society with a focus on energy systems and use. One of these scenarios, called *Vivace* (“Lively”), was deemed to be particularly relevant to the Agenda, for a number of reasons.

First, the *Vivace* scenario treats energy as a springboard for climate solutions, and from such a perspective, electricity is likely to be the most important energy carrier. Second, the scenario envisions a Sweden that acts proactively on sustainable innovation, emphasising advantages to be secured from a leadership position on green technological solutions. Such an approach will likely encourage the development of enabling technologies, including digitalization, which can be important to dynamic industrial processes based on electricity. Most specifically, the *Vivace* scenario includes a strong trend towards electrification in industry and the development of a more flexible grid.

Using Vivace as a starting point, the Agenda project proposes “Vivace+” as a contextual scenario for the changes in the relationship between industry and electricity. The ”+” indicates some additional assumptions about the development of the electricity market, its implications for industry, and the availability of different technologies for electrification.

In a “Vivace+” scenario, the push to introduce renewable electricity systems is the first priority of the transition, both because renewable electricity creates potential for other system transitions, and because technological capacity related to RES is seen as creating export opportunities for manufacturers. The restructuring of other systems -- including the grid, electricity markets, and industrial systems -- thus emerges in reaction to the RES revolution.

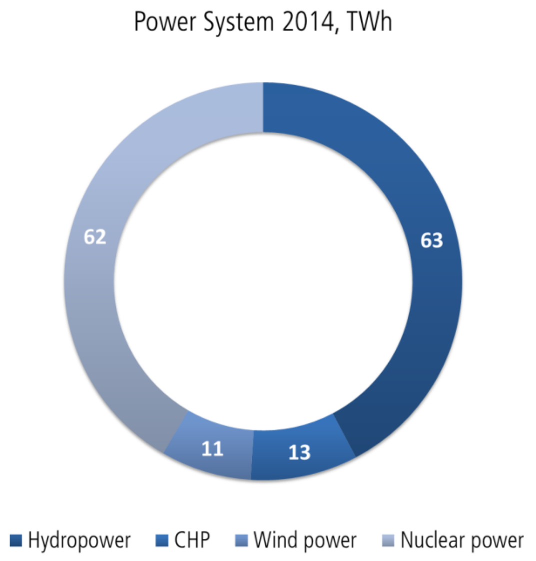

Figure 2: Power Generation 2014. Source: Swedish Energy Agency

Overcapacity and low price periods are a reality in the 2020s, and by 2035, nuclear power is playing a much smaller role, providing only 25% of generation, on its way to a complete phase out in the 2040s.While better transmission links to the European grid are sought, the process moves slower than Sweden's own electric power system transition, meaning that balancing is primarily a domestic challenge through 2040.

In such a scenario a certain amount of disruption can be expected, and opportunities for innovators emerge from this disruption. Some of the opportunities relate to market behaviour, and in this scenario both grid operators will consider both technological (e.g. storage) and market-based (e.g. demand-side) measures to maintain balance in the system. By the 2030s this scenario would see significant new electricity market services provided by industrial consumers. Other opportunities will relate to the use of electricity in industrial processes. A general timeline progressing from a focus on existing usage and flexibility towards new processes and products is expected (see Table 1 below).

Available technology	2015-2030	2030-2040	2040-2050
Electricity use and flexibility	▪ Adjustment of processes ▪ New electro-thermal processes	▪ Advanced process planning ▪ Combined heat/steam systems	▪ Hydrogen as a reducing agent (steel) ▪ (BE)CCS in cement/pulp and paper
Storage	▪ Stationary batteries ▪ Heat, cooling process media stored	▪ Electrolysis » hydrogen + fuel cells	▪ Hydrogen and hydrocarbons from electrolysis

Table 1: Assumed evolution of electrification in industry over time ("Vivace+")

The ways in which this might play out, seen from the perspective of the different actors involved, are the focus of the agenda, and the most important technological tools, market design issues and policy considerations will be highlighted along the way.

Actors and roles in the system – today and tomorrow

Actors and actions: the outline of a transition

Figure 4 below presents a visual representation of the transition from today's situation to the future "Vivace+" scenario, from the perspective of different groups of actors: Industrial firms, the power sector, consultants and brokers, public authorities and regulators, and research actors.

The actions and changing roles described in each 'bubble' are not comprehensive or prescriptive, but were those that emerged in the stakeholder workshop hosted as part of this Agenda. Nonetheless they are indicative of the evolution that would be necessary to deliver the "Vivace+" scenario. More context from different actor perspectives follows below.

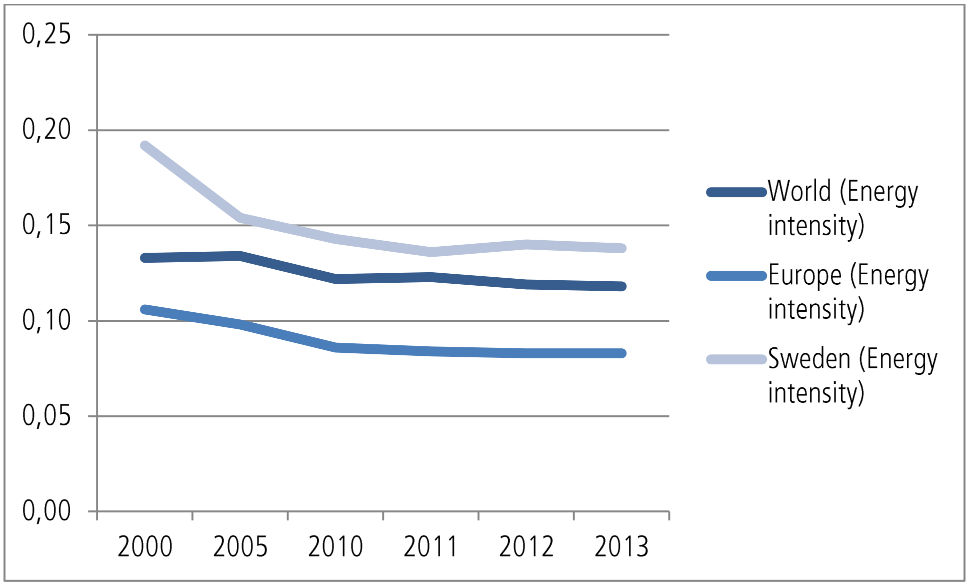

Figure 3: Energy intensity of industry relative to value added. Source: World Energy Council

Figure 4: Actors and actions in the transition. Lines indicate connections between actions/changing roles. Output from the Strategic Innovation Agenda stakeholder workshop.

Industrial users today

Sweden has one of the more energy-intensive economies in the OECD, largely due to the role that energy-intensive industry plays in the Swedish economy. According to the World Energy Council and Enerdata, the energy intensity of Swedish industry, as measured in consumption per unit of economic value added, remains higher than the average in Europe and even globally. This is despite significant improvements in the last decade and a half.

Much of this energy use is already in the form of electricity. Figure 5 illustrates the relative share of electricity in industrial energy consumption over the most recent 10 years for which data is available. The share of electricity has been almost constant -- between 32 and 33 percent -- over that period.

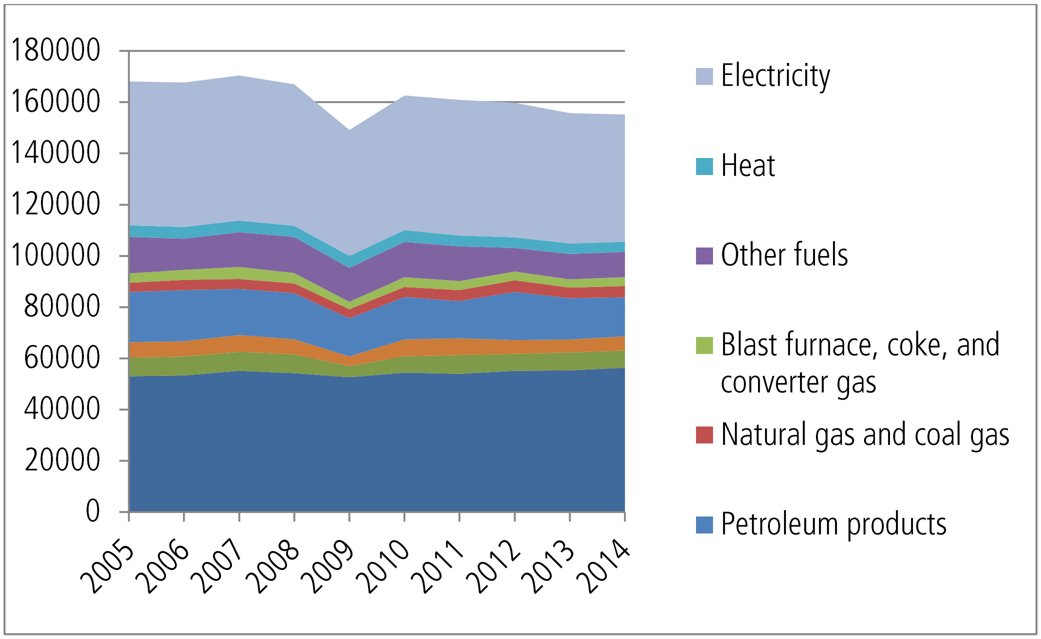

Figure 5: Energy use (including transport) in industry by source. Source: Swedish Energy Agency

Industry stands for 37% of all electricity demand in Sweden, so the sector naturally plays an important role in the electricity system in terms of shaping the demand curve and the requirements for stable supply. As shown in Figure 6, industry's share of total electricity demand has been steady between 37-39% over the course of the last 10 years.

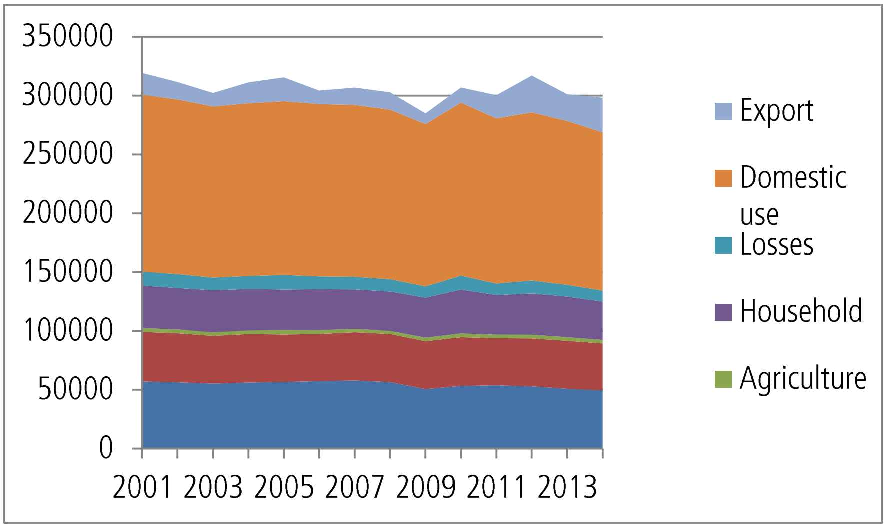

Figure 6: End use of electricity in Sweden (GWh). Source: SCB

Demand reduction as reserve capacity

Since 2003, industry has also played a role in providing flexibility services to the system, through the strategic Capacity Reserve maintained by the Swedish grid operator Svenska Kraftnät (SvK). This mechanism involves the annual procurement of reserve capacity, which can come from the power sector or from industrial users.

The reserve is focused on meeting unexpected periods of high demand during the winter, and bids can be based on available generation capacity or demand reduction. At present SvK has a non-binding goal of procuring up to 25% of this capacity based on demand reduction. Capacity must be available 24/7 from 16 November to 15 March. Remuneration for both capacity and delivered electricity is set in the annual procurement. For the winter of 2015-16 the Capacity Reserve amounted to 1000 MW: 660 MW of generation capacity from E.ON's oil-fired power plant at Karlshamnsverket, and 340 MW of industrial demand response.

The Capacity Reserve was designed as a temporary measure, based on the premise that more flexible demand and controllable supply resources would eventually make it unnecessary. As this has not yet emerged, the government has twice extended the measure, including an extension in 2016 covering 2020-2025. In the text of the law it is noted that the Capacity Reserve amounts to an interference with market signals, and that market-based solutions remain the preferred long-term mechanism.[7]

Type	Provider	Region	Capacity
Generation	E.ON Värmekraft Sverige AB (Karlshamnsverket -- Olja-eldade kondenskraft)	SE4	660 MW
Demand reduction	Storaenso AB	SE3, SE4	50 MW
Demand reduction	Holmens Bruk AB	SE3	290 MW

Table 2: Svenska kraftnät's Capacity Reserve, Winter 2015-6. Source: SvK

The grid operator manages other sources of reserve power, including both automatic and manually activated reserves, with a range of different requirements for activation speed and duration. The 'tertiary' level of reserve is the only level that is activated manually, and includes both the strategic Capacity Reserve and the Manual Frequency Restoration Reserve (mFRR). For this reserve, power volumes are procured two weeks ahead of delivery, and must be made available over a minimum of a one-hour period. Remuneration is based on spot market prices. While the grid operator is seeking participation by industrial consumers in the mFRR, engagement by firms outside of the power sector has been limited to date.

At the primary and secondary reserve levels, smaller/shorter variations are handled via automatically activated reserves, with a range of different requirements for activation speed and duration. While in the future end-users and industrial 'prosumers' may have the opportunity to deliver these services, today they are dominated by hydropower.

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[7] Regeringens proposition 2015/16:117. http://www.regeringen.se/contentassets/8e63c5454c5e46cea5c23263f8afb5ad/151611700webb.pdf

Vedbo wind farm. Source: Vindin.org

Industry-owned generation capacity

Industrial firms’ participation in regulating services is based today on demand reduction, but many larger firms, especially in the pulp and paper industry, have significant generation capacity of their own. This is generally combined heat and power based on industrial backpressure. The installed capacity (power) in industry is 1500MW(el), and generation is 6,5 TWh(el) per year. The pulp and paper industry stands for more than 90% of this generation, with the remainder based primarily in the iron and steel industry.[8]

In recent years, energy-intensive industries have begun to explore ownership of generating capacity based on renewables, primarily wind. A joint initiative among industrial firms called Vindin was established in 2006, with the objective of helping secure the firms’ access to low-cost electricity. Today Vindin operates two wind farms with a total generating capacity of 70-88 MW, and has a pipeline of four

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[8] SEA, 2013.

onshore projects in Sweden, representing 315MW. Vindin is also part owner in an offshore project in Blekinge which will have a capacity of 2500MW.

There is an expectation that basic industries will increase their direct investment in renewables, including capacity on-site, in the future. This is due in part to direct economic benefits from subsidies and in part to indirect benefits from the hedge against price volatility.

In terms of creating a new role in the electricity system, it is important to note the difference between CHP capacity and wind and solar capacity. In the near-to-medium term, only the former can provide flexibility in terms of capacity that can be altered to respond to system needs, or synchronized with changes in demand from production. For industry-owned production from intermittent renewables to play a role in system flexibility, both new market mechanisms and new technologies, such as automation and storage technologies, may be required.

Industrial users in the future electricity system

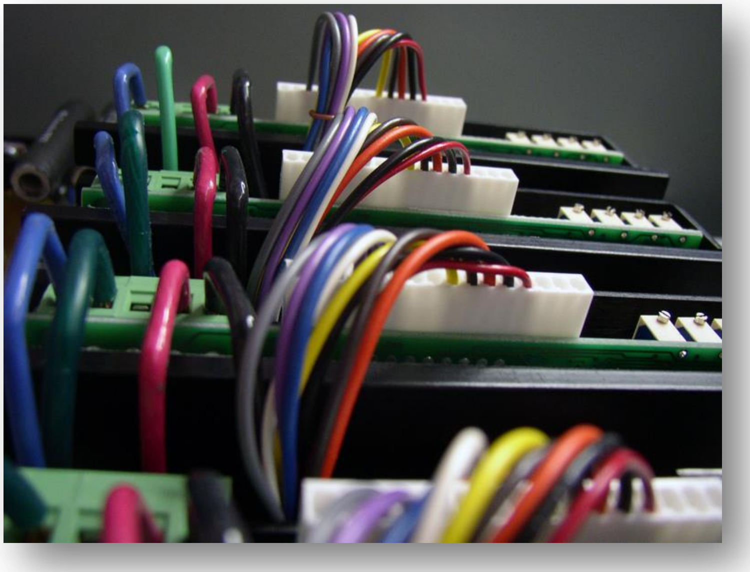
How might this picture change over time? In terms of overall demand, we can look to the *Vivace* scenario for an interpretation of how industrial electricity demand might develop in a future where growth, restructuring, and sustainability are the cornerstones.

In this scenario, industrial demand for electricity grows in absolute terms from 53 TWh per year today to 57 TWh in 2035 and 76 TWh in 2050. In terms of industry’s share of overall demand, which is important for the determination of its role in the electric power system, the change is more dramatic in the long term: from 37% today, to 38% in 2035, to 49% in 2050.

An important driver of this increase is likely to be the steel industry, where electricity generation can be used to produce hydrogen, which can be in turn be used as a reducing agent for iron, which is an important option for dealing with process emissions (see information on *Hydrogen-based reduction* below). Representatives from the steel industry estimate that the incremental electricity demand from shifting to hydrogen as a reducing agent could require roughly 15 TWh/year – equivalent to 30% of current industrial demand and more than 200% of Swedish industry’s total current on-site electricity production. Possibilities also exist to use electricity to generate synthetic hydrocarbons for use in energy and feedstock applications, for example in the chemicals industry.

In such a scenario, where industrial firms own and operate intermittent renewable energy generation at scale, they are likely to optimise their energy consumption and market behaviour in a different way, and potentially invest in energy storage. In the case of hydrogen and synthetic hydrocarbons, these products effectively act as a store of energy as they replace energy inputs in processes, thus allowing firms to plan and optimize their electricity consumption, and potentially provide services to the market.

For pulp and paper industries, options for electrification will be related to, for example, electric boilers and new electro-thermal processes for drying, etc. Expansion of internal backpressure capacity will in the near term be limited as investment in excess electricity and heat generation must compete with investments in production and core business. This situation could potentially be altered by industrial symbiosis, for example between pulp and paper and chemical industries, which increases the direct uses and value of electricity, process media and storage. Industrial symbiosis and clustering may also increase overall flexibility, in terms of production planning and optimization, which could support a more active role on the electricity markets.



Production planning, automation, and optimisation are a crucial part of the "Vivace+" scenario across multiple manufacturing industries. The existing Strategic Innovation Programmes "Process Industrial IT and Automation (PiiA)" and "Produktion 2030" both feature/prioritize the areas "Efficient Resource Use" and "Flexible Production"; however, to date electricity use and flexibility issues related to the electricity market have not featured prominently in these programmes' research portfolios. Some of the technological options related to planning and automation are discussed below. In general, their adoption may depend on a change in management practice related to energy. Maximizing the true cost/benefit of electricity and energy use will require both a decreased focus on price and an integrated view of energy management and production management.

Drivers of a new role for industry

Figure 1 above outlines the economy-level drivers of the "Vivace+" scenario and how they might interact with each other. These will differ in different industry contexts, however. Some of these drivers are reviewed below.

Economics of electrification

The economics of electrification are shaped by multiple factors, but the most important of these is the relative cost of using different energy carriers (direct energy inputs, feedstocks or both) in industrial processes.

A consideration of these costs in the future perspective must begin with the assumption that societal costs for greenhouse gas emissions are borne by the industrial process that generate them. The appropriate mechanisms for doing so, especially in the context of industries that compete globally, are much-debated and outside the scope of the Agenda. For the purposes of the "Vivace+" scenario, it is sufficient to assume that the transition has been managed in a way that successfully reduces greenhouse gas emissions from industry to a very low level without sacrificing Sweden's industrial base.

For the steel sector, the core economic issue is thus the relative cost of two low-CO2 solutions: fossil fuels + Carbon Capture and Storage (CCS) vs. the large quantities of electricity required to either produce hydrogen or undertake electrowinning. The costs of each approach will also depend on system design and integration. Nonetheless the electrification of the steel industry requires access to large volumes of inexpensive electricity.

The tradeoff for the chemical industry will similarly be between the cost of using electricity to generate synthetic hydrocarbons and the cost of replacing current fossil feedstocks with biomass alternatives. In the case of ligno-cellulosic fractions (e.g forestry and agrowaste) much of the cost of using biomass as a chemical feedstock relates to process complexity and energy requirements, rather than the cost of the feedstock itself. Once again the relative costs will be coupled to the system design, including the platforms used, the value of the core products and valorisation of side streams, and the integration with other industries such as forest product industries.

For the pulp and paper industry, biomass is already the basis for the core product, and the marginal cost of electricity generation (much of which is internal, based on combustion of waste streams) is very low. In the future scenario, a relatively low biomass price may allow the industry to increase its own generation and do more with electricity -- including electrifying existing processes and providing services to the electricity market. If the future features higher biomass prices, electrification could require the industry to buy electricity for the market, raising overall costs and altering the economic attractiveness of proactive electrification. In addition to costs of biomass inputs, increases in the value of side streams, for example through the valorisation of lignin as a feedstock for chemicals or materials, could impact the use of these side streams for their energy content.

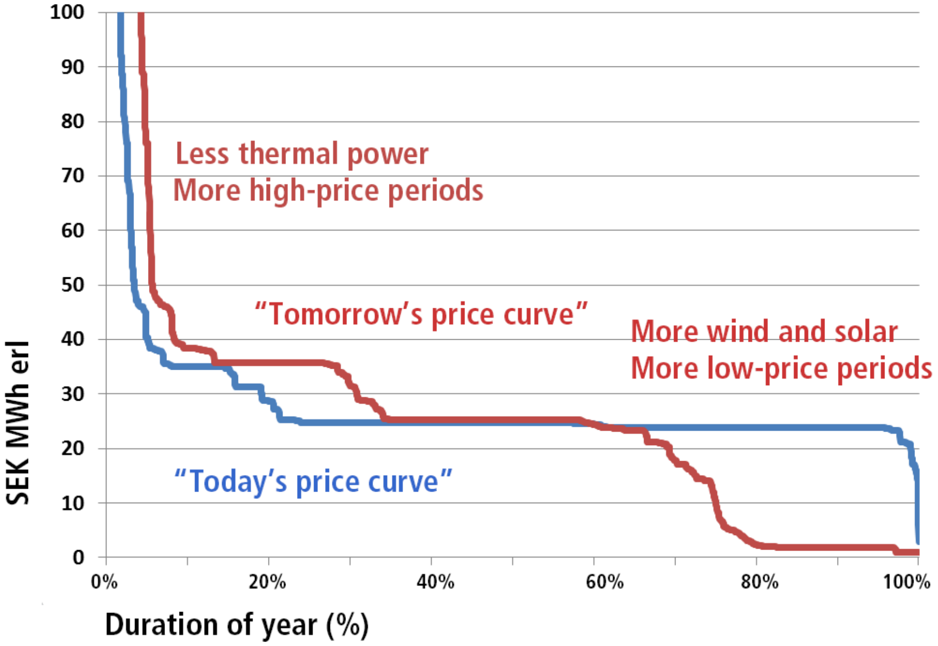


Figure 7. Electricity price curve in 2030 scenario. Results from the ELIN/EPOD models (Division of Energy Technology, Chalmers University of Technology).

Economics of electricity markets

In all of these industries, the economics of electricity use in the future are impacted by the likelihood that, in a system with increasing amounts of intermittent generation based on wind and solar power, there will be periods of high and (especially) low electricity prices. As a complement to the Swedish Energy Agency's scenario, we have also included analysis from the Chalmers University of Technology about how a high level of renewable generation, on par with that envisioned in *Vivace*, could affect market prices.

Figure 7 comes from a model that describes the Nordic power system in a scenario where Swedish production includes 70TWh from intermittent sources and an ongoing phase out of nuclear power. It provides a simple illustration of the effects of less thermal baseload power (greater frequency of higher prices), and of more intermittent power (greater frequency of near-zero prices).

This situation alone might not entail drastically changed economic incentives for industrial consumers, given the relatively similar average prices implied. Much of the need for balancing in the electricity system, it is worth noting, may not 'flow through' to the wholesale electricity markets as modelled here, but may nonetheless increase demand for regulating services, including in local distribution grids.

Nonetheless, this model describes a situation where high and extremely high prices are more than twice as common as today, and where perhaps 1500 hours per year feature zero- or nero-zero electricity prices. Such periods should create 'economics of flexibility.' There are essentially three kinds of flexibility envisioned. Two of these -- demand reduction and increased "behind the meter" or own generation by industry -- are mentioned above.

The third element of flexibility relates to increasing demand for electricity in response to very low prices. In practice, this option has often proven to be the most difficult for many industrial firms to put in place. Simply conceived, the default level of production is, in many cases, full capacity, which makes increases more problematic than decreases. In today's world, such 'positive' demand response might entail rethinking overall production planning, maintenance schedules, etc. A programme to incentivize such "Demand Turn Up," with a focus on increasing overnight demand and demand during the mid-day peak of solar generation, has been initiated by the National Grid in the United Kingdom.[9]

In the future, new process designs, production planning, optimisation and automation will be keys to realizing the economics of low-cost price intervals. As illustrated in Figure 8, most of these low cost intervals are relatively brief (6 hours or less). Innovations in process and production flexibility will have to be developed in accordance.

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[9] National Grid (2015)

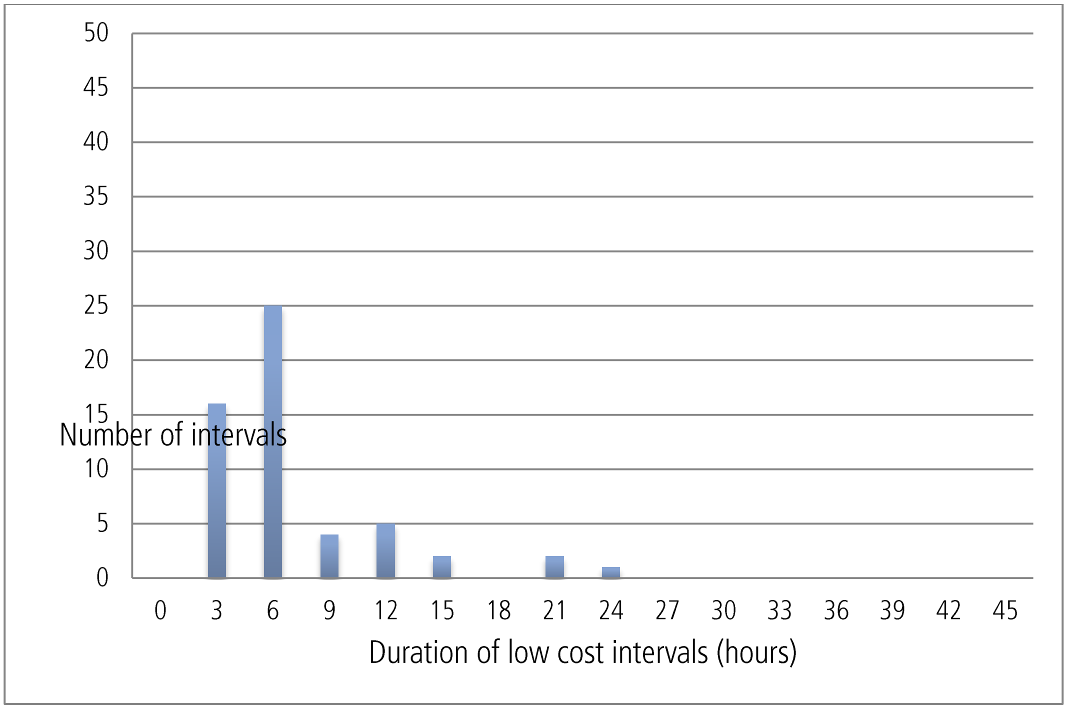

Figure 8. Duration of low-price periods in 2030 scenario. Results from the ELIN/EPOD models (Division of Energy Technology, Chalmers University of Technology).

Security of supply

Studies such as the above mentioned study from Chalmers and the Swedish Energy Agency suggest that increases in intermittent power are unlikely to create physical disruption in supply to consumers. Nonetheless, large industrial consumers have already signalled concerns about security of (affordable) supply.

This may reflect a concern over the decreased appetite for investment in generation assets by the power sector (discussed below). While this situation is driven by near-term expectations of overcapacity, consumers will understandably seek to avoid a shortfall should demand subsequently increase. This can incentivize industrial firms to invest in both flexibility and ownership of production and storage capacity that can in turn provide services to the power markets.

Barriers and needs

The factors described above may be necessary drivers of change, but they are likely not sufficient to alter industry's use of electricity and role on the electricity market. Many barriers are likely to slow or even prevent adoption of new technologies and new market behaviours. Awareness, information, analysis and action will be required within industry, by other actors in the electricity system, and by policy-makers.

Awareness

One barrier to creating a new role for industry in the electricity system may be awareness and access to information. Since 2015, the Swedish Energy Market Inspectorate (EI) has been pursuing an assignment on "Demand Flexibility in the Swedish Electricity System," with the objective of accelerating the development of a more effective electricity market through increased flexibility. As a part of this assignment, EI commissioned a study from Sweco on "Electricity Consumers' Opportunities for Flexible Use."[10] One general conclusion from the study was that awareness of the role of demand flexibility was low, and that information about options for flexibility was perceived to be in short supply.[11]

Among the largest electricity consumers, awareness was much higher, and six of the 15 interviewed companies participated in either the strategic Capacity Reserve or the Manual Frequency Restoration Reserve. However, even for larger firms, access to information can be an issue -- for example, participants in the agenda workshop suggested that the lack of real-time data on their own electricity consumption, as well as a lack of a centralised database covering the relevant electricity markets, may keep firms from investigating the economic potential of flexibility.

Uncertain economics

A half-step from lack of information lies uncertainty. For demand flexibility and electricity market services, there is doubt about the fundamental economics, and an absence of robust calculations. Participants in the EI/Sweco study noted how infrequently bids based on demand reduction in the mFRR were actually called, meaning that even firms already active in these markets had little data about the expected revenues. In terms of costs, firms also face uncertainty around investment and operational costs, as process redesign for flexible electricity consumption has knock-on effects across multiple functions.

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[10] Sweco (2016)

[11] SKGS, in its response to EI's investigation, noted the survey's low response rate and raised questions as to the validity of this finding.

For electrification of processes, fundamental uncertainties related to the relative prices between electricity, biomass, and CCS mentioned above presents a challenge to long-term investment in electricity-driven processes. Uncertainty about technological futures, for example the progress of battery technology and its implementation, or the relative prospects for early-stage technologies like electrolysis and synthetic hydrocarbon production, are also a major issue.

Organizational challenges

A fundamental barrier to a new role for industry in the electricity system is the fact that electricity market participation is not a core competence for industrial firms. This can manifest in a lack of knowledge about the options and potential to adjust processes, and a view of electricity markets and frequent changes as prohibitively complex. Respondents to the EI/Sweco study indicated in many cases a preference for energy efficiency over energy flexibility, even considering the potential for sub-optimal returns.

A related issue is organisational structure and internal barriers, so that even when a company has strengths in process and market knowledge, leveraging them can be a challenge, especially in the context of overall decisions on investments.

Participants in the agenda have also raised the issue of a lack of available capital. Though this may prove to be an issue in the long-run, the question in the short term appears to be more related to willingness to invest. Swedish industry as a whole is well capitalized,[12] so that the availability of capital is more likely to be driven by expectations of risk and return rather than by balance sheet considerations.

Demand flexibility in other sectors

While integration of high shares of variable renewable electricity is likely to lead to increased demand for flexibility, it is important to recognize that there are several ways to provide the required flexibility services. Providers of industrial demand flexibility will compete with flexibility providers in other sectors on the demand side as well as with flexibility resources (generation, grid investments, and storage) on the supply side of the electricity system. Thus, to provide a more complete picture of the role of industry as a provider of demand flexibility services these opportunities need to be evaluated from a system perspective. Boßmann and Eser (2016), in a comprehensive review of studies aimed at model-based assessments of demand-response measures, found that most studies to date have focused on end-use in the residential sector. They conclude that to accurately evaluate the potential for and

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[12] In 2012, Swedish investor Conni Jonsson argued that Swedish industry was "over-capitalized" http://www.svd.se/svenska-industribolag-ar-overkapitaliserade. The industry's long-term debt ratio has decreased since.

impacts of demand response measures on an electricity system the sectoral coverage needs to expanded. They stress that particular attention should be paid to the industrial and the tertiary sectors.

The future development of different areas of the electricity system may drive the value of flexibility in opposite directions. Transmission capacity investments, introduction of centralized or decentralized storage, increased penetration of alternative energy carriers, efficiency measures and structural changes on the demand side are all developments that may dampen the need for and value of demand flexibility. Examples of future development trends in other end-use sectors with potential to impact the overall load and load pattern in the electricity system (and thus the role of industry as provider of demand flexibility services) include:

Electrification of the vehicle fleet. An introduction, at scale, of electric vehicles would obviously lead to an increase in electricity demand (up to approximately 13 TWh according to one study).[13] With the right incentives and infrastructure in place, an increase in the number of electric vehicles has the potential to provide benefits to the network as a flexible load or even as a source of energy storage.[14] However, without proper charging strategies that manage variations in the electricity generation system, an electrification of the vehicle fleet could instead result in new stresses on the distribution network, further incentivizing flexibility from industry.

Control of electric heating and water heaters in the residential sector. While the introduction of smart appliances in combination with new systems for communication and metering has the potential to provide demand response services, the largest potential for demand flexibility in the household sector is related to the control of electric heating and water heaters.[15] A limiting factor may be that electricity demand for space heating is expected to decrease over time due to better insulation of buildings and a shift from direct electric heating to heat pumps with higher efficiencies.[16]

District heating:[17] District heating systems can offer flexibility by allowing flexible operation of thermal power plants and by utilisation of power for heat production at times of low electricity prices, e.g., connecting large-scale high-efficiency heat pumps or electric boilers to the district heating system.

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[13] IVA, 2016
[14] Saunders et al., 2016
[15] Nyholm, 2016
[16] IEA NETP, 2016

[17] NEPP, 2014; IEA NETP, 2016

Power generators today and tomorrow

In 2014 the generation mix in Sweden was 42% hydropower, 41% nuclear power, 9% combined heat and power, and 7% wind.[18] The ability of hydropower units to provide balancing power to the system has allowed the system to accommodate large-scale, must-run capacity from nuclear power (and, latterly, wind) without significant reliance on more flexible gas-and oil-fired capacity.

While deregulation has brought new companies into Swedish power generation, the dominant role of the large nuclear and hydro plants has meant that the former state utility Vattenfall still owns 35% of the country's generation capacity.

Within wind power, which is supported by a certificate system, no single actor plays a dominant role (for illustration, both Vattenfall and Norway's Statkraft each own about 5% of Sweden's installed wind power capacity). Subsidies have led wind capacity to expand even during times of stable and declining demand overall; this extra capacity and the low marginal cost of wind generation has hurt the overall economics of baseload generation, especially nuclear. This situation has been reinforced by rising maintenance investments.

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[18] Preliminary statistics for 2015 reflect lower nuclear generation and increased hydro and wind: 47% hydro, 34% nuclear, 9% CHP, and 11% wind.

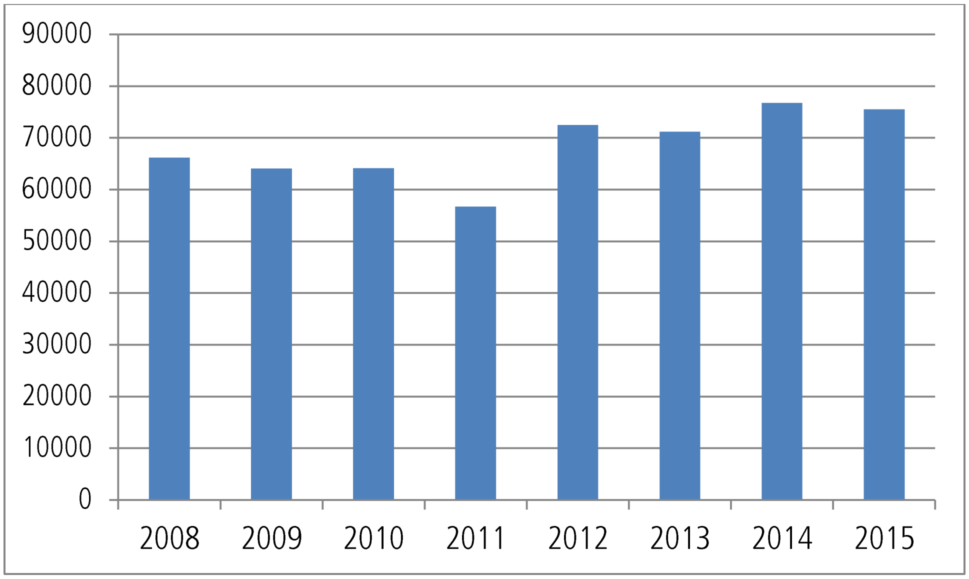


Figure 9: Investment (msek) in plant, machinery and inventory, electricity, gas and heat plants, 2008-2015. Source: SCB.

Thus while overall investments (both maintenance and expansion – see figure 9) in the sector have not declined, the expectation in the industry is that new investments in large-scale, centralised generation capacity other than wind will be increasingly difficult over time.

At the same time, as political directives continue to prioritize energy efficiency, power sector companies must consider whether to invest in service-oriented business models that can help them capture some of the value from their own reduced generation. Customer interest in green power has also led power companies to explore de-commodified generation at the retail level, most simply through guarantees of origin but also recently by providing services to consumers making their own investments in generation (largely solar photovoltaic capacity installed on rooftops).

From the perspective of this Innovation Agenda, one question is whether these trends signify a major change in the role of the power generation sector, from dominant provider of low-cost, commodity electricity to a more diversified provider of services related to electricity. The *Vivace* scenario seems to indicate a less than total overhaul: the share of solar power, the most distributed, small-scale, differentiated generation asset reaches only 6.5% in 2035 and 12.5% in 2050. While nuclear capacity is phased out, large-scale generation from wind and CHP achieve market shares in 2050 of 28% and 20% respectively.

If process electrification becomes a dominant strategy in industry, opportunities may emerge for power generators to "productify" electricity, helping large consumers integrate generation, storage, and process media in tailored ways. If flexibility in electricity use and market activity becomes a priority for industry, the power sector may choose to play a role as an aggregator of capacity and other flexibility services. Alternatively, these businesses may be dominated by new entrants while traditional power companies focus on the restructured power generation market.

Drivers of and barriers to new role for the power sector

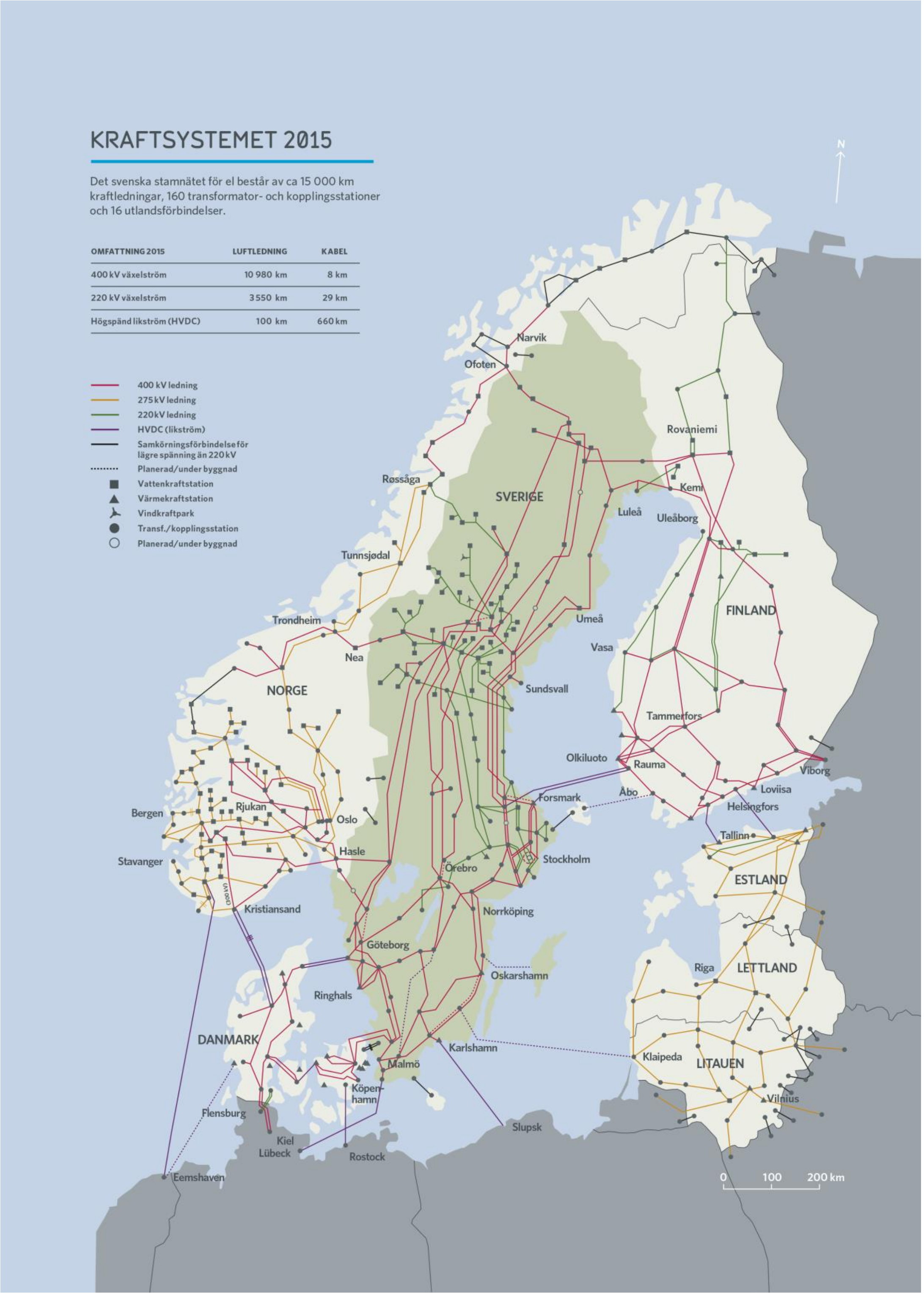
The primary driver of new, more service-oriented/value-added activities from the power sector will be industrial demand. The power sector has a chance to shape that demand by working with early adopters, and power companies are already involved in end-user services, aggregation through ‘virtual power plants’, and long-term development of process electrification (e.g. the Vattenfall/SSAB collaboration on HYBRIT discussed below).

Historically such investments have struggled to compete with generation investments for investment capital. Even if this situation is changing, power companies will face organisational barriers as management of a portfolio of large-scale engineering projects is replaced/complemented by a portfolio of smaller-scale, tailored engineering projects.

Transmission System Operator

Transmission System Operator (TSO) is the denotation of the actor owning and operating the electric transmission system, i.e. high-voltage lines and transformer stations on the 400-220 kV levels. The TSO is responsible for the momentary balance of the electric power system, and for ensuring that enough capacity exists in the system in order to keep this balance. However, the TSO does usually not have any production resources itself, but relies on the provision of balancing power from other parties on the market. This is the case for the Swedish TSO Svenska Kraftnät (SvK).

Sweden is synchronously connected to Norway, Finland and Eastern Denmark, which creates a need for extensive collaboration between the TSOs in these countries. This need has increased due to the introduction of intermittent electricity generation in the Nordic system. In order to enable the development of renewable production and the associated expansion of transmission capacity, the transmission grid has undergone significant development, and large grid reinforcement investments are being made, both within and between the Nordic countries as well as in connections between countries (see Figure 10).



KRAFTSYSTEMET 2015

Det svenska stamnätet för el består av ca 15 000 km kraftledningar, 160 transformator- och kopplingsstationer och 16 utlandsförbindelser.

OMFATTNING 2015	LUFTLEDNING	KABEL
400 kV växelström	10 980 km	8 km
220 kV växelström	3 550 km	29 km
Högspänd likström (HVDC)	100 km	660 km

Figure 10: Electricity system and interconnections, Nordic region. (Source: Svenska Kraftnät)

The role of the TSO from a legal perspective has remained the same. However, in order to achieve a reliable and efficient system, the TSO has found new ways to ensure the integrity of the system, and to procure reserves and purchase balancing power. The main tools for this are capacity markets and auction-based procurement. By developing new marketplaces and adapting market rules to the new market situation, the TSO has taken steps to meet requirements of reliability and efficiency. The role of the demand as a balancing resource has been expanded from mainly being a part of the strategic reserve to being considered as a natural factor during normal operation conditions, e.g. through participation in frequency control.

The relationship between the TSO and DSOs has also developed. Since the TSO's operation to a much larger extent is dependent on the state and operation of the distribution system, an increased flow of information from DSOs to the TSO has emerged, consisting of e.g. local production levels, reactive power production/consumption, etc. The DSOs also offer services to the TSO regarding e.g. voltage control and reactive power, which the TSO uses as appropriate.

Drivers of and barriers to a new role

The overall transition of the power system, in combination with strict responsibility for keeping the momentary balance in the system, constitutes a strong driving force for the TSO to find new and efficient means of balancing production and consumption in the system. This implies both identifying new resources that can be used for balancing purposes as well as developing innovative markets for supplementary balancing services. A primary challenge to making these resources available on the market is to create both incentives and a market design allowing the participation of non-traditional actors, e.g. aggregators and operators of virtual power plants.

From the Nordic perspective, there is a strong political ambition to make the system more integrated, both in terms of markets and increased physical transfer capacities between the countries. An example of this is the work on a common end-user market for the Nordic countries.[19] The ever-closer interaction between the countries requires also a closer collaboration between the Nordic TSOs on various aspects and at various system levels.

Among many countries and actors within EU, the Nordic system is envisaged as becoming the "battery of Europe" with its' high flexibility based on large amounts of installed hydropower. This is also in line with the EU vision for the Energy Union and an integrated European energy market. To realize this, stronger interconnections with continental Europe are needed. A recent example of such investment is the Hansa Powerbridge between Sweden and Germany, where a

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[19] http://www.nordicenergyregulators.org/projects/common-nordic-end-user-market/

feasibility study was performed during 2016.[20] This also requires market integration through harmonisation of market rules etc. Apart from utilizing Nordic hydropower as a source of flexibility, other flexibility resources can contribute to the Swedish and Nordic provision of balancing power. The market mechanisms for this and the interface with the European market and system however need to be refined and developed.

Distribution System Owners

The increase in distributed generation and an increase in energy autonomy of households have created new challenges for the distribution system owners and operators (DSOs), resulting in technical as well as "business" innovations. Further, the regulation of DSOs has been tightened to introduce new requirements on reliability and power quality. Hence the DSOs are facing challenges induced both from the customer side as well as from the regulator. As a result, the role of the DSO has already transformed from that of a "passive" actor, focusing on traditional asset management and meter readings, to a significantly more active role. The new role includes control of distributed resources in the system to mitigate negative impacts of local production and EVs on voltages and network stability. This requires more monitoring equipment in the network and communication systems in order to increase observability and improve the execution of control strategies.

Today DSOs must also accommodate the provision of system services by external parties, such as residential and industrial customers. As a result, the DSOs have developed new types of contracts to facilitate such system services. Innovative tariff structures are also important tools to incentivise customers to become flexible in their electricity consumption.

DSO demand is mainly for active power, but reactive power consumption is also important to achieving efficient voltage control in certain areas.

Drivers of a new role

Even though the role of DSOs has changed, they are still monopolistic actors and are monitored by a regulating agency, the Energy Markets Inspectorate (EMI). Hence, grid regulation is the main driver for DSOs and defines the investment options as well as the limitations on certain aspects of operations. This regulation has become stricter, and the requirements on reliability and cost efficiency of the grid have been tightened. This has given the DSOs incentives to further explore the possibility to use various distributed resources, including equipment at residential buildings and industries, for grid services. The coordination of distributed resources requires intelligent ICT systems for monitoring and control, as well as models for remuneration of external service suppliers of e.g. voltage control or demand

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[20] SvK Investerings- och finansieringsplan för åren 2017 – 2020, http://www.svk.se/siteassets/om-oss/rapporter/investerings--och-finansieringsplan-2017-2020.pdf

response. From an industry perspective the ability to control consumption levels or reactive power could thus generate value streams related to operation of the distribution grid.

Apart from regulation, the development of more local production and an increase in autonomy for households has resulted in an evolution of the DSO business. The development means that some customer groups view the surrounding system, including the distribution system, as a backup for their local production. Accordingly, tariffs are being developed to reflect this development while still generating sufficient positive cash flows to cover DSO operations and necessary investments. A variety of tariff structures have evolved to meet this new market environment, facilitated by development of regulation allowing innovative tariffs.

Barriers and needs

The regulation of DSO activities and income frames is very strict, and has a fundamental impact on the roles and business models that a DSO can pursue. Customer protection and non-discriminatory tariffs rely on strict regulation, though this regulation may create barriers to the efficient use of resources in the distribution system. Hence, there needs to be a balance between the flexibility of DSOs to define their business and the protection of customers' interests.

Service providers and retailers

The new system and market conditions have made the entry of new service and knowledge providers possible. Such actors include aggregators, energy service companies and consultants, and innovative retailers. Retailers have expanded their role from being purely 'passive' actors whose main challenge was to forecast hourly demand in their customer portfolios, to a more 'active' market position that includes direct or indirect control of their customers' load profiles. The retail offers to consumers have thereby become more complex and diverse, and the term 'aggregator' is often used to describe this new role. However, aggregators can also be third-party actors without the balance responsibility held by retailers.

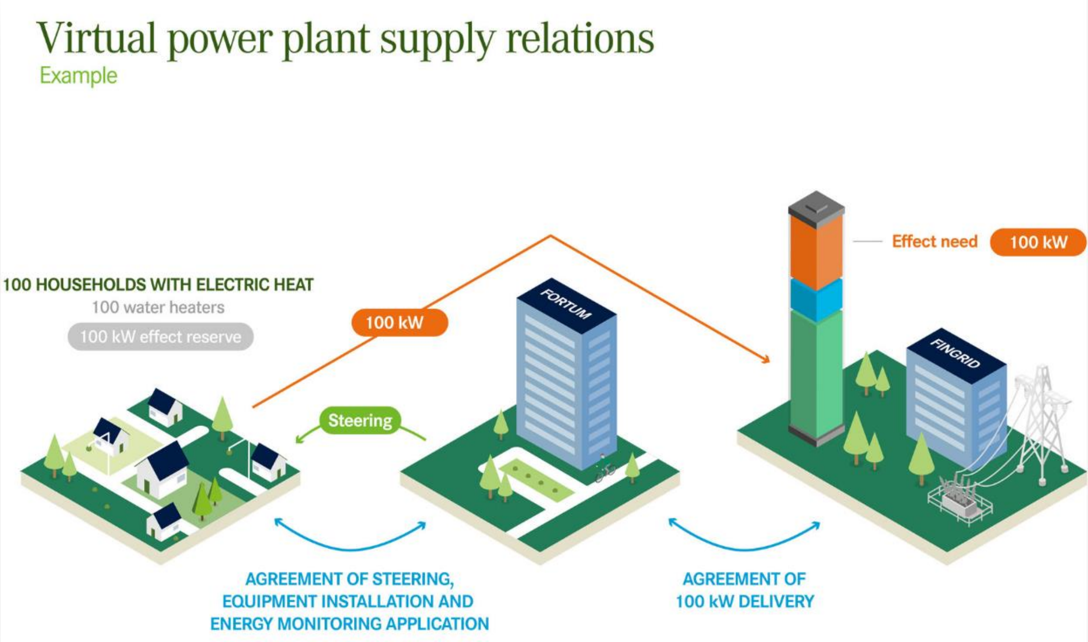

Figure 11. Source: Fortum.

Knowledge and service providers have played different roles during system development. In the initial phase, such actors provided insights on technical and business possibilities, thereby contributing to the development of new markets for e.g. flexibility. In the latter stage of the transformation process, these actors provide services targeting consumers on one end, and system and grid owners on the other. Concerning industrial electricity users, knowledge providers showed the flexibility potential that could be offered to the market and the values thereof. This has strongly contributed to the advanced position of industrial consumers on the electricity market.

The new market environment has created new possibilities for offering services and knowledge, and to generate value streams from the demand side flexibility. This includes the process from identifying to realising and monetising potential flexibility. During this process, different needs for competence and services can be identified. In the initial phase, consultants provide expertise in identifying flexibility potential, and can propose investments needed to realize it. This provides industry with the knowledge necessary to evaluate options. Industry may also engage service providers to generate value streams related to demand flexibility and other technical possibilities at the industries' sites. Aggregators (and retailers) can play this role, facilitating the process of bringing flexibility to the market and reducing peaks in the system. The goal of energy service companies (ESCOs) is to optimize the consumers' energy consumption, usually aiming at reducing the total energy cost.

Drivers and barriers

The development of new services and providers is the result of several driving forces:

- More intermittent production results in a need for more flexibility in the system, including increased demand for load flexibility.
- The strong competition on the retail side of the market, resulting in low margins for traditional business, creating incentives for new business models.
- An increased awareness among the general public and industries about sustainability and renewable energy has led to customer expectations about new services.

The main barriers for creating new services as described above are mainly related to policy and electricity market design. The traditional view – that demand is exogenous to power system operation -- has created barriers for a more active market position on the demand side. Market structures and rules need to be adapted to embrace the participation of demand on the wholesale market as well as on the market for system services.

Another potential barrier is the competence level and lack of awareness among customers regarding business opportunities related to electricity markets and systems. Significant marketing and outreach from service providers may be required, raising costs in the initial phase of the business.

Research Institutions

Research institutions, such as universities and institutes, develop new knowledge facilitating the industrial transformation towards sustainability, enhancing their abilities to meet future demands and requirements. This includes new knowledge on industrial energy efficiency and the role of industries in the electric power system and in power markets. In order to perform research in this area, new collaborations need to be established, bringing together research competences in electric power systems and economics, and in industrial processes and management. This leads to new insights concerning possibilities and limitations of the role of industries as integrated parts of the energy system as a whole, with particular focus on the electric power system.

A major part of the research is performed from a technical perspective at technical universities and institutes. However, policy and organizational aspects are of vital importance and departments of business and administration are also addressing questions on industry as an integrated part of the society, with special emphasis on the energy market and related challenges.

Drivers and barriers

The trans-sectoral research perspective on industries' role in the energy and electric power system is driven by the demand for a holistic view encompassing different knowledge areas. However, this requires combinations of different competences which can not necessarily be found within one research organisation or group. Thus one barrier to overcome is the organizational borders of research institutions.

Further, academic research is to a large extent incentivized by production of articles published in scientific journals. High-impact journals usually focus on a specific area, and interdisciplinary research tends to fall outside the scope. This could potentially also create barriers to academic research on the integrated topic of industries in electric power systems.

Research actors are heavily dependent on external funding to be able to perform research projects. Funding agencies and organizations therefore need to create new programs or adapt existing programs to encompass research on the role of industry in the future electric power system. Traditionally, industrial energy usage and electric power issues have mainly been considered in separate programs, resulting in a gap in funding opportunities for projects combining the two perspectives.

Industrial energy use and electrification

An overview of industrial energy use

Access to a reliable and relatively cheap supply of electricity has been, and continues to be, a key to industrial development in Sweden. Industry currently accounts for 37% of electricity use (and ~40% of the of total final energy consumption), with the manufacture of pulp and paper, refined petroleum products, chemicals and basic metals making up the bulk of industrial energy use.

However, two closely related drivers have the potential to profoundly change both overall demand and the patterns of electricity use in Swedish industry.

The effort to drastically reduce industrial CO_2 emissions will likely require utilization of the full range of mitigation measures available – including continued efforts to improve energy efficiency, increased use of biomass as feedstock and fuel and/or carbon capture and storage (CCS). One comparatively unexplored option, with potentially significant implications for industrial electricity use, would be to electrify the energy and feedstock supply for key emissions-intensive production processes.

The rise of renewable electricity generation. The interplay between manufacturing industry and an electricity system with a steadily increasing share of intermittent renewables will offer new opportunities and pose new challenges for Swedish industries. In analogy with old windmills and waterwheels, it is possible to imagine, in a carbon-constrained world, a manufacturing industry that is more adapted to interactions with intermittent sources of energy. This might include everything from adapting electric motor systems (pumps, compressors, motors, and fans) to respond in a more flexible manner to load patterns in the electricity grid, to the factoring in of wind conditions and solar radiation in the process scheduling and, in the extreme, to the relocation of electricity-intensive plants to regions with conditions favourable for renewable power production.

As is illustrated in Figure 12, the industrial sector is an important and integrated part of the Swedish energy system. Electricity and biomass (primarily used in the pulp and paper industry) are the dominant energy carriers. Electricity is used in a wide variety of applications, both directly in numerous production processes but also to power ancillary support systems.

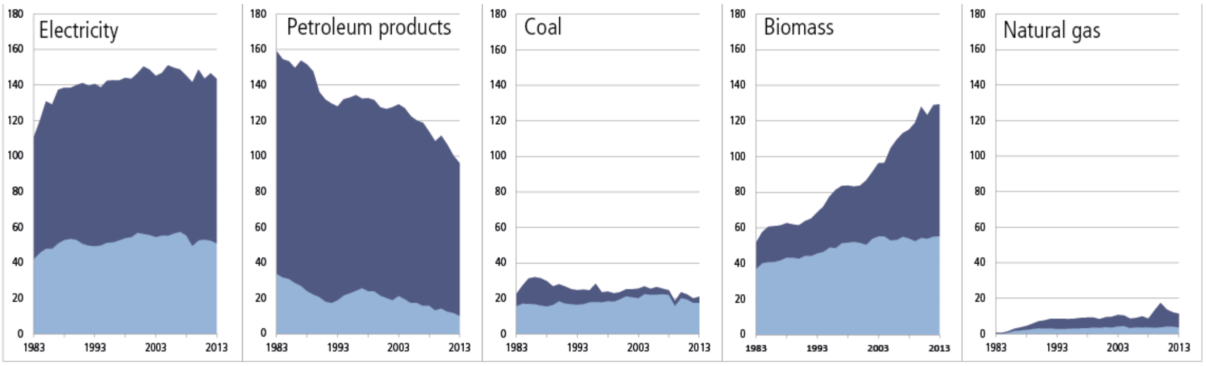

Figure 12. Swedish industries share of final energy use by energy carrier 1983–2013

The further electrification of industrial processes may be one of the few available options for phasing out remaining fossil fuel-based processes, and may also help free up biomass for alternative uses. The options available and challenges associated with the electrification of industrial processes, and the role of industry and industrial electrical processes in an electricity system with an increasing share of intermittent power generation are explored below.

Electrification

Electric processes (electromotive, electro-thermal, and electrolytic) are already in wide use in a broad range of industrial facilities and processes. This section presents a sample of novel electric processes for industrial application, with emphasis on processes with either applicability across a broad range of industrial facilities and processes, or with potential for major impacts on key manufacturing processes. The section below on automation, process flexibility, and own electricity production provides a more comprehensive overview of the electrical production technology in use in Swedish industry today.

The further electrification of industrial processes may have several justifications:[21]

- Improving energy efficiency: modern electro-thermal process technology (e.g. induction, dielectric heating or microwave) for heating and melting has the potential to reduce energy use by allowing for more precise control of the energy flows than possible in existing furnaces and ovens that must be fired continuously during production.
- Improving product quality: Electrical processes can enhance product quality by allowing precise control and the possibility to instantly adjust energy input to varying process conditions in, for example, drying and melting processes.
- Increasing the speed of production: There are several electro-technologies that offer improved rates of heat transfer and higher efficiency, which can speed up the rate of material heating in comparison to conventional ovens, heating tunnels and radiant heaters.
- Reducing greenhouse gas emissions: This can be achieved directly, by replacing existing fossil-fuelled technologies (e.g. furnaces and boilers) with more efficient electric technologies; or indirectly by utilising electricity for production of hydrogen and hydrocarbons for feedstock and energy purposes.

Electro-thermal processes for heating

The majority of industrial fuel is used to generate process heat. Industrial processes need heating at low (below 100 degrees), medium (between 100 to 400 degrees) and high temperatures (400-2000+ degrees). Supplying this heat through electricity instead of carbon fuels can be done in several ways:[22]

- Electric furnaces can supply heat with normal convection heating in all temperature ranges.
- Heat pumps can supply low-to-medium temperatures by using electricity and excess heat.
- Advanced electro-thermal technologies including, e.g., induction, infrared radiation, electromagnetic radiation, microwave heating, radio waves, ultraviolet light, electron beams and plasma technologies can potentially supply heat in all temperature ranges.

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[21] CEATI, 2007; EPRI, 2009; Lechtenböhmer et al., 2016

[22] Lechtenböhmer et al. 2009; EPRI, 2009

Hydrogen from electrolysis of water

The production of hydrogen through water electrolysis, enabling the storage of renewable electricity from RES, could potentially reduce the tension between energy use and environmental degradation. Hydrogen is currently produced (through steam reforming and partial oxidation of hydrocarbons) and used mostly in petroleum refineries to purify fuels, and in the chemical industry to manufacture ammonia and other compounds.[23]

While several challenges still remain to be resolved,[24] using hydrogen produced from "carbon neutral" electricity as an energy carrier or reactant/raw material in industrial processes, could enable the shift away from fossil fuels in, e.g., the chemical and petrochemical and steel industries, and create business opportunities in the production of vehicle fuels.[25]

Still, the low level of efficiency in transforming electricity to hydrogen and the challenges involved in developing an infrastructure for transporting, storing and delivering hydrogen to end users remain major hurdles to overcome.

Carbon Capture and Storage (CCS)

Application of CCS is, besides the processes for industrial electrification covered here, one of few options to achieve significant reductions (60–100%) of CO_2 emissions from petroleum refineries, steel works, cement plants, and petrochemical industries, as well as potentially 'negative' emissions from the pulp and paper industry. Deployment of CCS could, however, come at a significant cost in terms of energy usage. The effects on industrial electricity use will depend on choice of capture technology but air separation (for oxy-combustion), CO_2 separation and compression are all electricity intensive.

Opportunities by industry

The list of electrical technologies for industrial applications covered below is by no means exhaustive. Emphasis is on the most energy and CO_2 emission-intensive industrial activities in Swedish industry – petroleum refineries, steel works, cement plants, petrochemical industries, and pulp and paper mills – where options achieve significant reductions (60–100%) of CO_2 emissions tend to be limited.[26] While the particular setup of the production processes and the potential role of innovative electric processes vary considerably across the different branches of industry and between individual plants, since these industries are comprised of a relatively limited number of very large plants, changes in each single plant may have significant impacts on energy use and on potentially on regional and local electricity loads.

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[23] Ursua et al., 2012

[24] see e.g. Sovacool and Brossmann, 2010

[25] Lechtenböhmer et al. 2016

[26] Rootzén, 2015

Iron and steel

The iron and steel industry is highly energy-intensive. Two production routes account for the vast majority of Swedish (and global) steel production, iron ore-based manufacturing in integrated iron and steel plants, and secondary steel from scrap in electric arc furnaces (so-called 'mini mills'). The production of primary steel is associated with significant CO2 emissions

Integrated iron and steel plants involve a series of interconnected production units (coking ovens, sinter plants, pelletising plants, blast furnaces, basic oxygen furnaces, and continuous casting units), which process iron ore and scrap metal to crude steel. Coke, which is derived from coal, typically functions as both a fuel and reducing agent. SSAB's integrated iron and steel production plants in Luleå and Oxelösund account for approximately two thirds of the Swedish steel production and are among the largest point sources of GHG emissions in Sweden. The Oxelösund plant includes the entire production line, extending from raw materials to rolled plate. At the Luleå plant, which does not have a rolling mill, steel slabs are the final product. The final stages of the steel processing are carried out in Borlänge where SSAB has hot and cold roll mills in addition to coating and finishing lines. All of the three blast furnaces (one in Luleå and two in Oxelösund) use iron ore pellets, which are mined and processed in Sweden, as the main raw material input.

Industry	Mid-term (2030)	Long-term (2050)
Iron and steel (Primary and secondary production)	Increased production of secondary steel from scrap (electric arc furnace)	▪ Direct reduction ▪ Electrowinning ▪ CCS

In mini-mills scrap metal, direct reduced iron, and cast iron are processed in electrical arc furnaces to produce crude steel. There are currently ten plants producing secondary steel from scrap (in electric arc furnaces) which together account for one-third of the Swedish steel production.

Direct electrification

One approach to 'electrification' of the iron and steel industry is therefore increased and improved production of secondary steel from scrap in electric arc furnaces. Limitations exist however, including availability of scrap and the presence of tramp elements in scrap as the main charging material and higher nitrogen content compared to blast furnace operation. The manufacturing of high value-added flat product steel has always been a domain of the integrated mills. However with further process development the product range of mini-mills could be expanded.

Molten oxide electrolysis (Electrowinning)

This process, which is still in its infancy, would allow the reduction of iron ore by transformation of ore into metal and oxygen using only electrical energy.[27] Molten oxide electrolysis (MOE), by allowing direct production of metal in the liquid state from oxide feedstock, would both eradicate CO2 emissions and result in a simplification of the iron and steel production process and a significant reduction in energy consumption.[28]

Indirect electrification

Direct reduced iron (DRI) – involves the reduction of iron ores in their solid state at temperatures well below the metal's melting point.[29] There are several different types of reactor designs in commercial use, including shaft furnaces, rotary heat furnaces and fluidized bed reactors. Direct reduction makes it possible to use alternatives to metallurgical coke as reducing agents including oil, coal, natural gas and hydrogen. After the direct reduction the reduced iron is in solid state and for further processing the solid iron needs to be melted – typically in an EAF.

Hydrogen-based reduction

The concept of using hydrogen to reduce iron ore has been investigated at least since the 1960's (Ranzani da Costa et al., 2013). Lately the idea has gained new traction since the use of hydrogen as reducing agent, especially in the direct reduction production route, holds the potential to achieve low-or-zero CO_2 emissions. There are a number of ongoing projects involving the use of hydrogen as the main reducing agent in primary steel production (injection into the blast furnace or direct reduction process).[30] In the case of direct reduction with hydrogen several concepts have been suggested involving e.g. the direct reduction in a shaft furnace, direct reduction in a fluidized bed reactor[31] and flash ironmaking where iron ore concentrates would be sprayed directly into a furnace chamber.[32] So far, however, practical experiences remain limited. The Flash iron-melting process investigated in a laboratory at Utah University is the concept that appears to have come the furthest, with tests in a lab scale reactor (2007-2011) and a bench scale reactor (2012-2017) using both natural gas and hydrogen as reductants. Reports

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[27] Smil, 2015; ULCOS, 2016

[28] Allanore et al., 2013

[29] Smil, 2016

[30] Eurofer, 2013

[31] Xu and Cang, 2010; Fischedick et al., 2014

[32] Jahanshahi et al, 2016; Smil, 2016

from the project are scarce but the initial trials appear to have delivered promising results.[33] Further upscaling of the test reactor is currently under consideration to learn more about operational flexibility, process control, optimization and scale-up costs.

HYBRIT

The Swedish steel manufacturer SSAB, mining company LKAB and energy company Vattenfall recently launched a joint project aimed at developing processes for CO2-emission free ironmaking (SSAB, 2016). The centrepiece of the project is the Hydrogen Breakthrough Ironmaking Technology (HYBRIT). The idea is to replace the blast furnaces with an alternative process, using hydrogen produced from "carbon-neutral" electricity, to reduce iron ore. After an initial feasibility study the aim is to scale up to pilot plant trials in the period 2018-2024 with the ambition to move on to demonstration plant trials in the period 2025-2035.

Replacing the blast furnaces would require input of alternative fuel in the downstream metallurgy. That plan is to heat all processes up to 1000°C with electricity and some combustion of biomass.

In this early phase of the project the plan is to locate the HYBRIT plant somewhere between Malmberget (were the iron ore is mined) and Luleå (where 1 of the 2 existing integrated steel plants are located). Downstream metallurgy would then take place in Luleå, Borlänge and Oxelösund.

Electrowinning vs DRI

Even though hydrogen production implies efficiency losses compared to the electrowinning route, the decoupling of hydrogen production from continuous operation of the steel plant through hydrogen storage offers the opportunity to use cheap excess renewable electricity. This factor could make H-DR the most attractive route economically and environmentally thanks to its contribution to grid stabilisation in a 100% renewable energy system.

However, high investment costs and high dependency on electricity prices make a profitable implementation before 2030-2040 without further subsidies unlikely.

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[33] 95% metallization and held 1400 degrees for eight hours; prescribed gas and material flow rates solid feed rate <1 kg/hr in the end of 2015.

Hydrogen Direct Reduction	Molten oxide electrolysis (Electrowinning)
Advantages	**Advantages**
+ Low-or-zero CO_2 emissions	+ Low-or-zero CO_2 emissions
+ Improved energy efficiency (Significantly lower specific energy use (GJ/tHM) than in the conventional BF/BOF route)	+ Improved energy efficiency (Specific energy requirement (GJ/tHM) lower than for both the Hydrogen the traditional BF/BOF route)
+ The decoupling of hydrogen production from continuous operation of the steel plant through hydrogen storage offers the opportunity to use cheap excess renewable electricity	
Drawbacks	**Drawbacks**
- Does not allow the separation from gangue -- only ores with high iron and low gangue content can be used	- Sensitive to electricity price fluctuation since steady supply of electricity is needed for the continuous operation
- Total economy relies on an infrastructure for the supply of relatively low cost hydrogen (including high-capacity hydrogen storage)	

Cement

Cementa, which is part of the HeidelbergCement group, owns the three remaining cement plants in Sweden. The plants, which are located in Slite, Degerhamn and Skövde, together have a capacity of approximately 3 Mt cement/yr (HeidelbergCement, 2014). The largest of the three, the Slite plant, accounts for more than 70% of Swedish cement production. In a cement plant, calcium carbonate ($CaCO_3$) and different forms of additives are processed to form cement. Significant amounts of electricity (approximately 120 kWh/t cement) are used to power both raw material preparation and cement clinker grinding, and large quantities of fuel (approximately 3 GJ/t cement) are needed in the clinker burning process. The levels of energy use and related CO_2 emissions vary depending on the choice of production route and kiln technology. Since 2011 the Slite plant has had the capacity to utilize excess heat to produce electricity. The installed capacity is 10 MW and the annual electricity production is approximately 50 GWh, which corresponds to one fifth of the plant's internal electricity use (250 GWh/year).

Industry	Mid-term (2030)	Long-term (2050)
Cement industry	Induction and microwave heating	CCS

Direct electrification

Options for alternative heating/drying (microwaves, induction) exist. Advanced electrical heating, i.e., application of induction and microwave energy, has been suggested as options to improve clinkerisation of cement and to improve cementitious properties.

Chemical and petrochemical industry

The chemical and petrochemical industry undertakes some of the most electricity-intensive industrial activities in Sweden, with a share of more than 10% of Sweden's total industrial electricity use (5.5 TWh). Globally, with a product range covering thousands of products, the chemical and petrochemical industry is diverse and includes a wide range of organisations using different chemical processes to convert raw materials to final chemical product. Individual operations range from large-scale continuous processes making millions of tonnes per year of bulk products, to small batch processes making fine and speciality chemicals. However, the manufacture of just 18 products accounts for 80% of the industry's energy demand and 75% of its greenhouse gas emissions.

In the Swedish chemical industry energy use can be grossly divided into three categories:

- Electro-chemical processes are, as the name indicates, typically electricity intensive. Annual electricity use in the electrolytic process used to produce chlor-alkali and chlorate production alone is approximately 2 TWh.
- Support processes, which refer to pumps, fans, agitators and compressors, are used to control flows and pressures in the production processes.

- Thermal processes include, e.g., catalytic and non-catalytic cracking and reforming processes where thermal energy is supplied via combustion of fuels which are in many cases internally derived.

Industry	Mid-term (2030)	Long-term (2050)
Chemical and petrochemical industry	Electro-technology substitutes for distillation including adsorption and membranes	Hydrogen- and biomass-based hydrocarbons for feedstock and energy purposes CCS

Direct electrification

Electro-technology can substitute for distillation, including adsorption and membranes.

Indirect electrification

The use of hydrogen from renewable energy sources to produce ammonia and methanol would significantly reduce CO_2 emissions from the industry. The synthesis of ammonia from H_2 and nitrogen gas (N_2) could replace current production practices, which are based on steam reforming and/or water-gas shift from gas or coal.

Petroleum refining

Petroleum refining involves several production steps, whereby crude oil is purified, separated, and transformed into an array of petroleum products. The furnaces and boilers that feed the different sub-processes are fuelled by a mixture of petroleum coke, still gas (refinery gas, i.e., by-products of the refining process), petroleum fuels, and natural gas. Therefore, the total level of CO_2 emissions from a refinery is the sum of several emission sources of various sizes. Process heaters and steam boilers account for the major share of the CO_2 emitted from a typical refinery.

As of 2015 there are five petroleum refineries in Sweden the three largest of which account for 90% (396 kb/d) of the crude distillation capacity. The two Preem refineries in Lysekil and Gothenburg together have a distillation capacity of 316 kb/d, and the St1 refinery, also located in Gothenburg, has a capacity of 80 kb/d (Oil and Gas Journal, 2013). Total annual energy use in the Swedish refinery industry is approximately 11 GWh/year (10 GWh thermal and 1 GWh electric energy per year).

Direct electrification

Hybrid boilers can be used (in case of increased use of biomass as feedstock).

Indirect electrification

Power-2-Products concepts involve the use of electricity to generate liquid energy carriers.

Pulp and paper

The pulp and paper industry is the largest industrial energy consumer in Sweden.

Fossil fuel use has largely been phased out and reported carbon emissions of the sector are low because a majority of the energy used comes from biomass. Total annual emissions of carbon dioxide from the approximately 50 pulp and paper mills (including plants for the production of mechanical pulp, chemical pulp, paper and paperboard) currently in operation in 2015 were 21 MtCO2/year -- 97% of which was of biogenic origin and only 3% from the combustion of fossil fuels. Thus, while the ambition to reduce fossil CO2 emissions, cannot alone justify the introduction of processes for further electrification of pulp and pulp and paper manufacturing in Sweden, there are a number of other motives that could. Examples of such motives could be:

- Freeing up biomass for alternative uses
- Capturing revenues through demand response and system services in the electricity market, by installing electrical equipment adapted for load control

With respect to energy use and CO_2 emissions the pulp and paper industry can be divided into three subsectors: chemical/kraft pulp (and paper) mills, mechanical pulp (and paper) mills, and pure paper mills without any virgin pulp production.[34]

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[34] Jönsson, 2012

- Chemical/kraft pulp (and paper) mills. This business involves treating wood chips with chemicals to remove the lignin and extractives, thus separating and cleaning the fibres. Chemical pulp production is further distinguished into sulphite and sulphate (kraft) pulp. Sulphite pulp, where a sulphite chemical solution has been used to break down the pulp wood and remove the lignin, is used to produce fine and printing paper. Kraft pulp, where the pulp has been treated with sodium sulphide and sodium hydroxide solution, is used to produce bleached boxboard and linerboard used by the packaging industry.
- Mechanical pulp (and paper) mills. Involves the mechanical breakdown of pulp wood into fibres by grinding or refining. Since the lignin remains in the pulp, yield is higher but the quality and strength of the pulp is lower. Mechanical pulps are used principally to manufacture, e.g. newsprint, printing papers, towelling, and tissue papers that do not require high strength.
- Pure paper mills purchase chemical, mechanical and/or recycled pulp fibre. There are two main process steps: i) stock preparation, where the pulp is processed into a homogenous slurry with properties suitable for introduction into the paper machine, and, ii) web (i.e., sheet) forming, pressing, drying and finishing in a papermaking machine.

Industry	Mid-term (2030)	Long-term (2050)
Pulp and paper	Electric boilers/hybrid boilers Membranes (filtration)	BE-CCS

Direct electrification

Hybrid boilers with dual fuel systems (electricity + biomass) could be introduced.

Electricity end-use and the potential for demand flexibility

Industrial electricity end-use

Power demand from Swedish industry varies depending on the time of the day and on the season. The load from industri typically varies between 5 and 8 GW, but in cold winter days the load at times peak at around 10 GW.[35] The annual peak load in 2014 occurred on a cold winter afternoon (13th of January between 16-17 in the afternoon) and reached 24.76 GW.[36]

While statistics on branch-level electricity consumption are publicly available, there is no good overview of actual current industrial electricity end-use. The last comprehensive survey of the final end-use of industrial electricity was carried out more than 30 years ago. Table 3 reports the relative distribution between different end-uses obtained from this survey. While significant changes have occurred in some industry branches (i.e. increased share of electricity-intensive production of mechanical pulp in the pulp and paper industry), the industry structure in terms of electricity consumption is about the same as in the 1980s.[37] Thus, the data give an approximation of how industrial electricity consumption is allocated.

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[35] Henning, 2005

[36] (Energimyndigheten, 2015)

[37] SOU, 2003:38

End-use	%
Electricity in processes	
Electrolysis	8,0
Melting	7,1
Heating/ Heat treatment	2,9
Grinding and refining	11,5
Other processes	7,5
Sum Electricity in processes	**37,0**
Other electricity use	
Pumps and fans	27,3
Compressed air systems	3,1
Cooling equipment	1,3
Other motor operations	16,6
Lighting	5,5
Sum Other electricity use	**53,8**
Electric boilers, space heating	4,8
Small industries etc.	4,4
TOTAL	**100,0**

Table 3. Approximate allocation of industrial electricity end use

Industry as a provider of electricity market services

The possibility to manage industrial electricity loads first gained traction in the aftermath the oil crises of 1973 and 1979.[38] The increased penetration of variable renewable electricity generation has resulted in a renewed interest in Swedish industry's role as a provider of demand flexibility. Demand-side management, and particularly demand response, have traditionally been aimed at ensuring the efficient utilization of existing generation capacity and the existing grid infrastructure, thereby alleviating the need for additional investments in peak generation facilities and grid reinforcements. However, as more variable generation is introduced in the electricity system, a reduction in peak demand is not necessarily the only desired outcome of demand response. Depending on the generation profile of the installed variable generation capacity, a build-up of demand might be desirable to avoid curtailment and maximize utilization of, e.g., installed wind capacity in periods with favourable wind conditions.[39]

As discussed above, industry already plays a role in providing flexibility services to the system through the strategic capacity reserve, and companies with the possibility to respond flexibly can already do so by actively participating in, e.g., spot, intraday, and regulating markets.[40]

Previous surveys suggest that the potential for demand response in Swedish industry is in the range of 0.5-2 GW.[41] These studies also show that potential for and willingness to provide demand flexibility from industrial customers may vary considerably across different branches of industry and between individual firms. Table 4 provides a general overview of suggested opportunities for load flexibility.[42]

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[38] see e.g. Söderström and Johansson, 1983; Björk and Karlsson, 1985
[39] Nyholm and Steen, 2014; Nyholm, 2016
[40] SKGS, 2016
[41] Industribud, 2002; Elforsk, 2003; NEPP/SWECO, 2013; Esmailnajad and Sundquist, 2014; Sten and Åström, 2016
[42] Björk and Karlsson, 1985; Cronholm et al, 2006; Esmailnajad and Sundquist, 2014

Strategy	Enablers/challenges
Storage Shift electricity load by utilizing opportunities for thermal or product/process storages:	Requires inert thermal loads
Energy storage, involves thermal storage in material, object or media or in the building mass and indoor air Process storage, involves storage of intermediate products and or material, object or media	Storage capacity presents a bottleneck. Slimmed supply chains, i.e., short delivery times and limited stocks a limiting factor.
Process rescheduling Rescheduling of load from periods with high load to periods with low load (i.e., from weekdays to weekends, from day to night) or to periods with favourable conditions for variable renewable electricity generation	Depends on the possibility to reschedule the workforce. May be associated with significant increases in labour costs. Increased automation could be an enabler.
Load shedding or shifting Halting, delaying or advancing production or part of the production process temporarily	The possibility to halt production may be limited, e.g., if the production process is closely integrated, and relies on a scheduled sequence. Typically associated with significant costs.
Direct load control Modulating loads where the load can be controlled or be ramped up and down	Smart metering and data exchange equipment necessary. Loads having process interconnections or loads in a continuous process chain cannot be controlled independently.
Dual-fuel systems Boilers and furnaces that use the least expensive alternative between fuels or electricity, shifting electrical loads from peak periods to off-peak periods.	
Combined heat and power generation Industrial back-pressure. Excess capacity can be used as back-up in capacity reserve.	

Table 4. Overview of opportunities for load flexibility (Björk and Karlsson, 1985; Cronholm et al, 2006; Esmailnajad and Sundquist, 2014)

While these first estimates provides a point of reference, there are several factors that warrant continued and more detailed scrutiny of the role of industry as provider of demand flexibility services. These include but are not limited to:

I. the heterogeneity in firm level electricity use,
II. the possibility that the awareness of the role of demand flexibility in industry is still low (see above on the investigation led by the Energy Market Inspectorate),
III. the transformation of the electricity system (both the supply side and the demand side) has only just begun, and
IV. the tools that could provide economic incentives for the industry to engage in demand response still need to be developed and implemented.

Process-specific opportunities

The total electric load from an industry is, at each time point, the sum of a large number of sub-processes, including both production processes and support processes (cf. Table 3 above). Since the specific setup of the production processes tends to vary from one industry to another it is difficult to make any general claims with regards to load patterns. Still, for the purpose of discussing the potential for and challenges associated with demand response in industry it may be useful to introduce more electricity end-use sub-categories:[43]

- Production processes – this category refers to electricity-consuming process units or process equipment directly involved in the production. These production processes can in turn be subdivided according to a number of characteristic load patterns. A first distinction can be made depending on the typical scheduling of a process unit or a group of units:

- Batch processes, and
- Continuous processes (base load)

For the purpose of assessing the potential for demand flexibility it may be fruitful to make a further distinction between four basic load types from production:[44]

Binary Mechanical Load (BML) refers to manufacturing process equipment that exerts distinct electric charge or mechanical force during a defined time cycle. Examples of BML process equipment include grinders, chippers and press machines. This type of process is typically binary, which means that only two states

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[43] Henning, 2005; Esmailnajad and Sundquist, 2014; Starke and Alkadi, 2013; Gils, 2014
[44] Cronholm et al, 2006; Starke and Alkadi, 2013

are possible, either ON or OFF. These are best suited for demand response related to energy and capacity.

Modulatable Mechanical Load (MML) refers to process equipment that exerts consistent force on a moving, material object or media. Examples of MML process equipment include pumps, fans, blowers, air compressors, etc. This type of processes can, if equipped with appropriate controls systems, be modulated. MML could in theory provide demand response related to energy and/or capacity.

Continuous Thermal Load (CTL) refers to electricity-consuming process units that change the phase, composition or chemical characteristics of a material, object or media and run continuously. Examples of CTL process equipment include smelters, continuously operating metal heat treatment furnaces, electrolytic cells, and induction melting furnaces.

Inert Thermal Load (ITL) refers to electricity-consuming process units used to heat (or melt) and cool (or freeze) a material, object or media with potential for thermal storage. Examples of ITL processes with thermal storage capability include refrigeration compressors and cooling fans (VFD) used in industrial cold storage and heat treatment furnaces in the metals industry.

Loads from support processes include consuming units or equipment not directly related to manufacturing or production, but necessary for the business to be conducted. In this category indoor climate control and air quality control may provide the best opportunities for demand response. Here, diurnal, weekly and seasonal load patterns are typically most important when evaluating the potential for demand flexibility. The basic load types in support processes are:

Space heating and cooling loads. These are based on electricity-consuming units or equipment used for indoor climate control. This category includes heat pumps, electric radiators and AC compressors. These can be utilized for demand response purposes through thermal storage in the building mass and indoor air.

Ventilation loads. These are based on electricity-consuming units or equipment used for air quality control. This category includes exhaust vent fans and ventilation fans. These technologies may allow load shedding (on/off) or modulation through variable speed control.

Demand response type	Description	How fast to respond	Length of response
Regulation	Response to random unscheduled deviations in scheduled net load (bidirectional)	30 seconds	Energy neutral in 15 minutes
Flexibility	Additional load-following reserve for periods with un- forecasted wind/ solar generation (bidirectional)	5 minutes	1 hour
Contingency	Rapid and immediate response to a loss in supply	1 minute	≤ 30 minutes
Energy	Shed (Load shedding) or shift (Advance/Delay) energy consumption in time	5 minutes	≥ 1 hour
Capacity	Ability to serve as an alternative to generation	Function as the existing strategic capacity reserve.	

Table 5. Examples of five characteristic demand response services (Starke and Alkadi, 2013)

	End uses	Load types/patterns
Support processes	▪ Ventilation ▪ Space heating and cooling ▪ Hot tap water ▪ Lighting	Ventilation load Space heating and cooling loads Other auxiliary load Examples of characteristic load patterns: ▪ seasonal (outdoor temperatures) ▪ weekly (weekdays/weekends), ▪ diurnal (scheduled work hours)
Production processes	▪ Coating/Finishing ▪ Shaping/Forming ▪ Heating ▪ Melting ▪ Drying ▪ Packaging ▪ Decomposition (milling, grinding o crushing) ▪ Mixing ▪ Logging ▪ Assembling ▪ Cooling and freezing ▪ Internal transport service ▪ Steam ▪ Compressed air ▪ Pumping	Examples of basic load types : ▪ Mechanical loads where only two states are possible, either ON or OFF. (BML) ▪ Mechanical loads that allow for load control (MML) ▪ Continuous thermal loads (CTL)Thermal loads with potential thermal storage (ITL)

Table 6. Categories of industrial electricity end-uses and characteristic load types/patterns

Industry sector	Key manufacturing process	Spec. electricity use (kWh/t)	Load type
Pulp and paper	Mechanical wood pulp production (refiners and grinders), of which:	2000	
	Recycled paper processing		
	Paper machines	250	
	Chipper	425	BML
	Dewatering press		MML
Steel and metals	Aluminium electrolysis	14000	
	Electric arc steel production	525	
	Rolling mills		
Chemical	Chloralkali process (membrane)	2100	CTL
	Chloralkali process (mercury)	3600	CTL
	Compressors		MML
Mechanical engineering	Metal Cutting		
	Shaping/Forming		
	Coating/Finishing		
	Final Assembly		
Mining	Crushing		BML
	Electric furnace		ITL
Food, beverages, tobacco	Packaging		BML
	Refrigeration compressors and cooling fans		
	Electric heaters		ITL
Non-metallic minerals	Lime/Cement mills	110	BML
	Glass production		
	Electric furnaces		ITL
Wood products	Sawing		BML
	Planning		BML
Small industries and others			
Petroleum refining	Pumping		MML

Table 7. Examples of industry electricity end-uses suited for demand response (Fleiter et al., 2012; Starke and Alkadi, 2013; Gils, 2014)

Areas for advancing understanding of the potential for demand response in Swedish industry include:

Micro (firm) level

A. Continued efforts to identify processes and appliances suitable for demand response; annual electricity demands and installed capacities

B. Better characterization of technology-specific parameters and load profiles; including data describing characteristics and load profiles of process units or processes equipment currently installed.

C. Evaluation of operational challenges and constraints (minimum and maximum down and up time, ramp-up and ramp-down time, base and critical loads).[45]

D. Demonstrations of demand response strategies with industrial end-users, in order to assess customer acceptance and actual realizable potential.

Macro (branch/sector) level

A. Data describing characteristics and load profiles of new process units or process equipment including innovative electrical technologies for industrial applications

B. Analysis of geographical distribution of demand response potentials

C. Development of methods and tools for assessment of industrial demand flexibility services, in relation to options for demand response in other sectors on the demand side of the electricity system

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[45] see e.g. Marton et al., 2016

Advancing the Agenda: Priorities

In describing the emerging technologies and changing roles for different actors, this agenda has begun to identify priorities for action if such a transition is to be managed in a way that contributes to the innovation and green growth of the *Vivace* scenario. These priorities are examined across several themes below.

Technology

Many of the technologies described above are relatively immature, and a lack of knowledge and the presence of barriers to their development is to be expected. Nonetheless, the contributors to this agenda have identified a number of priorities that should be addressed in order to allow this development to proceed as smoothly as possible.

Competence development in flexible production processes

As noted above, increased flexibility of industrial production has already been identified as a top priority of two Strategic Innovation Programmes (PiiA and Produktion 2030). To date, however, electricity consumption, optimisation towards market prices, and provision of regulating services does not appear to be a major priority in the announced calls and projects. Integration of emerging IT, real-time metering of electricity consumption, and monitoring and maintenance are areas of importance to the realisation of a dynamic role for industry in the electricity system of the future.

Enabling technologies: wind, PV, and storage

For many of today's industrial consumers, becoming more flexible on the electricity markets will mean being *pro*sumers of electricity, owning generating assets that are used for processes directly, used to generate stored energy, used to guarantee affordable supply, and used to facilitate optimisation of the company's market position. For many firms this will mean owning solar PV, wind, and storage technologies.

The scenario assumes the continued progress of these technologies and their superior competitiveness in a long-term perspective. However, little analysis has been undertaken as to the optimal integration of such technologies into basic industry's operations. Today industry has begun by building parks in joint consortia, focusing on the economic benefits of ownership. Depending on the future availability of optimal wind sites, the relative competitiveness between wind and solar, and the importance of physical control over the assets, companies may move towards on-site generation, and work will need to be done to develop assets suited to physical integration in industrial sites.

A range of energy storage technologies will be needed to meet the diverse needs of different industries in terms of capacity, charge/discharge rates, and flexibility. For some industries the ability to efficiently bridge between different energy carriers may be especially valuable.

Development of standards

Standards development can be considered a general requirement for any technological systems transition. The transition discussed in this agenda may prove particularly demanding on this front as it will create direct and direct interfaces between systems. Standards relating to data, measurement and monitoring will need to be developed with sharing across currently separate systems in mind; standards for physical technology interfaces will be needed to allow a broader range of connections to and from the electricity system, with different requirements. This can relate to sources of consumption, production, and storage.

The first priority of the grid operator must be maintenance of grid safety and stability, but some industrial firms perceive the current requirements for participation in regulating services as too burdensome. Standardization, both in terms of technology and protocols, may also help to lower the threshold for actors to provide services to the grid.

Productification of electricity

In the long-term, a new role for industry in the electricity system may involve the "productification" of electricity. Productification can mean the differentiation of the current always-on service model into packages with different value propositions. A first step may involve low-cost "packages" of demand reduction and "turn-up" associated with system balancing. In the future providers of electricity may package services with behind-the-meter production and storage assets, and may even sell process, storage media, or chemicals directly.

While the shape of these products will be determined by long-term market development, differentiation in offerings is beginning today and will be important in providing industrial firms with options.

Policy

Contributors to this Agenda identified three levels of policy need, broadly speaking. Each level is important, and all three are interrelated.

Sustainability strategy

One level is the overall strategy for addressing climate and sustainability challenges, in terms of ambition, strategic priorities, and resource utilisation. To a certain extent the alternatives at this 'level' are elaborated in the Swedish Energy Agency's four scenarios, with *Vivace* illustrating a high level of ambition in transitioning to a Sustainable Energy System, an emphasis on proactive innovation and capturing new (including export) markets rather than protecting existing industry structures, and a willingness to allow the market to make the most important choices regarding, for example, electrification vs. increased biomass usage. While this Agenda used *Vivace* as a starting point for discussion, these strategic choices are not, at this point, clearly reflected in government strategy and policy, and other long-term approaches remain credible options.

Electricity system approach

The second level is also strategic, but focused on the overall approach to the electricity system. Philosophically, this might be described as a decision between prioritizing efficiency and prioritizing flexibility. The integration of high levels of intermittent renewable generation can arguably be done most efficiently through increasing transmission capacity and thereby linking different types of resources whose generation profiles are complementary. For Sweden, this approach would mean, inter alia, increasing transmission links with Europe, a measure with broad political support but whose timetable

for implementation is uncertain.

Should such transmission be put in place, the impacts on industry's role in the electricity system would not be clear. On the one hand, balancing needs from a domestic perspective may be reduced if portfolio effects on the supply-side are strong. On the other hand, portfolio effects on the demand side are unlikely and may even be negative, creating an opportunity for industry. Should Swedish industry manage to be first to market with flexibility and the ability to profitably provide services to the system, this advantage may be increased by connections to the continent.

A similar point may hold for energy storage: if companies expect large-scale storage planned, developed, and managed at the grid level, they are less likely to develop flexible resources within their operations. Current expectations, however, favor smaller-scale battery-based solutions, and if storage on the consumer side expands this may give demand response a head start.

Regulatory challenges

The third level emphasized by Agenda contributors is regulatory. While some specific regulatory tools are identifiable today, the major challenges for regulators will relate to the handling of issues which have not yet emerged. One of these entails managing the allocation of risk and benefit between public and private actors, both in the development and demonstration of new technologies based on electricity and in the encouragement of new participation in the electricity system. Incentives and programmes will have to find a balance between stimulating initial investment and maintaining confidence in the system over time.

With regard to promoting flexibility among electricity users, the Energy Market Inspectorate's ongoing work has so far identified a number of policy measures for further analysis. Among those most relevant to industrial users are:

1. An open interface in smart metering systems facilitating access to data by customers and service providers.
2. A campaign providing different customer segments with information about their flexibility options.
3. A responsibility for electricity retailers to provide customers with information about flexibility
4. Voluntary reporting of flexible plants into a registry of flexible resources
5. Reduction or removal of energy tax to increase the impact of the price signal

6. Shift from fixed to proportional energy tax to increase the impact of the price signal
7. Creation of a support system related to end use flexibility
8. Development of new options on the electricity exchange designed to improve the attractiveness of demand-side flexibility services
9. Loosening of some of the requirements for participation in reserve power markets
10. Promotion of user flexibility as a resource for automated reserves through
    a. Marginal pricing of capacity
    b. Improved transparency in market
    c. Financial support for investments in communication systems necessary for participation
11. Review and analysis of existing incentives for flexibility
12. Review of grid use and capacity to identify areas with the greatest need for flexibility

In addition to these measures, a range of options related to tariff formation are explored. It is worth noting, as the Swedish basic industries board SKGS has done in its response to the proposals, that there is a strong desire from industry to reduce complexity in the economics of electricity, which may be at cross-purposes with adjusting tariffs and regulations in ways that strengthen price signals.

Economics and Markets

Techno-economic analysis

The economics of industrial electrification and optimisation of processes for two-way electricity market participation are uncertain for a number of 'fundamental' reasons discussed above; for example relative prices of essential inputs, relative costs of technological alternatives, etc. This uncertainty is exacerbated, however, by the complex economics of process integration within companies.

For electrification and process optimisation to become priorities, in-depth techno-economic studies will need to be undertaken in a diverse range of industry contexts.

These studies can provide companies with increased confidence in the potential of various options, and help identify key systems integration issues which may be common to more companies. Undertaking some of these analyses in the context of publicly-funded open research could help ensure that the benefit of new knowledge is maximized.

Economic data (company- and system level)

One of the most important developments may relate to data availability and use. To maximize the potential of industry as a service provider to the electric power system, data relating to system needs and market movements will need to reach consumers in a format they can use. This may mean both the development of new and potentially more open databases as well as the development of improved monitoring, measurement, and data management on the industry side. Data will be useful in production planning, market-making, and, increasingly, algorithm development and automation. These data systems will have to be developed according to shared standards (and integrated via smart meters).

New market designs and mechanisms

The main marketplace for trading of electric energy in the Nordic system is the power exchange Nord Pool. Nord Pool operates mainly two marketplaces for physical delivery of electric energy: The day-ahead spot market and the intra-day adjustment market, also known as Elbas. The spot market is an auction-based power pool where hourly quantities of electrical energies are traded the day before

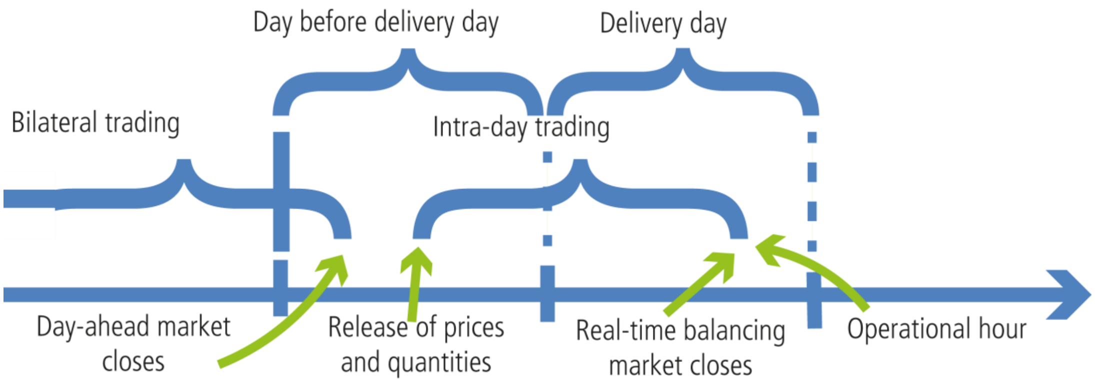

Figure. 13. Overview of the daily electricity market

the day of delivery. Elbas is an intra-day market where the traded volumes on the spot market can be adjusted in accordance to updates in production or consumption forecasts. The spot market and the Elbas market are one common market for the whole Nordic interconnected system. On a national level, the system operators also operate real-time balancing markets mainly for frequency control purposes.

The envisaged future system, including large amounts of intermittent production as well as a significant increase in distributed resources, implies new challenges on the operation of the system and the trading of electricity. The local perspective on electricity production and trading may imply local marketplaces, where suppliers and consumers can trade energy on a local basis. However, the majority of the electricity will still be traded through the centralized market place. The increased variability of the system emphasizes the role of the intra-day and the real-time balancing markets, and such marketplaces will become more important both for the system as a whole as well as for the market participants.

The growth of new production capacity with low marginal costs (mainly wind power) decreases the incentives for owners of conventional power plants to keep their production resources in operation. The economic risks involved are not considered to be compensated for by the expected revenues from selling energy on the market. Hence, a problem with keeping production capacity in the system is emerging. This can be resolved by introducing e.g. capacity payments, but such compensations also potentially distort the energy price signal from being a representation of the marginal cost in the system.

Business models for system services

The development of successful business models is largely a function of the marketplace. The responsibility for business model innovation lies with firms, who seek advantage through tailored and sometimes proprietary approaches, and who understand that the failure of some business models is a result of healthy competition.

However, in the face of a technological and/or system transition, the absence of proven business models suited to the new reality, or a limited understanding of what factors will affect the prospects of different business models, can increase the risks perceived by companies and discourage investment and innovation.

In their study of business model innovation in electricity supply markets, Hall and Roelich focus on the challenge of "complex value," which they define as "the production of financial, developmental, social and environmental benefits which accrue to different parties, across multiple spaces and times, and through several systems. Business models with complex value propositions must effectively capture several value streams across various systems in order to remain viable."[46] While the authors are most interested in the potential for communities to supply electricity based on distributed generation, the idea of complex value holds for industry's potential new role in the electricity markets as well, as it will require combining value streams from electricity generation and sales, provision of capacity and regulating services, trading activities, and production optimisation.

One of the challenges of complex value business models is monetisation and value capture: not all value created by innovation is reflected in available revenue streams. Uncertainty about CO2 prices and other incentives is one example, as is uncertainty about non-economic values held by future consumers and citizens, which may promote localism and drive distributed generation and dynamic grids as a preferred option for electricity system development. Even more tangible economic value generation -- such as a reduction in the need for grid reinforcement over time -- may be difficult to capture through the electricity markets; Hall and Roelich note

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[46] Hall and Roelich (2016)

that "the transaction costs associated with monitoring and verification of [such] benefits are high."

They classify the barriers to business model innovation in the electricity system into three groups: Regulation (for example, who can provide system services and on what terms, how grid access tariffs encourage/discourage demand response and participation, etc.); Capacity (e.g. modelling and trading expertise, access to risk capital, etc.); and Uncertainty/Risk (especially related to complexity). These categories hold well for the case of industry's future role in the electricity system, and are reflected in the priorities outlined in this section.

Indeed business model development should be seen as integrated with the other priorities here. To the extent that research has a role to play in business model development, it should focus on the technological, economic, and policy issues relate to the specific business models that begin to emerge during the transition.

Conclusions and a Plan for Action

Much of what is required to make this transition a successful one characterised by high levels of innovation, growth, and fast CO2 reduction must be done at the level of national climate and energy strategy, rather than through narrower research and innovation policy and action.

Nonetheless the Swedish Energy Agency's *Vivace* scenario may be a useful tool for focusing strategy. The decisions implied by that scenario – a strong commitment to a climate leadership and green growth and exports; proactive transitioning to RES; strong state support for innovation in industrial technology; promotion of market-based solutions for balancing – will be the fundamentals underpinning a new role for industry in the electricity system.

On this front we are encouraged by

- The report from the government's analysis group for a green transition and competitiveness, which advocates a proactive approach, strategic investment in CO2 technology development, and market creation for low-CO2 solutions
- Recent support for research and development in electrification, including financing from the Swedish Energy Agency for the HYBRIT Phase 1 and PROCEL projects
- The investigation by the Energy market inspectorate into demand flexibility in industry

At the level of research and innovation (R&I) and R&I policy, much more can be done. This agenda identifies several measures that can be taken immediately or in the relatively near-term to support electrification and a new role for industry.

Improve data on electricity use in industry. The most current data on use by processes and technologies in industry is decades out of date. Assessing options for change from a Swedish perspective will require a better understanding of the current status. Although the energy audits led by the Swedish Energy Agency are not currently seeking data of this kind, consideration should be given to leveraging these processes to initiate improved data collection on electricity consumption by source.

Study the technical and economic potential for flexibility in industrial electricity use. While studies of flexibility have been undertaken, these are focused on existing technologies and do not consider geographic dimensions. Looking at new and future technologies as well as potential by region will improve the relevance of this data to the changing electricity system.

Study the economic and CO2 effects of electrification options. These decision support studies should compare across sectors as well as compare industrial with non-industrial options (transport, buildings, etc.). Such studies should include existing as well as long-term new technologies. The PROCEL project is an important first step in this direction. Harder-to-quantify issues such as systemic complexity and acceptance will be important complementary considerations to cost/benefit analyses.

Use existing Strategic Innovation Programmes to develop flexibility technologies related to electricity use. The existing programmes “PiiA” and “Produktion 2030” could be used to finance relevant projects. Continued efforts to improve energy efficiency in industrial production processes is important but a more holistic approach, considering also when in time energy and electricity is used, may provide new insights and new solutions and avoid sub-optimization. Treating flexibility of energy use as a naturally integrated aspect of the foreseen automation and IT revolution could potentially provide synergies and co-benefits.

Develop new channels for overcoming silo effects. Currently research and innovation funding for industrial technology is separate from the funding for electric power system technologies. Channels where this gap can be crossed (such as the SIPs mentioned above) should be developed and exploited.

Continue evaluation of policy options including Impact Assessment. The results from the Energy market Inspectorate’s work on demand flexibility will be policy recommendations. Work should continue to assess the potential impact of these policies, possibly in conjunction with the studies of potential in electrification. Undertaking an ex-ante Impact Assessment can inform policy but also generate information related to technical and economic potential for electricity market and balancing services that could be of use to companies.

Develop platforms for data sharing and collaboration. Industrial firms are necessarily careful about data related to their energy use and their plans for future development. Collaboration – from cross-industry fora that continue on from this agenda to more action-oriented collaborations such as research projects and joint ventures – need to be structured in ways that encourage responsible data sharing and are open to new actors with new business models.

Support a wide range of large-scale, long-term demonstration projects related to industrial electricity use. The HYBRIT collaboration will hopefully provide a strong example for other industries. Currently demonstration of power-to-liquids technology, for example, is advancing in Europe. Will this be relevant in Sweden?

A useful analogue for the IndEEl transition may be the history of energy efficiency. In the wake of the oil crisis of the 1970s, efforts were launched in Sweden and internationally to investigate the potential for energy efficiency across the economy, efforts which continued for several decades and have played an important role in guiding policy and investment strategies. A similar effort may be required for "flexible electrification."

One of the questions facing stakeholders is what comes first: will the need to electrify to reduce industrial emissions drive increased flexibility, or will the need for system services in the electricity system encourage more (and more flexible) electricity use in industry? For an individual company today, this uncertainty affects their planning. But from a system perspective, what matters is an understanding that whichever development comes first, implications for the other side of the equation will follow.

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