Future Electricity Production in Sweden

A project report

IVA *Electricity Crossroads* project

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Foreword

IVA's project Electricity Crossroads examines how the electricity system might look like in the timeframe 2030 to 2050. Future Electricity Production in Sweden is a project report from Electricity Crossroads which discusses various technical options that exist for Sweden's long-term electricity supply. One point of departure has been to determine how large the demand for electricity might be and for this the Electricity Production work group referred to the analysis in the "Future Electricity Use" project report.

Our report contains a discussion of four alternative electricity systems, all of which should be regarded as extremes in their particular area in terms of expansion of resources such as wind power and hydropower. The intention has been to find the limits for what at this time, with the knowledge and experience The Electricity Production work group have today, believe to be technically possible to achieve. The electricity system in 2030–2050 will be largely determined by which energy and climate policies are pursued as well as technology development and the economic conditions.

Stockholm, January 2016

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The work was carried out in 2015 and was informed by facts known at that time as well as relevant assessments on future technology and cost trends. The work group is well aware that future technology leaps and changed market conditions in the future may alter the hypotheses on which the analysis and conclusions presented here are based.

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1. Conclusions and summary

Sweden's electricity system is almost fossil-free today. There is a good chance that it will be fossil-free in 2030–2050 too and based on hydropower, biofuels, solar and wind power or new nuclear power.

Future Electricity Production in Sweden is a project report from Electricity Crossroads and was produced by the Electricity Production work group. The assignment has involved analysing and presenting various alternatives to show what Sweden's electricity supply could look like over the long term. The following assumptions are the basis for the analysis:

- The electricity system must be fossil-free over the year. This means that within the country the amount of fossil-free electricity produced annually must equal the amount consumed.
- The analysis is based on domestic production resources being able to meet total electric energy load.
- Demand flexibility is assumed to be at least 10 percent of peak load.

The electricity demand that needs to be met was calculated by the Electricity Usage work group within Electricity Crossroads and is in the range of 140–180 TWh with estimated maximum power of 26–30 GW. The scenarios for the range in energy and power are presented as "low", "medium" and "high" in the report. The results presented show general potential with limited attention being paid to environmental and economic aspects. The results will be further developed within the Electricity Crossroads project.

This report is divided into two parts. Initially there is a discussion on the gross potential of different types of energy sources, after which four different extreme alternatives for the future design of the electricity system are created. Table 1 shows the gross potential for different energy sources, without taking into account economics or environmental aspects, and which criteria must be met in order to fulfil this potential.

Four different extreme alternatives have been created for the electricity system's design 2030–2050. All of them consist of at least 65 TWh hydro-

Table 1: Gross potential for different energy sources.

Energy source	Production capacity today	Gross potential	Necessary conditions
Hydropower	65 TWh	100 TWh	Expansion in all rivers and streams that are protected today
Wind power	15 TWh	> 100 TWh	All land-based wind power projects currently in the pipeline are realised, representing 160 TWh. There is also potential for offshore wind power.
Solar power	0.1 TWh	50 TWh	All suitable roofs are fitted with solar cell panels. There is also potential in fields.
Bioenergy	20 TWh	60 TWh	New, more efficient technology replaces conventional technology in all CHP plants, operating time is increased over the year by using condensation, and CHP is expanded in more district heating grids.
Nuclear power	65 TWh	> 100 TWh	Today's reactors are replaced by new ones.

power, continued expansion of wind power and solar, and increased use of biofuel-based power production. One alternative consists of new nuclear and another of an expansion of hydropower. All of the alternatives contain a mix of energy sources, but each one has a different main focus. They are:

1. "More solar and wind"
2. "More bioenergy"
3. "New nuclear power"
4. "More hydropower"

One early conclusion reached in the project was that there are several paths for Sweden to choose from to achieve a fossil-free power system. One assumption is that domestic production must be equivalent to consumption over the year. This means that Sweden is self-sufficient in energy, but not necessarily in power.

In order to maintain a balance during all the hours in the year, the main alternatives may need to be supplemented in varying degrees by other solutions, such as flexible capacity from, for example, gas turbines, imports/exports, demand control or storage. Below these solutions are called "supplementary systems" and the four production alternatives are called "basic systems."

Below is a summary of the observations made for each system alternative.

Primary observations for "More solar and wind"

In the "More solar and wind" option, variable power sources account for to 50 percent of the annual energy. The system is able to generate a lot of energy, but its ability to guarantee power is limited. Such a system would therefore to a greater extent require various types of technical supplementary systems to handle situations when solar and wind power production is low but electricity consumption is high. The reverse situation also needs to be dealt with, i.e. when there is a large surplus of electricity.

Examples of supplementary technical measures are:

- Expansion of transfer capacity – both within Sweden and to surrounding countries. A general plan for northern Europe is also needed to handle deficits and surpluses of electricity between different regions.
- There is a need to be able to store energy, preferably over a period of at least a few weeks, in order to save energy produced on windy days to be used on less windy days. Seasonal storage is not necessary to even out variations in wind power generation.
- In addition to hydropower and CHP, additional baseload production capacity is needed in the form of gas turbines or similar flexible production solutions that can be on standby and used during consumption peaks. Incentives and opportunities for more flexible electricity consumption are also necessary.

Primary observations for "More bioenergy"

The "More bioenergy" alternative has the potential to create a situation where Sweden is self-sufficient in energy and power. This system is primarily based on domestic fuel and production being close to consumption, reducing the need for new transmission capacity.

To reach full potential, technical development and demonstration plants are needed for new CHP technology – both large scale plants with significantly higher power generation efficiency than today's plants, and small-scale CHP plants.

To increase electricity generation from biofuel-based CHP, electricity generation needs to be independent of the heat source through the installation of extra cooling solutions. Conventional condensing power plants are a more expensive solution and not as fuel-efficient.

Increased investment in larger scale bioenergy solutions could be limited because there will be competition for biomass.

Primary observations for "New nuclear power"

The "New nuclear power" alternative is the one that is the most similar to today's system. This system will not require any substantial investment in new supplementary systems.

Technology is being developed for a number of new concepts. It is likely that generation 3+ technology may be available in the period 2030–2040. Generation 4 could come after that. If new

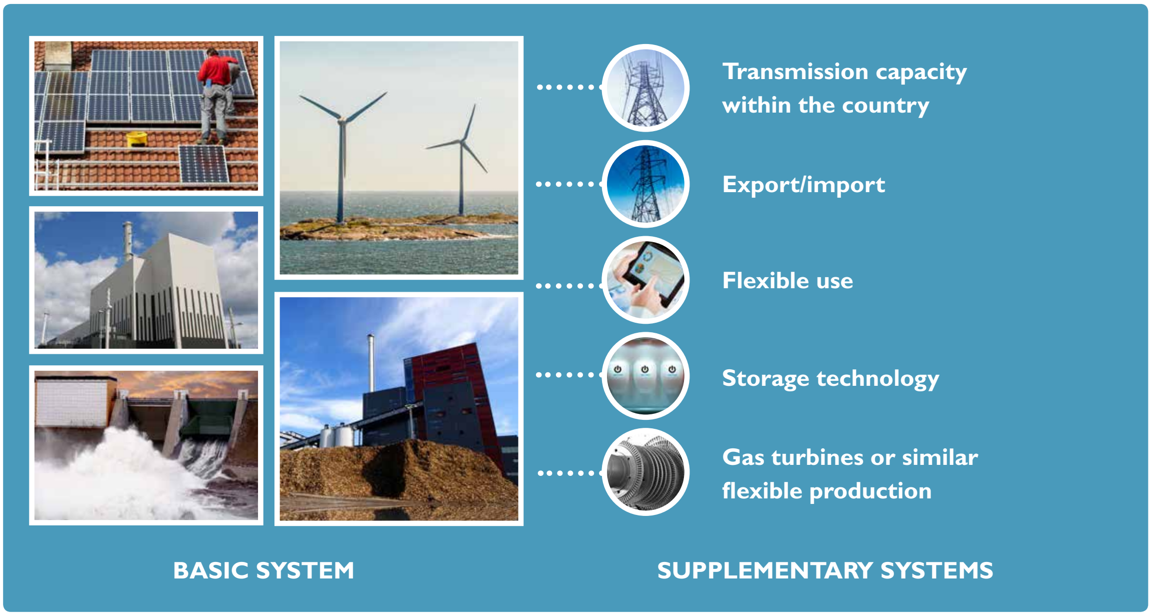


Figure 1: The illustration of how the analysis differs in the "basic system" – production facilities, and "supplementary systems" – the technical solutions required for the basic system to work.

nuclear is to be an option, Sweden should monitor technology development and experiences gained internationally to ensure the country have the necessary expertise to make well-informed decisions on which technology to choose.

Building new nuclear power plants is a long-term undertaking as they have a long technical and economic life.

Primary observations for "More hydropower"

The "More hydropower" alternative has the potential to create a system where Sweden is self-sufficient in energy and power. Hydropower is the most flexible energy source and can also be stored. Annual energy generation depends on precipitation, but the available power is not affected in the short term. A significant portion of the new hydropower capacity is in northern Sweden and investment will be needed in transmission capacity southwards. An increased share of hydropower will result in large differences in domestic energy production between wet years and dry years, which will require an increased energy exchange with neighbouring countries.

The "More hydropower" alternative in the "high" scenario would involve expansion in rivers and streams that are protected at this time. The laws will need to be changed in order for this to happen. Building new hydropower plants is a long-term undertaking as they have a long technical and economic life.

Economic comparison of the alternatives

A simplified economic comparison has been made of the different production alternatives. The comparison is based partly on estimates from Elforsk of the total production costs today for each technology (per kWh) and partly on estimates made by WEO (World Energy Outlook) of the cost reductions, mainly in solar and wind. A simplified analysis shows that there are only marginal differences between the average costs for the different alternatives. These estimates take into account different investment needs for transmission capacity and reserve power. The investments vary between the different production alternatives and may be considerable.

As this analysis is very general, it is not only a question of which future electricity production options are the most cost effective, but also how much the supplementary systems, in the form of transmission capacity and reserve production, will cost. To gain a complete picture it is important to identify and, to the greatest extent possible, quantify other factors and costs of significance in choosing a power system.

2. Introduction

Future Electricity Production in Sweden is a project report from Electricity Crossroads and was produced by the Electricity Production work group. The assignment has involved producing and analysing various alternatives for what Sweden's electricity supply will look like in the long term and commenting on what is needed in order for these systems to be realised.

The results presented are meant to be seen as potential scenarios based on what is possible to achieve from a technical perspective. The system solutions proposed will be analysed by other Electricity Crossroad's work groups, primarily the Environment and Climate group and the Public Finances and Electricity Market group. The alternative scenarios for production have also been used to inform the work of the Distribution and Transmission group, while the User group's assessments have been a resource in the task of designing the production system. Thus, the alternatives presented here for how to design the electricity system serve as a "gross" version in which limited attention has been paid to environmental and economic aspects. These will be covered in the synthesis process, in which the final "paths" will be established and evaluated. The methods used in the work process and calculations are presented in Appendix 2.

The different alternatives presented represent a "basic system" which can supply Sweden with energy throughout the year. All alternatives consist of a mix of different types of production. Depending on the nature of the respective production combinations, the system will need to be supplemented by various types of "supplementary systems" to maintain a power balance and ensure delivery reliability. It may, for example, be necessary to invest in transmission capacity, flexible electricity production or storage technology.

Based on the assessments from the Electricity Usage work group, electricity production in Sweden will need to reach 140–180 TWh per year, with a power demand of 26–30 GW. The range in the alternatives is expressed as "low", "medium" and "high" scenarios (see Appendix 2. Methods).


VOLVO

3. Trends and challenges on the electricity market

Today the electricity production system is evolving from large central plants with long operating periods over the year to smaller decentralised ones where production is largely dependent on the weather. This transition in the structure of the electricity market is impacting the situation for existing plants as well as investments in new ones.

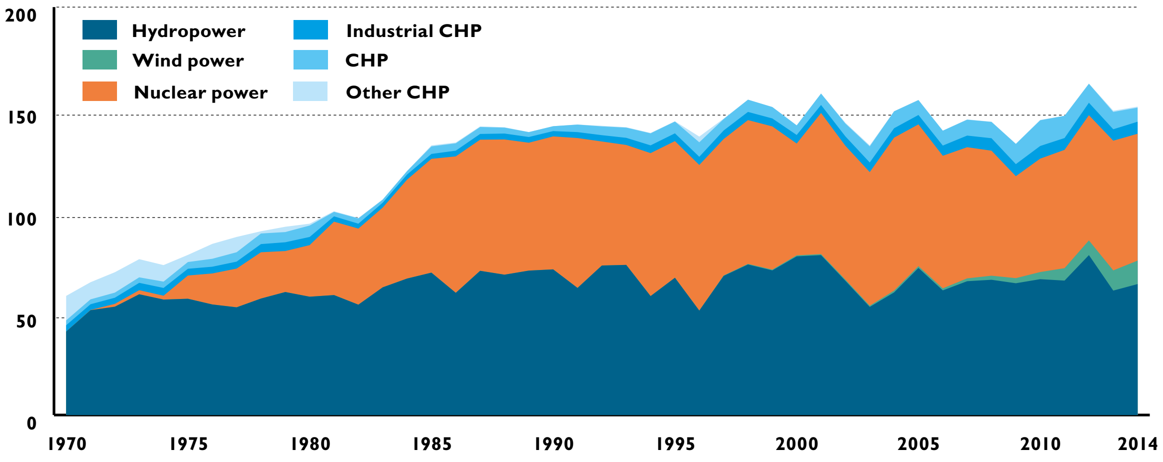
Large capital-intense plants – in Sweden mainly nuclear power plants – will have fewer hours of operating time and a lower earning capacity when an increasing proportion of wind power with very low variable costs periodically puts pressure on the electricity price. The low price of electricity will also make it more difficult to invest in new plants. The same trend is affecting all of Europe.

Sweden's electricity production has been relatively stable over the past 20 years, but now the conditions are fundamentally changing. Electricity production today consists of about 40 percent nuclear power, 40 percent hydropower, 10 percent CHP and 10 percent wind power. Wind power has increased significantly over the past decade, from just under 1 to around 15 TWh a year (rolling 12 months). One important driver has been the energy certificate system.

Other changes can be expected. In October 2015 Vattenfall and E.ON. announced plans to close four nuclear reactors over the next five years. They are Ringhals 1, Ringhals 2, Oskarshamn 1 and Oskarshamn 2. They have a total installed capacity of 2.8 GW, which is equivalent to 30 percent of the installed capacity of nuclear power totalling 9.5 GW. The main reason for the planned closures is poor profitability.

The fact that variable energy resources are growing at the same time as conventional pow-

Figure 2: Electricity production in Sweden 1970–2014 TWh. Source: Energiläget i siffror, Swedish Energy Agency.



er plants are being closed is a challenge and the power system will therefore need further development. The ability to forecast output from variable energy resources is limited, which means more capacity and flexibility in the system are needed. The location of the plants is also mainly determined by good conditions in terms of wind and sun and not by where electricity is needed, which requires adaptation of the power system. Solar and wind power do not have mechanical inertia and are therefore not currently able to provide stability in the event of disruptions (Svenska kraftnät, 2015).

Sweden today has a strong power balance and under normal[1] conditions is able to have net exports of electricity. The energy supply today is not a problem, and is not likely to be a problem for many years to come. One challenge will, on the other hand, be access to capacity.

Sweden today has installed capacity of around 40 GW, which can be compared with the highest power output ever recorded in Sweden, 27 GW which happened on 5 February 2001. Today the forecasts for a particularly strained situation, a so-called 10-year winter (cold winter), are still at 27.1 GW and for a normal winter at 25.6 GW.

This does not mean that there are large margins in the system. It is not possible to count on all capacity being available at the same time. Hydropower and energy sources based on fuel that can be stored are more readily available than wind power which is only produced when the wind is blowing. Statistically, the wind is always blowing somewhere in Sweden, which means that wind power is assigned a certain capacity value. The power balance is particularly strained in the winter and it is assumed that solar will not be able to help restore it. Furthermore, the energy needs to be available in the right part of the country. In the northern parts of Sweden the power balance is significantly stronger than in the southern parts, where most of the consumption takes place.

Below is an example of how the power balance was expected to be heading into the winter of 2015/2016. The installed capacity amounts to 40.4 GW and the available capacity 28.2 GW. The installed capacity in gas turbines is mainly for disruption reserves and is therefore not available capacity. Svenska kraftnät (Sweden's national grid) is responsible for guaranteeing the country's short-term power balance, i.e. the balance between supply (production and imports) and demand (electricity consumption). To maintain a power balance during the coldest part of winter, Svenska kraftnät (Sweden's national grid) has been tasked with securing a special power reserve during the period 16 November to 15 March not exceeding 2 GW. This power reserve will either be secured through increased production or a reduction in electricity consumption by large users. The current law is in effect until 16 March 2020 (Svenska kraftnät, 2015). The Government is preparing a proposal to extend the power reserve law until 2025.

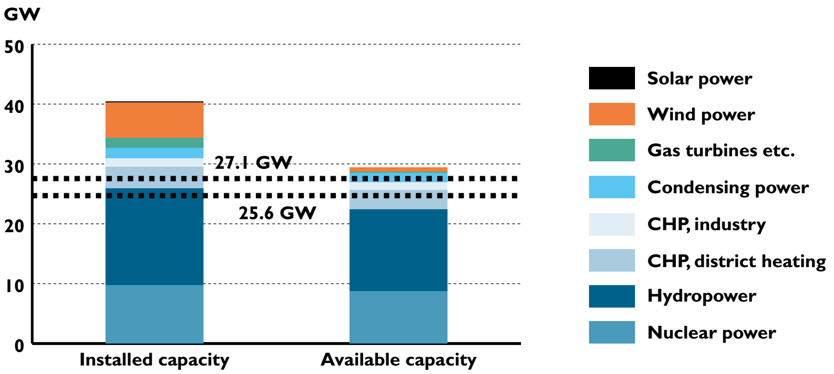


Figure 3: Estimated power balance before winter 2015/2017 with the levels marked for 10-year (cold) winter (27.1 GW) and normal year winter (25.6 GW). Source: Kraftbalansen på den svenska elmarknaden vintrarna 2014/2015 och 2015/2016. Svenska kraftnät 2015.

4. Power system properties

An optimally functioning power system delivers the same amount of electric energy as the demand at any given time. The system is robust and can handle different types of disruptions without them having any consequences for electricity users. As industrial processes and equipment become more and more sophisticated and technically advanced, the required quality standards for the electricity delivered increases. The electricity systems in different countries may look different and the necessary services may be provided in different ways. The combination of different types of production facilities, transmission capacity in the country, and integration with neighbouring countries are all important factors in the efficiency of the system.

Important properties

Energy generation

- Sufficient electric energy entering the market over the course of the year. This can be ensured through production facilities being located nationwide or through imports from different countries. All types of power production facilities deliver energy, but not all production can be planned.

Power

- In order for the electricity demand to be met at any given time, the power balance must be able to be maintained; i.e. the supply of electricity must correspond to the consumption at every moment. This requires access to baseload production reserves, such as CHP, hydropower and gas turbines, or imports from other countries. Flexible power consumption can be a contributing factor in maintaining the power balance. The ability of an energy source to reduce the risk of a power deficit represents its "capacity value."

Voltage

- To keep consumers' and producers' facilities in operation the voltage in the electricity system needs to be constantly stable. Stable voltage is also necessary for energy transmission.

Balance (frequency)

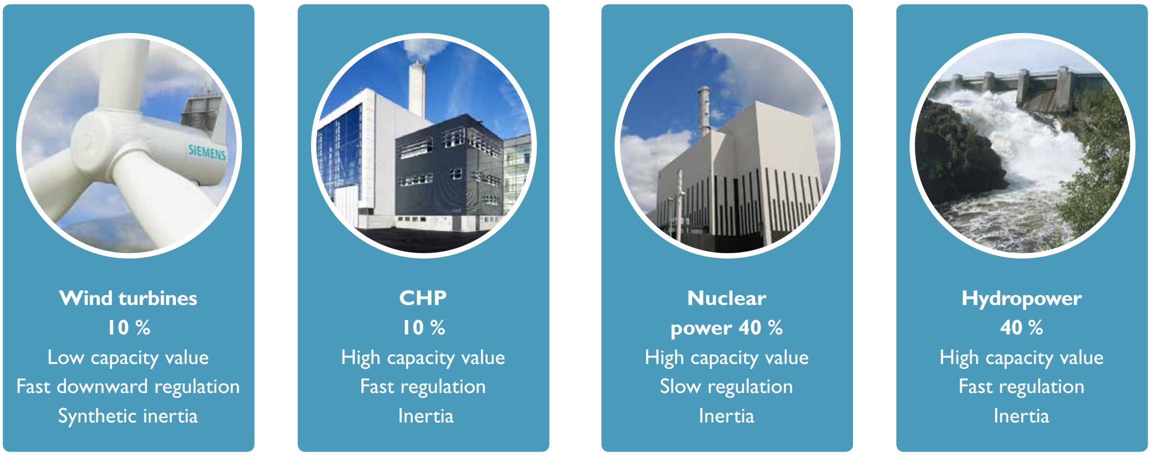
- To maintain the quality of the electricity system there needs to be a balance between production and consumption of electricity. One indication of balance is that the frequency in the system is kept stable. The frequency should be at 50 Hz, but is permitted to vary between 49.9 and 50.1 Hz.

  The balance is maintained initially, for 5–10 seconds (Karlsson & Lindahl, 2015), through inertia in the system, and then, as needed, different types of load-balancing resources kick in, primarily in the form of hydropower.

The energy sources that exist in the Swedish product mix have different roles in the electricity market, as illustrated below.

Hydropower accounts for 40 percent of electricity production, but is also the most important load-balancing resource. It is used in everything from seasonal load balancing to instantaneous load balancing to maintain the frequency in the system. Water is stored in reservoirs during periods of high inflow to be used for electricity generation when the demand increases. Hydropower can always supply a large amount of power, although annual energy production varies between wet years and dry years.

Figure 4: Summary of the energy sources' properties and their share of electricity production today. Source: Electricity Crossroads Production work group 2015.



CHP plants (combined heat and power) produce electricity and heat at the same time, and therefore deliver mainly during the winter when the demand for heat is high. If there is a heat source the available capacity is high. The plants can also be equipped with alternative cooling technology, which extends the operating time and supply of power. CHP is not used today for load-balancing, although it is technically possible.

Nuclear power has a high capacity value, but is not normally used for load-balancing regulation. The Swedish nuclear power plants can be used for slow load-balancing in the interval 100 to 65 percent of installed capacity, with a capacity adjustment of 3–5 percent a minute. However, regulation involves a disruption that could lead to undesirable stoppages. (Persson, et al., 2011)

Wind turbines produce energy when the wind is blowing and therefore have a low capacity value relative to installed capacity. On the other hand, it is easy to regulate electricity production downwards when necessary.

The other energy sources have mechanical inertia from the kinetic energy in their rotors. There is inertia in wind power too, but because production is not synchronised with the frequency in the system, special control equipment needs to be fitted.

5. Gross potential of different production methods

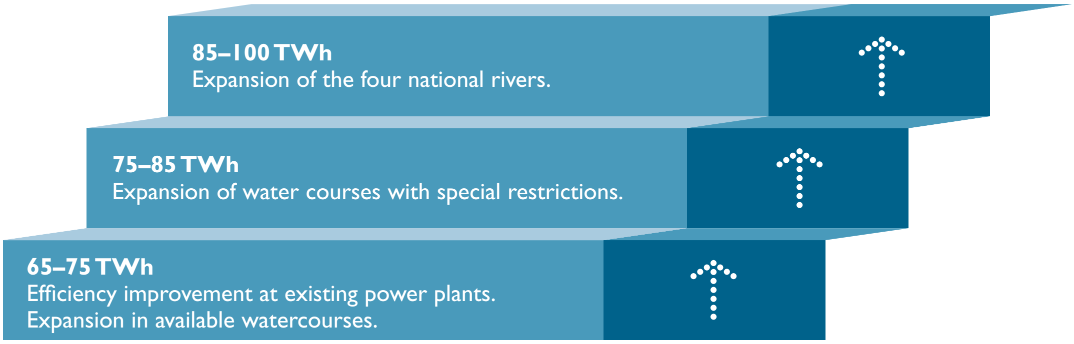
Below is a discussion on the potential of different energy sources in a long-term perspective, up to 2050. A theoretical technical potential is limited in practice, both by factors in the technical system itself, and by economic and political factors. One assumption is that the electricity system will be fossil-free, but other sustainability aspects are also very important to consider. The potential discussed below is based on what is technically possible. An assessment of environmental factors and economics is being done by other Electricity Crossroads work groups within the Electricity Crossroads project. The final analysis will be the responsibility of the Electricity Crossroads steering committee.

HYDROPOWER

On average hydropower delivers 65 TWh a year, but depending on precipitation, this may vary between 50 and 80 TWh. The installed capacity is 16.2 GW, but the power delivered during the year varies from between 2.5 and 13.7 GW and is determined by demand and the supply of water. Water is stored during periods when there is a large inflow and used for electricity generation when demand is high. The capacity for seasonal storage in Sweden is 33.7 TWh (Swedenergy 2015). Part of this storage capacity can also be used between dry and wet years.

There is technical potential to expand hydropower further by around 30 TWh (Korsfeldt, 2011). Most of the potential cannot, however, be used due to a political decision to protect the four national rivers (Kalixälven, Piteälven, Torneälven and Vindelälven) and many other watercourses. There are also protected stretches of the rivers that are being used. The remaining potential amounts to 6 TWh, based on established technology. Through renewal and efficiency improvement it is estimated that production could

Figure 5: Illustration of the gross potential for expanding hydropower. Today hydropower produces 65 TWh of electricity during a normal year.



increase in existing power plants by 2–4 TWh (Electricity Production work group, 2015).

Hydropower could be adapted to offer even greater storage potential and load-balancing capacity, but this will require a change in the water rulings for increased short-term load balancing, higher dams, higher wave amplitude, higher maximum flows etc.

WIND POWER

Wind power has increased significantly in recent years, with production amounting to just under 12 TWh of electricity in 2014. On an annual basis, production is now at 15 TWh and installed capacity is at 5.7 GW (Svensk Vindenergi, 2015).

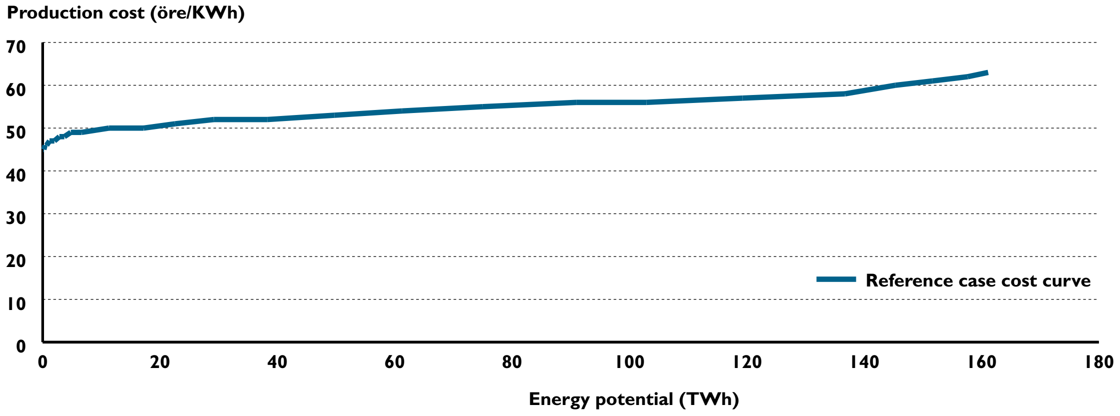
Wind power production cannot be planned and advanced planning is determined by how far in the future it is possible to forecast wind levels, which is usually just a few days. When the wind is blowing, wind power would be able to fulfil a load-balancing function through downwards regulation. This is not happening today. Wind turbines generally produce at full capacity when they are given the opportunity. The capacity value is significantly lower than the installed capacity and is estimated to be 11 percent (Svenska kraftnät, 2015), which today means 0.6 GW. The capacity value is, however, expected to increase in the future through new technology and longer usage periods.

Sweden is a sparsely populated country with long stretches of coastline. The technical potential for land-based wind power is therefore very substantial, approaching 160 TWh (Swedish Energy Agency, 2014). The diagram below shows a cost curve for 1,382 land-based wind power projects in Sweden in 2014 (Swedish Energy Agency, 2014). The cost interval of 45–50 öre/kWh represents around 12 TWh, and the 50–60 öre/kWh interval 140 TWh. There is also potential for offshore wind power. Here too, new technology could increase the potential and improve the use of the energy in the wind, but the costs today are much higher.

Where is wind power being built?

Today's wind farms are mainly in southern Sweden, close to the coast along the whole West Coast and in Skåne, as well as on the islands of Öland and Gotland. There are also many wind turbines by the Vänern and Vättern lakes. In recent years wind power turbines have also been

Figure 6: Production cost curve for wind power projects in Sweden, 2014. Source: Swedish Energy Agency.



erected in forests. The expansion of new wind power will most likely take place:

- On land with an increasing number in forests and in cold climates as the know-how and technology for this are developed. Much of the expansion will be in northern Sweden.
- A generational shift will take place in coastal areas and in other areas that are already being used to a large extent today. Older wind turbines in good locations will be replaced by new, more efficient ones.
- In the longer term, it is also likely that larger offshore wind power parks will be built. In the short term this is expensive compared to other alternatives.

SOLAR POWER

Electricity generated by solar cells amounts to 0.08 TWh and the installed capacity today is around 0.08 GW. With the current subsidies (2016–2019), the installed capacity is expected to increase to at least 0.5 GW. Solar power is mainly produced from March to October and is therefore not assigned any capacity value because demand is highest during the winter. On the other hand it is possible to forecast production for the coming days. Theoretically there is great potential for solar energy generation on roofs and in fields around the country. One calculation shows that if all available, and for the purpose appropriate, roofs, a total of 319 KM2, were fitted with solar cells, they would be able to generate close to 50 TWh of electricity, and power of 48 GW (Kamp, 2013). Solar cells on roofs are connected directly to the user and the system – if supplemented with batteries – could be self-sufficient periodically.

BIOENERGY

The potential for biofuel-based electricity production is determined both by the availability of bio raw materials and by which technology is used.

Bio raw materials

Biofuels referred to here are mainly fuels originating from the forest or from energy crops. Today (2013) a total of 128 TWh of biofuels are used for energy production, of which 14 TWh is used for electricity generation, 37 TWh for heat production in district heating systems and 55 TWh in industry. The remaining portion is small-scale use of wood and pellets for heating homes and bio-based fuel used in vehicles (Swedish Energy Agency, 2015). In the short term the extraction of biomass could increase by the equivalent of 35–45 TWh in current conditions and without directly competing with other agricultural and forest production. Within 30 to 50 years the potential could increase by 55–70 TWh from today's levels. The forest has net growth, which means that wood extraction could be increased. This in turn could generate additional residual products to be used for biofuel. This potential is estimated at an additional 50 TWh a year (Börjesson, 2015).

Biofuel for energy production consists almost exclusively of residual products from the forest industry, which includes timber sawmills and the pulp and paper industry. There is, however, a trend whereby more and more industries are seeing an opportunity to use forest raw materials to produce renewable materials and products. This could result in competition for the raw material. In the short term, however, the greater the turnover of forest raw materials in the forest industry, the more will be available for fuel production. Not all forest residues are being used today and there is net growth in the forests equivalent to 100–150 TW a year (Börjesson, 2013).

Biofuel for energy and heat production is usually in the form of chips or pellets. Biogas can be used as well, thereby expanding the raw material base. The advantage of producing biogas is that biomass can be used. Biogas is usually produced through anaerobic digestion of biological waste, such as sewage sludge, agricultural waste or food waste, but can also be produced through thermal gasification. All organic materials such as forest residues, various field crops and agricultural waste, as well as industrial and household waste with a biological origin can be gasified. The biogas potential by 2030 is estimated at 22 TWh, half of which will be from anaerobic digestion

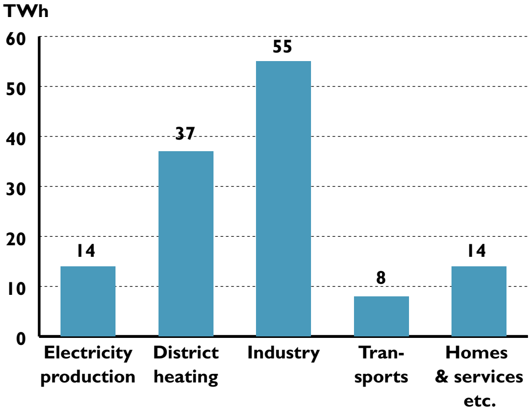


Figure 7: Use of biofuel in different sectors 2013, total of 128 TWh. Source: Energiläget i siffror 2015, Swedish Energy Agency.

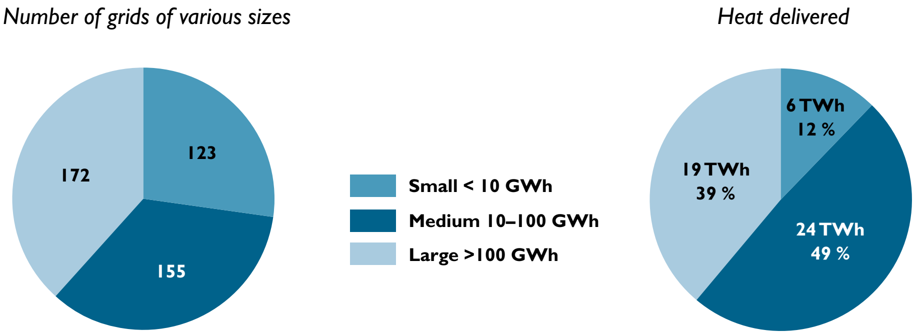


Figure 8: Number of district heating grids of different sizes and heat deliveries from these. Source: Swedish District Heating Association.

and half from thermal gasification of forest residues. By 2050 the potential could reach 70 TWh of biomethane, of which forest residues could account for 80 percent and the rest other types of biological waste (Jannasch & Ragnar, 2015). Thus there is an alternative where forest waste could either be incinerated directly or gasified and the gas then used for production of electricity and heat. There is also competition for the raw materials here, in this case for fuel production. In the longer perspective, when more vehicle fleets will likely be electrified, biogas could instead be used for electricity production.

Electricity production based on biofuel

Electricity production based on biofuel in Sweden is mainly taking place at CHP plants, i.e. during the simultaneous generation of power and heat. The heat demand therefore determines the amount of electricity that can be produced. Electricity is also produced in the forest industry where the amount produced is mainly determined by the price of electricity. The extent of electricity production in the forest industry in the future will depend on how the industry develops.

Today 11 TWh of electricity are produced in biofuel-based CHP plants in district heating systems and in industry. An additional 2 TWh or so of electricity are produced in waste incineration plants. The installed capacity is around 3.7 GWe at CHP plants and 1.4 GWe in industry (Swedenergy, 2015). The production capacity in existing CHP plants in the district heating system is 16–17 TWh[2]. If industry[3] is included, it would be possible to produce 23TWh of electricity in existing plants with today's technology. In addition to bioenergy plants there are also several natural gas fired combined-cycle power plants, two of which are modern plants in Gothenburg and Malmö. They could be converted to use biomethane instead of natural gas and contribute a few more TWh of electricity. Combined-cycle power plants operated for combined heat and power have power generation efficiency of around 50 percent, and are highly suitable as a load-balancing resource.

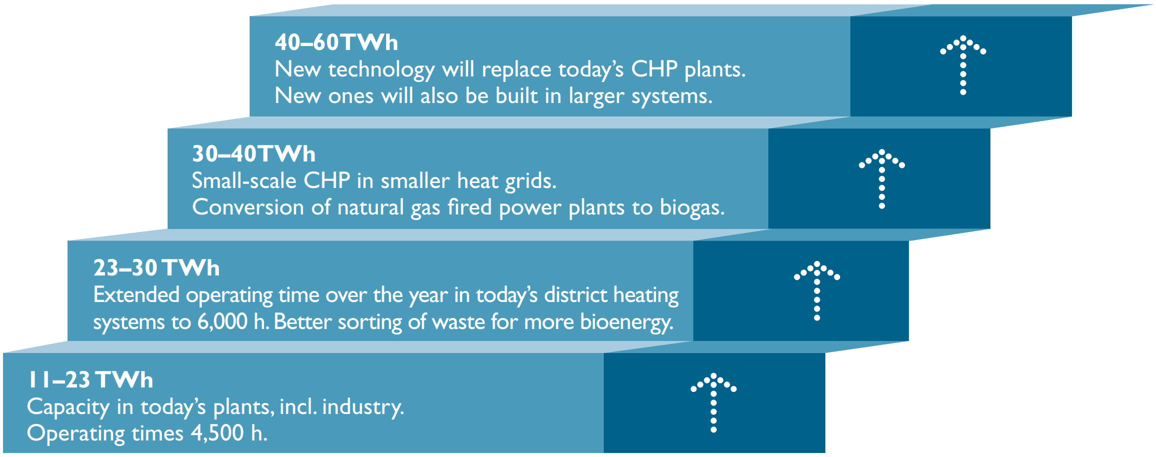
The way most of CHP plants are designed today, the amount of electricity generated in a CHP plant in a district heating system is determined by the heat demand. By equipping the power plants with additional cooling equipment, their operating time over a year could be extended, and the amount of electricity they generate could theoretically be increased to more than 30 TWh.

When today's CHP plants age out and need to be replaced by new ones, new technology should be available to provide significantly higher power generation efficiency than today. One example of this is top spool technology, which Vattenfall and others are developing (Hansson, 2015). The technology is based on an integrated gasification process specifically developed for biofuel. Further development and demonstration projects on an industrial scale are needed before top spool technology can be launched on a broad front. The time perspective for this is 5–10 years. Conventional CHP plants have a power generation efficiency of around 25–28 percent (Nohlgren, et al., 2014), while top spool technology has an efficiency of 55–60 percent. Switching to the new technology could almost double electricity generation in today's CHP system.

There are around 450 district heating systems in Sweden today and about 90 of them have CHP. There is therefore potential to expand CHP further in the existing heating system in, for example, the rest of the larger systems of which there are around 50, and various types of small-scale CHP applications in systems where that have incinerators today. Small-scale CHP technology also requires development and demonstration. The potential of small-scale CHP is hard to estimate. It depends on the availability of the technology. Theoretically, based on the available heat sources, 5–7 TWh of electricity could be produced (Electricity Production work group, 2015).

Today 2 TWh of electricity is produced in waste incineration plants. Sweden has a greater

Figure 9: Illustration of the gross potential for expanding bioenergy. Source: The Electricity Crossroads Electricity Production work group, 2015.



capacity for waste incineration than the amount of waste generated in the country and waste is therefore being imported. Electricity production from waste incineration plants could be increased, but this is not expected to have any significant potential for Sweden's electricity supply. Improved separation of biological waste from other waste would, however, make it possible to produce more biogas.

NUCLEAR POWER

According to current laws, when today's reactors are closed down they could be replaced by new ones at the same locations as the old ones. The nuclear power plants being built today have an installed capacity of 1,200–1,600 MW, (Nuclear Energy Agency, International Energy Agency, 2015). If ten new reactors are built in Sweden with an installed capacity of 1,400 MW and an estimated operating time of 7,500 hours, the technical potential would be more than 100 TWh with a total installed capacity of 14 GW. With availability of 85 percent, the four reactors set for closure represent generation of around 20 TWh, and the remaining six with the same assumption represent generation of around 50 TWh.

New nuclear technology is being developed – both to improve safety and to use other potential fuels. One important development focus is towards a high degree of standardisation and modular reactors that can be produced, transported and assembled more efficiently. Another is scaling down the size of the plants to a few hundred megawatts. Over the next five to ten years more such nuclear power plants will be built and put into operation, which will mean that, at the end of the 2020s, there be strategically important nuclear power experience which Sweden will be able to use (Nuclear Energy Agency, International Energy Agency, 2015).

Nuclear power is in general not suitable for flexible operation and instantaneous load balancing, but this might be possible in the future. Sweden has experience from, for example, weekend load-balancing and France has a nuclear power plant that is specifically adapted to operate with some flexibility (Persson, et al., 2011).

COORDINATION OF THE ELECTRICITY AND HEAT MARKETS

CHP plants combine two energy systems: a system for electricity generation and a system for local district heat production. The electricity generated is also used to heat homes and commercial premises, both in electric central heating and through heat pumps.

The total amount of electricity used for heating homes and services amounted to 18.6 TWh in 2013 (Swedish Energy Agency, 2015), of which 76 percent was for houses. The information includes electricity used for heat pumps. There are around a million of these installed in Sweden today. One of the great challenges in the future electricity market will be to handle peak load – both in production and in use. Electric heating is one of the main causes of consumption peaks during the winter. The power demand can be estimated at 7–8 GW[4], i.e. around 25 percent of the maximum capacity of a 10-year (cold) winter.

Electric central heating is often replaced by heat pumps, which, depending on the type of pump, have a limited impact on the maximum power demand. There are two alternatives to avoid peak loads: either extensive insulation of buildings or switching to some other form of heating. If some electric heating is replaced by district heating, installation of small-scale CHP production would be a possibility. This would reduce peak loads in the winter at the same time as it would increase electricity generation.

Large electricity production peaks resulting when there is a large percentage of variable energy resources in the system can lead to very low electricity prices if the demand for electricity is low. The surplus electricity could be used for heating, through heat pumps or electric boilers in the district heating system, or be stored in another way.

The Electricity Production work group have not had the opportunity during the course of our work within the Electricity Production group to analyse whether or not coordination between the electricity and heat markets could reduce the pressure on the electricity system, but the work groupwould like to highlight this possibility.

6. Four alternatives for the electricity system 2030–2050

Sweden's future electricity supply will probably come from a combination of the alternatives available, taking into account production costs, political control mechanisms and electricity demand. In order to get an idea of the different alternatives from a technical system perspective, they have been explored in detail taking into account the identified. This analysis does not purport to be an "absolute truth" but rather illustrates what could be possible and what the general system requirements would be. All of the alternatives represent a mix of different energy sources. Apart from the "basic system" in the form of the various energy sources presented, there is also a discussion on which "supplementary systems" will be needed in the form of power grids, storage flexible use etc.

Sweden has a strong potential capacity to build an electricity system based on renewable and fossil-free energy sources. Hydropower is the most important asset in the system – due to its load-balancing and its energy production capacity. It needs to remain at least at today's levels in all of the alternative systems presented. Electricity generation based on biofuels is expanded in all of the alternatives in order to replace, in varying degrees, today's nuclear power plants. Wind power will continue to be expanded at varying paces, depending on the alternative. Solar power will also be able to deliver greater amounts of electricity in the period up to 2050. One alternative includes new nuclear power and the expansion is based on today's legislation allowing new reactors to replace the current ones when they are closed down.

Based on analysis by the Electricity Usage work group, electricity production in Sweden will need to reach 140–180 TWh per year with a

Figure 10: The project involved presenting four different alternatives for a climate-neutral power system in 2050. Source: The Electricity Crossroads Electricity Production work group, 2015.

"More solar and wind"

"More bioenergy"

"New nuclear power"

"More hydropower"

power demand of 26–30 GW. The scenarios are called “low”, “medium” and “high” below.

See also the method description in Appendix 2.

ALTERNATIVE 1. “MORE SOLAR AND WIND”

The “More solar and wind” alternative is based on a system with a large percentage of variable energy resources Taking into account the potential discussed in the previous chapter, based on known conditions, wind power production could reach a maximum of 70 TWh and solar 20 TWh. This means that variable energy resources would account for about 35–50 percent of electricity production, of which wind power would deliver 30–40 percent, from the “low” to “high” scenarios. Production of solar energy mainly takes place from March to October, while wind power statistically has higher production potential during the winter (Svenska kraftnät, 2015). Solar and wind power complement each other to some extent and can therefore balance out production peaks.

The assumption is that hydropower in general will remain at today’s level, while biofuel-based energy production will be double today’s level, around 25 TWh. The time perspective is 2050. It will take this much time for the potential to be reached, even taking into account the necessary grid adaptations. The diagram below shows the production mix for the “medium” scenario, 160 TW, as well as installed capacity, available power and power demand.

The production system was dimensioned to be able to produce sufficient electric energy over the year. The result is that the installed capacity is double the estimated electricity demand for a ten-year (cold) winter, while available power is around 20 percent lower than the estimated maximum demand. The power deficit, including demand flexibility of 10 percent, amounts to around 3–5 GW, depending on the scenario. If the power demand goes down in the summer to 10 GW, a large surplus would be generated instead, because the installed capacity at that time is 4–6 times the demand.

In order for the “More solar and wind” alternative to be a reality, transmission capacity would need to be expanded – both domestically and between countries. Since there are similar variations in weather conditions among neighbouring countries, and Denmark, Germany and Poland are also increasing the percentage

Figure 11: The production mix for alternative 1 “More solar and wind” according to the medium scenario, which represents total electricity production of 160 TWh, and an illustration of the power balance. Source: The Electricity Crossroads Electricity Production work group, 2015.

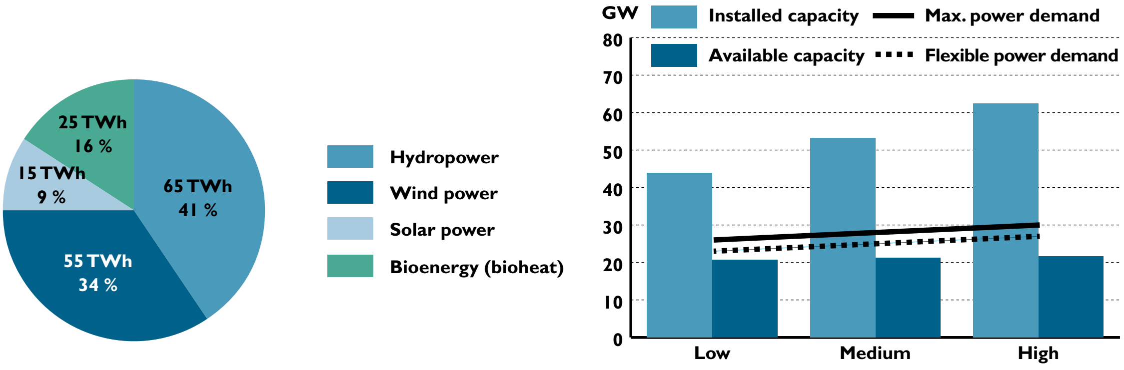
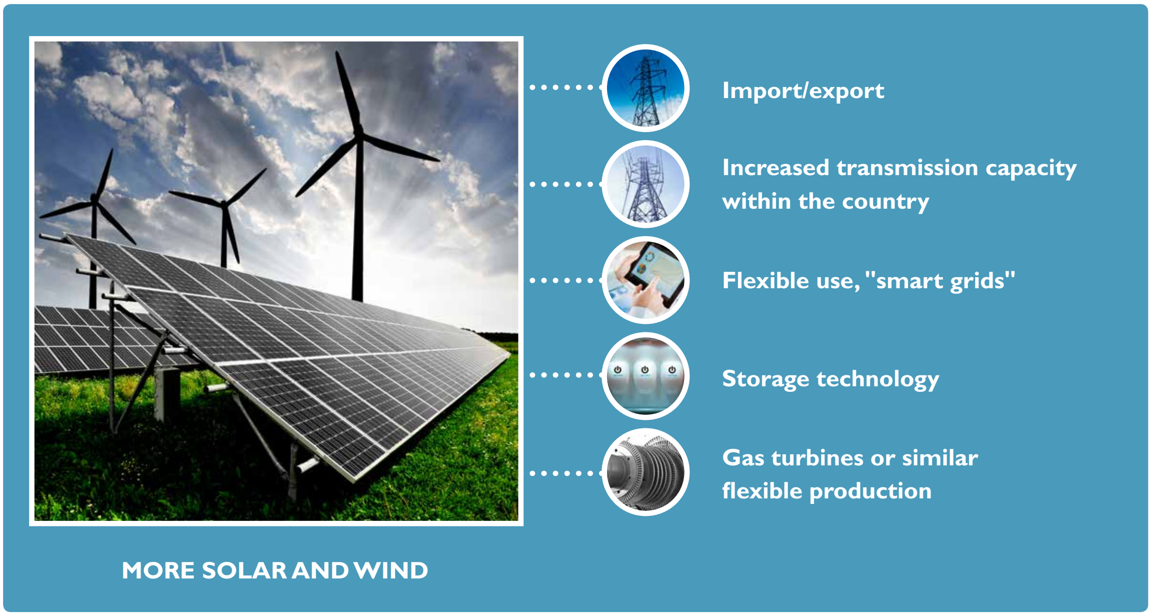


Figure 12: Illustration of which supplementary systems will mainly be required for the "More solar and wind" alternative.



of variable energy resources in their systems, a strategy is needed for a pan-European transmission system to handle variations involving large amounts of solar and wind power. Both surpluses and deficits need to be handled.

With an installed capacity that is several times greater than demand during large parts of the year, the surplus could momentarily be very significant but it is not long periods or large volumes of energy over the course of a year from a nationwide perspective (Electricity Production work group, 2015). The situation may be different locally. A large power surplus only lasting a few hours can still put a great deal of pressure on the grid and generate an energy surplus that should be put to use. In periods when there is a surplus the electricity price will be very low or even negative, as a result of the unregulated production being greater than the electricity demand and other load-balancing options.

To make efficient use of the electric energy that can be produced, electricity storage technology other that storage in hydropower dams would be very valuable. Examples of storage technologies are batteries and "power-to-gas." Power-to-gas is chemical storage of electricity in the form of hydrogen gas or methane, where electricity is used to break water down into oxygen and hydrogen. The batteries are best suited to small-scale applications, e.g. in households, with storage periods greater than a 24-hour period or a few days, while power-to-gas is best suited in a slightly larger system solution connected to a gas infrastructure (Byman, 2015). The possibility of expanding pumped hydropower plants is also being considered.

One option is to regulate hydropower production downwards when electricity is not needed. This actually involves wasting the electric energy, but it may be necessary if the transmission and receiving capacity are not adequate.

Managing possible power deficits is not just a concern in the coldest winter hours. Backup is needed year-round for the hours when there is no wind or sunshine. In addition to electricity exchange between countries across large regions, and access to hydropower and CHP, there will likely be a need for additional baseload power in the form of gas turbines or similar flexible production that can be on standby.

Primary observations for the "More solar and wind" alternative

In the "More solar and wind" option variable energy resources account for 50 percent of annual energy. The system is able to generate a lot of energy, but its ability to guarantee power is limited. Such a system would therefore require various types of technical supplementary systems to handle situations when solar and wind power generation is low but electricity consumption is high. The reverse situation also needs to be dealt with, i.e. when there is a large surplus of electricity.

Examples of supplementary technical measures are:

- Expansion of transfer capacity – both within Sweden and to surrounding countries. A general plan for northern Europe is also needed to handle deficits and surpluses of electricity between different regions.

- Energy needs to be able be stored, preferably over a period of at least a few weeks, in order to save energy produced on windy days for use on less windy days. Seasonal storage is not necessary to even out variations in wind power production.

- In addition to hydropower and CHP, additional baseload production capacity is needed in the form of gas turbines or similar flexible generation resources that can be on standby and used during consumption peaks. Incentives and opportunities for more flexible electricity consumption is also necessary.

ALTERNATIVE 2: "MORE BIOENERGY"

The "More bioenergy" option is based on a large amount of energy based on biofuels, taking into consideration the discussions in the previous chapter on the potential of this resource. Biofuels here mainly means fuels originating in the forest or biogas that may also have a different biogenic origin. Energy generated using biofuels is assumed to amount to 40–60 TWh from the "low" to "high" scenario for electricity usage. The fuel requirement is expected to be around 60–90 TWh[5], depending on the type of power plant and power generation efficiency. Today electricity production based on biofuels amounts to 14 TWh, so there will be a need for an additional 45–75 TWh.

This alternative is dimensioned to handle the electric energy load in the different scenarios.

Figure 13: The production mix for alternative 2 "More bioenergy" according to the "medium" scenario, which represents total electricity production of 160 TWh, and an illustration of the power balance. Source: The Electricity Crossroads Electricity Production work group, 2015.

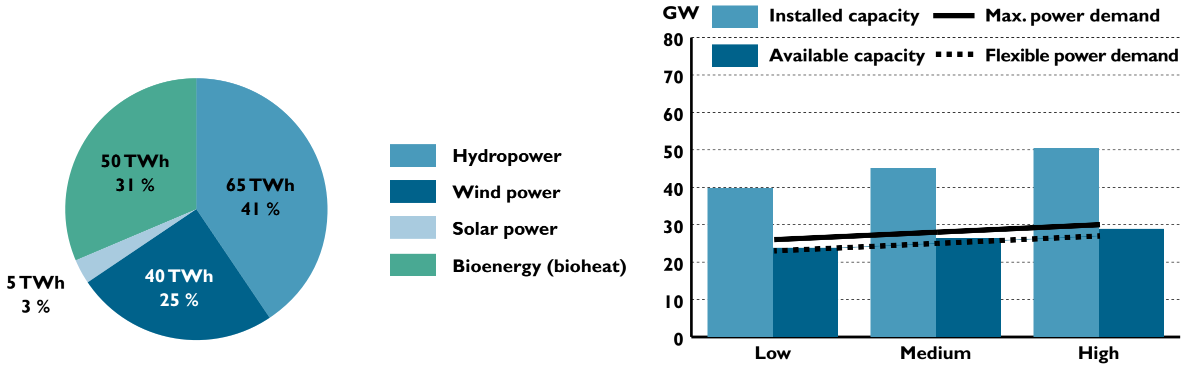


Figure 14: Illustration of which main supplementary systems will be required for the "More bioenergy" alternative.

In addition to an expansion of biofuel-based power production, wind power will be expanded to 30–50 TWh, and solar energy to 5 TWh. Hydropower will remain at today's level. The percentage of variable energy is between 25 and 30 percent, of which wind power accounts for 20–30 percent. The diagram in Figure 13 shows the production mix for the "medium" scenario, 160 TW, as well as installed capacity, available power and power demand.

The "More biofuel" alternative maintains a power balance, including an assumed demand flexibility of 10 percent. The production plants will mainly be located where CHP plants already exist today, or in heat systems located in population centres where there is no CHP today. This alternative will therefore not require any significant expansion of the energy infrastructure. On the other hand, the logistics for biofuel need to be developed to ensure greater availability in the market. More active forestry and a successful forest industry could contribute to an increased supply of biofuel. To ensure the fuel is used efficiently in electricity generation, technology advances are needed in CHP production, which in turn requires more development and demonstration facilities for the new technology.

Electricity production in CHP plants is closely linked to heat production. All alternatives should aim for better coordination between the electricity and heat markets, but this is particularly important in the "More bioenergy" alternative.

Primary observations for the "More bioenergy" alternative

- The "More bioenergy" alternative has the potential to make Sweden self-sufficient in energy and power. This system is primarily based on domestic fuel and production being close to consumption, reducing the transmission capacity needs.
- To reach full potential, technical development and demonstration plants are needed for new CHP technology – both large scale plants with significantly higher power generation efficiency than today's plants, and small-scale CHP plants.
- To increase energy production from biofuel-based CHP, electricity generation needs to be independent of the heat source through installation of extra cooling equipment and/or larger heat accumulators. Conventional condensing power plants are a more expensive solution and not as fuel-efficient.

- Increased investment in larger scale bioenergy solutions could be limited by competition for biomass.

ALTERNATIVE 3: “NEW NUCLEAR POWER”

This alternative is based on building new nuclear power plants, primarily to replace the ones that exist today. The six reactors remaining when the four oldest ones[6] now in operation are closed down, have a planned operating time of 60 years, i.e. they will be closed between 2040 and 2045. It is estimated that they will produce 50 TWh/year until then. In 2050 they will have been replaced by new reactors that produce 30–70 TWh of electricity, depending on how the electricity demand develops. Hydropower will remain at today’s levels, 65 TWh a year. In addition, wind power production will increase to 20 TWh, solar to 5 TWh and bio-based energy production to 20 TWh.

This alternative has strong similarities with the power system in Sweden today. The system is essentially in balance. The percentage of variable energy at most is just under 20 percent.

Production of 30–70 TWh, represents three to seven reactors at 1.4 GW. In theory more, smaller plants could also be built. In Great Britain there are, for example, opportunities to build small-scale, modular nuclear power reactors, with a maximum capacity of 300 MW. Rather than being built on site, the reactors are built industrially and then assembled at the site. The advantage here is that the reactors are standardised and the construction process is shorter. The investment is therefore not large and risky.

It is important for Sweden to monitor and be committed to research and development for new types of reactors, because this alternative is based on Sweden’s energy supply in 2050 also being based on new nuclear power. The diagram below shows the production mix for the “medium” scenario 160 TW, as well as installed capacity, available power and power demand.

If the remaining six reactors were to be replaced by new ones, these would need to be completed no later than in the late 2030s or beginning of the 2040s, which means decisions need to be made in the 2020s. This will probably be in the form of generation 3+ light water reactors. In nuclear physics terms, generation 3+ reactors function like today’s reactors, but safety is improved due to systematic work where experience from today’s reactors has been taken into account early in the construction phase. From a financial perspective they will be able to benefit from what is known about rational con-

Figure 15: The production mix for alternative 3 “New nuclear power” according to the “medium” scenario, which represents total electricity production of 160 TWh, and an illustration of the power balance.
Source: The Electricity Crossroads Electricity Production work group, 2015.

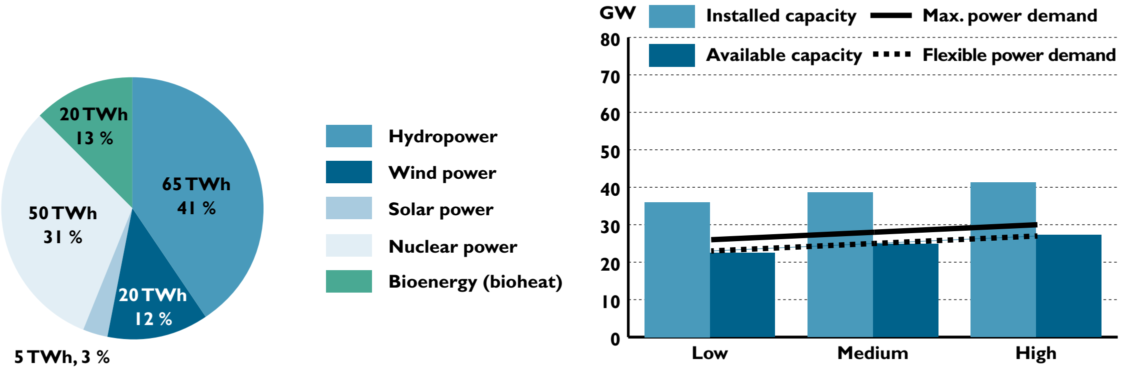


Figure 16: Illustration of which main supplementary systems will be required for the "New nuclear power" alternative.

struction and standardisation now and what can be learned in the coming decades. International bodies like the IEA and the IAEA predict that the installed capacity of nuclear power up to 2040 will be almost doubled. The biggest expansion will be in Asia, but there will also be expansion in countries like the UK, Poland, Hungary and Finland.

Generation 4 reactors using different fuel cycles than today's light water reactors are being built and will be built in the future, but they are not expected to be available for commercial, large-scale power generation until 2040 (Nuclear Energy Agency, International Energy Agency, 2015). It is difficult at this time to make a more detailed assessment of these reactors.

To obtain strategically important information and also stimulate competence development for the reactors that are in operation, Sweden should invest in research in generation 4 reactors. Small modular reactors will also be developed, both generation 3 and 4. If new, generation 3+ light water reactors are built in Sweden, most of the current fuel and waste infrastructure will be able to be used.

Primary observations for the "New nuclear power" alternative

- The "New nuclear power" alternative is the one that is the most similar to the current system. This system will not require any substantial investments in new supplementary systems.
- Technology for a number of new concepts is being developed. It is likely that generation 3+ technology will be available sometime between 2030 and 2040. After this will be generation 4. If new nuclear is to be an option, Sweden should monitor technology development and experiences gained internationally to ensure the country has the necessary expertise to make well-informed decisions on which technology to choose.
- Building new nuclear power plants is a long-term undertaking as they have a long technical and economic life.

ALTERNATIVE 4: "MORE HYDROPOWER"

This alternative is based on it being possible to expand hydropower according to the discussion on its potential in the previous chapter. This could take place by improving the efficiency of existing power plants, expansion in rivers and streams that are already being exploited, and expansion in untouched rivers.

In the different scenarios, hydropower production will increase from today's 65 TWh to between 75 TWh in the "low" scenario up to 95 TWh in the "high" scenario. The latter will also involve expansion in the four protected national rivers in the Norrland region. But that is not enough. To ensure an energy balance, bioenergy also needs to be expanded to between 30 and 40 TWh, wind power to the same extent and solar needs to generate 5 TWh a year.

The percentage of variable energy resources is around 25 percent and the power system is essentially in balance. The system is similar to the one Sweden has today and requires an exchange with neighbouring countries. Periodically there will be a large production surplus that can be exported, but during dry years, energy will need to be imported.

Since the "More hydropower" alternative will mainly involve increasing production in northern Sweden, the transmission capacity between northern and southern parts of the country will need to be further expanded. During wet years it will be necessary to be able to export electricity, while in dry years there may be a deficit that will need to be covered through imports. Hydropower can also be exported as a load-balancing service to other countries.

Primary observations for the "More hydropower" alternative

- The "More hydropower" alternative has the potential to create a system where Sweden is self-sufficient in energy and power. Hydropower is the most flexible energy source and can also be stored. Annual energy production depends on precipitation, but the available power is not affected in the short term.

- A significant portion of the new hydropower will be in northern Sweden and investment will be needed in transmission capacity southwards.

- An increased amount of hydropower will result in large differences in domestic energy production between wet years and dry years, which will require an increased energy exchange with surrounding countries.

Figure 17: The production mix for alternative 4 "More hydropower" according to the "medium" scenario, which represents total electricity production of 160 TWh, and an illustration of the power balance. Source: The Electricity Crossroads Production group, 2015.

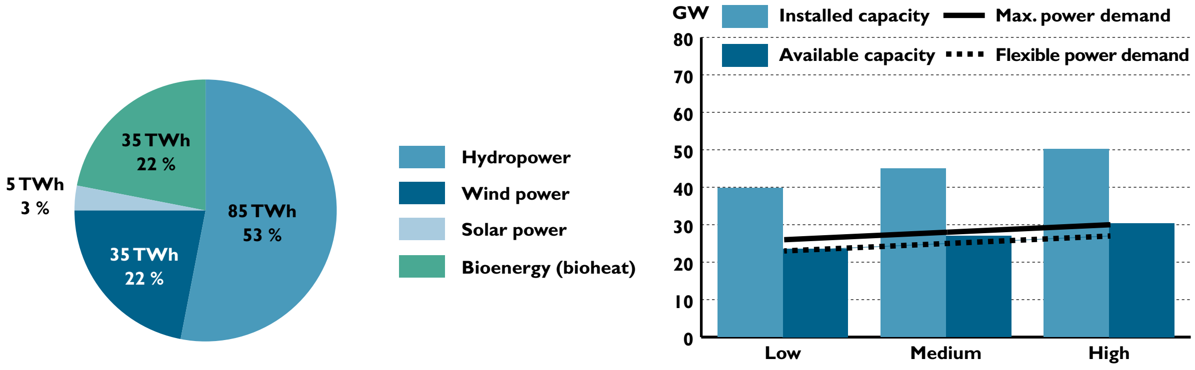
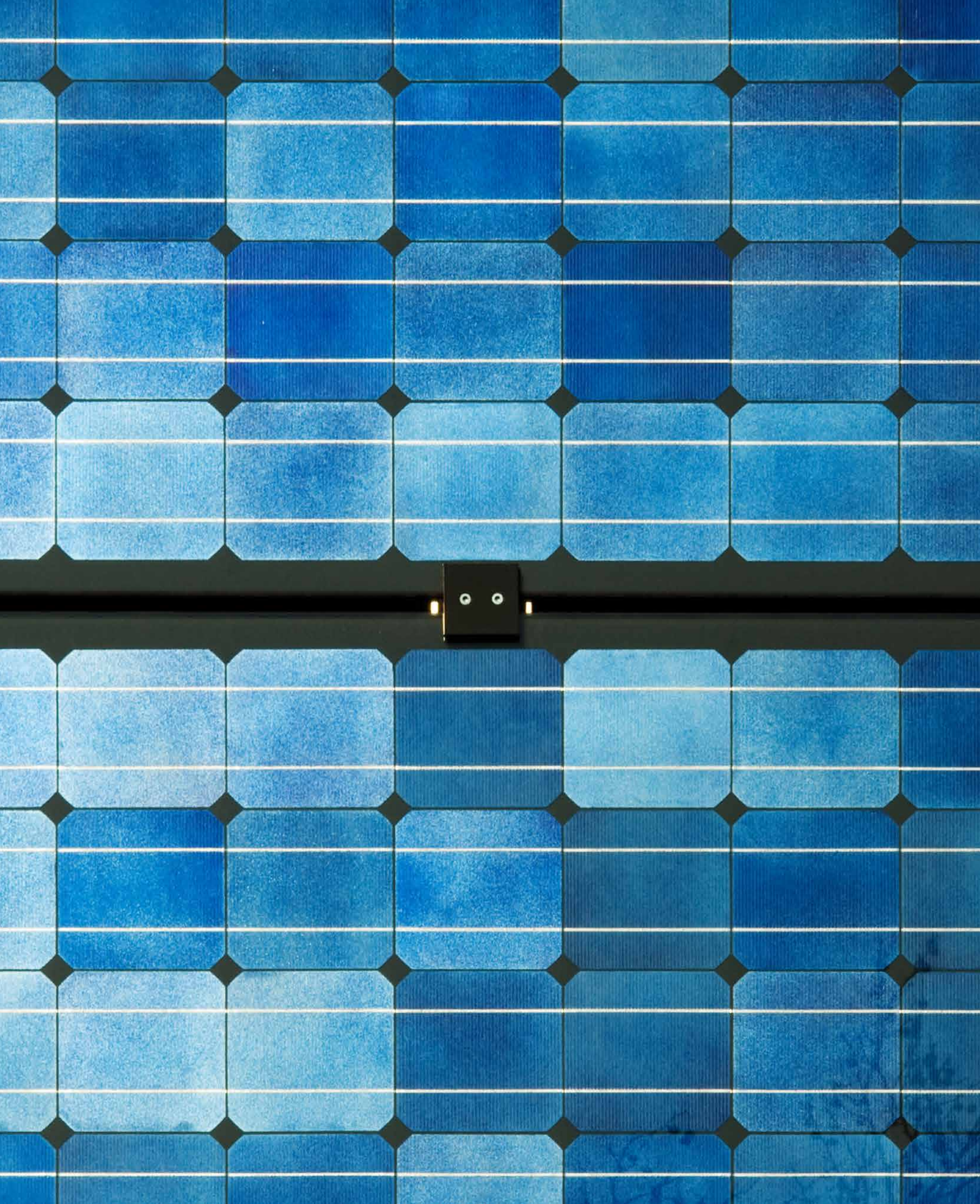


Figure 18: Illustration of which main supplementary systems mainly be required for the "More hydropower" alternative.

- The "More hydropower" alternative in the "high" scenario would involve expansion in protected rivers and streams. A change in the legislation is needed, in order for this to happen.
- Building new hydropower plants is a long-term undertaking as they have a long technical and economic life.



7. Comparison of total production costs

The power system alternatives described in the previous chapter have many similarities but differ in terms of the percentage of variable energy resources they include. This means that the total system solution, including transmission capacity in the country and between countries, as well as load-balancing measures, will look different for the different alternatives. The total system cost for each alternative will, in addition to the costs for production capacity, include necessary investment in transmission and distribution cables, extra load-balancing capacity, e.g. from gas turbines, consumption flexibility and possibly also investment in energy storage.

The total system is not addressed here because this is outside the scope of the Production group's assignment. There is, however, some value in attempting to make a financial evaluation of the different alternatives. The following calculation is grossly simplified and based on the total production cost for each energy source, excluding control mechanisms, beyond 2040 (see Appendix 2: Methods). Note that the calculation is only for the "basic system" and that "supplementary systems", i.e. transmission capacity, addition load-balancing capacity etc., are not included.

The total electricity production cost per year for the "medium" scenario of 160 TWh amounts to SEK 75–80 billion for all alternatives. This information should be regarded as very general and merely illustrative, and it only covers the production system.

Primary observations

- The most important observation regarding the calculations described below is that the costs of the different alternatives, based on today's assessments, are fairly similar. The annual production costs are in the same ball park for all alternatives.

- This analysis is very general and it is therefore not only a matter of which future electricity production systems will be the most cost-effective, but more importantly how much the supplementary systems will cost.

- To gain a complete picture it is important to identify and, as far as possible, to quantify other factors and costs of significance in choosing a system.

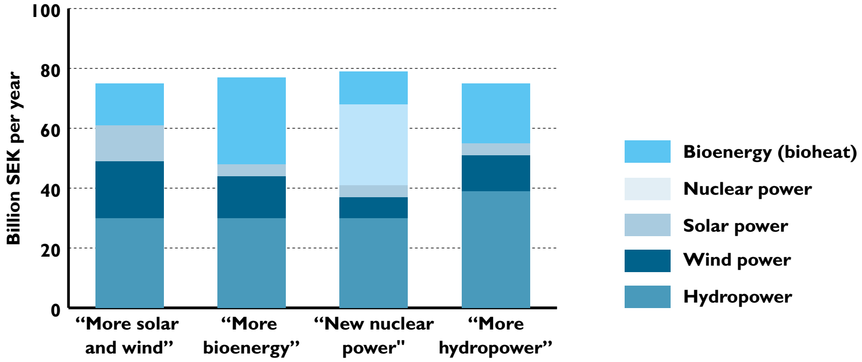


Figure 19: Simplified calculation of the total annual production costs for each alternative, SEK billions per year. Source: El från nya och framtida anläggningar 2014, Elforsk, World Energy Outlook 2015 (IEA); Electricity Crossroads Electricity Production work group, 2015.

Appendix 1: Glossary

ALPHA VALUE
The relation between electricity production and heat production in a combined heat and power (CHP) plant, calculated as electricity production divided by heat production.

PARTIAL LOAD
When a power plant is operating at a lower production level than its installed capacity allows.

POWER BALANCE
To maintain a stable frequency of 50 Hz, a balance between generation and usage is needed. If the system is out of balance, the frequency will fluctuate.

CAPACITY VALUE/CAPACITY CREDIT
The potential for an energy source to reduce the risk of a power deficit is called its "capacity value" or "capacity credit" and is expressed as a percentage of installed capacity. Also called "availability factor."

SUPPLY SECURITY
Ensuring that electricity consumers receive electricity in sufficient amounts when then need it. Security is determined by: the production system's ability to deliver, the possibility of important electricity and the transmission capacity in the transmission and distribution grid.

FREQUENCY
The Nordic power grid has an alternating current frequency of 50 Hz. Frequency indicates the number of periods per second. There is a definite relationship between a generator's rotational speed and the frequency generated.

COMBINED-CYCLE POWER PLANT
A plant where a gas turbine is combined with an exhaust gas boiler and a steam turbine.

GENERATOR
Kinetic energy is converted in a generator into electric energy when a copper spool rotates in a magnetic field.

VARIABLE ENERGY RESOURCE
Electricity generation technology where the output cannot be planned, but where the maximum possible output is determined by the prevailing weather conditions, for example wind and solar. Often also called "weather-dependent" or "volatile" power.

OPEN CYCLE
The simplest type of gas turbine where combustion gases expand through a turbine which drives a generator.

BASELOAD POWER
Electricity generation technology the output of which can be planned regardless of the weather conditions, such as nuclear power, gas turbine, CHP and hydropower technology.

PRIMARY CONTROL
Reserves (hydropower) activated automatically in response to deviation from the frequency of 50.0 Hz. The reserves are activated between 49.9 and 50.1 Hz and between 49.5 and 49.9 Hz.

REGULATING POWER
Electricity generation technology that can be regulated – increased or decreased – according to energy demand, for example hydropower and CHP.

LOAD-BALANCING RESOURCE

Production or usage that can be adjusted during operation for the purpose of achieving a balance between production and consumption.

RESERVES, RESERVE POWER, POWER RESERVES

Reserves are a collective load-balancing resource used to ensure balanced power in the grid and by extension, operational reliability and quality in energy delivery.

INERTIA

All rotating machines (generators and engines) that are directly connected to the synchronous system have inertia. If an imbalance arises between production and consumption, the rotational energy slows the frequency adjustment. Wind turbines also have inertia, but special control technology is needed in order for the system to benefit from it. This is so-called "synthetic inertia."

TOTAL EFFICIENCY

Some power plants produce both thermal energy in the form of steam or hot water for consumers, while also producing electric energy. The total efficiency is the percentage of the energy supplied that can be used in the form of heat energy and electric energy, just outside the plant.

TURBINE

In a turbine, kinetic energy in a liquid or gas is converted into mechanical work in the form of a rotating turbine axle.

OPERATING TIME

A theoretical calculation of the number of hours a power plant would need to operate at full power to generate the same amount of energy that the plant actually generates, but with a variable load, i.e. total energy production divided by installed capacity. Also called "equivalent full-load hours" or "duration."

HEAT SOURCE

For energy production in a CHP plant, an outlet is required for the cooled heat energy, normally through a district heating system or an industrial process.

Appendix 2: Methods and assumptions

The assignment has involved producing and analysing various alternatives to show what Sweden's electricity production system could in a perspective up to 2050. Project work was performed through prepared discussion meetings within the Electricity Production work group for Electricity Crossroads, by studying literature and through analysis. The analysis was mainly qualitative in nature, based on knowledge and proven experience within the group, but general calculations at the system level were also performed.

Within the framework of the project a special study "Electricity production – technics for producing electricity," was also produced. In this study, which is a report providing input for the work in progress, various production methods were discussed in more detail. Technology and cost development for different energy sources in the coming decades may result in significant changes in the conditions that were assumed in this study.

The following assumptions were used in the analysis and calculations made for the electricity supply in 2050:

- The electricity system is fossil-free over the year. This means that, domestically, the amount of fossil-free electricity produced annually is equal the amount consumed. In individual periods fossil-based energy may be imported. This is offset by exports of fossil-free electricity during other periods. Fossil-free is not the same thing as climate neutral, even if this would have been a desirable assumption. From a life-cycle perspective, all energy sources have an impact on the climate. This applies to both renewable energy production and nuclear power.

- The analysis is based on domestic production resources being able to meet total electric energy load. The different energy sources have different operating times per year, thus the installed capacity needs will vary between the different alternatives.

- Demand flexibility is assumed to be at least 10 percent of peak load. Today it is difficult to estimate how price elasticity will be changed in the electricity market. It is very limited today, but is likely to develop as "smarter" appliances and installations are developed.

CALCULATION METHODS APPLIED FOR THE SYSTEM ALTERNATIVES

The estimated electricity demand in Sweden is used as the basis for calculating how much electricity will need to be produced in 2050. The Electricity Production work group within Electricity Crossroads has presented a range for the domestic electricity demand of 128 to 165 TWh, excluding losses, "beyond 2040" (Liljeblad & the Electricity Usage group, 2015). Transmission and distribution losses arise today for around 7 percent of electricity usage (Statistiska centralbyrån, 2014). This means an electricity demand of 137 to 177 TWh in 2050. Since all information is in the form of long-term assessments, and the amount of losses may vary depending on the types of energy sources that are prioritised depending on what the transmission system will look like, the targets are rounded off for long-term electricity generation to range from 140 to 180 TWh. The calculations made by the Electricity Production group

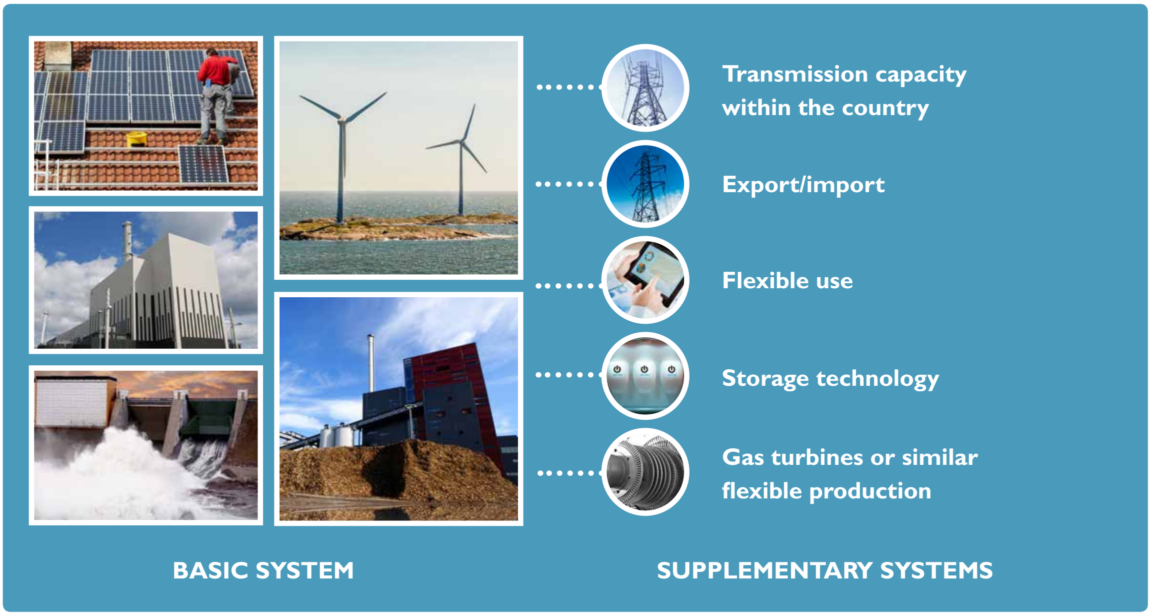


Figure 20: The illustration of analysis showing the difference between "basic system" – production facilities, and "supplementary systems" – the technical solutions required for the basic system to work.

are based on the three scenarios: "low" 140 TWh, "medium" 160 TWh and "high" 180 TWh.

Demand for power generation is assumed to be in proportion to the electricity demand (Liljeblad & the Electricity Usage group, 2015). Today it is estimated that the amount of power generation capacity needed in a 10-year (cold) winter will be 27 GW (Svenska kraftnät, 2015), while the electricity demand will be 135 TWh (2014), with an average of 140 TWh per year 2010–2014. In 2014 the capacity needed in January was around 24 GW and in July around 10 GW (Swedenergy, 2015)

In 2050 it is assumed that the peak load will range from 26 to 30 GW. Here too, the calculations were made according to the three scenarios: "low" 26 GW, "medium" 28 GW and "high" 30 GW. The peak load is lowered through increased demand flexibility, which is assumed to be at least 10 percent of the peak load.

Four different alternatives have been produced for the electricity system's design in 2050. All of them consist of at least 65 TWh hydropower, continued expansion of wind power and solar, and increased use of biofuel-based power production. One alternative consists of new nuclear and another of an expansion of hydropower. All of the alternatives involve a mix of energy sources, but each one has a different main focus, where individual energy sources are taken to the extremes to illustrate what impact they will have on the system overall. They are:

1. "More solar and wind"
2. "More bioenergy"
3. "New nuclear power"
4. "More hydropower"

For each energy source an assessment has been made of possible technical potential in Sweden. The mix of resources in the different alternatives has been compiled based on this potential. The dimensions of the respective electricity systems are determined by the energy demand that needs to be met, which in turn, determines the installed capacity, depending on the different assumptions. The "basic system" in the form of different energy sources for which dimensions are being determined must then be supplemented by various "supplementary systems" to ensure an acceptable and secure supply in the electricity market. Examples of supplementary systems are transmission capacity at different levels, both within the country and between countries, storage technologies, flexible consumption and gas turbines or other flexible power generation resources that can be on stand-by to ensure the power balance is maintained. See the illustration in Figure 20. The same approach is used in all alternatives depending on the mix of energy sources.

Installed capacity is calculated based on an assumption on the number of full-load hours for each energy source. Full-load hours for wind power are expected to increase from today's level of 2,500 hours, to 3,500 hours when new technology is introduced. Other energy sources will remain at today's levels. Solar energy and other energy generation resources that electricity users, such as property owners, have installed are assumed to be part of the supply system (production system), even if this electricity is not delivered via a grid. To calculate "capacity value" (sometimes called "capacity credit"), the capacity that is expected to be available in the coldest winter hours, an availability factor has been produced by Svenska kraftnät (Svenska kraftnät, 2015). See table 2: This information can be regarded as a "reasonable" assumption. Other assumptions about the future could also be made. The calculations presented in this report can all be regarded as sample calculations based on today's knowledge and experiences.

METHODS FOR MAKING ECONOMIC COMPARISONS OF THE ALTERNATIVES

This report was prepared by the Electricity Production work group within the Electricity Crossroads project. The Public Finances and Electricity Market work group is analysing how the different alternatives (paths) will impact the economy. It may still be relevant to make a financial assessment of the different alternatives discussed here too. The calculations are highly simplified and illustrative only. They are based on the total production costs, including capital costs but excluding today's control mechanisms, for each energy source.

The data is taken from the Elforsk report *El från nya och framtida anläggningar 2014* (Electricity from new and future plants 2014) and has been revised taking into account an

Table 2: Assumptions on full-load hours and capacity value.

	Hydropower	Wind power	Solar power	Nuclear power	Bioenergy
Full-load hours, h	4,000.	3,500	1,000	7,500	4,000.
Availability factor, %	85 %	11 %	0 %	90 %	90 %

Table 3: Total production costs excluding today's control mechanisms and specific investment costs for some representative energy sources. Source: El från nya och framtida anläggningar 2014, Elforsk, World Energy Outlook 2015 (IEA); Electricity Crossroads Electricity Production work group, 2015.

	SEK/MWh	Comment
Hydropower	460	Elforsk
Wind power	350	Elforsk and price fall according to WEO 2015
Solar power	770	Elforsk and price fall according to WEO 2015
Nuclear power	540	Elforsk
Bio-CHP	570	Elforsk revised based on assessment made by the Electricity Production work group.

estimated cost reduction, mainly for solar and wind power. Statistics on the extent of the cost reductions by 2040 are taken from World Energy Outlook 2015. The costs have also been reduced slightly for bioenergy based on the group's assessments. Costs can probably be expected to go down for new nuclear as well in industrial production of generation 3+ reactors, but here Elforsk's data has been used in the absence of other data.

For a closer description of the basis for the calculations, please refer to the Elforsk report. The cost calculations are based on the "medium" scenario for each alternative. The metrics used are shown in table 3.

Appendix 3: Footnotes

1. Abnormal circumstances could be extremely dry years, very cold and long winters or low production capacity at nuclear power plants.

2. Installed capacity 3.7 GW 2014 (Swedenergy, 2015) assumed operating time of 4,500 hours.

3. Installed capacity 1.4 GWh in 2014 (Swedenergy, 2015). Produced 6 TWh electricity 2013 (Statistics Sweden, 2014). Gives an operating time of 4,500 hours.

4. The work group's calculations: Today there are around one million heat pumps. Sales picked up at the end of the 1990s and increased significantly in the 2000s. Heat pumps provide more fluctuations in a load curve than a curve for electric heating only. The metric for calculating peak loads in a heating system (Bengt-Göran Dahlman) is 2,900 h, which cannot be applied to today's electric heating market. Since heat pumps are replacing electric heating to a large extent and electric heating in the mid-1990s used around 26 TWh, this gives an indication of the total amount of power needed for heating. 26 TWh / 2,900 h = 8.6 GW. Geothermal heat pumps lower the power demand, while the heating factor of normal heat pumps approach one in very cold weather. A rough estimate of the installed capacity could therefore be 7–8 GW.

5. Calculated based on a mix of generation facilities, including assumptions on new technology, with different power generation efficiency in relation to fuel consumption. In the "low" scenarios (40 TWh of bioenergy) conventional CHP technology is used, while the higher scenarios are based on new technology with a higher power generation efficiency. Producing electricity and heat at the same time provides very efficient use of fuel, and additional fuel is needed for increased electricity generation with high efficiency estimated at 80 percent. To further increase electricity generation, production needs to be independent of the heat source, which increases the amount of biofuel needed proportionately. Gas turbines have a power generation efficiency of around 40 percent. With new technology they could generate 55–60 percent more.

6. Ringhals 1 and 2, and Oskarshamn 1 and 2.

Appendix 4: References

Electricity Production work group, 2015. *Kunskap, erfarenhet och beräkningar inom Produktionsgruppen.* u.o.:u.n.

Byman, K., 2015. *Lokaliseringsstudie för power to gas. Systemlösning för framtidens energisystem.* Stockholm: Elforsk.

Börjesson, P., 2013. *Fossilfrihet på väg, chapter 10 Biodrivmedel.* u.o.:SOU 2013:84 Study on fossil-free vehicle traffic.

Börjesson, P., 2015. *Biomassepotentialen från svenskt skog- och jordbruk – uppdaterade uppskattningar*, Lund: Lund University.

Swedish Energy Agency, 2015. *Energiläget i siffror.* Eskilstuna: Swedish Energy Agency.

Hansson, H.-E., 2015. *PM Biokraft i Sverige 2025–2050.* Stockholm: Euroturbine AB.

Jannasch, A.-K. & Ragnar, M., 2015. *Gasens roll i det framtida energisystemet.* Report 2015:183: Energiforsk AB.

Kamp, S., 2013. *Sveriges potential för elproduktion från takmonterade solceller.* Uppsala: Uppsala University.

Karlsson, D. & Lindahl, S., 2015. *Svängmassans roll i framtida elsystem.* Gothenburg: Gothia Power.

Korsfeldt, T., 2011. *Vattenkraftens roll i ett hållbart energisystem.* Stockholm: Swedenergy.

Liljeblad, A. & Electricity Usage group, 2015. *Elanvändning bortom 2030.* Stockholm: IVA Electricity Crossroads.

Nohlgren, I., Herstad Svärd, S., Jansson, M. & Rodin, J., 2014. *El från nya och framtida anläggningar.* Stockholm: Elforsk report 14:40.

Nuclear Energy Agency, International Energy Agency, 2015. *Technology Roadmap.* 2015 Edition red. Paris: OECD NEA, IEA.

Persson, J. o.a., 2011. *Lastföljning i kärnkraftverk.* 12:08 red. Stockholm: Elforsk.

Persson, J. o.a., 2011. *Lastföljning i kärnkraftverk. Möjliga effektregleringar för svenska kärnkraftverk utifrån ett internationellt perspektiv.* Stockholm: Elforsk report 12:08.

Sköldberg, H. & Rydén, B., 2014. *Värmemarknaden i Sverige.* Gothenburg: Projektet Värmemarknaden i Sverige.

Swedish Energy Agency, 2014. *Produktionskostnadsbedömning för vindkraft i Sverige.* ER 2014:16 red. Eskilstuna: Statens energimyndighet.

Statistics Sweden, 2014. *El, gas- och fjärrvärmeförsörjningen 2013.* EN 11 SM 1401, corrected version. Örebro: Statistics Sweden.

Svebio, 2011. *Biokraft 2011 (plansch).*

Swedenergy, 2015. *Elåret, Verksamheten 2014.* Stockholm: Swedenergy.

Swedish Wind Energy, 2015.
Vindkraftsstatistik och prognos Kv 3, 2015.
Stockholm: Svensk Vindenergi.

Svenska kraftnät, 2015. *Anpassning av elsystemet med en stor mängd förnybar elproduktion*. Stockholm: Svenska kraftnät.

Svenska kraftnät, 2015. *http://www.svk.se/aktorsportalen/elmarknad/effektreserv/.* Stockholm.

Svenska kraftnät, 2015. *Kraftbalansen på den svenska elmarknaden vintrarna 2014/2015 och 2015/2016*. Stockholm: Svenska kraftnät.

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