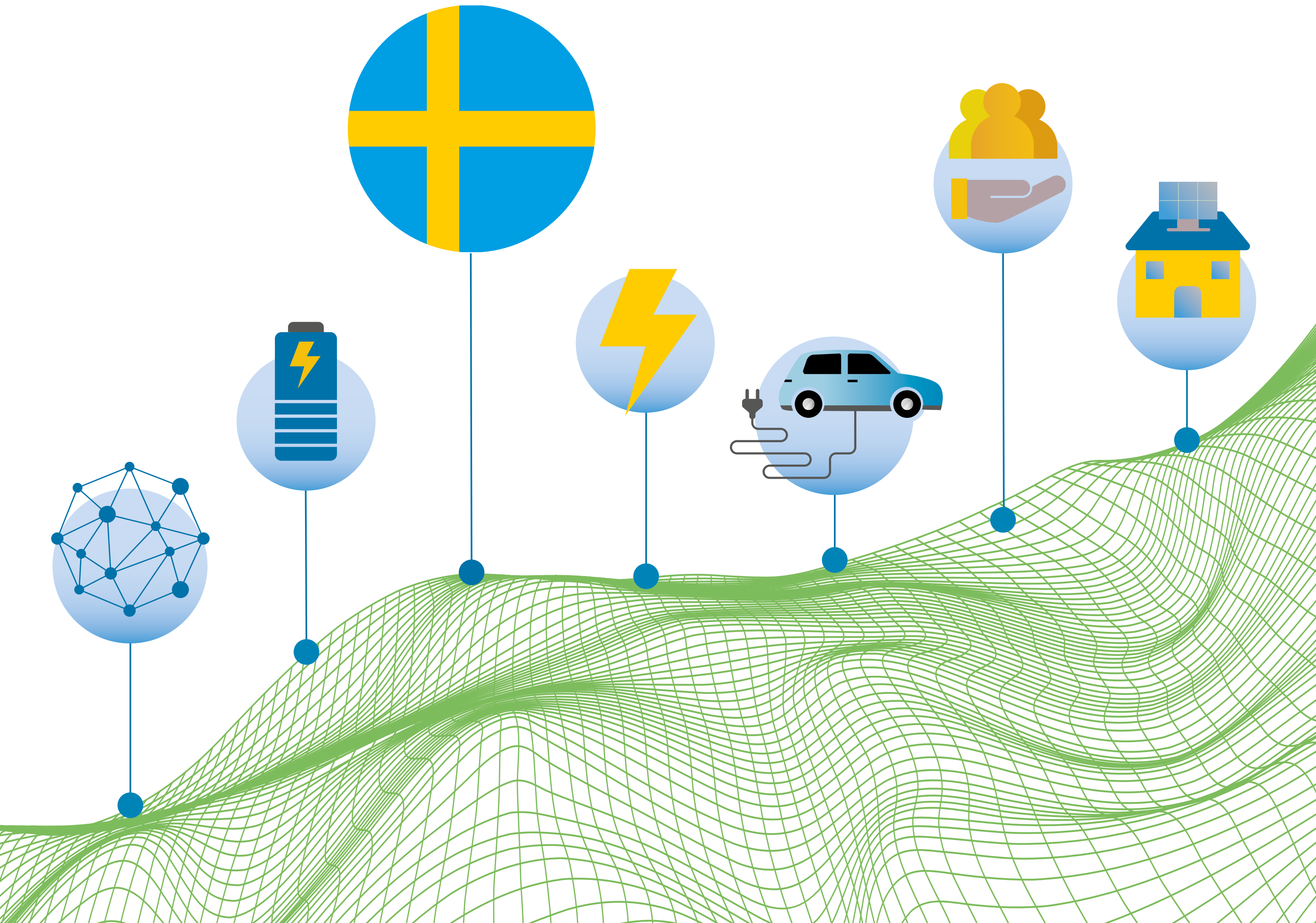
IRENA
International Renewable Energy Agency

INNOVATIVE SOLUTIONS FOR **100% RENEWABLE POWER IN SWEDEN**



Citation: IRENA (2020), *Innovative solutions for 100% renewable power in Sweden*, International Renewable Energy Agency, Abu Dhabi.

ISBN 978-92-9260-169-0

About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. **www.irena.org**

Acknowledgements

Valuable review was provided by Hanna Ek-Fälth, Sara Grettve and Klaus Hammes (Swedish Energy Agency), Pia Grahn (Swedish Energy Markets Inspectorate), Svend Søyland (Nordic Energy Research), Tomas Kåberger (Chalmers University of Technology), Saman Nimali Gunasekara (KTH Royal Institute of Technology Stockholm), along with Luis Janeiro, Asami Miketa, Bilal Hussain, Alessandra Salgado, Nadeem Goussous, Emanuele Taibi, Carlos Fernandez, Raul Miranda, Emma Aberg, Paul Komor, Paul Durrant and Roland Roesch (IRENA). The editor of this report was Lisa Mastny.

This report was prepared by the Innovation team the IRENA Innovation and Technology Centre (IITC) under the guidance of Dolf Gielen, with text authored by Elena Ocenic, Nina Litman-Roventa and Arina Anisie.

IRENA is grateful for the generous support of the Government of Sweden.

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ABBREVIATIONS

AC	alternating current
ACER	Agency for the Cooperation of Energy Regulators
CAISO	California Independent System Operator
CCS	Carbon capture and storage
CHP	combined heat and power
CO_2	carbon dioxide
DC	direct current
EI	Swedish Energy Markets Inspectorate
ENTSO-E	European Network of Transmission System Operators
EU	European Union
EUR	Euro
EV	electric vehicle
FCEV	fuel cell electric vehicle
GW	gigawatt
GWh	gigawatt-hour
H2FC	hydrogen fuel cells
ICT	information and communications technologies
IRENA	International Renewable Energy Agency
kV	kilovolt
kW	kilowatt
kWh	kilowatt-hour
kWp	kilowatt peak
MW	megawatt
MWh	megawatt-hour
MWp	megawatt peak
NECP	National Energy and Climate Plan
NYISO	New York Independent System Operator
PV	photovoltaic
R&D	research and development
RCC	regional co-ordination centre
SDAC	single day-ahead coupling
SEK	Swedish krona
SIDC	single intraday coupling
TWh	terawatt-hour
XBID	cross-border intraday coupling
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States dollar
V2G	vehicle-to-grid
VRE	variable renewable energy

EXECUTIVE SUMMARY

SWEDISH CONTEXT

Sweden is well positioned to help the world meet the aims of the Paris Agreement. The country's power system is almost entirely decarbonised already, based on extensive hydropower resources and nuclear power, as well as district heating fuelled by biomass. In 2017, the Swedish electricity production comprised around 40% hydropower, 39% nuclear, 11% wind power and 10% combined heat and power fueled predominantly by renewable sources. Interconnections with neighbouring countries, participation in the highly integrated pan-European electricity market, climate-friendly, market-based policies, and strong support for innovation are also significant assets.

Sweden's older, conventional power plants will likely shut down before 2045 as they reach the end of their life cycles, by which time demand for electricity in the country is likely to rise due to the increasing electrification of end-use sectors such as transport and industry.

Sweden's policy goals call for achieving 100% renewable power by 2040 and net zero carbon emissions by 2045.

The aim to establish a 100% renewable power system in Sweden, while also ensuring energy security, affordability and environmental sustainability, faces challenges in both the policy/regulatory and the system operation spheres.

OBJECTIVES OF THE STUDY

This study has two main aims. First, it considers how systemic innovations to integrate high shares of renewables (including from variable renewable energy, VRE) into the power system could help to meet Sweden's ambitious policy target of 100% renewable electricity by 2040. This is done by proposing four innovative solutions to be further explored and by highlighting the most innovative pilot projects seen internationally. Second, by showcasing actions that have put Sweden at the forefront of the global energy transition, the study aims to inspire other countries to scale up their ambitions for renewable power targets via international co-operation.

The study reflects the outcomes of four workshops held during 2019 with other members of the International Renewable Energy Agency (IRENA), including European countries with similar policy objectives (Denmark, Germany and Spain) and other countries with applicable experience in operating power systems with very high shares of renewables, including a growing share of solar and wind power complementing conventional hydropower (Costa Rica, Paraguay and Uruguay). The present analysis includes an assessment of the likely impacts of those innovative solutions, as well as recommendations on how to implement them.

GLOBAL ENERGY TRANSFORMATION

An increasing number of policies are being adopted and implemented worldwide to decarbonise the energy sector to meet international commitments, including the Paris Agreement. Driven by unprecedented public concern, such policies enable the transition to a sustainable, low-carbon future.

In the global energy transformation, renewable electricity, combined with deep electrification of transport and heat applications, can achieve 60% of the energy-related carbon dioxide (CO_2) emissions reductions needed by 2050 (IRENA, 2019a). Power generation from renewable energy sources, such as wind and solar photovoltaic (PV), in addition to other direct-uses of renewables, such as solar thermal, geothermal and biomass, can deliver over 90% of the energy-related CO_2 emission reductions needed by 2050, when combined with improved energy efficiency. For this reason, VRE sources such as wind and solar PV must be integrated into existing power systems at a large scale.

TAILOR-MADE, SYSTEM-WIDE, INNOVATIVE SOLUTIONS

Sweden needs innovative solutions to meet its ambitious policy goal of 100% renewable power by 2040. IRENA, in consultation with the Swedish Energy Agency (Energimyndigheten), has therefore proposed four tailor-made solutions based on a systemic approach to address the country's specific challenges in scaling up VRE.

Figure 1 also looks at each proposed solution from the perspective of **enabling technologies**, **business models**, **market design** and **system operation** (IRENA, 2019b).

By combining innovations in these four dimensions, the solutions tackle different challenges at various points in the value chain of the Swedish power system (**Figure 2**).

Figure 1: Four innovative solutions for Sweden's power system

Enabling technologies

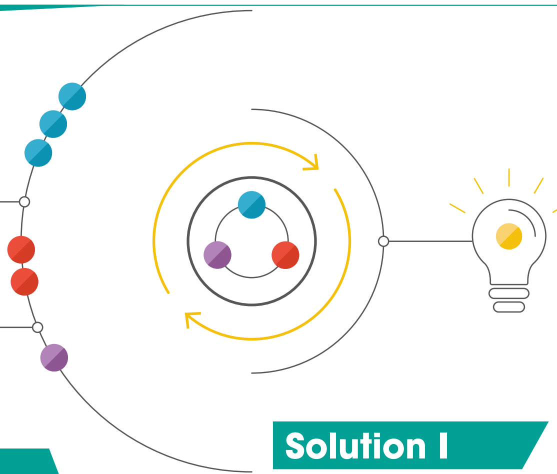
- Utility-scale batteries
- Internet of Things
- Artificial intelligence and big data

Market design

- Increasing time granularity in electricity markets
- Innovative ancillary services

System operation

- Advanced weather forecasting of variable renewable power generation



- Provides innovative ancillary services both from conventional and variable renewable energy sources;
- Ensures the security and stability of the power system and the provision of new ancillary services, including frequency and voltage support from VRE sources;
- Enables the provision of such ancillary services with the help of more precise solar and wind power generation forecasts.

Solution I

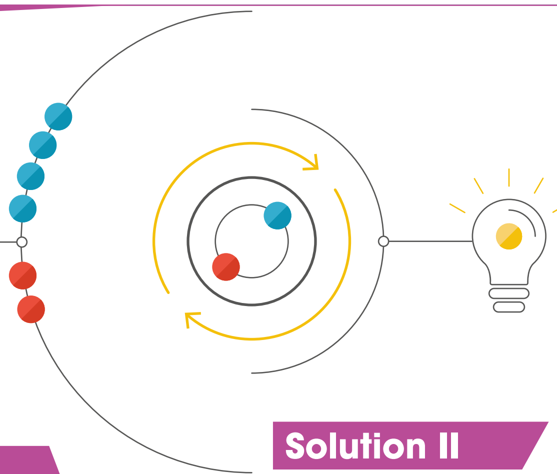
Innovative ancillary services from both conventional and variable renewable energy sources

Enabling technologies

- Internet of Things
- Artificial intelligence and big data
- Blockchain
- Supergrids

Market design

- Increasing time granularity in electricity markets
- Regional markets



- Improves flexibility in the existing pan-European market design;
- Fosters collaboration among system operators in Sweden, the Nordic, Baltic and wider European region;
- Ensures clear and effective division of responsibilities to manage an increasingly complex, decentralised and digitalised power system.

Solution II

Pan-European market as flexibility provider with effective collaboration among system operators

Sweden needs innovative solutions to meet its ambitious policy goal of 100% renewable power by 2040

Figure 1: Four innovative solutions for Sweden's power system

Enabling technologies

- Behind-the-meter batteries
- EV smart charging
- Renewable power-to-heat
- Internet of Things
- Artificial intelligence and big data
- Blockchain

Business models

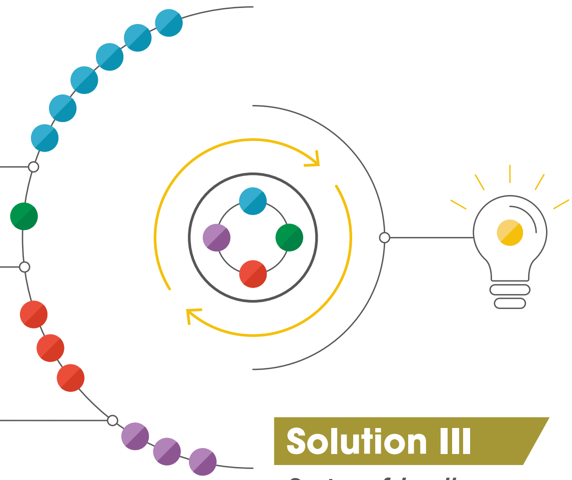
- Aggregators

Market design

- Time-of-use tariffs
- Innovative ancillary services
- Market integration of distributed energy resources

System operation

- Future role of distribution system operators
- Co-operation between transmission and distribution system operators
- Virtual power lines



Solution III

System-friendly integration of distributed energy resources

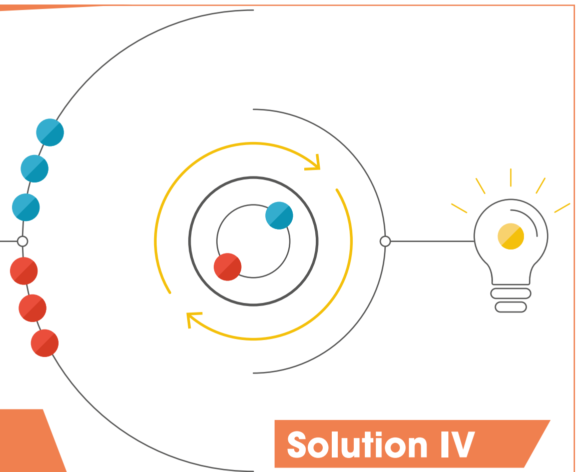
- ▹ Aggregates distributed energy resources to optimise distribution system operation;
- ▹ Balances supply and demand daily;
- ▹ Manages network congestion at the distribution level in the context of wind shortage/surplus in the short term, until transmission projects with long lead times are implemented.

Enabling technologies

- Renewable power-to-heat
- Renewable power-to-hydrogen
- Artificial intelligence and big data

Market design

- Increasing time granularity in electricity markets
- Innovative ancillary services
- Regional markets



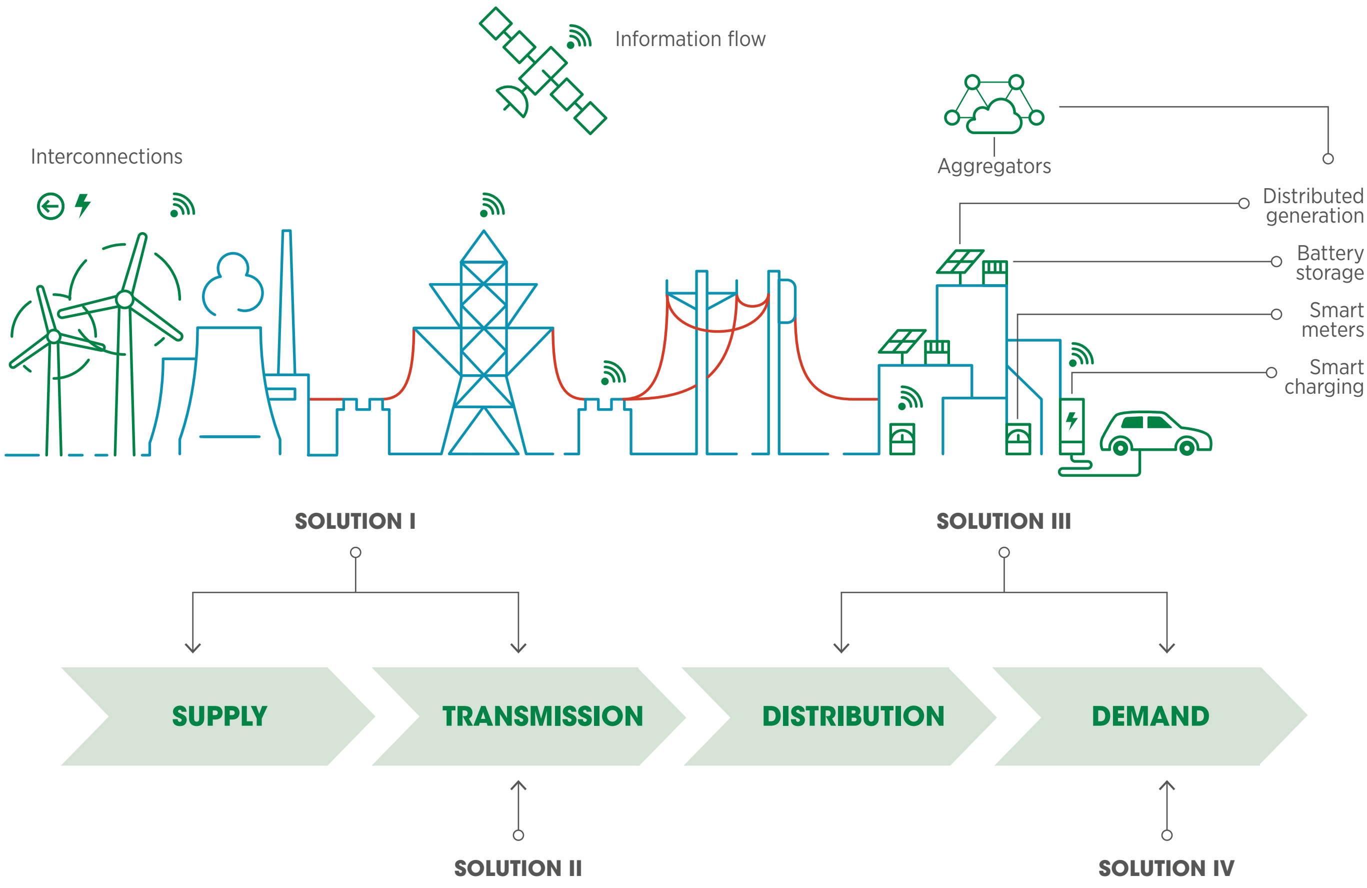
Solution IV

Decarbonisation of end-use sectors via electrification with renewable energy sources

- ▹ Decarbonises end use sectors such as direct heat and transport via electrification with renewable energy sources;
- ▹ Enhances flexibility and helps maintain system stability via direct and indirect electrification via power-to-X technologies (such as renewable power-to-heat and renewable power-to-hydrogen);
- ▹ Is part of a truly complex, yet disruptive solution, for sectors that are difficult to decarbonise, such as iron and steel industries.

To successfully implement innovative solutions for a 100% renewable-powered future, consultation with all relevant stakeholders involved in the power sector is essential

Figure 2: The four solutions positioned in the power system value chain

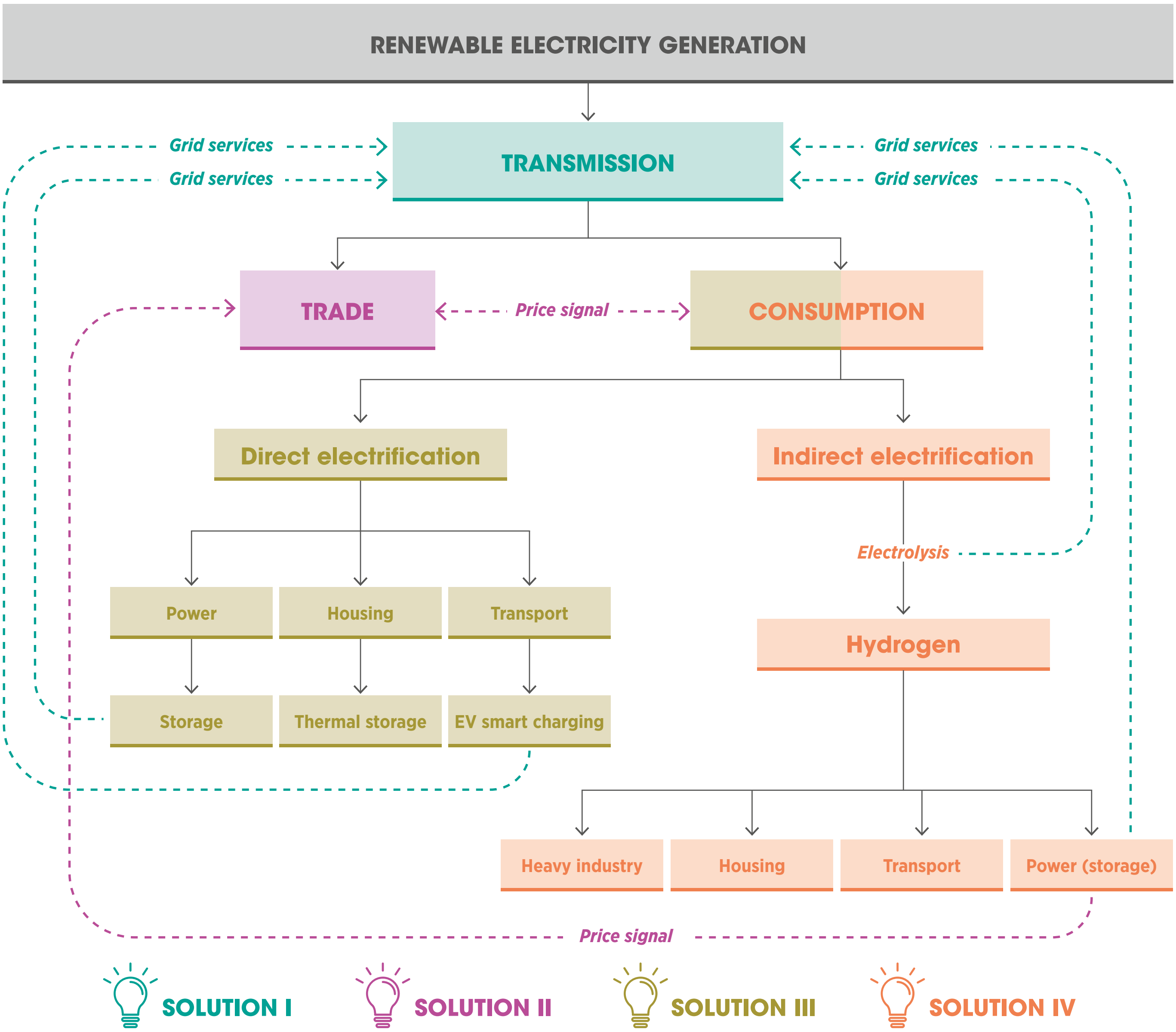


A systemic approach to innovation calls for a systemic approach to power system regulation and development

While each combination of innovations offers a solution for certain segments of the power sector's value chain, the combination of the four solutions creates major system-wide flexibility options, as illustrated in **Figure 3**. The decision whether to consume or trade renewable power on the pan-European market with a low level of time granularity would be based on electricity market price signals. If not locally stored or consumed, renewable electricity could contribute to:

- **Direct electricity use**, including in heating and cooling or transport. This in turn opens the door to electricity and heat storage, as well as smart charging for electric vehicles (EVs). See **Solution III**.
- **Indirect electrification through hydrogen**, produced using renewables and stored or supplied for transport, housing and industrial applications. See **Solution IV**.
- **Long-term hydrogen storage**, allowing the stored renewable-based energy to be reconverted to power and traded in electricity markets when profitable. See **Solution II**.
- **Provision of ancillary services**, including electrolysis, hydrogen storage and storage via EV batteries and smart charging, to provide flexibility for transmission system operators. See **Solution I**.

Figure 3: Innovative options for renewable power in Sweden



KEY LESSONS BASED ON INTERNATIONAL EXPERIENCE

An IRENA study, *Innovation landscape for a renewable-powered future*, notes significant lessons and results from over 200 real-world examples of pilot projects that have tested innovative enabling technologies, business models, market designs and system operation (IRENA, 2019b). Additional pilot projects were subsequently selected based on their replicability in Sweden.

In 2018, renewable energy sources accounted for 99% of the power generated in Costa Rica, while renewables accounted for 97% of the power produced in Uruguay in the same year. Both countries have relatively high penetration rates of VRE in their power systems, with wind accounting in 2018 for 16% of the power generation in Costa Rica and 22% in Uruguay (IRENA, 2019c). In 2018, Denmark's share of VRE in electricity generation was over 51% (48% wind, 3% solar PV) (DEA, 2020). Moreover, in 2019, VRE sources represented 34% of the German electricity mix (25% wind, 9% solar PV) (Fraunhofer ISE, 2020).

Overall, these experiences indicate that obtaining a 100% renewable power system in Sweden with an increasingly higher share of VRE from 11% today up to over 42% (39% wind, 3% solar PV) by 2040 is achievable under certain conditions.

In Europe and in the United States, new rules have been defined in ancillary service markets where VRE can now also participate. The pan-European regional electricity market helps integrate renewables by reaping benefits from a wider geographical area with a diverse portfolio of resources for power generation, which can complement each other on different time scales. Distributed energy resources, including demand response, behind-the-meter batteries, EV smart charging technologies and power-to-heat, can all support increased integration of VRE, especially in large regional markets like Europe. If coupled with digital technologies and managed in a "smart" way, these represent an important flexibility source, providing ancillary services to system operators and monetary benefits to asset owners. Adequate regulations must be in place to incentivise such arrangements.

1. INTRODUCTION

1.1 GLOBAL ENERGY TRANSFORMATION

The scientific consensus that climate change is causing unparalleled damaging impacts and that greenhouse gas emissions need to be reduced at an accelerated pace is indisputable. Driven by unprecedented public concern, an increasing number of targets and policies to decarbonise the energy sector are being implemented worldwide to enable the transition towards a sustainable, low-carbon future. This is strongly reflected within the United Nations' Sustainable Development Goals and the Paris Agreement[1].

In the global energy transformation, renewable electricity combined with deep electrification of transport and heat applications can achieve 60% of the energy-related carbon dioxide (CO_2) emissions reductions needed by 2050, according to the latest scenarios from the International Renewable Energy Agency (IRENA) (IRENA, 2019a). Electricity is becoming the most rapidly growing energy end-use sector[2], as well as the main energy carrier, and its share in final energy consumption can double from around 20% today to almost 50% by 2050 in IRENA's scenario to meet the Paris Agreement (IRENA, 2019a). In addition to other direct-uses of renewables, such as solar thermal, geothermal and biomass, as well as improved energy efficiency, these combined measures can deliver over 90% of the energy-related CO_2 emission reductions needed by 2050.

To achieve these emission reductions, the pace of renewable energy deployment in final energy consumption needs to increase globally by a factor of six compared to the pace set out in current and planned governmental policies. At the same time, energy efficiency measures need to be scaled up substantially. Close co-operation between the public and private sectors, while unlocking investments to scale up renewable projects and enabling infrastructure, will be key.

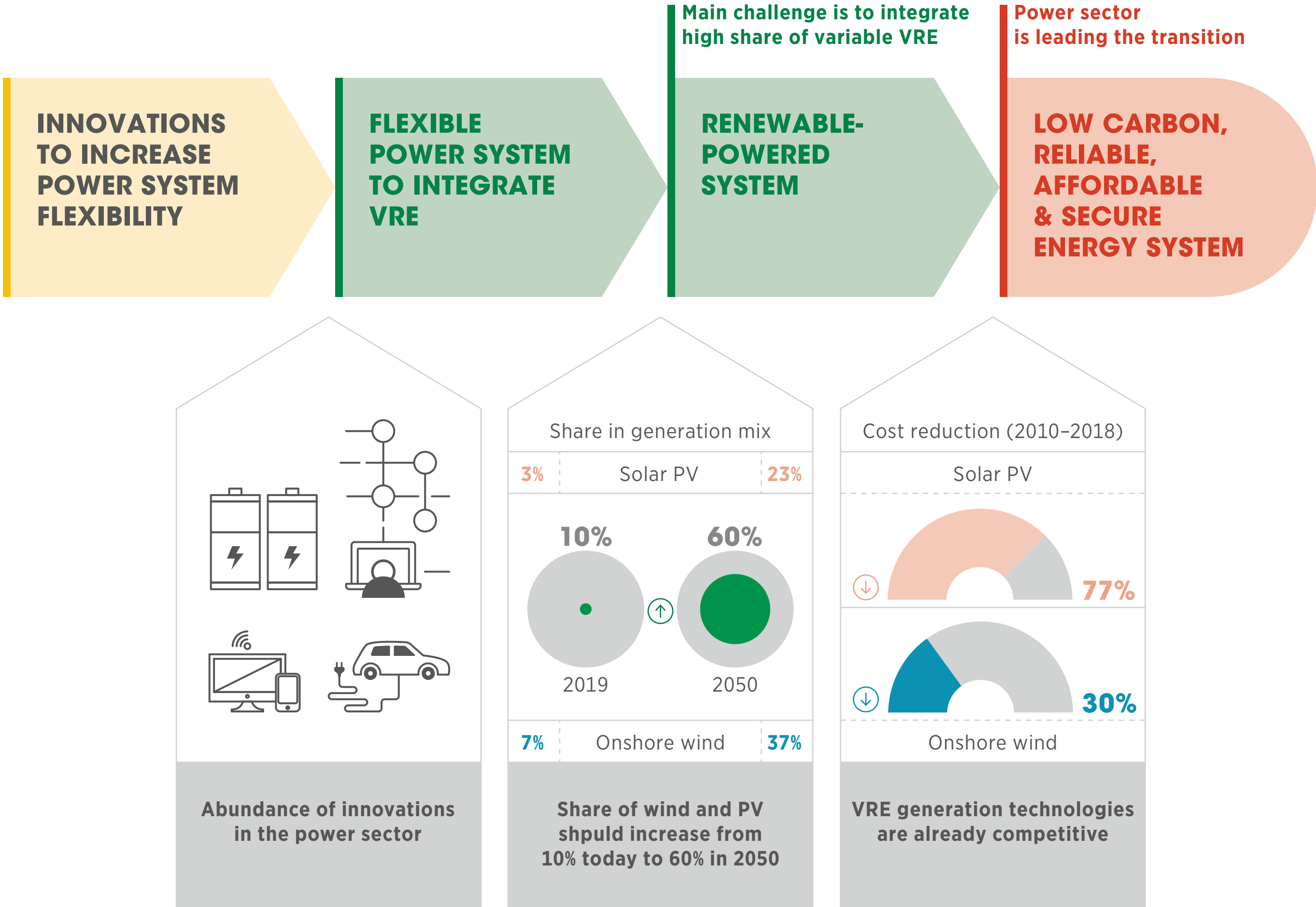
As shown in Figure 4, renewable power generation technologies are at the core of the global energy transformation, especially given the rapid and continuously decreasing costs for these technologies over the past decade. For example, the global weighted-average cost[3] of solar photovoltaic (PV) power decreased by 77% over the 2010–2018 period (IRENA, 2019d). While countries can now plan for a future with high shares of renewable power, the integration of these resources, and especially the integration of variable renewable energy (VRE) sources such as wind and solar PV, requires more flexible and integrated power systems. This is why innovation is broadening beyond power generation to address transmission and distribution as well as demand-side issues such as providing demand-side response or aggregation of distributed energy resources.

1 An agreement within the United Nations Framework Convention on Climate Change (UNFCCC) dealing with greenhouse gas emissions mitigation, adaptation and finance starting in the year 2020, signed by representatives of 196 parties at the 21st Conference of the Parties of the UNFCCC in Paris, France in 2015.

2 According to Bloomberg New Energy Finance's latest analysis (2018), global electricity demand may increase 57% by 2050 from a 2017 baseline.

3 Levelised cost of electricity for utility-scale solar PV projects.

Figure 4: Towards a low-carbon, reliable, affordable and secure power system



Source: IRENA, 2019b

Moreover, with increasing levels of digitalisation and decentralisation of energy systems, it is crucial to consider that innovation is broader than technologies for power generation and enabling technologies for the integration of VRE into systems. As such, innovations are emerging across various dimensions, including new business models, new ways in which markets are designed and regulated, and expanding to novel system operation practices. In this context, adopting a systemic perspective to harness the benefits of emerging innovations and the synergies created between two or more innovations is imperative given the complexity and interconnected nature of energy systems.

1.2 SWEDISH CONTEXT

Since the 1970s Sweden's dependence on imported fossil fuels has decreased significantly. The country's total energy supply from fossil fuels such as coal, coke, crude oil and petroleum products declined from 81% in 1970 to 27% in 2017. In 2017, various forms of biomass provided 62% of district heating consumption, including in the industrial, services and residential segments. Swedish electricity production comprised around 39% nuclear energy (from three nuclear power plants with a total of eight reactors), 51% renewable energy sources[4], mainly hydropower and wind, and 10% combined heat and power (CHP),

4 The share of renewable energy sources reaches 59% if bio-fuelled CHP is included, such as the non-fossil portions of waste incineration.

fuelled predominantly[5] by renewable sources (SEA, 2019a). The remaining challenge of phasing out fossil fuels lies mainly in the transport sector and in the energy-intensive industrial sector, providing an opportunity to explore the potential of innovations such as electric vehicle (EV) smart charging, renewable power-to-heat and renewable power-to-hydrogen, among others.

Sweden is already leading the global energy transformation in many aspects. The country's power system is almost entirely decarbonised, and climate-friendly, market-based policies and public and private support for innovation are in place. These factors put Sweden at the forefront of innovative countries in the European Union (EU) and beyond. Thanks to important hydropower resources, district heating fuelled mainly by biomass, a well-functioning energy-only electricity market, and interconnection within the Nordic electricity market as well as more broadly with the Baltic and wider European regions – in addition to ambitious climate and energy policy goals – Sweden is well positioned to meet the Paris Agreement (Skytte *et al.*, 2019).

Although the Swedish power sector is almost entirely decarbonised, integrating high shares of VRE into the power system will be key in the coming decades. Because the forecasted installed capacity of solar PV is relatively low compared to the forecasted installed wind power capacity, integrating wind into the Swedish power system is relevant for the following reasons: 1) nuclear reactors will likely shut down before 2045 due to the end of their economic life times, which calls for the deployment of renewable sources in this energy transition; 2) the demand for electricity is likely to increase due to electrification of the transport and industrial sectors, as well as increased demand from new consumers, such as data centres[6]; 3) the long-term target for Sweden is to have zero CO_2 emissions by 2045 and 4) the long-term target is to achieve a 100% renewable power system by 2040[7].

1.3 STRUCTURE OF THE STUDY

The study consists of a forward-looking analysis considering how systemic innovations for integrating very high shares of renewables into the power system, such as those identified in the IRENA report *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables* (IRENA, 2019b), can contribute to achieving 100% renewable power by 2040 in Sweden.

With a wide range of innovative solutions available to be deployed and scaled up, the focus of the study is on the integration of VRE into the power sector, including through "sector coupling", or coupling the power sector with other sectors of the economy via electrification. Heating and cooling in buildings as well as the transport and industrial sectors are also considered. Among the various renewable energy sources, both hydropower and VRE sources are discussed, with focus on integrating new wind power and solar PV generation capacity.

The study is structured as follows: **Chapter 2** summarises the key challenges expected in the operation of a 100% renewable power system by 2040. **Chapters 3, 4, 5** and **6** provide details for each innovative solution proposed, including the challenges that these solutions are addressing as well as detailed descriptions of each solution, indicating the combination of innovations required, the status of implementation in Sweden, as well as examples of similar solutions implemented in other countries. This is followed by a qualitative cost-benefit analysis that also identifies the various stakeholder actions required. **Chapter 7** contains recommendations for policy makers based on the analysis contained in the previous chapters.

Annex 1 presents an overview of the methodology applied, and **Annex 2** contains a brief presentation of the key concepts covered in IRENA's report *Innovation landscape for a renewable-powered future* that are used throughout this study. **Annex 3** provides an overview of the Swedish power sector.

5 12 terawatt-hours (TWh) out of 15 TWh of CHP generation was renewable in 2018

6 New data centres would benefit from relatively low electricity prices and low-carbon power supply.

7 2040 is not a definitive date for nuclear power phase-out.

2. CHALLENGES AND SOLUTIONS IN OPERATING A 100% RENEWABLE POWER SYSTEM BY 2040

Policy makers and the transmission system operator in Sweden have identified numerous challenges in operating a 100% renewable power system by 2040, which are interrelated and overlap in many respects. The following two sections provide an overview of the key issues that would need to be addressed going forward, both from a policy and regulatory perspective and from a system operation perspective.

2.1 KEY CHALLENGES FROM A POLICY AND REGULATORY PERSPECTIVE

In the process of achieving the policy goal of a 100% renewable power system by 2040, several factors are expected to affect the Swedish power system, based on input received by IRENA from the Swedish Ministry of Infrastructure and the Swedish Energy Agency. From a policy and regulatory perspective, the key challenges in operating a 100% renewable power system in Sweden, while ensuring a secure, affordable and environmentally sustainable transformation of the power sector, can be summarised into four interrelated categories, as illustrated in Figure 5:

- **Market design** refers to the Swedish, and more broadly European, market-based approach, in which well-functioning, energy-only markets will play an important role in achieving desired policy targets by 2040, including price signals to incentivise increased flexibility across the power value chain in a system-friendly way. For example, in a 100% renewable electricity system, when the system is tight due to low VRE generation, prices will be relatively higher, so non-VRE generators (such as hydropower plants) would benefit from such price increases. Therefore, a "well thought-through" market design, as well as further regional and continent-wide collaboration, is required.

  → To address this challenge, several solutions across the entire value chain of the power sector could be explored, which are further elaborated in the following chapters. These include: ***Solution I:*** *Innovative ancillary services from both conventional and variable renewable energy sources* (supply-side flexibility solution); ***Solution II:*** *Pan-European market as flexibility provider with effective collaboration among system operators* (grid flexibility solution); and ***Solution III:*** *Aggregation of distributed energy resources to optimise distribution system operation* (demand-side flexibility solutions).

- **Security of supply**, which refers to generation adequacy, is interrelated with the market design category in the sense that markets would need to provide efficient and reliable price signals for investors to deploy the required generation capacity. It also refers to the challenge of ensuring that, in addition to encouraging flexibility, markets help to meet system needs and to deliver reliable electricity supply, in the context of higher demand, much higher shares of wind power, a potential nuclear phase-out and the emergence of new actors such as "prosumers" (who both consume and produce electricity). According to the Swedish Energy Agency, older

Challenges in operating a 100% renewable power system by 2040 are interrelated

power plants[8], including nuclear, wind and CHP plants with a cumulative yearly production of 100 TWh, will be likely decommissioned by 2040. In this context, efficient planning and permitting processes for renewable generators, including the renewal of existing hydropower permits and the grant of new permits for VRE generators, especially from wind, will be key in ensuring that the permitting pace is rapid enough to meet the need for new renewable power to reach the target.

→ To address this challenge, two solutions that can offer demand-side flexibility options, reducing the need for generation, as well as a system-wide flexibility option with the possibility of long-term seasonal storage could be further explored. These are elaborated in the coming chapters: ***Solution III:*** *Aggregation of distributed energy resources to optimise distribution system operation* (demand flexibility solution); and ***Solution IV:*** *Decarbonisation of end-use sectors via electrification with renewable energy sources* (demand flexibility solution).

- **Distribution and transmission infrastructure** refers to the challenge for policy makers in ensuring adequate grid infrastructure to face major challenges in the generation and consumption of electricity in the next 20–30 years. Continued efforts to review the planning regulations that are needed to strengthen and refurbish existing infrastructure, as well as to construct new transmission lines, are paramount. For example, while some power lines are reaching the end of their technical life times, more transmission capacity is required in a 100% renewable-powered system, driven by the need to integrate more wind generation or to match the new generation with the demand centres from north to south and at the entry points of large cities.

Several industrial players in Sweden face difficulties in increasing their production or building new factories due to a regional shortage of electricity and have considered investing in other European countries as a consequence.

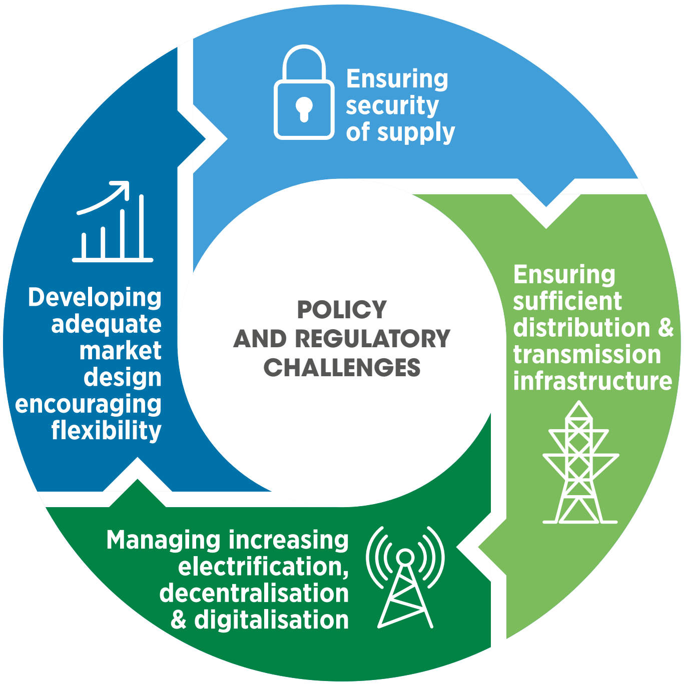
→ To address this challenge, ***Solution III:*** *Aggregation of distributed energy resources to optimise distribution system operation* (demand-side flexibility solution) could be further explored.

- **Electrification, decentralisation and digitalisation** are key innovation trends observed globally. Electricity is becoming an increasingly important energy carrier due to its potential role in decarbonising other sectors. In Sweden, the way that electricity is consumed is shifting thanks to increasing automation of processes, the emergence of new technologies, the creation of new industries, rapid urbanisation, a rising prosumer base and the emergence of sector coupling (*i.e.*, coupling the power sector with other sectors of the economy via electrification of heating and cooling as well as transport and industry). Moreover, some industrial and other large commercial consumers, such as battery factories and data centres, may benefit from the localisation of their facilities near where renewable energy, including from variable sources, is abundant. Managing the increasingly complex power system is a key challenge, given that the shift towards "smarter" networks poses new challenges, including higher vulnerability to information technology-related threats.

→ To address this challenge, ***Solution II:*** *Pan-European market as flexibility provider with effective collaboration among system operators* (grid flexibility solution) could be further explored.

8 Power plants likely to be decommissioned by 2040 encompass mainly nuclear power plants as well as small shares of wind and biomass CHP generators reaching the end of their assumed life times (SEA, 2019b).

Figure 5: Key interrelated policy and regulatory challenges towards 100% renewable power in Sweden



Another important challenge refers to the broader society, in which raising consumer awareness and engaging with all stakeholders involved in the power sector – including power generators, regulated entities, traders and prosumers, among others – would be required for a successful energy transformation by 2040.

For example, success will depend on obtaining social acceptance of the expansion of the transmission grid, as well as of the installation of new onshore wind parks. However, addressing this challenge would require a more specific and in-depth study.

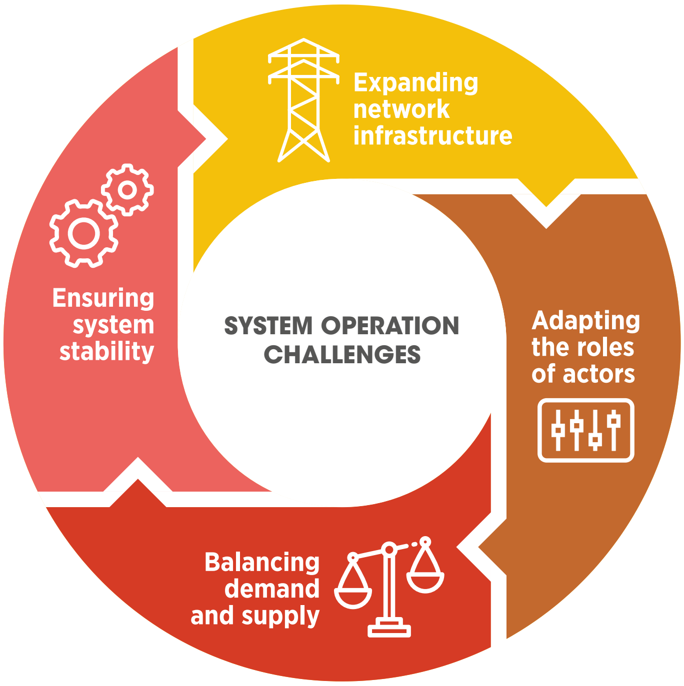
Despite the above-mentioned challenges, according to the Swedish Energy Agency achieving this policy objective with an adequate level of generation by 2040 is realistic, provided that different stakeholders take action and collaborate to address the challenges. This conclusion is based on an overall assessment including several modelling results of the electricity market in a scenario with a 100% renewable power system, using different renewable generation portfolios.

While this electricity market model would need to be complemented by studies considering further technical aspects, it shows that:

- **Demand is almost always met** in all scenarios without any major adaptations to the power system. In the scenario relying heavily on CHP, demand is met in all hours. In the scenarios relying heavily on wind and on solar PV, the results show that eight and nine hours, respectively, are faced with a lack of supply to meet demand. However, demand is met overall both by imports and domestic production.

- **Renewables are cost-competitive today**, and further cost reductions for wind and solar PV are expected in the coming years. For example, new onshore wind projects at USD 0.045 per kilowatt-hour (kWh) in the IRENA database are expected to cost less than the marginal operating cost of nearly 900 gigawatts (GW) of coal capacity potentially online in 2020 (IRENA, 2019d). Moreover, given that Sweden has good preconditions for wind power production, the costs might drop even further.

Figure 6: Key interrelated system operation challenges towards 100% renewable power in Sweden



- **Important flexibility potential** remains to be tapped from the current system, as well as from new resources, including VRE. This could be done with the help of innovations, for example via demand-response schemes and sector coupling. Some of the insecurities in how to best realise this potential are addressed in this study.

2.2 KEY CHALLENGES FROM A SYSTEM OPERATION PERSPECTIVE

Integrating growing shares of VRE raises questions not only from a policy and regulatory perspective but also from a system operation perspective. Sweden's transmission system operator, Svenska Kraftnät, has identified a set of complex system operation challenges in various reports, including the recently published *System Development Plan 2018–2027.* Based on its analysis, key challenges in achieving and operating a 100% renewable-powered system in Sweden, considering system operation and generation adequacy, can be split into four interrelated categories (see also Figure 6):

- **Ensuring system stability** in a safe and cost-effective manner becomes increasingly challenging in the face of growing shares of VRE coupled with reduced system inertia due to the gradual phase-out of nuclear capacity with synchronous generators.

  According to scenarios developed by Svenska Kraftnät (Svenska Kraftnät, 2017), annual mean inertia is expected to decrease from 202 GW in 2020 to 159 GW in 2040. Recent analyses already indicate a deterioration of the frequency quality in the Nordic power system. This leads to higher costs as more frequency response is required, and also increases the risk of more drastic consequences if major disturbances occur. In addition, the growth of asynchronous VRE generation sources creates uncertainty regarding the access to adequate ancillary services. Consequently, ensuring high levels of stability using the most cost-effective range of ancillary services[9] becomes crucial.

9 Ancillary services can be defined as the "services required by the transmission or distribution system operator to enable them to maintain the integrity and stability of the transmission or distribution system as well as the power quality" (Eurelectric, 2004). Such services, which can be categorised into frequency and non-frequency (voltage control, black start) services, are vital to support the operation of power systems (IRENA, 2019e).

The Swedish transmission system operator therefore calls for an adapted market design, encouraging system flexibility with adequate incentives.

→ To address this challenge, several solutions across the entire value chain of the power sector could be explored, which are further elaborated in the coming chapters. These include: ***Solution I:*** *Innovative ancillary services from both conventional and variable renewable energy sources* (supply-side flexibility solution); ***Solution II:*** *Pan-European market as flexibility provider with effective collaboration among system operators* (grid flexibility solution); and ***Solution III:*** *Aggregation of distributed energy resources to optimise distribution system operation* (demand-side flexibility solutions).

- **Balancing demand and supply** becomes increasingly complex, especially because of greater consumption and lower generation capacity in the southern bidding zones (SE3 and SE4). These factors also lead to growing price differences between these areas and bidding zones with high hydropower generation in the north (SE1 and SE2) and raises concerns about the maintenance of generation adequacy. While in 2019 most wind capacity was installed in SE2 (3 000 megawatts, MW) and SE3 (2 600 MW), the addition of more wind capacity in SE1 and SE2 in the future could exacerbate these differences. Svenska Kraftnät underscores the increasing risk of power outages in metropolitan areas in southern Sweden as well as the growing complexity of meeting peak power demand in periods of low VRE generation. The opposite challenge occurs when high wind power generation coincides with low electricity demand, resulting in a surplus of electricity and the need for curtailment of wind generation. Therefore, there is a further need to consider the most cost-effective use of surplus renewable generation, especially once the power system has very high shares of VRE.

→ To address this challenge, two solutions could be further explored, which are elaborated in the coming chapters: ***Solution III:*** *Aggregation of distributed energy resources to optimise distribution system operation* (demand flexibility solution); and ***Solution IV:*** *Decarbonisation of end-use sectors via electrification with renewable energy sources* (demand-side flexibility solution).

- **Expanding network infrastructure** refers to the challenge of ensuring reliability and limiting network congestion via grid reinforcements and investments. This is of utmost importance in light of growing power transfers from the north to the south, and of the lack of local and regional distribution capacity, which is putting increasing pressure on the Swedish transmission network. Grid investments are now at a historical high in the entire Nordic region and are expected to remain so in the coming years, with an estimated EUR 15 billion (USD 16.7 billion) to be invested by 2025 (Figure7). Nonetheless, according to Svenska Kraftnät, due to long lead times for approving and implementing transmission projects, these is growing concern whether grid capacity can be increased at the same rate as the rapid growth in power demand. Sweden's ageing transmission infrastructure and relatively low electricity prices, which frequently lead applicants to suspend the connection of renewable generation prior to final implementation, further exacerbate this challenge.

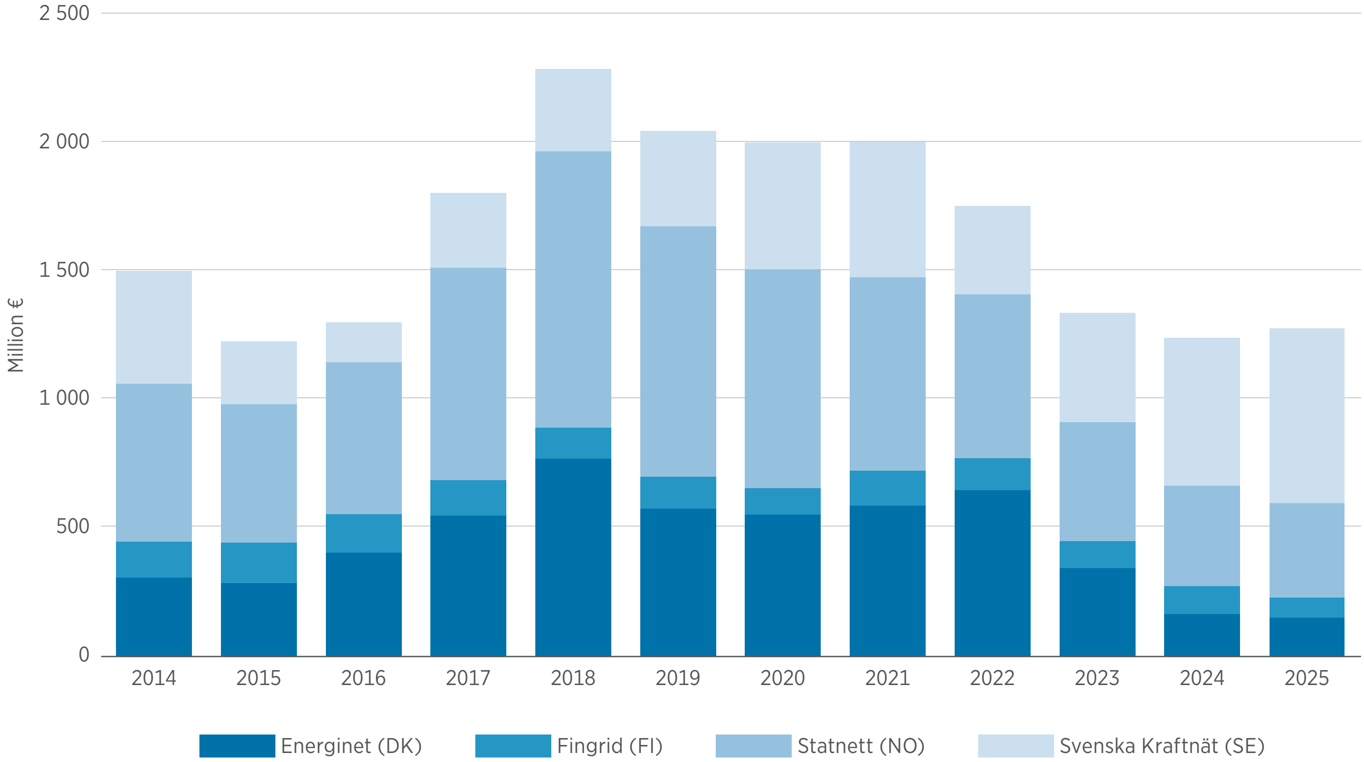
→ To address this challenge ***Solution III:*** *Aggregation of distributed energy resources to optimise distribution system operation* (demand-side flexibility solution) could be further explored.

- **Adapting the roles of actors** to ensure security of supply is strongly interrelated with all aforementioned categories. Sweden's transmission system operator highlights the missing division of roles and duties of the diversity of stakeholders in Sweden's power sector to effectively manage the system.

With the responsibility for security of supply being ambiguously split between Svenska Kraftnät and owners of regional and local grids, and in the absence of clear targets for security of supply, risks may be amplified in the longer term.

→ To address this challenge, ***Solution II:*** *Pan-European market as flexibility provider with effective collaboration among system operators* (grid flexibility solution) could be further explored.

Figure 7: Expected grid reinforcement investments by transmission system operators in the Nordic region, 2014–2025 (EUR million)



Source: Statnett, 2017a

3. SOLUTION I: INNOVATIVE ANCILLARY SERVICES FROM BOTH CONVENTIONAL AND VARIABLE RENEWABLE ENERGY SOURCES

3.1 DESCRIPTION OF THE INNOVATIVE SOLUTION

One of the key challenges identified in Sweden is how to ensure power system stability (frequency, voltage and rotor angle stability) in the face of the reduced system inertia due to the decommissioning of generation sources with synchronous generators (nuclear power) and growing shares of VRE, mainly wind generation, as shown in Table 1. Because wind generation is asynchronous and is connected via power electronic inverters, which decouple the instantaneous mechanical response during frequency events, it is delaying the inertia response even further. However, if coupled with batteries and/or grid-forming inverters that can provide synthetic inertia, VRE sources can help to ensure power system stability and could better provide ancillary services to the system.

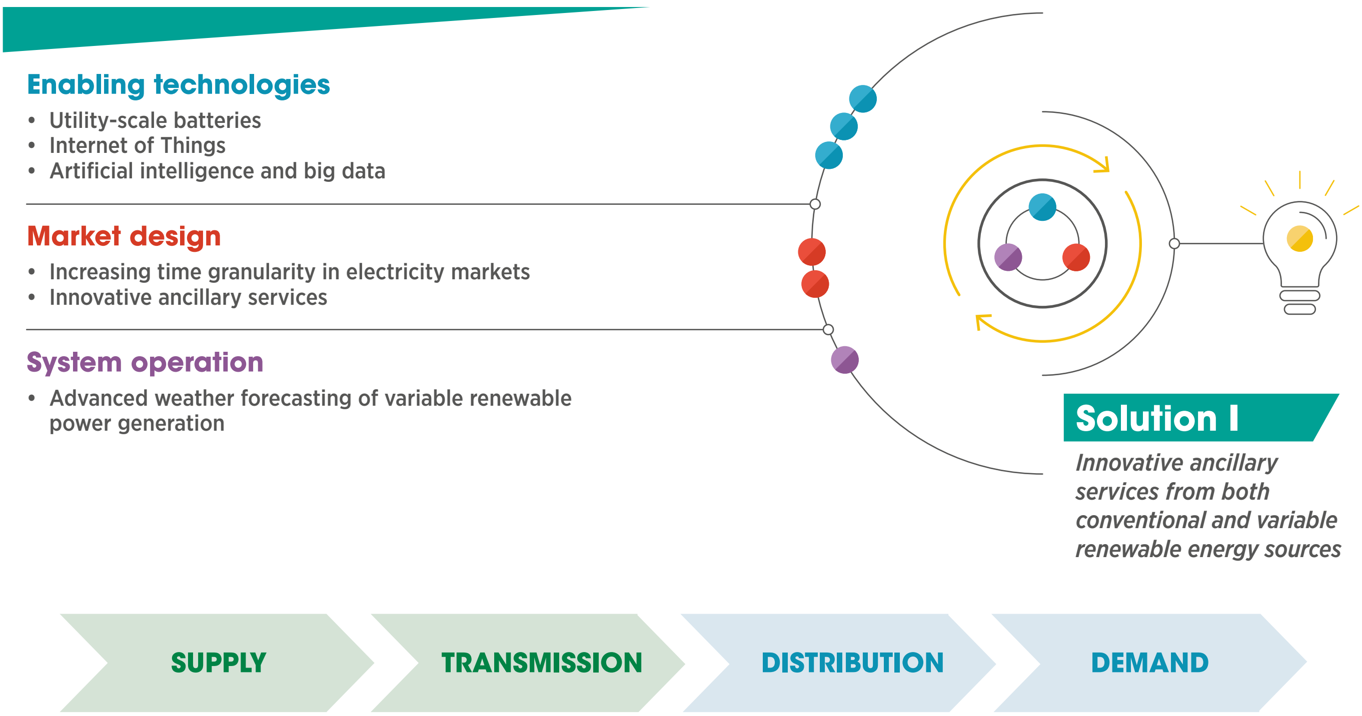
Additionally, daily balancing of supply and demand in the context of wind shortage or surplus remains challenging in a 100% renewable-powered system.

From a **policy and regulatory perspective**, addressing this challenge requires the development of an adequate market design that encourages flexibility. From a **system operation perspective**, it requires measures to ensure system stability, as well as options for the transmission system operator to access adequate ancillary services, in the case of lower inertia from conventional generators. Therefore, the first innovative solution refers to the provision of innovative ancillary services from conventional (hydropower) and VRE sources, such as solar and especially wind.

Table 1: Key challenges addressed by Solution I

INNOVATIVE SOLUTION	POLICY AND REGULATORY DIMENSION	SYSTEM OPERATION CHALLENGES	DETAILS ON THE CHALLENGE	FLEXIBILITY TIME SCALE	FLEXIBILITY NEED
Solution I: Innovative ancillary services from conventional and variable renewable energy sources	Developing an adequate market design encouraging flexibility	Ensuring system security and stability and accessing adequate ancillary services	Ensuring power system security and stability (frequency, voltage and rotor angle stability) in the face of the reduced system inertia due to the decommissioning of generation sources with synchronous generators (nuclear power) and growing proportions of VRE shares	Seconds to minutes	Supply-side flexibility solutions

Figure 8: Schematic representation of innovative Solution I



Implementation of the first solution requires innovations in enabling technologies, market design and system operation, which are indicated in Figure 8.

On the *supply side* of the power system, and with regard to the *transmission grid*, this solution aims to solve operational challenges twofold. On the one hand, it aims to incentivise conventional renewable power plants, *i.e.,* hydropower generators, to provide better ancillary services. On the other hand, it aims to incentivise VRE sources to be balancing responsible parties and provide ancillary services to the transmission system operator, so that the burden of system balancing and system stability is shared among all renewable generators[10].

The implementation of ***enabling technologies***, such as utility-scale batteries, artificial intelligence and the Internet of Things (IRENA, 2019f), offer the opportunity to collect more data and establish real-time information systems to greatly enhance controllability, improve data used by traders, improve the accuracy of VRE generation forecasts and provide better ancillary services to the grid.

Innovations in ***system operation***, such as advanced weather forecasting technologies, could help both hydropower and VRE asset owners better forecast prices. This could be done based on refined weather forecasts, thereby incentivising them to better operate their assets and to dispatch these when the system needs them the most.

From a ***market design*** and regulatory perspective, encouraging VRE generation assets to operate as balancing resources, together with conventional hydropower generation assets, will require innovative market regulations that remunerate and incentivise power plant operators to make these changes. This could be incentivised by increasing the time granularity in wholesale electricity markets (for example, introducing sub-hourly products in the intraday and balancing market and bringing the gate closing time closer to physical delivery in the intraday

10 While this solution focuses on the provision of ancillary services from renewable generators, ancillary services could also be provided from power-to-X technologies, such as power-to-heat and power-to-hydrogen, which are discussed in Solutions III and IV.

electricity market) and by reducing the imbalance settlement period in Sweden from 60 minutes currently to 15 minutes.

This is as per EU Regulation 2017/2195 and 2019/943, which establishes harmonisation rules at the EU level (see Innovation landscape brief: Increasing time granularity in electricity markets (IRENA, 2019e)). Such measures, which are planned to be introduced by the Swedish transmission system operator by the end of 2020 (Svenska Kraftnät, 2018a), would help to better capture the flexibility needs in the system and to value the response from generators to changing system conditions.

Currently, given the relatively low share of wind generation in the Swedish power mix (11%), compared to nuclear (40%) and hydropower (40%), which have historically resulted in relatively stable and low wholesale market prices, when compared to other EU member countries[11], sending market-based price signals to market participants will become increasingly important in the future, when wind power is expected to represent more of the overall power mix, because more variable power is expected to lead to more price variations.

Moreover, innovative ancillary services, both frequency and non-frequency services (*i.e.*, voltage control, black start) are crucial to support power system operation and especially increased system flexibility (see Innovation landscape brief: Innovative ancillary services (IRENA, 2019e)). Due to their flexibility, hydropower plants are very efficient in providing a wide range of ancillary services, including rapid changing of the active power output. This explains why hydropower plants are preferred assets to provide such services. Sweden is already using hydropower generators as regulating power on all time scales, and these are the only power producers currently providing frequency regulation.

Currently, the operational ancillary service market in Sweden is open to the participation of external generators. These include generators from neighbouring Nordic countries, VRE generators (for frequency control, spinning reserves, standing reserves and black start capacity) and the transmission system operator (for voltage control/reactive power). In the future, however, it could also be opened to network devices (for voltage control, such as synchronous compensators or wind parks) and the demand side, such as large and interruptible customers (for spinning and standing reserves), including commercial or even residential consumers via aggregation (Eurelectric, 2004).

To address the variability and uncertainty of increasing wind shares in the power mix, products in the ancillary service markets could be defined to incentivise fast-response and ramping ability by introducing the necessary remuneration mechanism for these new actors. For example, VRE generators, coupled with batteries, could provide downward balancing and even short-term upward balancing services. Moreover, wind power plants could provide inertial response from wind turbines through power electronic converters. Solar PV installations, direct current (DC) systems and batteries could also provide synthetic inertial response if the inverter is programmed as such. However, while synthetic inertia capability from solar and wind generators is technically feasible, it is not yet deployed commercially at a large scale.

3.2 IMPLEMENTATION EXAMPLES FROM SWEDEN

The following two sections contain examples of ongoing initiatives or pilot projects where parts of Solution I are being implemented or trialled, first in Sweden, then outside of Sweden or in an international context. To show the extent to which the examples correspond to the proposed solution, and as an indication of the replicability of the examples in the Swedish context, each innovation proposed in the solution and also considered in the implemented solution is shown with a ticked box.

11 For example, in 2017 the average annual day-ahead electricity prices were in the range of EUR 30.84 to EUR 32.18 per megawatt-hour (MWh) in Sweden (depending on the bidding zone), compared to EUR 44.96 per MWh in France and EUR 52.23 per MWh in Spain (ACER, 2018).

Sweden – VRE participating in the existing ancillary service market

	Utility-scale batteries
	Internet of Things
	Artificial intelligence and big data
	Increasing time granularity in electricity markets
✔	Innovative ancillary services
	Advanced weather forecasting of variable renewable power

As the power system inertia in Sweden decreases due to some conventional, synchronous generators (for example, nuclear power plants) reaching the end of their economic life times, lower system inertia translates into faster frequency variations in case of a contingency (because inertia affects the Rate of Change of Frequency, RoCoF). This leads to faster wear and tear in units that provide frequency control to the power system, including hydropower turbines. Wind parks can participate in ancillary service markets by providing **synthetic inertial response**, to address the critical problem of frequency stability when the system is faced with large disturbances by using the rotational mass in the wind turbine. For example, energy stored in systems behind power electronic interfaces, such as batteries or rotating masses in wind turbines, are required for wind parks to provide synthetic inertial response.

Wind power generators are already allowed to provide balancing and ancillary services in eight European countries (Belgium, Denmark, Estonia, Finland, the Netherlands, Poland, Spain and the United Kingdom (UK)), in addition to Sweden. More reforms are happening throughout the EU with the implementation of network codes for balancing markets and system operation, including the procurement of ancillary services by transmission system operators (applicable in all EU member states).

Sweden – Battery energy storage system at Forshuvud hydropower plant for better ancillary services

✔	Utility-scale batteries
	Internet of Things
	Artificial intelligence and big data
	Increasing time granularity in electricity markets
✔	Innovative ancillary services
	Advanced weather forecasting of variable renewable power

Synthetic inertia using a linear controller for improved frequency quality and reduced hydropower wear and tear is one technical solution that is being actively explored in Sweden, in addition to the synthetic inertial response provided by wind power plants. A new type of synthetic inertia, which is linear and continuously active, is expected to mitigate these impacts in existing hydropower plants by using a controller that can effectively replace the synchronous inertia and damping, therefore improving the frequency quality.

One project that aims to offer better services to the grid by enhancing the speed and the precision of response of hydropower plants with the help of batteries is the battery energy storage system at the 44 MW Forshuvud hydropower plant in Sweden. Similar to the Batcave battery at Fortum's Järvenpää biomass plant in Finland, where a 2 MW/1 MWh battery has provided frequency regulation to the grid since March 2017, Fortum announced the installation of a 5 MW/6.2 MWh battery energy storage system at the Forshuvud hydropower plant. The purpose of this project, which has an estimated investment of EUR 3 million (USD 3.3 million), is to provide frequency regulation services in addition to the around 210 gigawatt-hours (GWh) of electricity generated annually by the hydropower plant.

As a hybrid system, together with the hydropower turbine, the batteries provide a linear step-response to frequency deviations in the power system which is needed to provide ancillary services, such as frequency containment reserves. The batteries are also expected to reduce the wear and tear on the hydropower turbines (Colthorpe, 2018).

3.3 EXAMPLES OF SIMILAR IMPLEMENTED SOLUTIONS

United States – Flexibility incentivised in California with innovative ancillary services

	Utility-scale batteries
	Internet of Things
	Artificial intelligence and big data
✔	Increasing time granularity in electricity markets
✔	Innovative ancillary services
	Advanced weather forecasting of variable renewable power

The California Independent System Operator (CAISO) has proposed several changes in the power market to incentivise system flexibility due to large solar PV generation. One of the changes being proposed is in the day-ahead market, to change the granularity from 1 hour to 15 minutes. The reduction in scheduling intervals would allow power generating resources to follow the load curve as forecasted by CAISO more closely. CAISO may also be able to reduce procurement from the real-time market, especially during morning and evening ramping times.

In November 2016 CAISO implemented a separate flexibility ramping product on the ancillary service market: Flexible Ramp Up and Flexible Ramp Down Uncertainty Awards, which are products to procure ramp-up and ramp-down capability for 15-minute and 5-minute time intervals through the ancillary service market.

The product is procured in terms of megawatts of ramping required in a five-minute duration, and any resource capable of fulfilling the ramping requirement can participate. The price for providing ramp-up service is capped at USD 247 per MWh, and the price for providing ramp-down service is capped at USD 152 per MWh (CAISO, 2018). Following CAISO's successful implementation, the New York Independent System Operator (NYISO) proposed a similar flexible ramping product as part of its 2018 Master Plan (Avallone, 2018).

Germany – EWeLiNE, ORKA, ORKA2 and Gridcast projects improving VRE generation forecasts

	Utility-scale batteries
✔	Internet of Things
✔	Artificial intelligence and big data
	Increasing time granularity in electricity markets
	Innovative ancillary services
✔	Advanced weather forecasting of variable renewable power

Since 2012 the Deutscher Wetterdienst (German Meteorological Service) has been working on optimising its weather forecasts for renewable energy applications within the two research projects EWeLiNE and ORKA, funded by the Federal Ministry for Economic Affairs and Energy (BMWi). Based on the findings of the ORKA project in December 2015, this successful co-operation was continued in a new project, ORKA2, implemented since 2016, followed by a new subsequent project called Gridcast since 2017. In these projects, the German Meteorological Service and the Fraunhofer Institute for Wind Energy and Energy System Technology worked with the three German transmission system operators (Amprion GmbH, TenneT TSO GmbH and 50 Hertz Transmission GmbH), one manufacturer of wind energy systems and two distribution system operators.

Their goal was to improve the weather and power forecasts for wind turbines and solar PV plants and to develop new forecast products focusing specifically on grid stability. These projects allowed them to use real-time data from solar panels and wind turbines around Germany and to feed it into an algorithm that uses machine learning to calculate the renewable energy output. Following tests, the researchers concluded that the newly developed forecast models have better forecast accuracy with higher temporal and spatial resolution, when compared to conventional models. The new models also have better weather warnings that are adapted to grid operation, especially when faced with extreme weather conditions, such as strong winds. Therefore, solar radiation data are calculated every 15 minutes, enabling the system operators to better estimate if they need additional resource to maintain grid stability. As a next step, the Gridcast project aims to integrate satellite images for solar forecasts in addition to the existing weather forecast data, thereby helping system operators better manage the system with high shares of VRE.

3.4 QUALITATIVE COST-BENEFIT ASSESSMENT

Defining and mandating clear technical criteria for new ancillary services in addition to more accurate price signals would be an incentive for existing and new market participants to provide such services to the transmission system operator. For example, defining performance-based products for system stability, separating capacity and energy products, and contracting periods, or separating upward and downward balancing products, as per EU Regulation 2019/943, would provide more clarity.

Innovations for advanced weather forecasting reducing VRE generation uncertainty exist and could be implemented, especially by wind generators if incentivised to do so.

This could occur through the **definition of shorter imbalance settlement periods in the balancing market**, for example from 60 minutes today to 15 minutes scheduled for 2020, as per EU Regulation 2017/2195 establishing a guideline on electricity balancing. While there is less potential for applying advanced weather forecasting for solar PV in Sweden (due to low forecasted installed capacity), wind generators could benefit from this innovation.

To reap social welfare benefits Europe-wide, it is important for Svenska Kraftnät to continue the collaboration with neighbouring transmission system operators Energinet (Denmark), Fingrid (Finland) and Statnett (Norway) and to strengthen the existing collaboration towards the **development of a common European platform for balancing reserves** to make use of the locational complementarity of resources. This includes an integrated pan-European balancing market, as well as tools to estimate how much inertia is available in the system and to propose adaptation of the market to meet the operational needs.

Conducting detailed qualitative and quantitative assessments to evaluate the cost, complexity and benefits[12] of the proposed solution would provide more evidence of the advantages of implementing such a solution. For example, the benefits of opening the ancillary service market to new market participants beyond Sweden, including utility-scale batteries, distributed solar PV and wind parks, could also be used as a basis for further decision making in the pan-European context.

Monitoring the effective implementation of EU regulations containing legally binding rules (network codes and guidelines) for balancing markets and system operation by the competent authorities will be crucial. Such regulations include EU Regulation 2017/2195 establishing a guideline on electricity balancing and EU Regulation 2017/1485 establishing a guideline on electricity transmission system operation.

12 Benefits assessed could include the profitability of private stakeholders.

Power generators will also play a role in implementation of this solution by **equipping VRE generation units with advanced weather forecasting technology** that would reduce the uncertainty and variability of wind power plants. Moreover, **power generators could play a significant role by participating in the ancillary service market** and providing ancillary services to the transmission system operator by adapting their equipment, as necessary. This could be done, for example, through hybridisation of power plants; connecting batteries with hydropower plants; or benefiting from local synergies and daily and seasonal complementarity between wind and hydropower sources; equipping wind turbines with power electronic converters and control devices to enable inertial response; inverters enabling solar PV plants to provide ancillary services, etc.

Overall, these actions require the engagement, consultation and/or co-ordination of two or more stakeholders in the Swedish power sector.

Table 2 contains a summary of some of the key actions needed for the implementation of Solution I, together with an indication of the relevant stakeholders that could be involved in taking further action to implement this solution.

Table 2: Stakeholder action and engagement required for the implementation of Solution I

TYPE OF STAKEHOLDER	**MINISTRY**	**GOVERNMENT AGENCY**	**GOVERNMENT AGENCY**	**REGULATOR**	**MARKET OPERATOR**	**SUPPLY**	**TSO**	**DSO**	**DEMAND**	**DEMAND**	**DEMAND**
Stakeholder Engagement & Action	**Ministry of Infrastructure**	**Swedish Energy Agency**	**Vinnova**	**Swedish Energy Markets Inspectorate**	**Nord Pool**	**Power generators**	**Svenska Kraftnät**	**Ellevio, Vattenfall Eldistribution, E.ON Energidistribution & co.**	**Retailers**	**New actors (aggregators)**	**Consumers**
Promote innovations for the power sector transformation	✔	✔	✔								
Define security of supply standards & responsibilities	✔	✔		✔			✔	✔			
Monitor the effective implementation of EU directives and regulations related to the internal electricity market and the Energy Union	✔	✔		✔							
Harmonise the balancing market at the European level		✔		✔			✔	✔			
Perform generation adequacy assessments		✔		✔		✔	✔				
Define & implement a shorter imbalance settlement period				✔		✔	✔				
Mandate new ancillary services	✔	✔		✔							
Define technical criteria for new ancillary services	✔	✔		✔		✔	✔	✔			
Define remuneration mechanism for new ancillary services		✔		✔			✔				
Equip VRE generation units with advanced weather forecasting technology						✔					
Participate in the ancillary service market						✔					
Evaluate the costs, complexity and benefits of the proposed solution		✔		✔		✔	✔				

***Note**: Proposed actions for the four solutions are not meant to be treated in isolation, but could be done simultaneously and in co-ordination with two or more parties.*

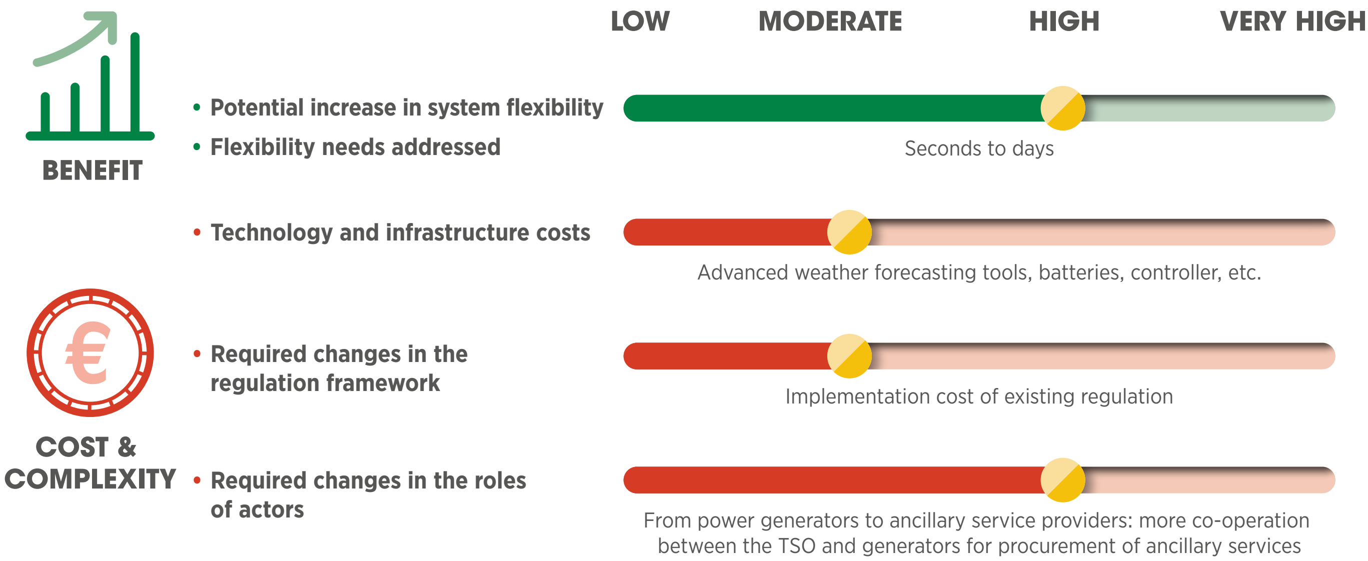
While the order of the stakeholders listed is not an indication of which stakeholder should act or be engaged first, it should be noted that a co-ordination process involving such a large number of parties is very complex. Identifying which party would need to act or be engaged, before creating the necessary conditions for another one, would require further work and consultation. For example, regulations or markets might need to be altered to give incentives to consumers or generators to provide a certain type of service. However, to make meaningful changes to the regulatory framework, the authority altering the market needs to know which services would technically be required and who could provide these. Therefore, the proposed actions should be read as simultaneous actions, rather than as consequent steps.

Implementing a systemic innovative solution that aims to better define the services required by the transmission system operator via the definition of innovative ancillary services is expected to provide a very high level of flexibility to the system, from seconds, minutes, hours and even days. Moreover, ensuring that the hydropower and VRE generators receive the necessary price signal or remuneration mechanism to operate their existing assets more flexibly can play a crucial role in supporting the implementation of this solution. Even more importantly, some of the environmental issues regarding Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for Community action in the field of water policy (the so-called EU Water Framework Directive) and the process of permit renewal planned for 2022–2040 would need to be overcome to allow the existing hydropower generators to operate flexibly.

The main challenge in implementing this solution lies in transposing existing European directives into national laws, equipping the existing and new generation units with the necessary technical equipment (for example, using advanced weather forecasting tools for wind parks) and the required changes in the roles of actors. Generators would be required to co-operate more closely with the transmission system operator in Sweden, as well as with neighbouring countries (and Europe-wide) to provide the necessary ancillary service required for a stable power system.

As shown in Figure 9, the costs and complexities of implementing a new and regionally harmonised ancillary service market are estimated to be moderate to high, compared to the benefits, which are expected to be high, therefore leading to an overall slightly positive cost-benefit assessment.

Figure 9: Estimated benefits, costs and complexity for the implementation of Solution I



***Note**: The benefits, costs and degree of complexity are indicative for each solution and were provided following an expert-based estimation, by comparing the four solutions to each other.*

4. SOLUTION II: PAN-EUROPEAN MARKET AS FLEXIBILITY PROVIDER

4.1 DESCRIPTION OF THE INNOVATIVE SOLUTION

As shown in Table 3, two of the key challenges identified in Sweden can be addressed via the effective collaboration among system operators in the Nordic synchronous area and more broadly within the European interconnected power system, based on which the pan-European electricity market is functioning.

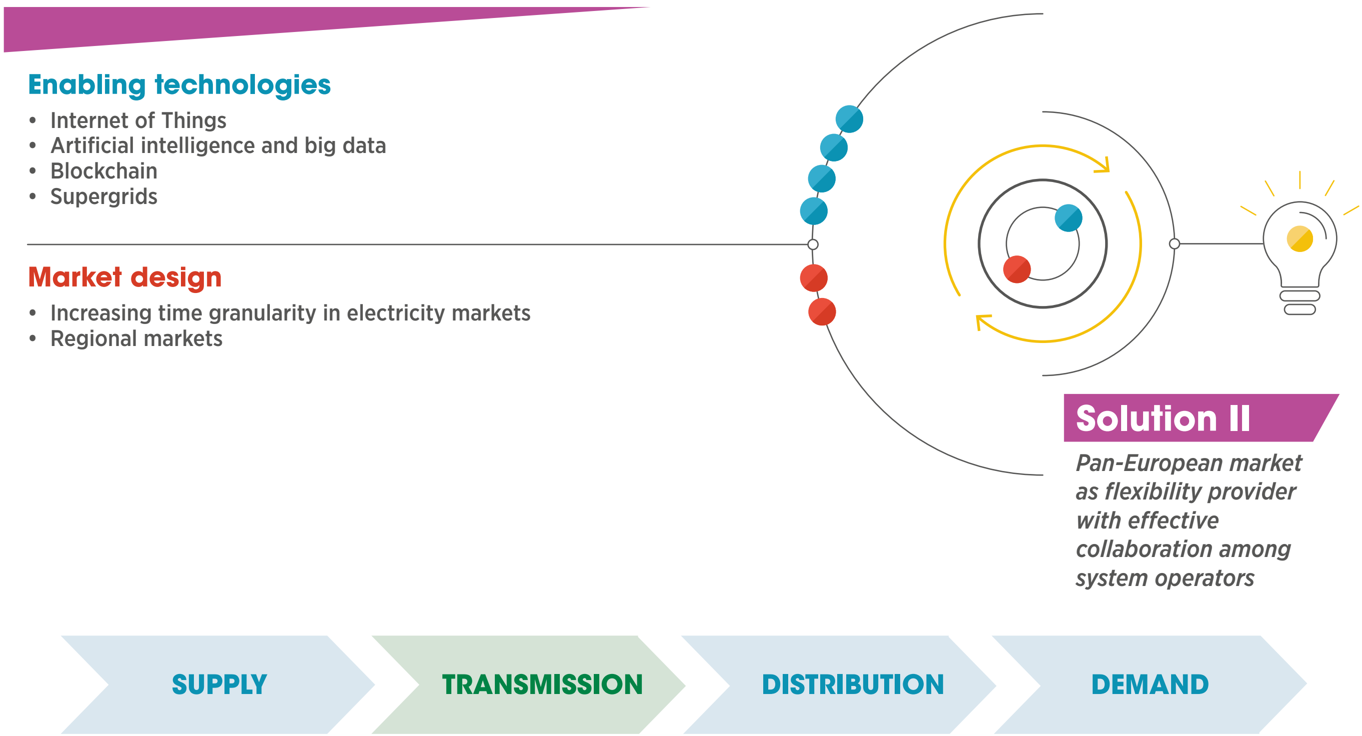
Similar to Solution I, from a **policy and regulatory perspective**, addressing these challenges requires the development of an adequate market design that encourages flexibility, while effectively and efficiently managing the increasing decentralisation and digitalisation of the increasingly complex power system. From a **system operation perspective**, it requires measures to ensure system security and stability, as well as options for the transmission system operator to access and procure adequate ancillary services, in the absence of inertia from conventional generators. At the same time, it requires a clear division of responsibilities to effectively manage the increasingly complex power system in Sweden and beyond.

For the implementation of the second solution, there is a need to combine six innovations across two innovation dimensions, covering enabling technologies and market design. An overview of the innovative solution and the innovations required are provided in Figure 10.

Table 3: Key challenges addressed by Solution II

INNOVATIVE SOLUTION	POLICY AND REGULATORY DIMENSION	SYSTEM OPERATION CHALLENGES	DETAILS ON THE CHALLENGE	FLEXIBILITY TIME SCALE	FLEXIBILITY NEED
Solution II: Pan-European market as flexibility provider with effective collaboration amongst system operators	Developing an adequate market design encouraging flexibility	Ensuring system security and stability and accessing adequate ancillary services	Uncertainty from where ancillary services will come from and challenge to find most effective range of ancillary service products	Seconds to hours	Grid flexibility solutions
	Managing increasing decentralisation and digitalisation	Division of responsibilities to effectively manage the system	The split of responsibilities between Svenska Kraftnät and the owners of regional and local grids	Seconds to hours	Grid flexibility solutions

Figure 10: Schematic representation of innovative Solution II



This solution aims to harness the full potential of the interconnected transmission grid as a flexibility provider by exploring synergies and managing fluctuations of VRE generation within regional power markets, which combine several national, sub-national and local systems. As a *grid flexibility* solution, the regional, pan-European electricity market couples nationally organised markets via interconnections within a larger balancing area across several control areas with a wide geographic diversity of resources that can be used to balance supply and demand by taking full advantage of weather and resource diversity and differences in load patterns.

A well-integrated regional market can create both locational and temporal synergies between renewable energy sources and demand patterns across the entire region. Moreover, benefits can span to investment planning in new power generation assets across the larger region, provided that the necessary co-ordination framework is in place.

In general, regional markets require the harmonisation of market rules for electricity to flow freely in response to market-based price signals. The level of market integration can be defined as being 1) relatively narrow with bilateral contracts, 2) shallow with additional harmonisation of wholesale market rules, or 3) a deeper level of market integration with more harmonised rules, including also the ancillary service and possibly capacity markets (see Innovation landscape brief: Regional markets (IRENA, 2019e)).

The regional pan-European market is one of the most integrated globally, especially compared to other regional markets such as the Eastern Africa Power Pool, the Greater Mekong Sub-region, the Nile Basin Initiative, the West African Power Pool, the Central America Power Market and the Southern African Power Pool. Most of the progress was made with respect to the implementation of single day-ahead coupling (SDAC) via EU Regulation 2015/1222 establishing a guideline on capacity allocation and congestion management, which sets the rules for co-ordinated European day-ahead and intraday markets (EC, 2015). At the end of 2018, the SDAC covered 25 European countries: Austria, Belgium, Croatia, the Czech Republic, Germany, Denmark, Estonia, Finland, France, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, the Netherlands, Norway, Poland, Portugal, Romania, the Slovak Republic, Slovenia, Spain, Sweden and the UK. As shown in Figure 46 in Annex 3, this was a gradual market integration process that started in the 1990s with the Nordic and Baltic countries, including Sweden.

This solution is already implemented in Sweden, in the Nordic region and more broadly on the European continent, where electricity markets are liberalised, open and with unbundled utilities. The solution also illustrates how the incremental market integration that occurred in recent decades to ensure security of supply and reduce welfare costs by increasing competition can be leveraged even further for the integration of larger shares of VRE, although this was not the main driver of the creation of this regional market. The key benefit of regional markets is the increased flexibility that is enabled through expansion of the balancing area, while providing advantages of spatial complementarity of VRE generation and reduced system operation costs in a co-ordinated generation planning process. The key enabling factors are physical interconnections with sufficient capacity available for trade, a regional mindset with strong institutional arrangements or governance models, as well as robust information technology systems for optimal market operation.

In Sweden, in the Nordic region and more broadly on the European continent, electricity markets are liberalised and open, with unbundled utilities

In terms of **market design**, this implies further harmonisation of rules in electricity wholesale and ancillary service markets, including stronger integration among Nordic and Baltic countries as well as the rest of continental Europe. New regulations in the wholesale markets would be needed to increase the time granularity and further integrate markets in a regional setting. This would encourage flexibility from a larger number of market participants. At the same time, it would send better price signals both for the exchange of electricity and for the remuneration of grid services. For example, in the Swedish market areas only hourly intraday products can be traded, as opposed to lower granularities (sub-hourly) in other market areas. Similarly, there are benefits for VRE integration when trading gate closing times are set closer to real-time delivery of electricity, when information about system constraints is more accurate. However, in Swedish market areas, the gate closing times are set at 60 minutes before physical delivery, while other market areas have gate closing times closer to real time (less than 60 minutes).

As both the time granularity and the geographical scope of electricity markets increase, modelling regional power markets becomes more complex. In this context, **enabling technologies**, such as artificial intelligence, big data and the Internet of Things, can contribute by matching orders from all participating national power systems more transparently and efficiently. Blockchain technology may further facilitate monetary transactions among the increasing number of actors involved (see Innovation landscape brief: Blockchain (IRENA, 2019f)).

All of these digital technologies are introducing new applications in the power sector, changing the boundaries and dynamics of the industry and helping to optimise the operation of renewable assets. At the same time, new grids, including “smart grids” and especially “supergrids” – which are large transmission networks composed of high-voltage direct current power lines (greater than or equal to 500 kilovolts, kV) or ultra-high-voltage direct current power lines (greater than or equal to 800 kV) – enable new ways to manage VRE integration, for example by fostering the trade of large electricity volumes over vast territories.

4.2 IMPLEMENTATION EXAMPLES FROM SWEDEN

The following two sections contain examples of ongoing initiatives or pilot projects where parts of this solution are being implemented or trialled, first in Sweden as part of the European market, then in the wider European context. Examples with market design elements were selected only from the European context, as these are deemed more relevant for Sweden, which participates fully in what is considered the most integrated power market globally. To show the extent to which each of the examples correspond to the solution proposed and as an indicator of the replicability of these European pilots, each innovation considered in the examples is shown with a ticked box.

Europe – intraday trading between non-adjacent market areas

✔	Internet of Things
✔	Artificial intelligence and big data
	Blockchain
✔	Supergrids
✔	Increasing time granularity in electricity markets
✔	Regional markets

An important step towards further integration of European wholesale markets, in addition to the day-ahead market, was taken in June 2018 with the establishment of single intraday coupling (SIDC), one of the key elements of market design envisaged in EU Regulation 2015/1222 of 24 July 2015, establishing a guideline on capacity allocation and congestion management. SIDC materialised with the going live of the commercial cross-border intraday (XBID) project, which uses the artificial intelligence-based EUPHEMIA[13] coupling algorithm covering 25 countries, including Sweden.

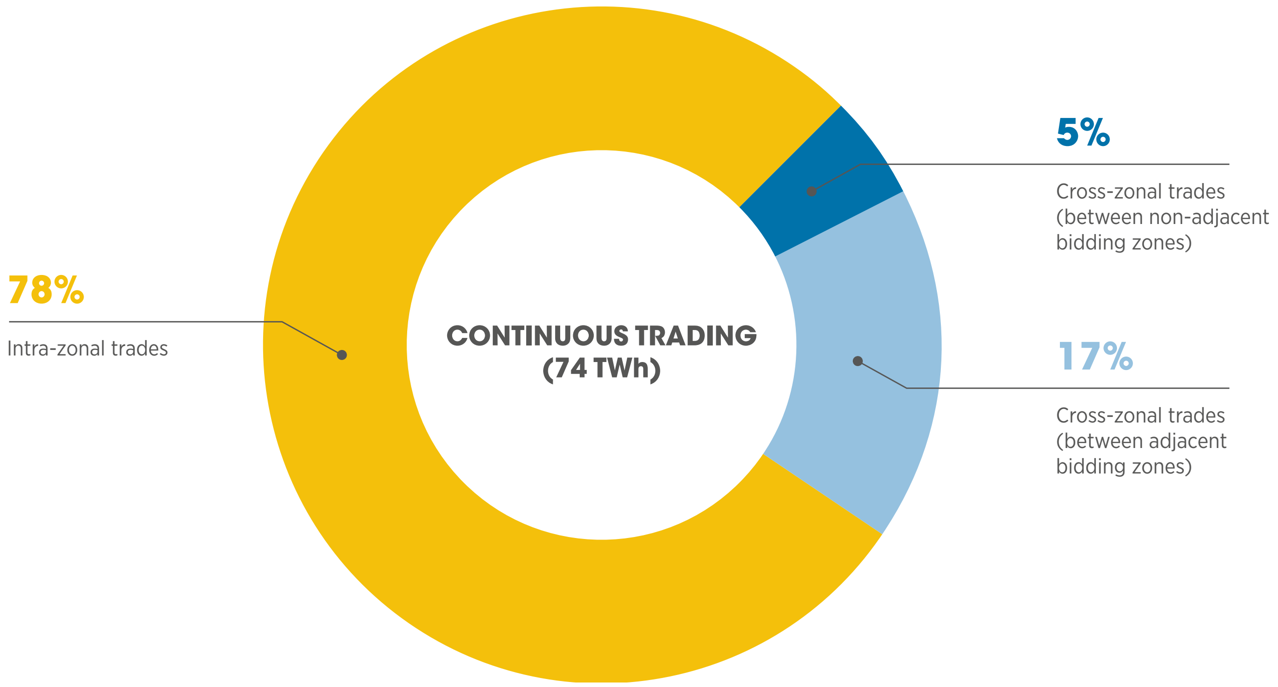
As it becomes challenging to be in balance after the closing of the day-ahead market with increased shares of VRE, there is increasing interest from market participants in participating in exchanges in the intraday time frame, which is expected to facilitate the integration of more VRE into the wholesale electricity market. For example, with the going live of the XBID, one of the key improvements expected is the increase in intraday volumes traded between both adjacent and non-adjacent market zones, or market areas that are not situated next to each other geographically or that do not share a direct interconnection, such as SE4 and France.

The share of volumes exchanged between adjacent and non-adjacent borders in Europe was 17% and 5% in 2017, respectively, as shown in Figure 11, but with deeper market integration more locational complementarities among renewable resources across Europe could be reaped. Moreover, as shown in the example presented under Solution II, entitled "*Europe – 15- and 30-minute intraday products traded closer to real-time delivery*", several nationally organised markets have previously introduced sub-hourly intraday products, such as 15- and 30-minute products, which are also supported by the XBID platform in the respective market area.

An important step towards further integration of European wholesale markets was taken in June 2018 with the establishment of single intraday coupling

13 Acronym of Pan-European Hybrid Electricity Market Integration Algorithm.

Figure 11: Volume shares of intra-zonal versus cross-zonal trades in continuous intraday markets in Europe, 2017



Source: ACER, 2018

Europe – 15- and 30-minute intraday products traded closer to real-time delivery

	Internet of Things
✔	Artificial intelligence and big data
	Blockchain
	Supergrids
✔	Increasing time granularity in electricity markets
✔	Regional markets

The power exchange operating in the German market, EPEX SPOT, introduced in 2011 a new product in the intraday time frame of the wholesale electricity market for continuous trading (as opposed to auctions) in order to value the flexibility in this renewable-driven market. Following the trade of 4.5 TWh between 2011 and 2013, where 5% of the liquidity was concentrated in the first 15 minutes after the gate opening time, the power exchange introduced an additional intraday auction for a quarter-hourly (15-minute) product to help market participants model the solar irradiation patterns (EPEX SPOT, 2014). In the meantime, several other nationally organised markets have introduced sub-hourly intraday products, as shown in Table 4, such as 30-minute products for continuous trading in France, Germany and Switzerland since March 2017 and 15-minute products for continuous trading in the Netherlands and Belgium since July 2018 (ACER, 2018).

Since the going live of pan-European single intraday coupling in 2018 via the XBID project, using the artificial intelligence-based EUPHEMIA coupling algorithm covering 25 European countries in the day-ahead time frame, the same sub-hourly products are supported by the XBID system in the specific market areas. Additionally, reducing the gate closure time in intraday markets from 60 minutes to 30, 15 or even 5 minutes is expected to bring benefits. For example, it could provide market participants with more time to adjust their balances closer to real time. At the same time, it would provide transmission system operators with the necessary time for scheduling and balancing, which is important for network and operational security.

As such, the intraday gate closing time of 30 minutes before delivery, which is piloted on the Estonian-Finnish border, "should not be considered as an exception, but rather as a preferred solution", as per ACER decision No. 04/2018 of 24 April 2018. This decision is harmonising the intraday gate opening at 3 p.m. on the day before physical delivery. At the same time, this decision sets the rule for a harmonised closing times of 60 minutes for the pan-European intraday market (see Innovation landscape brief: Increasing time granularity in electricity markets (IRENA, 2019e)).

Table 4: Availability of sub-hourly products in European intraday markets as of 2017

	AUCTION			CONTINOUS TRADING		
Country	**Hourly**	**Half-hourly**	**Quarter-hourly**	**Hourly**	**Half-hourly**	**Quarter-hourly**
Austria	✖	✖	✖	✔	✖	✔
Belgium	✖	✖	✖	✔	✖	✖
France	✖	✖	✖	✔	✔	✖
Germany	✖	✖	✔	✔	✔	✔
Hungary	✖	✖	✖	✔	✖	✔
Ireland	✖	✔	✖	✖	✖	✖
Luxemburg	✖	✖	✔	✔	✔	✔
Netherlands	✖	✖	✖	✔	✖	✖
Slovenia	✔	✖	✖	✔	✖	✔
Switzerland	✖	✖	✖	✔	✔	✔
United Kingdom	✖	✖	✖	✔	✔	✖

Source: *Adapted from ACER, 2018*

4.3 EXAMPLES OF SIMILAR IMPLEMENTED SOLUTIONS

Denmark – 53% VRE integration thanks to supergrids and regional market

	Internet of Things
	Artificial intelligence and big data
	Blockchain
✔	Supergrids
	Increasing time granularity in electricity markets
✔	Regional markets

The power grid of the EU is one of the most (if not the most) interconnected transmission networks in the world. Denmark, being part of the EU and participating in the pan-European wholesale electricity market, benefits from strong interconnections with neighbouring countries. Denmark has supergrids – *i.e.*, large transmission networks composed of high-voltage direct current power lines or ultra-high-voltage direct current power lines – to and from Germany, Norway, Sweden and the Netherlands. In addition to the strong national transmission system, Denmark has an interconnection capacity with its neighbouring countries that is almost equal to its peak demand of 6.5 GW, combining an import capacity of 2.2 GW from Germany, 2 GW from Sweden and 1.6 GW from Norway.

This allowed the integration of a very high (relative to other countries) share of 53% VRE into the Danish power mix in 2017. The surplus wind power is exported to the Nordic countries, which in turn can benefit from relatively cheaper wind power, while keeping the hydropower resources as reserves. Advanced weather forecasting has also been implemented in the operational procedures, which results in a more accurate forecast updated every five minutes (IRENA, 2019b). As an enabling infrastructure underlying well-functioning regional markets, supergrids are usually independent but can also interact with the conventional alternating current grids.

European transmission system operators – pilots for a common balancing market

✔	Internet of Things
✔	Artificial intelligence and big data
	Blockchain
✔	Supergrids
	Increasing time granularity in electricity markets
✔	Regional markets

In addition to an integrated European electricity market in the day-ahead and intraday trading time frame, a regional balancing reserve market would reduce the need for the total balancing reserves requirements if these are shared across several balancing areas across different countries. The regulatory framework that sets the harmonised rules for transmission system operators on the operation of a common electricity balancing market at the European level is provided by EU Regulation 2017/2195 of 23 November 2017 establishing a guideline on electricity balancing (EC, 2017).

In addition to several cross-border pilot projects among transmission system operators that are being conducted to implement this grid code across Europe, another effort is the Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation (PICASSO). Initially, eight transmission system operators across five European countries participated in this project (Austria, Belgium, France, Germany and the Netherlands) with the aim of designing, implementing and operating a common platform for automatic frequency restoration reserves (aFRR), a balancing product. Transmission system operators from the Czech Republic, Denmark, Finland, Hungary, Norway, Slovenia, Spain and Sweden have also joined the project, which is now considered the reference project within the ENTSO-E framework for this particular product.

Another pilot project conducted within the ENTSO-E framework among the transmission system operators of seven European countries (Austria, Belgium, western Denmark, France, Germany, the Netherlands and Switzerland) illustrated that with geographical expansion of the balancing area when procuring frequency containment reserves, the prices of this balancing product decreased and converged steadily across the participating markets between 2014 and 2017 (ACER, 2018). The Internet of Things and artificial intelligence are innovations that would optimise the operation of such markets.

4.4 QUALITATIVE COST-BENEFIT ASSESSMENT

A regional mindset, trust, strong institutional arrangements and a regulatory framework for cross-border co-ordination among various stakeholders – including, but not limited to, policy makers, regulators, transmission system operators, distribution system operators and market participants – is a crucial pre-requisite for a well-functioning regional market. Effective co-operation would facilitate the creation and operation of cross-border institutions, such as regional regulatory agencies or market operators, while also ensuring adequate market surveillance to avoid market manipulation and increase trust among market participants even further.

For the implementation of this solution, two types of enabling technologies are needed. On the one hand, it is important to have the enabling digital technologies, such as a combination of software with robust information technology systems, automatic process and high computational power able to process bids from a large number of market actors. On the other hand, the underlying hardware, *i.e.*, physical interconnection capacity among power systems, plays an important role in enabling power trade within a larger region. **Building supergrids**, or high-voltage interconnections to neighbouring countries, in addition to existing interconnections is a capital-intensive investment that requires careful weighting of the costs and benefits. However, equally if not more important is **making efficient use of the existing transmission infrastructure** that links Sweden to the Nordic and Baltic regions as well as to continental Europe (via interconnection to Poland) by making this cross-border transmission capacity available for trade.

In terms of market design and regulatory framework, to fully benefit from the regional market, **effective, efficient and timely implementation of all legal provisions of EU directives and regulations** is crucial from all EU member countries, including Sweden. Having the necessary harmonised regional framework for co-ordinated scheduling, dispatching and investment planning in place, current key legislation refers to grid codes and governance acts on the Energy Union and the internal electricity market, such as:

- EU Regulation 2015/1222 of 24 July 2015 establishing a guideline on capacity allocation and congestion management;
- EU Regulation 2017/2195 of 23 November 2017 establishing a guideline on electricity balancing;
- EU Regulation 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action;
- EU Regulation 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity;
- EU Directive 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity;
- EU Regulation 2019/941 of the European Parliament and of the Council of 5 June 2019 on risk-preparedness in the electricity sector.

In addition to the implementation or transposition of these acts into national law, a **clear and transparent pricing methodology** in the regional pan-European market across all power trading time frames (long-term, day-ahead, intraday and balancing markets) would be useful to send market-based price signals to generators, grid operators and consumers.

Moreover, **further harmonising some market design elements that are not mandatory**, such as having the same gate opening and closure times for trading, and the same scheduling intervals or products, would bring additional benefits from cross-border trading. Sweden plans to introduce 15-minute products in the electricity markets in the intraday and balancing trading time frame in 2020, and it could further **increase the time granularity in intraday markets** by bringing gate closing time closer to physical delivery (*i.e.*, reduce it from 60 minutes to 30 minutes or less). Similar approaches are seen on the Estonian-Finnish border and in certain transmission system operator areas in Austria, Germany and Luxemburg and are proven to benefit wind generators.

Given the evolving nature of responsibilities of the grid operators, system operation practises at the EU level will change in several ways, highlighting the importance of **ensuring effective co-operation between Svenska Kraftnät and other transmission system operators within regional co-ordination centres (RCCs)**.[14]

Because integrating even higher shares of VRE will pose similar challenges to other system operators in the pan-European market, ensuring that the RCCs are fully and effectively operational by 2022 will be key.

Table 5: Stakeholder action and engagement required for the implementation of Solution II

TYPE OF STAKEHOLDER	MINISTRY	GOVERNMENT AGENCY	GOVERNMENT AGENCY	REGULATOR	MARKET OPERATOR	SUPPLY	TSO	DSO	DEMAND	DEMAND	DEMAND
Stakeholder Engagement & Action	**Ministry of Infrastructure**	**Swedish Energy Agency**	**Vinnova**	**Swedish Energy Markets Inspectorate**	**Nord Pool**	**Power generators**	**Svenska Kraftnät**	**Ellevio, Vattenfall Eldistribution, E.ON Energidistribution & co.**	**Retailers**	**New actors (aggregators)**	**Consumers**
Promote a regional mindset, trust, strong institutional arrangements and a regulatory framework for cross-border co-ordination among various stakeholders	✔	✔	✔	✔	✔		✔	✔			
Build supergrids and make efficient use of the existing transmission infrastructure	✔	✔		✔			✔				
Implement effectively, efficiently and in a timely manner all legal provisions of EU directives and regulations related to the internal electricity market and the Energy Union	✔	✔		✔	✔		✔	✔	✔		
Develop clear and transparent pricing methodologies in all trading time frames				✔	✔						
Harmonise with neighbours market design elements which are not mandatory				✔	✔		✔				
Ensure effective co-operation within regional co-ordination centres (RCCs)		✔		✔			✔				
Evaluate the costs, complexity and benefits of the proposed solution	✔	✔		✔			✔				

Note: *Proposed actions for the four solutions are not meant to be treated in isolation, but could be done simultaneously and in co-ordination with two or more parties.*

14 Co-ordination among European transmission system operators is mandatory by participating in regional co-ordination centres (RCCs) as per new EU Regulation 2019/943 on the internal market for electricity. Among others, RCCs will carry out calculations of the cross-border capacity to be made available for trading on the electricity market in different time frames, as well as short-, medium- and long-term adequacy assessments, including day-, week-, six-month, year- and 10-year-ahead adequacy assessments.

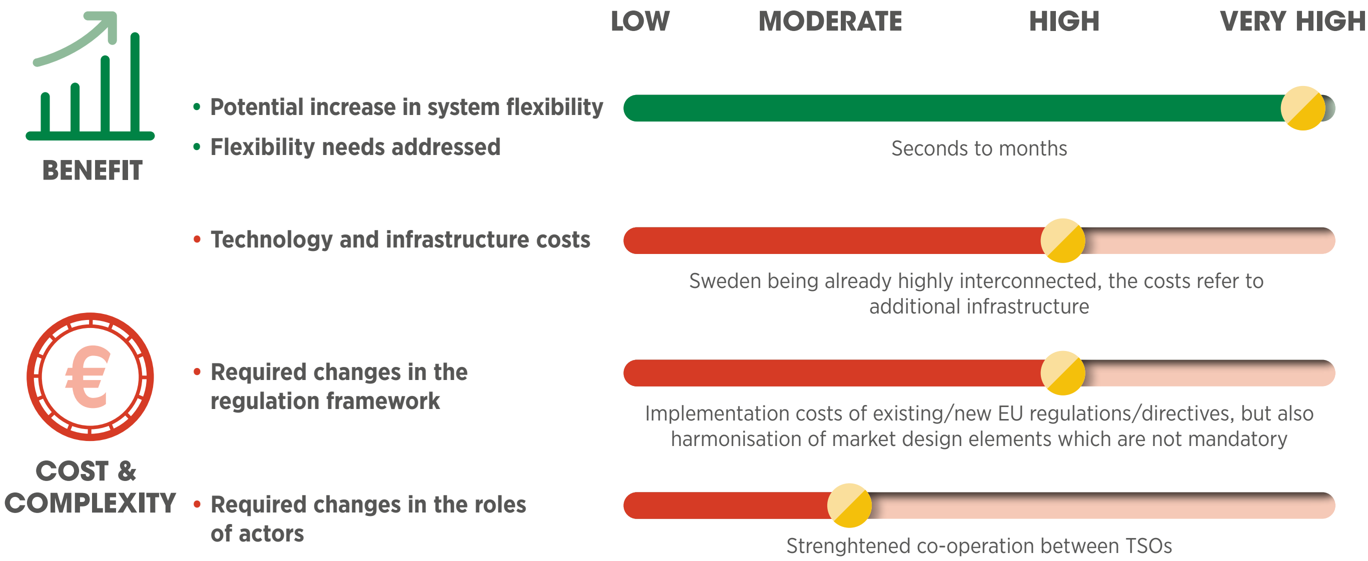
Implementing a systemic innovative solution that aims to maximise the welfare benefits of the regional electricity market that is already in place is expected to provide a very high level of flexibility to the power system in Sweden, from seconds to minutes, days and even months, as it can benefit from temporal and spatial complementarities with other renewable resources from neighbouring national markets.

Given that Sweden is already highly interconnected with Denmark, Finland, Germany, Lithuania, Norway and Poland, the technology and infrastructure costs for the implementation of this solution relate to additional investment in supergrids between the market areas with the highest price differences, such as the following borders: SE4-DE, SE4-PL and NO4-SE1, where the day-ahead price differentials in 2017 averaged EUR 7.9 per MWh, EUR 5.5 per MWh and EUR 5.4 per MWh, respectively (ACER, 2018).

The costs and complexities of implementing or transposing EU directives and regulations can be assumed to be relatively high. This is due to the required involvement of several stakeholders and the costs of harmonising market design elements that are not mandatory, such as the introduction of sub-hourly electricity trading products in short-term markets.

At the same time, the required change in the role of actors refers mainly to the transmission system operators and the new legal provisions with respect to the RCCs, which are expected to be relatively moderate, given that Svenska Kraftnät already co-ordinates its operations with the neighbouring transmission system operators. Strengthened co-ordination among Nordic and Baltic transmission system operators and an even more important increase in co-ordination between Svenska Kraftnät and transmission system operators from continental Europe can be expected. Overall, given the pioneering role of Sweden and the historical experience with an integrated regional market that has its inception in the Nordic region, pursuing and improving the implementation of this solution is expected to lead to a positive cost-benefit assessment for the integration of VRE assets.

Figure 12: Estimated benefits, costs and complexity for the implementation of Solution II



Note: *The benefits, costs and degree of complexity are indicative for each solution and were provided following an expert-based estimation, by comparing the four solutions to each other.*

5. SOLUTION III: SYSTEM-FRIENDLY INTEGRATION OF DISTRIBUTED ENERGY RESOURCES

5.1 DESCRIPTION OF THE INNOVATIVE SOLUTION

As high shares of asynchronous VRE shares are integrated in Sweden's power generation matrix, a significant challenge in the future is power system reliability. This challenge is two-fold as it encompasses both power system security (including stability[15]) and adequacy (generation and transmission capacity).

On the one hand, an increased amount of VRE generation (especially from wind) engenders the need for more ancillary services in the system, which could potentially be provided cost-effectively using distributed energy resources such as batteries, demand response and thermal storage, in addition to the conventional sources of ancillary services, such as hydropower assets.

On the other hand, Sweden experiences increasing price differences between its southern and northern price zones due to greater consumption and lower generation capacity in the south. With the need to transport larger shares of hydropower from the north to the south, this may cause transmission congestion. These factors, coupled with the growing challenge of guaranteeing adequate power during peak times in periods of low wind generation, engender increasing concerns and risks of power outages.

The challenge of ensuring security of supply from a **policy and regulatory perspective** is intertwined with developing a market design that incentivises local flexibility at the distribution system operator level but also ensuring adequate transmission grid infrastructure to transport power from the resource-abundant north to the consumption centres in the south. From a **system operation perspective**, ensuring system stability and system balancing become increasingly complex. The time discrepancy between long lead times of the construction of new transmission projects and rapid changes in generation and demand (especially in metropolitan areas) exacerbate these challenges and lead to more pressure on transmission grids. In the meantime, this calls for an alternative, innovative solution that makes use of the existing and new resources at the distribution level.

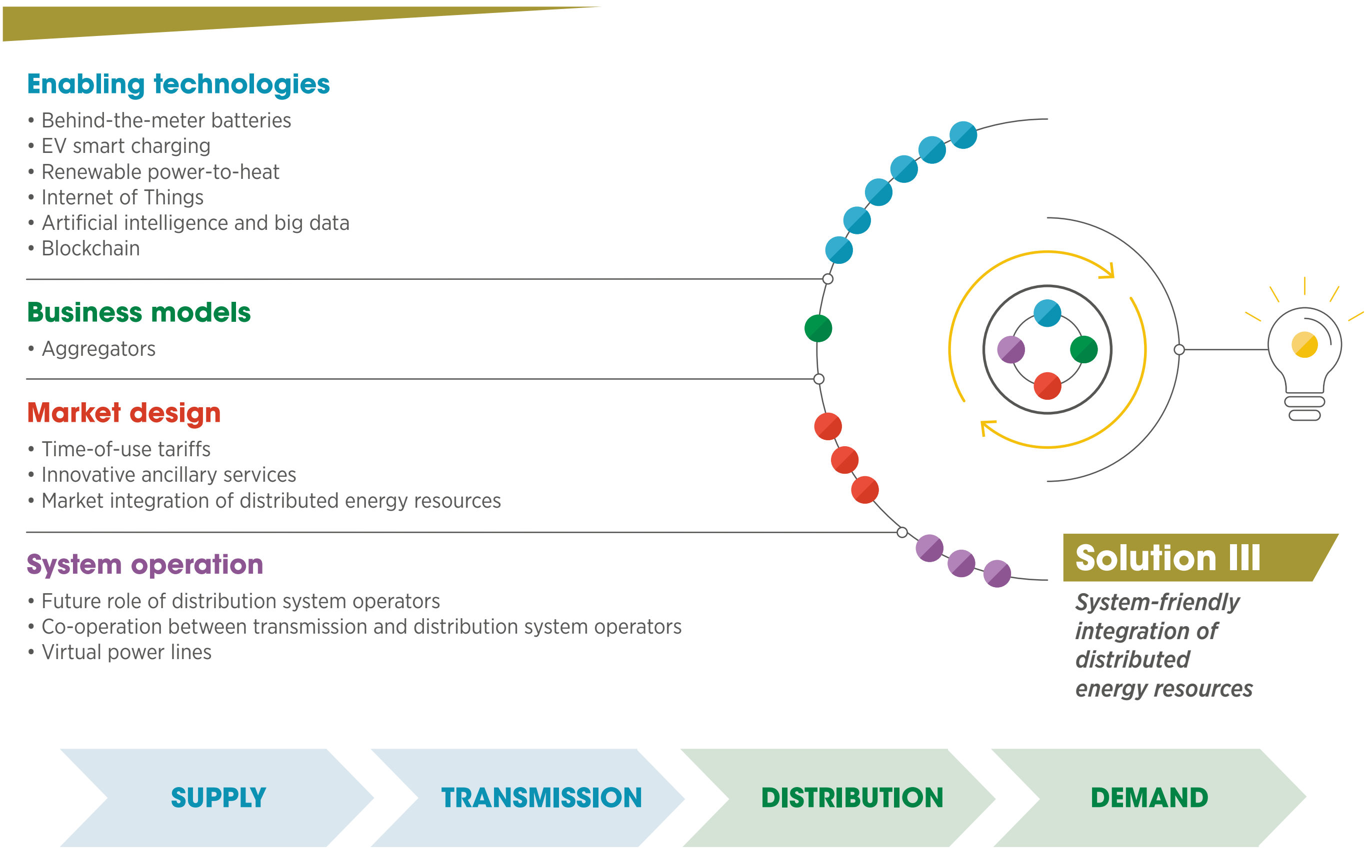
For the implementation of Solution III, 13 innovations across all 4 innovation dimensions, namely **enabling technologies**, **business models**, **market design** and **system operation**, would need to be combined. An overview of this solution and the innovations required are provided in Figure 13.

15 According to IRENA (2017), the key power system properties are firm capacity, flexibility, transmission capacity, voltage control and stability. Security refers to the robustness of the power system in continuing operation during both normal and contingency situations. Security has an additional dimension, which is stability, *i.e.*, the robustness of the power system in continuing to operate during contingency events.

Table 6: Key challenges addressed by Solution III

INNOVATIVE SOLUTION	POLICY AND REGULATORY DIMENSION	SYSTEM OPERATION CHALLENGES	DETAILS ON THE CHALLENGE	FLEXIBILITY TIME SCALE	FLEXIBILITY NEED
Solution III: DER aggregation of distributed energy resources to optimise distribution system operation	Ensuring security of supply	Daily balancing of supply and demand in the context of wind shortage or surplus	Increasing price differences between SE2 and SE3 (in Southern Sweden) due to greater consumption and lower generation capacity leading to a degradation of generation adequacy and risks of power shortages. Guaranteeing adequate power during peak times with low wind power generation.	Minutes to days	Demand flexibility solutions
	Ensuring adequate grid infrastructure	Network congestions and long lead times for new network projects to be implemented	Time discrepancy between long lead times of transmission projects and rapid changes in generation and demand (especially in metropolitan areas) leading to increasing pressure on transmission grids and grid capacity becoming a limiting factor	Minutes to hours	Demand-side flexibility solutions

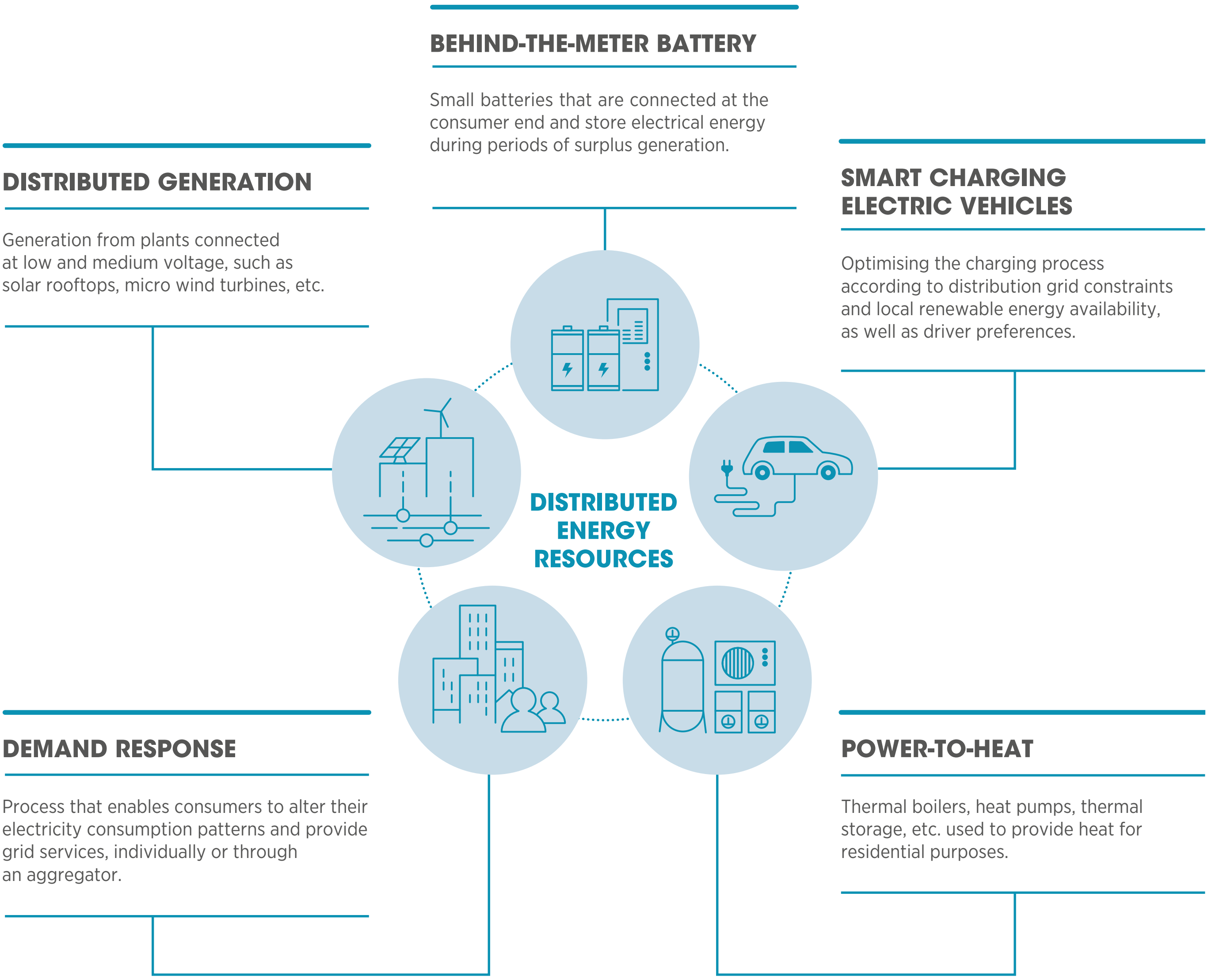
Figure 13: Schematic representation of innovative Solution III



Measures taken on the supply side usually have corresponding demand-side countermeasures, which deliver the flexibility required for the integration of VRE shares. For example, different responses at various time scales can be provided within a day when substantial variability in generation occurs (Cappers, 2014).

Solution III therefore targets the effective management of the *demand side* by aggregating distributed energy resources, such as behind-the-meter batteries and controllable loads or distributed generation, to provide flexibility sources for the Swedish power system (Figure 14). More generally, this solution refers to the direct electrification of end-use sectors, with a focus on the transport and housing sectors.

Figure 14: Types of distributed energy resources



Source: *IRENA, 2019b*

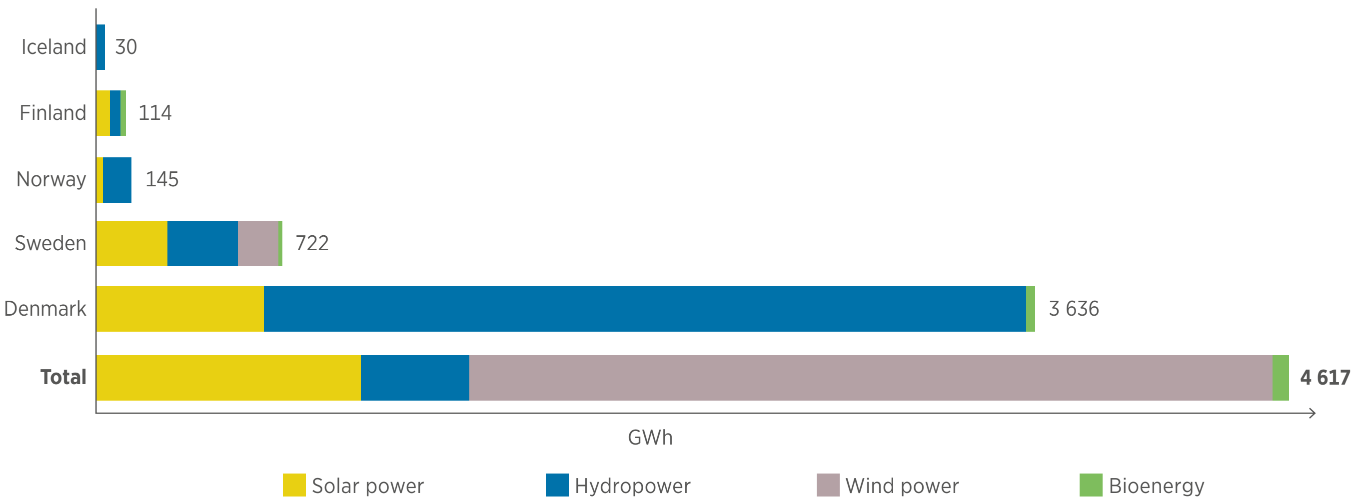
Distributed energy resources and demand-side flexibility are expected to play a significant role in the Swedish power system in order to achieve 100% renewable power. In the Swedish Energy Agency's analysis of the Swedish energy system beyond 2020, for example, the two scenarios with the highest share of renewables in the power sector are also the scenarios with the highest degree of demand flexibility (SEA, 2016).

Given that the transport sector is one of the major contributors to climate change and generates the second largest share of global greenhouse gas emissions after energy industries (Biresselioglu *et al.*, 2018), finding other fuels to meet future transport energy demand is increasingly crucial.

Electric vehicles with smart charging technologies and fuel cell vehicles (discussed in Solution IV), when connected to the grid at the distribution level, represent such an alternative.

The increase in the number of distributed energy resources is reflected by the growth in EVs and their supporting infrastructure in Sweden. EV stocks in the country increased more than 2.6-fold between 2016 and 2018, while the number of EV charging stations more than tripled over this period[16] (IEA, 2019a). Moreover, as shown in Figure 15, the electricity from distributed renewable energy generation in Sweden, with an installed capacity below 1 MW, was estimated at 722 GWh in 2017, which corresponds to the second largest potential in the Nordic countries after Denmark.

Figure 15: Estimated distributed renewable energy generation (<1 MWp) in the Nordic countries, 2017 (GWh)



Source: Oslo Economics, 2019

16 Between 2016 and 2018, the number of EVs in Sweden increased from 2 933 000 to 7 863 000, while the number of charging stations (slow and fast) increased from 2 162 to 7 000.

Solution III proposes to solve both aspects of this challenge, which is two-fold. On the one hand, at the distribution grid level, distribution system operations can be optimised using an increasing number of connected distributed energy resources by enabling market participation from these resources in the provision of ancillary services via aggregation, demand response and EV smart charging technologies.

This is confirmed by a recent study from the Nordic Council of Ministers, which shows that in the Nordic countries demand-side flexibility will be required mainly to solve local congestion problems rather than wholesale balancing issues, since significant shares of controllable hydropower already offer flexibility at the transmission grid level (Nordic Council of Ministers, 2017).

On the other hand, at the transmission grid level, while investments will still be required and cannot be completely offset (especially between the bidding zones with high price differentials, where market signals indicate the need for further investments), distributed energy resources could help to reduce some network investments via virtual power lines and demand response.

By optimising operations and installing decentralised generation closer to the consumption points in the south to solve congestion at the distribution level, spillover benefits include the provision of ancillary services to deal with congestion issues encountered at the transmission level. Furthermore, in a distributed energy system with large shares of renewables, Sweden's extensive district heating infrastructure can be used as thermal storage and can contribute in balancing the power grid by accommodating excess generation (Di Lucia and Ericsson, 2014).

As the amount of frequency and voltage support provided by a single resource is limited, **business models** such as aggregators that enable the accumulation of distributed energy resources may contribute by managing numerous distributed units as an individual, large and predictable resource (IRENA, 2019g).

In addition to the business model of aggregators bundling distributed energy resources to engage as a single entity in power or service markets, this solution is based on progress in digital metering and in information and communication technologies (ICT) emerging in so-called smart homes, unlocking opportunities for demand response. **Enabling technologies**, such as the Internet of Things, artificial intelligence and big data, are key in gathering and managing large amounts of data, enabling automation processes and connecting devices such as residential battery storage with rooftop solar PV and smart meters.

All Nordic countries, including Sweden, are moving towards the implementation of data hubs for electricity meter data and market processes, as part of the further harmonisation efforts of the internal electricity market. Governments and regulators in Denmark, Finland, Norway and Sweden have given transmission system operators the responsibility of introducing a data hub for each of the national electricity retail markets. The Danish data hub is fully implemented and handles all communication between suppliers and distribution system operators. The Norwegian data hub, Elhub, went live in February 2019. According to the respective national transmission system operators, the Finnish data hub will go live in spring 2021 and the Swedish data hub by 2022 at the earliest (NordREG, 2018). All data hubs have the common task of giving suppliers a central access point for all metering data of their customers, thus removing the need for intermediaries.

Table 7: Status of data hub implementation in Nordic countries

IMPLEMENTATION	DENMARK	FINLAND	NORWAY	SWEDEN
Status	Operational	Planned	Operational	Planned
Year	2013	2021	2019	2022

Source: Fingrid, 2018; Svenska Kraftnät, 2019; Statnett, 2019; NordREG, 2018

The data hubs will connect (or are already connecting) all smart meters on the distribution network, making it possible to extract accurate information about the network. This will reduce the cost of billing and, more importantly, make it possible to use the information to operate the distribution network more efficiently. Aggregators will use this information and create services that can serve both the customers and the distribution grid, by maximising the use of the flexibility potential from consumers. Additionally, the data hubs would provide timely information for automated supplier switching processes, improved customer relationships, faster invoice payments and the provision of new retail offers. Aggregators could therefore help manage the digitalised demand in existing markets more efficiently.

In addition to digital enabling technologies, renewable power-to-heat plays a significant role in this solution because all major cities and towns in Sweden have district heating systems, and around 50% of the country's housing stock is heated by such networks (compared to 10% across Europe as a whole). District heating in Sweden is a rare case of an effective transition from fossil fuels to renewable energy sources and is characterised by high security of supply and low greenhouse gas emissions. However, reaping the benefits of digitalisation of heat supply in sub-stations considering customer demand, communication, load management and error identification poses a significant challenge in the future (Werner, 2017). In this case as well, digital enabling technologies will need to play a pivotal role.

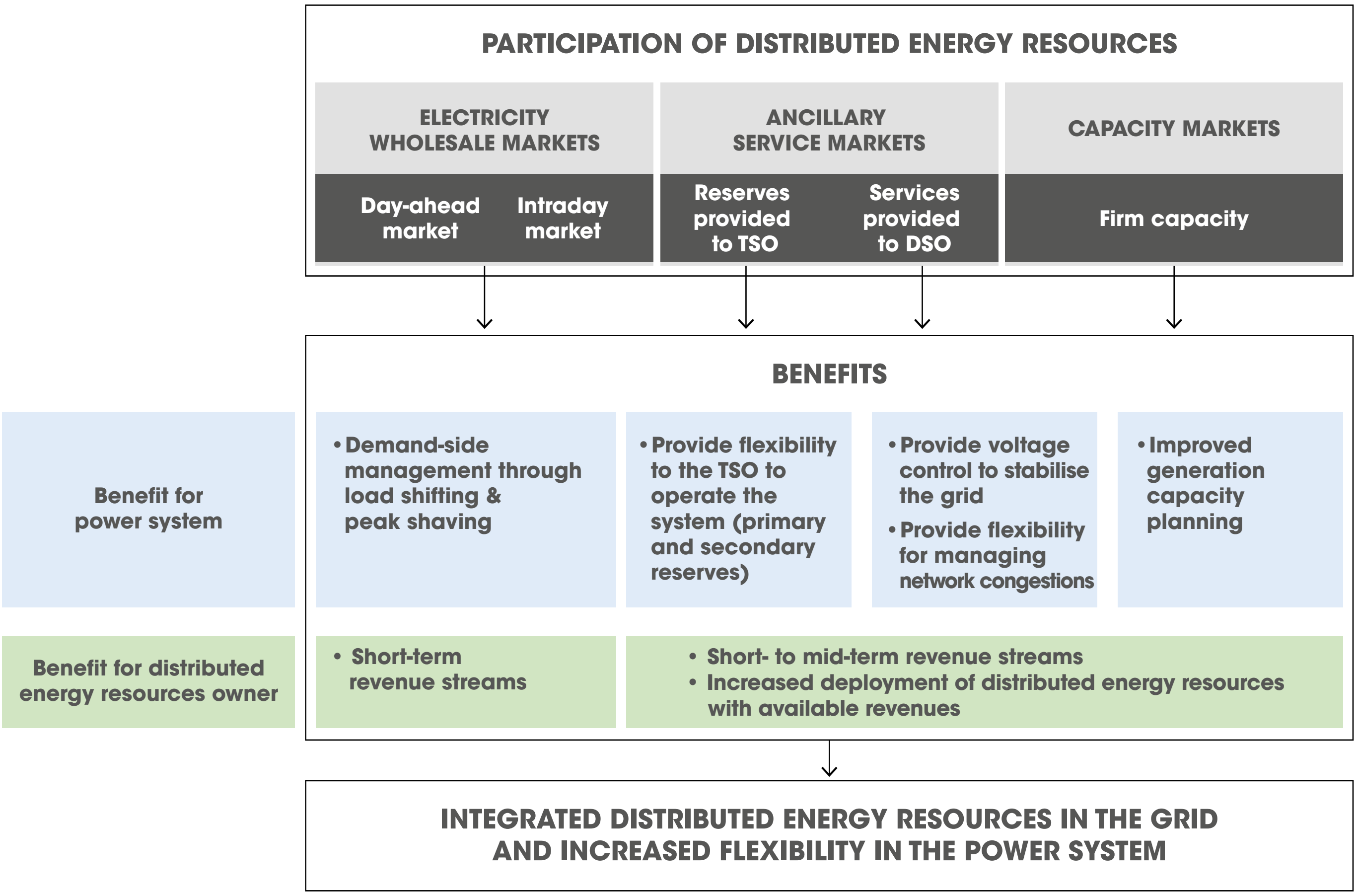
To maximise flexibility sources from distributed energy resources from "smart homes" or from "smart energy systems" in the industry, which could support the power system by responding to changing system conditions and provide necessary ancillary services, adequate **market design** is required to incentivise consumers to shift loads and respond to market price signals. In Sweden, this could be done via time-of-use tariffs (see Innovation landscape brief: Time-of-use tariffs (IRENA, 2019e)) or by allowing these resources to participate in the wholesale and ancillary service markets, either by aggregating distributed energy resources or by reducing the capacity limit in these markets.

Currently, the minimum bid size on the day-ahead and intraday markets in Sweden is 0.1 MW, which is lower than the minimum bid size across the EU that is set within the Clean Energy Package at 500 kilowatts (kW) "to allow for the effective participation of demand-side response, energy storage and small-scale renewables including direct participation by customers" (European Parliament, 2019). However, minimum bid sizes on the regulating power market are by comparison much higher and amount to 5 MW in bidding zone SE4 and 10 MW in bidding zones SE1, SE2 and SE3 (Energimarknadsinspektionen, 2018).

As shown in Figure 16, distributed energy resources can participate across different markets and offer various grid services, which could increase power system flexibility and facilitate further grid integration of VRE resources. In December 2017, for example, the New York Independent System Operator (NYISO) released a concept proposal of market design changes to enable the participation of distributed energy resources in both wholesale and ancillary service markets. According to this proposal, distributed energy resources will be treated on par with other market players and will be able to participate in capacity reserve and regulation service markets either directly or via aggregators of small-scale distributed energy resources (<100 kW) (NYISO, 2017). In contrast to this example, balance responsibility of renewable generators applies in the EU, by derogation, only for those installations with an installed capacity of over 400 kW, which is reduced to 200 kW starting 1 January 2026 (European Parliament, 2019).

Distributed energy resources and demand-side flexibility are crucial for the Swedish system to achieve 100% renewable power

Figure 16: Benefits of market integration of distributed energy resources



Source: IRENA, 2019e

Innovation in **system operation** is further needed in increasingly decentralised systems. With more balancing reserve capacity expected to be situated at distribution levels for the reasons explained above, the responsibilities of distribution system operators will expand in order to effectively integrate this in the market and maximise the available flexibility options.

This implies a new role for distribution system operators, which will shift from being passive network facilitators to act increasingly as system operators, accommodating bi-directional flows of electricity and efficiently exploiting flexibility and ancillary services provided by distributed energy resources to maximise benefits for the system (Lamberti, 2015).

When peak demand is met through locally generated electricity, less electricity needs to be transported by transmission system operators. Therefore, this solution may defer costly investments in network reinforcement, as an interim solution to guarantee security of supply while network expansion or reinforcement projects are being built. In the UK, for example, an online local flexibility marketplace called Piclo, which is already being tested in auctions, enables distribution system operators to access location-specific flexible resources for the effective integration of distributed energy resources with the help of digital enabling technologies. Under the condition that distribution system operators can quickly and easily access flexible assets on the grid, it has been estimated that a "smart" and flexible network in the UK can realise savings up to EUR 4 billion (USD 4.5 billion) by 2030 (see Innovation landscape brief: Market integration of distributed energy resources (IRENA, 2019e).

5.2 IMPLEMENTATION EXAMPLES FROM SWEDEN

The following two sections contain examples of ongoing initiatives or pilot projects where parts of this solution are being implemented or trialled, first in Sweden, then outside of Sweden or in an international context. To show the extent to which the examples correspond to the proposed solution, and as an indication of the replicability of the examples in the Swedish context, each innovation proposed in the solution and also considered in the implemented solution is shown with a ticked box.

Sweden – Time-of-use tariffs

	Behind-the-meter batteries
	EV smart charging
✔	Renewable power-to-heat
✔	Internet of Things
	Artificial intelligence and big data
	Blockchain
	Aggregators
✔	Time-of-use tariffs
	Market integration of distributed energy resources
	Innovative ancillary services
✔	Future role of distribution system operator
✔	Co-operation between transmission and distribution system operators
	Virtual power lines

According to the Nordic Council of Ministers (2017), a feasible potential of around 8 GW of demand-side flexibility is available in Sweden if consumers adopted time-of-use tariffs.

In a pilot project conducted in Gotland, Sweden around 300 customers with electric residential heating participated in a programme that used dynamic price signals – which combined the wholesale electricity price with a time-of-use grid tariff and a wind component – in order to justify an increase of the hosting capacity of variable power generation.

In addition to the overall project goal, further objectives of the pilot were to improve understandings of customers' behaviour and to reduce electricity costs for active customers. The market test started in December 2013 and concluded in April 2016 (Svalstedt and Loef, 2017).

During the initial stage of the programme, 23% of total electricity consumption was experienced during the five most expensive hours. This fell to 19% and 20% in the first and second years of the programme, respectively. Findings from the project revealed that price signals can be used to achieve a load shift from periods of high load to periods of low load, without affecting customers' comfort. Nevertheless, despite the possibility of consumers to choose a time-of-use tariff, the necessary motivation for consumers to choose these tariffs is missing in Sweden. This may be explained by the lack of consumer awareness of the benefits of time-of-use tariffs, or by perceived insufficient savings from their use. These are the two main barriers indicated by European regulators when asked what hampers the adoption of dynamic pricing for supplying electricity to household consumers (ACER/CEER, 2016).

Sweden – Smart Heat Grids

	Behind-the-meter batteries
	EV smart charging
	Renewable power-to-heat
✔	Internet of Things
✔	Artificial intelligence and big data
	Blockchain
	Aggregators
	Time-of-use tariffs
	Market integration of distributed energy resources
✔	Innovative ancillary services
	Future role of distribution system operator
	Co-operation between transmission and distribution system operators
	Virtual power lines

The companies Kalmar Energi and Noda Intelligent Systems are working together on a "smart", environmentally sustainable and cost-effective district heating network in Kalmar, Sweden. The so-called Smart Heat Grid is a platform optimising district heating network operation, automatically and in real time, by calculating and managing the virtual energy storage in buildings.

Almost every property has virtual stored thermal energy. When properties are connected, real-time analyses can be carried out to optimise the use of this heat inertia, which can contribute to reducing peak load without affecting the indoor climate. This evens out the load on the grid over a 24-hour period and reduces or even eliminates the need for oil-fuelled peak-load burners, which is both cost effective and sustainable. To achieve this, the following three steps work together automatically within Noda's Smart Heat Grid:

1. Measurement of inputs from the existing environment such as temperature, pressure and power flow, heat/power generation conditions, consumption data and building occupancy behaviour;
2. Analysis and evaluation of measurement values to convert the input data into information;
3. Control of power output and energy use based on the information from the analysis.

Price signals can be used for load shifting without affecting customer comfort

Around 50 properties in Kalmar are equipped with Noda's innovative system, thus establishing a significant energy reserve. Kalmar Energi is working on linking a further 40 premises, including the new Linnaeus University (Noda Intelligent Systems, 2019).

Sweden – CoordiNet project

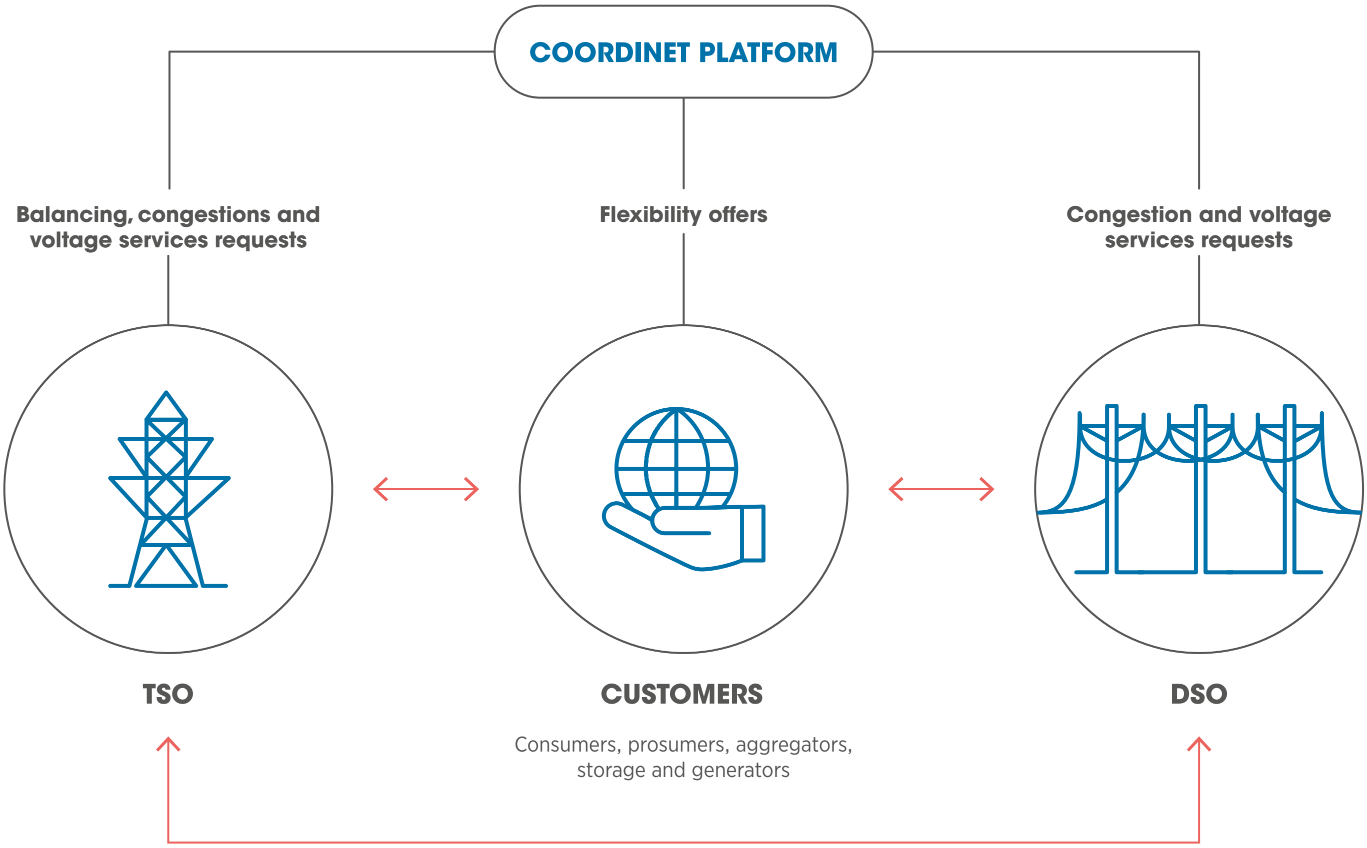
	Behind-the-meter batteries
	EV smart charging
	Renewable power-to-heat
✔	Internet of Things
✔	Artificial intelligence and big data
✔	Blockchain
✔	Aggregators
	Time-of-use tariffs
✔	Market integration of distributed energy resources
✔	Innovative ancillary services
✔	Future role of distribution system operator
✔	Co-operation between transmission and distribution system operators
	Virtual power lines

CoordiNet is an EU Horizon 2020 project comprising three large-scale demonstrators in 10 demonstration sites, implemented by transmission and distribution system operators in Greece, Spain and Sweden. Between 2019 and 2022, a total of 23 companies and institutions from 10 countries will participate in the project. In Sweden, CoordiNet is being carried out by the transmission system operator, Svenska Kraftnät, as well as two distribution system operators, Vattenfall and E.ON. The project aims to develop standardised co-ordination schemes that allow efficient co-operation between transmission and distribution system operators for the provision of electricity grid services from renewables.

Among others, the CoordiNet project explores disruptive enabling technologies, such as the Internet of Things, artificial intelligence and big data, and blockchain, while demonstrating how market integration of distributed energy resources, including prosumers, could provide ancillary services to the system operators.

The project started in 2019 and is being trialled in different areas of Sweden, such as Uppland and Gottland, until 2022. Although not many results and conclusions can be drawn at this stage, the project is expected to bring added value by increasing the flexibility in local markets, supporting the integration of new actors into the pan-European electricity market and identifying modifications needed to grid codes.

Figure 17: Model for co-operation between transmission and distribution system operators proposed by the CoordiNet project



Source: CoordiNet, 2019

5.3 EXAMPLES OF SIMILAR IMPLEMENTED SOLUTIONS

Germany – Aggregator providing grid services to the transmission system operator

✔	Behind-the-meter batteries
	EV smart charging
	Renewable power-to-heat
	Internet of Things
	Artificial intelligence and big data
✔	Blockchain
✔	Aggregators
	Time-of-use tariffs
✔	Market integration of distributed energy resources
✔	Innovative ancillary services
	Future role of distribution system operator
✔	Co-operation between transmission and distribution system operators
✔	Virtual power lines

The sonnenCommunity is an aggregator in Germany consisting of around 10 000 customers with battery storage, solar PV generation or both. Launched in 2015, the sonnenCommunity was used mostly for peer-to-peer trading within a virtual power plant. However, in summer 2017 the virtual power plant became available to the power grid to provide frequency regulation services. Compared to other alternatives, such as pumped hydropower storage, this distributed "virtual" storage resource can react very quickly (sub-second), making it a useful provider of primary frequency services.

By charging the batteries when there is excess generation, this solution helps to reduce wind power curtailment. This minimises both the variability in renewable power generation and expensive grid expansion requirements. By being paid for these benefits via the frequency response market, the sonnenCommunity provides battery owners with "free" electricity in return.

Since the battery is needed only sporadically (for a few minutes a week), the availability, performance and life span of the battery remain practically unaffected.

Later, Sonnen partnered with the German transmission system operator TenneT to launch the pilot project Sonnen eServices. This project integrated batteries into the power system via a blockchain solution (developed by IBM). In this pilot project, a network of residential solar batteries will be made available to help reduce the limitations imposed on wind energy at times of insufficient transmission capacity. In 2016 alone, the measures to manage grid congestion cost Germany around EUR 800 million (USD 890 million), much of which was for wind curtailment (Grey Cells Energy, 2018).

The platform is designed to ensure, through the use of blockchain, the verifiability and transparency of the transactions made by the small-scale batteries. It simplifies the way that suppliers of locally distributed flexible energy can provide services to support power grid operators in the future. It also is being tested to ensure that it can fulfil TenneT's requirements for data security, restricted access and privacy (TenneT, 2017).

Netherlands – EV batteries for grid stability

	Behind-the-meter batteries
✔	EV smart charging
	Renewable power-to-heat
✔	Internet of Things
✔	Artificial intelligence and big data
	Blockchain
✔	Aggregators
	Time-of-use tariffs
✔	Market integration of distributed energy resources
✔	Innovative ancillary services
	Future role of distribution system operator
✔	Co-operation between transmission and distribution system operators
	Virtual power lines

EV batteries can provide the fast response needed for some ancillary services, but their power capacity is limited. Therefore, a single EV cannot provide these services, and at least 1–2 MW of capacity must be traded to make EV power provision viable at the wholesale level. However, the business model of aggregators could facilitate the use of EVs as a source of flexibility, which results in the creation of a virtual power plant with fast frequency response and the ability to provide ancillary services for the required time period. The German virtual power plant operator Next Kraftwerke, along with the EV aggregator Jedlix and an EV smart charging platform provider, have launched an international pilot project that uses EV batteries to deliver secondary control reserve to the Netherlands' transmission system operator TenneT. Jedlix will be able to combine user charging and driving preferences, vehicle data, and charging station information to provide a continuous forecast of the available capacity. This is then used by Next Kraftwerke in the bidding process for TenneT's procurement of grid services (North Sea Wind Power Hub, 2019).

Denmark – Parker Project

	Behind-the-meter batteries
✔	EV smart charging
	Renewable power-to-heat
✔	Internet of Things
	Artificial intelligence and big data
	Blockchain
✔	Aggregators
	Time-of-use tariffs
✔	Market integration of distributed energy resources
✔	Innovative ancillary services
	Future role of distribution system operator
	Co-operation between transmission and distribution system operators
	Virtual power lines

Building on previous projects, the Parker Project, which concluded in 2019, was conducted among several stakeholders including academia (Technical University of Denmark), an aggregator (Nuvve), car manufacturers, a power supplier (Frederiksberg Forsyning) and a demand-side management provider (Enel X). This Danish demonstration project explored the integration of EVs into the power grid by focusing on bi-directional vehicle-to-grid (V2G) charging technology. Over the demonstration period, the project showed that the EV portfolio tested, including cars manufactured by Mitsubishi, Nissan and PSA, was technically ready to provide frequency regulation services necessary for the Danish grid when equipped with the V2G technology composed of DC chargers from Enel X.

Over a period of two years, the Parker Project showed that one single van, the electric Nissan eNV200, which was trialled in the project under relaxed market conditions, could provide the transmission system operator with more than 13 000 hours of frequency containment reserves, a specific ancillary service. The average revenue for one car for the provision of such a service was EUR 1 860 per year. In addition to providing services to the transmission system operator, the EVs using the same technology could provide services to the distribution system operators. Last, but not least, the project measured the reaction time, which amounted to 5–6 seconds, when the services were contracted via an aggregator, while the reaction time was lower in the case of direct control of the car and its charger (Andersen *et al.*, 2019).

A single van can provide over 13 000 hours of frequency containment reserves, a valuable ancillary service for the transmission system operator

5.4 QUALITATIVE COST-BENEFIT ASSESSMENT

A **supportive policy framework encouraging power system decentralisation** for the deferral of costly transmission grid infrastructure investments should be encouraged by the Swedish Ministry of Infrastructure, together with the Swedish Energy Agency and with support from the Swedish Smart Grid Forum. Policies should define a concrete vision for the deployment of distributed energy resources by containing measures relating to implementation and planning while optimising the location of distributed resources.

Unlocking demand-side flexibility requires **incentive-based policy and regulatory frameworks** to not only encourage consumers owning distributed energy resource assets, such as behind-the-meter batteries and EVs, **to evolve into prosumers providing flexibility but also guaranteeing the secure handling of their data.** The market participation of end customers and small enterprises via aggregation (of power generating units or demand response facilities) is enshrined in the principles regarding the operation of electricity markets at the EU level in Regulation (EC) 943/2019 on the internal market for electricity (recast) of the Clean Energy for All Europeans legislative package, applicable as of 1 January 2020 (European Parliament, 2019).

Furthermore, the Swedish Energy Agency, retailers and regulators should join forces to raise consumer awareness about available options and consumer rights, as well as to better understand customer behaviour to incentivise load management. Retailers must further adequately inform their customers about the risks and opportunities of dynamic pricing contracts, or ideally involve customers in the design of such tariffs, to take into account their preferences which may ultimately improve the social acceptance of dynamic pricing schemes. This is of utmost importance, as the lack of public interest and knowledge about “smart” energy solutions usually leads to low levels of participation.

As per EU Regulation 2019/943, future regulatory frameworks need to reduce minimum bid sizes or allow for the aggregation of distributed energy resources.

Such frameworks, prepared by the Swedish Energy Markets Inspectorate ideally in consultation with transmission and distribution system operators and the Swedish Energy Agency and the wider public, need to **enable the participation of distributed energy resources in the wholesale electricity, balancing and ancillary service market.**

The responsibilities of distribution system operators could expand by taking advantage of already connected assets to optimise network operations according to grid constraints. Future regulations therefore need to turn Swedish **distribution system operators into active and neutral facilitators**, which can procure ancillary services from distributed energy resources and use these to manage grid congestion and provide flexibility. Innovative regulations should be based on performance rather than costs, as well as on new operationally complex procedures. Incentive regimes should be included that support buying services (operating expenditures, OPEX) instead of building assets (capital expenditures, CAPEX).

In addition to the change in roles and responsibilities of distribution system operators, **co-operation between transmission and distribution system operators should also be strengthened on both the national and European levels**, to enable the flow of information on available flexibility in both directions. Robust regulations are required to ensure that the aforementioned entities collaborate and act in a neutral and transparent manner when procuring services from distributed energy resources. Distribution system operators and Svenska Kraftnät should also work with other electricity market actors, such as retailers, suppliers and aggregators, to **increase the visibility of types and capabilities of distributed energy resources**.

In a broader perspective, facilitating co-operation between the European transmission system operators (including Svenska Kraftnät) within ENTSO-E and the European distribution system operators within the soon-to-be established entity of distribution system operators in the EU (the so-called EU DSO entity as per EU Regulation 2019/943) would bring additional benefits, given the expectation that more distributed energy resources will be connected at the distribution level across the EU in the coming years.

The Swedish Energy Agency, together with Vinnova, the Swedish Smart Grid Forum, and other innovation centres and research institutes, should continue their pioneering work and innovation efforts **by investing in pilot programmes to test and promote the innovative operation of distributed energy resources through digital enabling technologies (such as artificial intelligence, the Internet of Things and blockchain) and dynamic pricing**.

Pilot projects should also target the development of adequate communication systems that enable price-based, frequency-based or voltage-based signals between system operators and distributed energy resource aggregators.

Findings should be further disseminated in the wider Nordic and European communities.

Overall, these actions require the engagement, consultation and/or co-ordination of two or more stakeholders in the Swedish power sector. Table 8 contains a summary of some of the key actions needed for the implementation of Solution III, together with an indication of the relevant stakeholders that could be involved in taking further action to implement this solution.

Table 8: Stakeholder action and engagement required for the implementation of Solution III

TYPE OF STAKEHOLDER	MINISTRY	GOVERNMENT AGENCY	GOVERNMENT AGENCY	REGULATOR	MARKET OPERATOR	SUPPLY	SUPPLY	TSO	DSO	DEMAND	DEMAND
Stakeholder Engagement & Action	**Ministry of Infra-structure**	**Swedish Energy Agency**	**Vinnova**	**Swedish Energy Markets Inspectorate**	**Nord Pool**	**Power generators**	**Retailers**	**Svenska Kraftnät**	**Ellevio, Vattenfall Eldistribu-tion, E.ON Energidistri-bution & co.**	**New actors (aggre-gators)**	**Consumers**
Create a policy framework encouraging power system decentralisation	✔	✔		✔							
Devise incentive-based policies and stable regulations to encourage 'prosumerism'	✔	✔		✔			✔	✔	✔		✔
Continue initiatives and support research focusing on better understanding consumer behavior		✔	✔				✔				✔
Enable, as per EU regulation, DERs' participation in the wholesale electricity and ancillary service markets		✔		✔				✔	✔	✔	
Safeguard role of Swedish DSOs as active and neutral facilitators		✔		✔				✔	✔		
Mandate new ancillary services	✔	✔		✔				✔	✔		
Invest in pilot programmes and innovation for innovative DER operation		✔	✔			✔			✔	✔	✔
Increase the visibility on available types and capacities of DERs		✔		✔		✔			✔	✔	✔
Participate in the ancillary service market						✔				✔	✔
Evaluate the costs, complexity and benefits of the proposed solution		✔		✔				✔	✔		

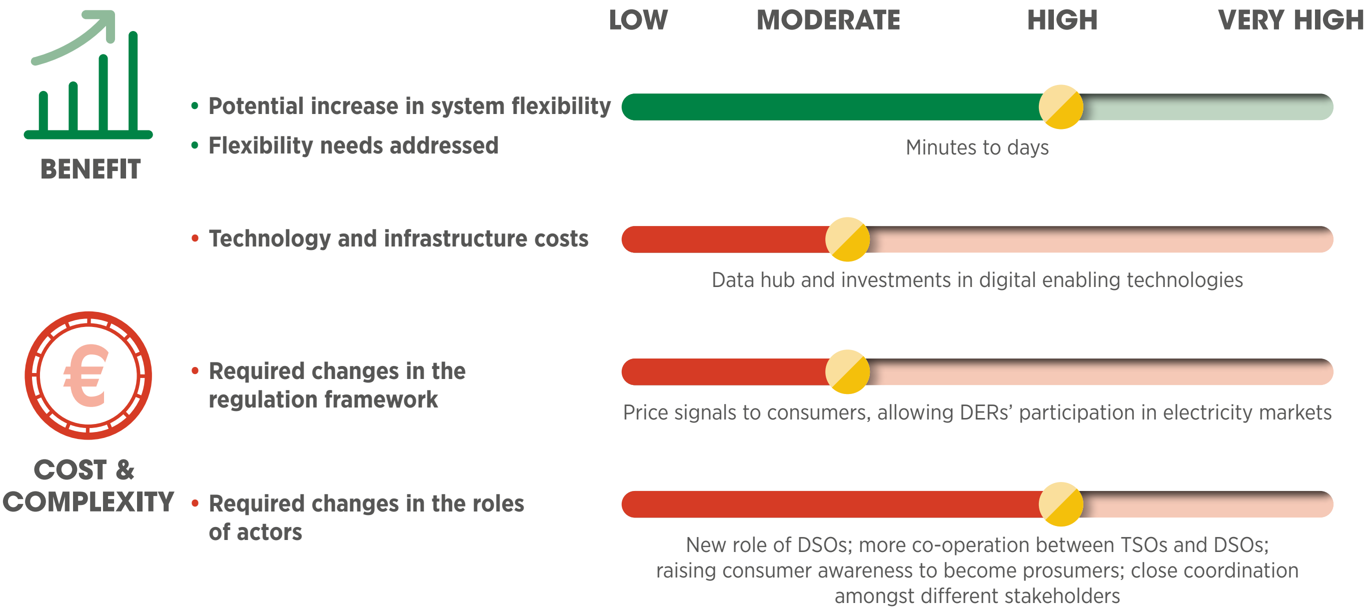
Note: *Proposed actions for the four solutions are not meant to be treated in isolation, but could be done simultaneously and in co-ordination with two or more parties. Other stakeholders, such as real estate developers and municipalities should be involved for the implementation of Solution III as well.*

Demand-side solutions have great potential to unlock power system flexibility. From a technological perspective, achieving effective demand-side management requires the deployment of smart meters and digital technologies to enable automation. Sweden is one of very few countries that have realised a 100% roll-out of smart meters. Furthermore, the current deployment of distributed energy resources, such as solar PV and EVs, is providing the opportunity for prosumer participation in the wholesale and local markets. Given these realities, major investments in technology and infrastructure are not required. Instead, regulations need to be adapted to harness the benefits and services that the already deployed technologies, connected at the distribution level, may provide to the Swedish power system.

As noted previously, this calls for the co-ordination and changing roles of many actors, from prosumers to transmission and distribution system operators. However, adapting the duties and responsibilities of stakeholders engenders high complexity rather than significant costs.

Achieving effective aggregation of distributed energy resources to optimise distribution system operation is expected to provide a high level of flexibility to the system while deferring expensive investments in network reinforcement. Costs to implement this demand-side solution are estimated to be moderate to high, which thus equates to an overall positive cost-benefit assessment.

Figure 18: Estimated benefits, costs and complexity for the implementation of Solution III



Note: *The benefits, costs and degree of complexity are indicative for each solution and were provided following an expert-based estimation, by comparing the four solutions to each other.*

6. SOLUTION IV: DECARBONISATION OF END-USE SECTORS VIA ELECTRIFICATION WITH RENEWABLE ENERGY SOURCES

6.1 DESCRIPTION OF THE INNOVATIVE SOLUTION

With growing shares of VRE in the Swedish power system, high wind energy generation is expected to increasingly coincide with periods of low electricity consumption, which can result in a surplus of electricity during those hours. At the same time, with growing shares of VRE, more seasonal variation in renewable output can be anticipated. However, higher shares of wind generation in the overall power mix represents an opportunity to electrify and decarbonise other end-use sectors, which are carbon intensive.

Although the Swedish power system is almost entirely decarbonised, the decarbonisation of other end-use sectors (*i.e.*, heating and cooling, transport and industry) will be key for the energy transition and to meet long-term climate targets such as zero CO_2 emissions by 2045. The decarbonisation of these end-use sectors via electrification with renewable energy sources, especially with the use of renewable power-to-hydrogen and renewable power-to-heat enabling technologies, while representing a challenge, can be part of a truly complex yet disruptive solution.

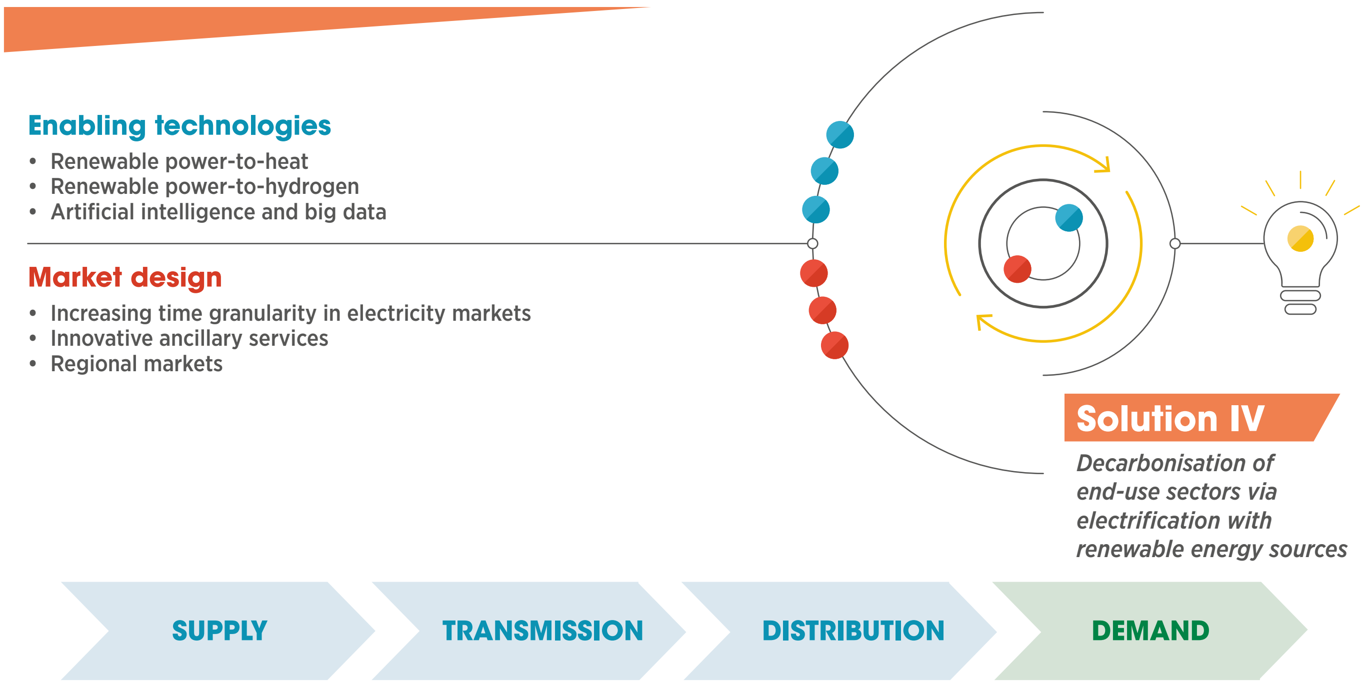
From a **policy and regulatory perspective**, addressing this challenge requires the development of an adequate market design and policy framework that, in addition to encouraging flexibility, provides the necessary foundation to meet system needs and enables the decarbonisation of end-use sectors. From a **system operation perspective**, measures unlocking opportunities for seasonal flexibility are needed to deal with the growing complexity of balancing demand and supply in the context of wind power shortage or surplus.

While Solution III focused on decentralised assets connected at the distribution level, such as EVs and heat pumps, Solution IV discusses some of the most disruptive innovations identified, especially renewable power-to-X technologies. Therefore, this solution looks into how enabling technologies connected at the transmission level, *i.e.*, renewable power-to-hydrogen and renewable power-to-heat, paired with digital technologies, can help decarbonise other end-use sectors. However, it must be noted that hydrogen production currently relies predominantly on fossil fuels, and major technological and economic barriers, such as round-trip efficiency and production costs, still need to be overcome to enable the transition to a renewable hydrogen economy.

Table 9: Key challenges addressed by Solution IV

INNOVATIVE SOLUTION	POLICY AND REGULATORY DIMENSION	SYSTEM OPERATION CHALLENGES	DETAILS ON THE CHALLENGE	FLEXIBILITY TIMESCALE	FLEXIBILITY NEED
Solution IV: Decarbonisation of end-use sectors via electrification with renewable energy sources	Ensuring security of supply	Daily balancing of supply and demand in the context of wind shortage or surplus	High wind power generation coincides with low electricity consumption which results in a surplus of electricity. Avoiding curtailment and making use of the surplus renewable generation, once the power system has very high shares of renewables	Seconds to months	Demand flexibility solutions

Figure 19: Schematic representation of innovative Solution IV



For the implementation of Solution IV, six innovations across two innovation dimensions, namely enabling technologies and market design, need to be combined. An overview of the innovative solution and the innovations required are provided in Figure 19.

Solution IV is a *demand-side flexibility* solution that refers to the decarbonisation of end-use sectors, such as heating and cooling in buildings, transport and industry, with surplus VRE generation via indirect electrification. In a more holistic approach, when coupled with Solution II, these innovations could additionally provide the opportunity to trade the power stored over longer periods of time on the pan-European electricity market.

Two key **enabling technologies** – power-to-heat and power-to-hydrogen (also jointly referred to as power-to-X innovations) – could open doors to new markets for renewable generation as well as new ways to consume renewable electricity, especially when the grid is congested and (wind) power cannot be transmitted directly to demand centres. In the case of wind power surplus in Sweden, the excess generation could be either decoupled from demand by converting it into heat or hydrogen for end-use sectors or stored and traded later, when demand is high but VRE generation is scarce.

Advanced digital technologies, such as the Internet of Things, artificial intelligence and big data, may optimise the management and operation of such complex energy and ICT networks. Moreover, as demonstrated in the examples below, in addition to new options for renewable electricity consumption, such configurations are providing services to the grid.

To effectively trade the stored power and make use of spatial complementarities of VRE generation, adaptations in **market design** are needed. More precisely, regulatory updates that enhance the efficiency of the pan-European regional market with increased temporal resolution would be required.

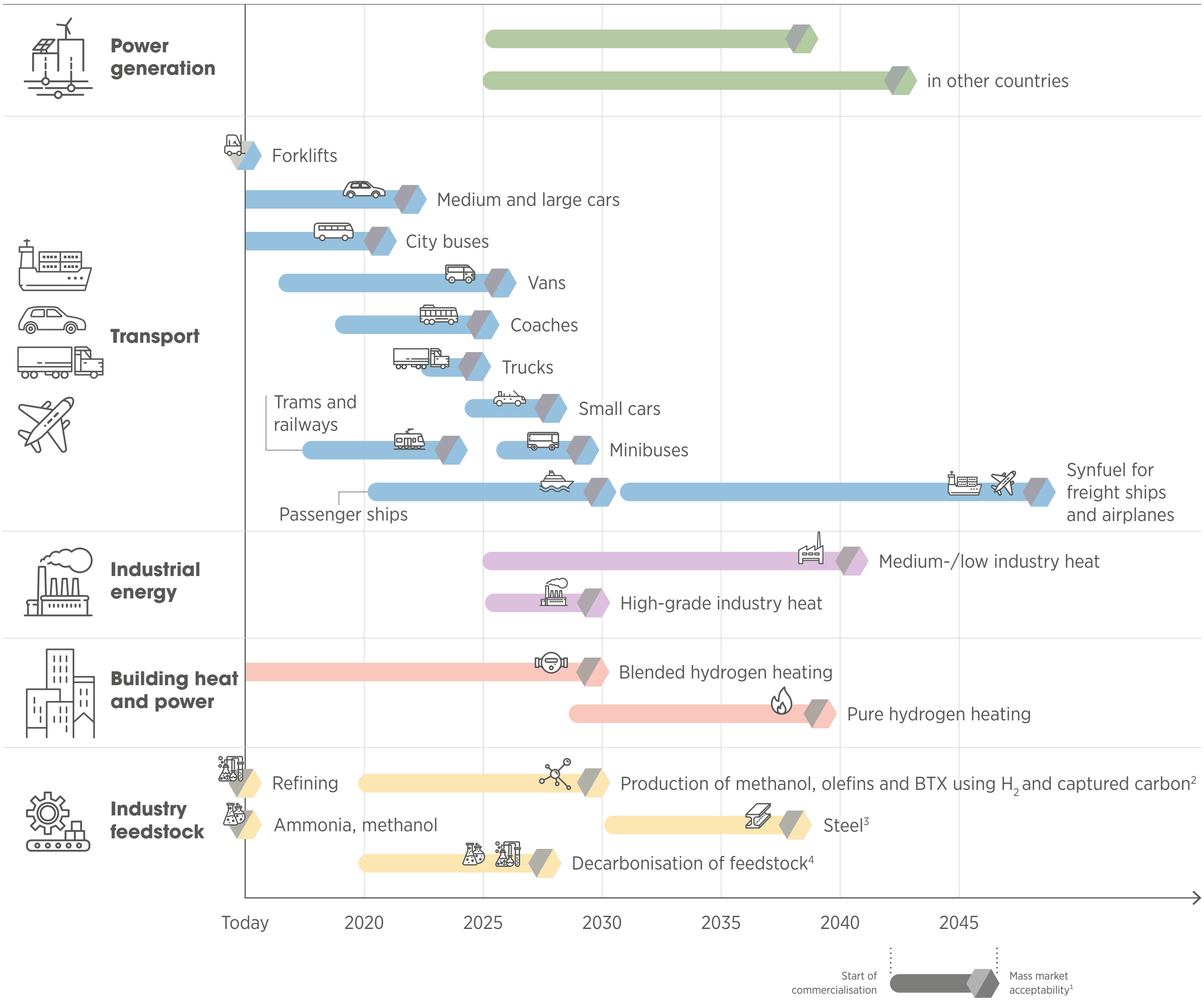
Synergies may be further explored and created between direct and indirect electrification, as power-to-X solutions might play a key role in coupling end-use sectors. With power-to-gas innovations, where electrolysis also generates gaseous hydrogen from renewable electricity, final products may be used for industrial or heating applications, or supplied to vehicles as a direct replacement for fossil fuels. Hydrogen could be also employed as feedstock to produce chemicals, such as ammonia, used for industrial purposes (IRENA, 2018a).

In a system based fully on renewable power in 2050, a recent study estimated the marginal cost of power-based ammonia production in Northern European countries (including Sweden) at between EUR 431 and EUR 528 (USD 480 and USD 588) per tonne, which is in the range of current ammonia prices (Ikaheimo *et al.*, 2018).

Because the electricity consumption of electrolysers can be adjusted to follow wind and solar power generation, they offer a flexible load and can also provide grid balancing services (upward and downward frequency regulation) while operating at optimal capacity to meet demand for hydrogen from the industry and transport sectors. Enabling the procurement of frequency and voltage control from electrolysers used in other end-use applications could further support VRE integration and grid balancing.

Recent research has further demonstrated that controlled electrolytic hydrogen production can facilitate the integration of VRE in California, with electrolysers providing net load valley-to-peak shifting and ramp mitigation, while producing a clean fuel for transport uses. This underscores the significant synergies that can be created between power systems and end-use sectors (Wang *et al.*, 2018). Figure 20 shows an overview of the existing applications of renewable power-to-hydrogen technology and the expected timeline for commercial deployment.

Figure 20: Overview of renewable power-to-hydrogen applications and deployment timeline



Source: *Air Liquide, based on Hydrogen Council, 2017*
Note: *1. Mass market acceptability is defined as sales >1% within segment in priority markets; 2. Market share refers to the amount of production that uses hydrogen and captured carbon to replace feedstock; 3. Direct reduced iron (DRI) with green hydrogen, iron reduction in blast furnaces and other low-carbon steel making processes using hydrogen; 4. Market share refers to the amount of feedstock that is produced from low-carbon sources.*

6.2 IMPLEMENTATION EXAMPLES FROM SWEDEN

The following two sections contain examples of ongoing initiatives or pilot projects where parts of this solution are being implemented or trialled, first in Sweden, then outside of Sweden or in an international context. To show the extent to which the examples correspond to the proposed solution, and as an indication of the replicability of the examples in the Swedish context, each innovation proposed in the solution and also considered in the implemented solution is shown with a ticked box.

Sweden – Decarbonising the building sector (blocks and houses)

✔	Renewable power-to-heat
✔	Renewable power-to-hydrogen
	Artificial intelligence and big data
	Increasing time granularity in electricity markets
	Innovative ancillary services
	Regional markets

Since 2018, the world's first off-grid, energy self-sufficient housing complex combining on-site solar generation and hydrogen fuel cells has been under development in the Vårgårda Municipality of Sweden. This innovative project is being realised by the municipal housing company Vårgårda Bostäder, along with the Danish firm Better Energy and Sweden-based Nilsson Energy. All 172 apartments across six blocks will meet their electricity and heating needs from on-site solar PV systems (659 kWp) and hydrogen storage (Macdermott, 2019).

Surplus energy and overproduction in summer from the residential solar systems passes through an inverter and is stored in a battery that powers an electrolyser that produces hydrogen through electrolysis. The hydrogen is then compressed to 300 bar and stored in a pressure tank.

When power is required for consumption, especially in the winter months, the hydrogen can be converted back into electricity through fuel cells, with the only emissions being oxygen and water vapour. This solution is beneficial because it not only results in zero emissions and high reliability of power, but also unlocks opportunities for long-term storage and seasonal flexibility.

In a similar vein, Hans-Olof Nilsson, an engineer, energy pioneer and founder of Nilsson Energy, has invested his own capital into converting his family home near Gothenburg into a state-of-the-art off-grid house. The house also generates enough electricity for the daily charging of two EVs. Excess solar energy is stored in batteries, and when these are 85% charged, electricity from the solar PV is redirected to hydrogen production for long-term storage via water electrolysis. When the batteries' charge level drops below 30%, such as on cloudy days with low PV production, the hydrogen is reconverted back into electricity by fuel cell technology to recharge the batteries (Jensen, 2017). The entire design, construction and installation of this state-of-the-art house was conducted by a single person, namely Mr. Nilsson himself.

Sweden – Decarbonising the iron and steel industry – HYBRIT project

	Renewable power-to-heat
✔	Renewable power-to-hydrogen
✔	Artificial intelligence and big data
	Increasing time granularity in electricity markets
✔	Innovative ancillary services
	Regional markets

With the increasing availability of low-cost renewable power, significant opportunities emerge to reduce CO_2 emissions in iron and steelmaking processes using renewable hydrogen.

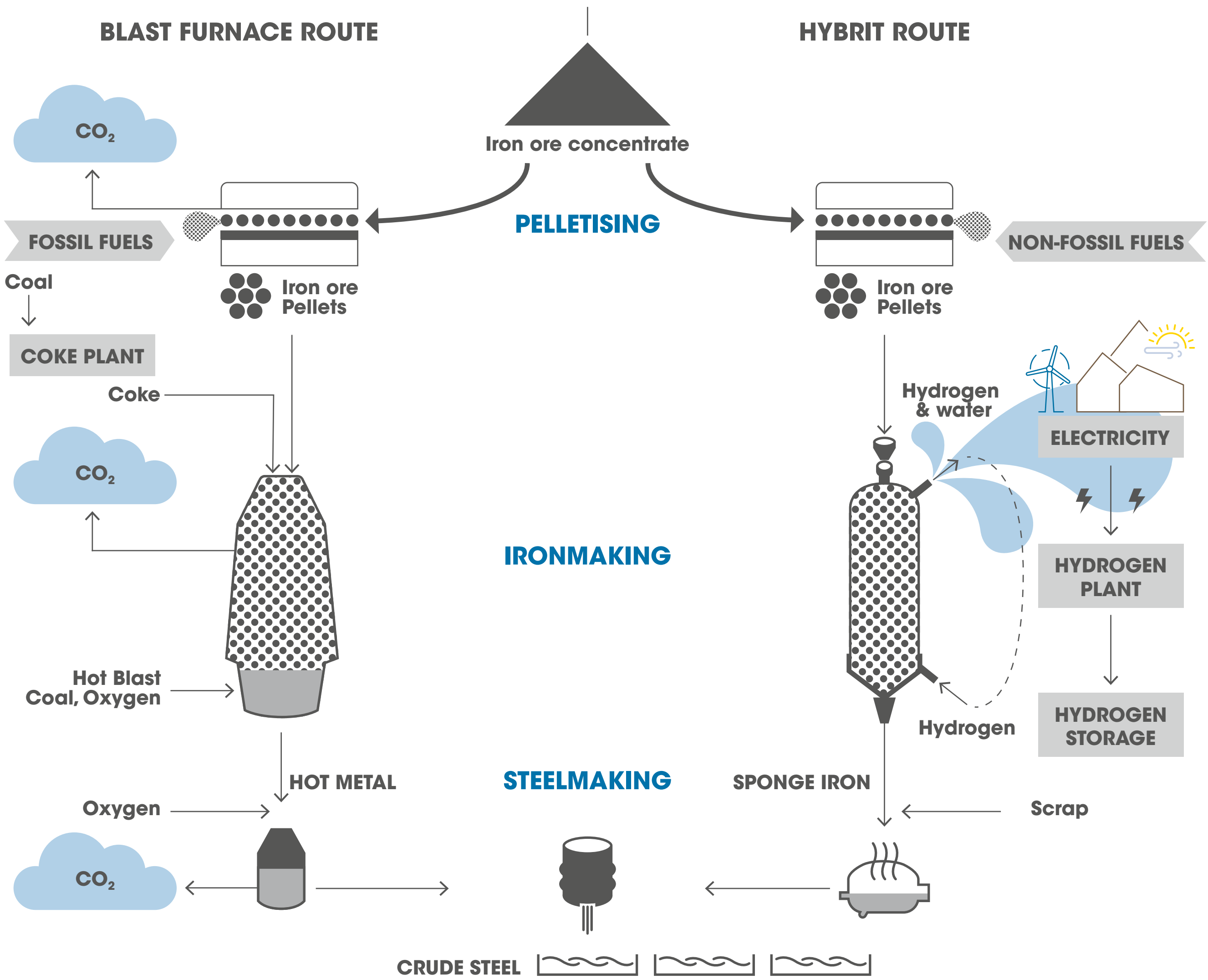
Increasing efforts in the global steel industry are focusing on renewable hydrogen production to achieve mitigation and decarbonisation (Gielen *et al.*, forthcoming).[17]

One such effort to decarbonise the steel industry is the HYBRIT (Hydrogen Breakthrough Ironmaking Technology) project in Sweden, which aims to substitute coal with hydrogen. This innovative project is conducted through the consortium of Swedish steelmaker SSAB, power utility Vattenfall, and LKAB, Europe's largest iron ore producer.

The Swedish government provided a subsidy of EUR 50–60 million (USD 56–67 million) for a demonstration plant.

The goal is to have a pilot plant (proof of concept) operational by 2020 and a demonstration plant operational post-2024. Hydrogen production and storage is also expected to contribute to power system flexibility and thus facilitate VRE integration in power generation. According to the consortium, HYBRIT could not only help meet Sweden's national target to achieve zero net emissions by 2045, but also, "if realised on an industrial scale, the technology could make Sweden the world's first country to produce fossil-free ore-based steel" (HYBRIT, 2018). Currently, the steel industry accounts for around 7% of global CO_2 emissions and 10% of Swedish CO_2 emissions, respectively.

Figure 21: The HYBRIT concept compared to the conventional steelmaking process



Source: HYBRIT, 2018

17 Iron production with renewable hydrogen is expected to become the least-cost supply option at a CO_2 price of approximately USD 67 per tonne by 2050.

Sweden – Decarbonising the heating and cooling sector – Ectogrid project

✔	Renewable power-to-heat
	Renewable power-to-hydrogen
✔	Artificial intelligence and big data
	Increasing time granularity in electricity markets
	Innovative ancillary services
	Regional markets

In Sweden, E.ON's Ectogrid technology enables a number of buildings to be connected to a thermal grid, using heat pumps and cooling machines to distribute flows of thermal energy and to balance the building's energy demands against each other. In such a configuration, only a single thermal grid is needed, which serves simultaneously for thermal distribution for heating and cooling but also for storage and flexibility, ultimately enabling larger shares of VRE in power systems.

By balancing thermal energy flows between the connected buildings, the Ectogrid technology uses and reuses the available thermal energy to decrease the overall energy consumption. Digital enabling technologies including artificial intelligence and the Internet of Things are employed in the cloud-based management system "ectocloud", which controls and adds flexibility to the system by using the thermal inertia of the buildings and grid as storage (Ectogrid, 2019). The world's first ectogrid is being built to connect buildings at Medicon Village, a science and research park in Lund (Sweden) and will serve as the international demonstration site for this technology. The full capacity is scheduled for mid-2020 and the project is expected to greatly decrease energy supply and costs (Medicon Village, 2018).

6.3 EXAMPLES OF SIMILAR IMPLEMENTED SOLUTIONS

Examples of pilot projects focused on the electrification of the transport sector using technologies for EV smart charging were presented under Solution III, which proposed addressing the challenges at the distribution level and from a demand-side management point of view. In contrast, the following examples refer to more system-wide challenges, and include the use of renewable power-to-hydrogen in the transport sector.

Renewable power-to-hydrogen can be adopted in virtually any transport application where greenhouse gas-emitting fossil fuels are currently used. This stands in line with the broader concept of a hydrogen economy, which can be defined as "a future economy in which hydrogen is adopted for mobile applications and electric grid load balancing" (Hajimiragha *et al.*, 2011, p. 6 359). This energy carrier, with high gravimetric density, has been gaining prominence in recent years, especially since it can be produced with locally available renewable energy sources and emits only water at the point of usage (Singh *et al.*, 2015).

Europe, Asia – Decarbonising the transport sector (ships, trains, cars and bikes)

	Renewable power-to-heat
✔	Renewable power-to-hydrogen
	Artificial intelligence and big data
	Increasing time granularity in electricity markets
✔	Innovative ancillary services
	Regional markets

Scotland – Renewable hydrogen in passenger ferry – HYSeas III project

In the spirit of shaping a successful hydrogen economy, several innovative pilot projects in the transport sector are being trialled and implemented. Under HySeas III, the world's first passenger ferry fuelled by hydrogen as an energy source is being developed in Orkney, Scotland. The vessel's carbon-free hydrogen will be produced from renewable electricity, marking a paradigm shift towards entirely emissions-free marine transport. HySeas III, which benefits from more than EUR 9 million (USD 10 million) in EU funding, is jointly led by Ferguson Marine and the University of St Andrews and includes the Orkney Islands Council, Kongsberg Maritime (Norway), Ballard Power Systems Europe (Denmark), McPhy (France), DLR (the German aerospace agency) and Interferry (Belgium/US). The aim of the consortium is to launch the first hydrogen ferry by 2021 (Internationales-Verkehrswesen, 2018). The HySeas III project also examines the vessel fuelling infrastructure as well as techno-economic and social factors impacting the transition to zero-emission marine transport.

France – Renewable hydrogen ship for research – Energy Observer vessel

Another noteworthy example in the field of maritime transport is the *Energy Observer* research ship. It is the first hydrogen vessel, powered by electric propulsion that relies on a mix of solar, wind and hydropower generation and on-board battery storage, as well as a carbon-free hydrogen production system using seawater. During its six-year global expedition from 2017–2022, visiting 50 countries and 101 ports, the vessel will release neither greenhouse gas emissions nor fine particles into the atmosphere (Energy Observer, 2019a). As of the end of 2019, the *Energy Observer* had already travelled almost 18 000 nautical miles, visited 25 countries and even reached the Arctic Circle (Plugboats, 2019).

Figure 22: The *Energy Observer* reaching the Arctic Circle off the island of Spitsbergen, Norway

Source: Energy Observer, 2019b

Europe – (Renewable) hydrogen trains, cars and bikes

Other innovative hydrogen applications and projects in the transport sector include the roll-out of the world's first hydrogen train in Lower Saxony (Germany) by Alstom as well as the first commercially available fuel cell electric bikes by Pragma Industries (France).

Meanwhile, the network of hydrogen filling stations for cars is rapidly expanding across Europe, and 75 stations are already operational in Germany alone with additional filling stations in different planning stages (H2, 2019).

Figure 23: Hydrogen filling stations across Europe as of October 2019

Source: H2, 2019

Disclaimer: Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

Asia – Deployment of fuel cell electric vehicles and (renewable) hydrogen filling stations

Japan and the Republic of Korea count among the most driven countries in the world in the development of a renewable hydrogen economy. These countries are promoting the path to renewable hydrogen through ambitious targets and technological roadmaps, especially in the field of mobility.

Japan aims to increase the number of fuel cell electric vehicles (FCEVs) from 2 926 units as of the end of 2018 to 200 000 units by 2025 and 800 000 units by 2030. It aims to increase the number of hydrogen refuelling stations from 100 in 2018 to 320 by 2025 and 900 by 2030. Procuring large amounts of hydrogen from relatively low-cost surplus renewable power has been identified as key in the realisation of future low-cost hydrogen (METI, 2017).

Figure 24: Hydrogen refuelling station in Kawasaki, Kanagawa Prefecture, Japan

Source: Japan Times, 2019

The government of the Republic of Korea also conducts multiple programmes to develop hydrogen production from renewable sources and to commercialise stationary fuel cells and FCEVs. The country's hydrogen economy roadmap includes plans to foster the growth of FCEVs from 900 vehicles in 2018 to 6.2 million vehicles by 2040 and to increase the number of refuelling stations from 14 in 2018 to 1 200 by 2040. The government also intends to introduce 40 000 hydrogen-fuelled buses, 80 000 taxis and 30 000 trucks by 2040 while advancing the development of hydrogen ships, trains and machinery (Netherlands Enterprise Agency, 2019).

Progress in the extensive use of hydrogen-powered vehicles is also expected to play a vital role in China in reducing air pollution and promoting a renewable hydrogen economy. In 2018, the country's fiscal subsidy policies for new energy vehicles were adjusted in favour of FCEVs. That same year, large state-owned enterprises in the power, manufacturing and automotive sectors joined forces to establish the China National Alliance of Hydrogen and Fuel Cells ("China Hydrogen Alliance") (Holland Innovation Network China, 2019). The Chinese government has expressed several ambitious targets and commitments, including having 1 million FCEVs on the roads and 1 000 refuelling stations by 2030 as well as making Wuhan the first Chinese Hydrogen City by 2025. As of the end of 2018, there were 1 791 FCEVs and 15 hydrogen refuelling stations in China (IEA, 2019b).

Renewable power-to-hydrogen can be adopted in virtually any transport application where greenhouse gas-emitting fossil fuels are currently used

Austria – Decarbonising the steel industry – H2FUTURE project

	Renewable power-to-heat
✔	Renewable power-to-hydrogen
✔	Artificial intelligence and big data
	Increasing time granularity in electricity markets
✔	Innovative ancillary services
	Regional markets

H2FUTURE is a European flagship project bringing together utilities, the steel industry, technology providers and research institutes to study the use of renewable power-to-hydrogen to supply hydrogen for steel manufacturing and the use of electrolysers to provide grid balancing services.

Under the co-ordination of Austrian utility Verbund, steel manufacturer Voestalpine and German electrolyser manufacturer Siemens have installed a large-scale 6 MW proton exchange membrane electrolysis system at the Voestalpine steel plant in Linz, Austria.

The electrolysis process used in the project can be scaled up and used for rapid frequency response, making it an ideal choice for new industrial processes and grid services. In the course of the project's implementation, one of the use cases developed will focus on the automatic provision of primary control/frequency containment reserve by changing the power consumption of the electrolyser based on local grid frequency measurements.

In the demonstration phase, the electrolyser will – after successful prequalification – provide these services to Austria's transmission system operator, Austrian Power Grid. Research institutes in the Netherlands and Austria study the replicability of the pilot project's findings on larger scales for the steel industry in the EU.

H2FUTURE demonstrates that to face critical innovation challenges, intense co-operation is needed across sectors (*i.e.*, co-operation among steel and power sector players) with scientific and industrial partners, on both the national and European levels (H2FUTURE, 2018).

Uruguay – Decarbonising the industry – Renewable power-to-heat coupled with wind power

✔	Renewable power-to-heat
	Renewable power-to-hydrogen
✔	Artificial intelligence and big data
	Increasing time granularity in electricity markets
	Innovative ancillary services
	Regional markets

In Uruguay, renewable energy surplus equates to around 18% of domestic demand. Therefore, ongoing analyses are assessing cost-effective uses of these large surpluses to satisfy industrial demand instead of curtailing renewable power generation. In 2012, a wool laundry factory 50 kilometres from Montevideo installed a 1.8 MW wind turbine for self-consumption (around 1.1 MW), injecting the generation surplus into the grid. Various options for using the energy surplus were analysed, since it was no longer economically viable to transfer it to the network.

Consequently, various projects were proposed to exploit the surplus power produced by the turbine and to use it for internal purposes rather than feeding it into the grid. Because the factory consumes large amounts of hot water, which is heated by two steam boilers using fuel oil and wood, solutions have targeted increasing the factory's energy efficiency by eliminating the use of fuel oil. An electric boiler to produce steam (1.5 MW) was installed, which has both eliminated the use of fuel oil for steam generation (up to 14 500 litres per month) and optimised the power generation from the wind turbine, as steam can be produced using surplus power and hence excess electricity does not need to be injected into the grid.

In addition, a robust and reliable data network has been created for continuous data collection to develop an adaptive control strategy that maximises the generation of the wind turbine. Artificial intelligence models have been used for generation forecasts. As of the end of 2019 the system had been running for several months, and over 100 MWh can be tapped per month, with the power being locally consumed rather than injected into the grid.

Figure 25: Renewable power-to-heat to decarbonise a wool laundry factory, Uruguay

Source: IRENA, 2019c

6.4 QUALITATIVE COST-BENEFIT ASSESSMENT

The Ministry of Infrastructure, the Swedish Energy Agency and Vinnova could work together to devise a **stable and encouraging policy framework**, with policies creating a market pull for technologies needed to decarbonise end-use sectors, while considering the costs and benefits of enabling technologies such as renewable power-to heat and renewable hydrogen for the mobility, heating and industrial sectors. To facilitate the large-scale integration of VRE and to achieve the fossil fuel neutrality of end-use sectors in Sweden, power-to-X technologies should not be considered in isolation or perceived as competing with other flexibility measures. Instead, future policies need to assess these options in combination, including direct electrification, renewable power-to-heat, renewable power-to-hydrogen, EV smart charging and power-to-gas schemes.

Future policy frameworks should consider the synergies that exist among different innovations, which may lead to lower investments when implementing them in conjunction. Therefore, the aforementioned institutions should also **leverage and promote synergies among different innovations**. For example, investing in digital technologies could enable system operation and trade at increased time granularity, and also play a key role in the development of communication protocols supporting real-time data exchange between transmission and distribution system operators.

Low-cost renewable power creates opportunities to use green hydrogen, including to reduce CO_2 emissions in iron and steel making

If considered to be of strategic importance for the decarbonisation of end-use sectors in Sweden, given its complexity, the deployment of hydrogen infrastructure would need a co-ordinated approach among various stakeholders, including the Ministry of Infrastructure, the Swedish Energy Agency and Vinnova alongside the energy regulator and the transmission system operator.

These actors would need to collaborate in developing and adopting **a comprehensive national action plan for the decarbonisation of end-use sectors,** for example through Sweden's draft integrated national energy and climate plan(s), as per EU Regulation 2018/1999 of the European Parliament and of the Council on the Governance of the Energy Union and Climate Action**.** Such a strategic roadmap, with clear goals to stimulate the deployment of the necessary infrastructure, is required to mitigate the risks and realise the benefits of the deployment of power-to-X technologies.

This is of utmost importance given that some investments (for example, in renewable power-to-hydrogen infrastructure) are capital intensive and rely on a relatively long time commitment of 10–20 years for financial viability.

Roles and responsibilities of system operators have to be adapted to mandate more co-operation between transmission and distribution system operators for effective and timely congestion management as well as system balancing. This is also essential for the efficient procurement of services of an increasing number of distributed energy resources, such as EVs resulting from the electrification of the transport sector. This implies rethinking the governance structures of local, regional and national grid owners in Sweden, with future regulations turning local and regional system operators into active market facilitators by allowing them to access ancillary services.

To improve the economic viability of some of these technologies, it is crucial to provide the necessary incentives. For example, policy makers would need to **allow electrolysers to participate in electricity markets** while building a platform that enables monetisation and revenue stacking both from the power supplied and from all ancillary services provided by electrolysers to the grid. Simultaneously, regulatory changes are required to recognise and reward the ancillary services that VRE generators can offer to the grid. Changes may further require the reassessment of curtailment management regulations to truly make use of the rapid cost reduction of electricity from VRE sources, which creates a significant opportunity for cost-effective hydrogen production. This should be co-ordinated among the Swedish Energy Markets Inspectorate, the transmission system operator and the Swedish Energy Agency.

The creation of a new market for innovative ancillary grid services to remunerate individual services more effectively could come together with the **implementation of a more time-granular wholesale electricity market**. Enabling and facilitating greater trade of ancillary services in the Nordic region, but also in an expanded pan-European regional electricity market, is also key in increasing both the overall flexibility of the existing transmission system and the cost-efficiency of balancing. The recent implementation of EU Regulation 2017/2195 on the operation of balancing markets in the EU already provides the necessary framework for greater cross-border trading and for cost-efficient procurement of ancillary services by transmission system operators.

A strategic roadmap can mitigate the risks and realise the benefits of the deployment of power-to-X technologies

Finally, in collaboration with the Swedish government, system operators and research institutes and industrial actors should collaborate to **devise measurable targets and cost-effective decarbonisation strategies** through renewable power-to-X projects, for example with the aim of scaling the size of electrolysers to achieve mass production and cost reductions, engendering welfare benefits.

Overall, these actions require the engagement, consultation and/or co-ordination of two or more stakeholders in the Swedish power sector. Table 10 contains a summary of some of the key actions needed for the implementation of Solution IV, together with an indication of the relevant stakeholders that could be involved in taking further action to implement this solution.

Table 10: Stakeholder action and engagement required for the implementation of Solution IV

TYPE OF STAKEHOLDER	MINISTRY	GOVERNMENT AGENCY	GOVERNMENT AGENCY	REGULATOR	MARKET OPERATOR	SUPPLY	SUPPLY	TSO	DSO	DEMAND	DEMAND
Stakeholder Engagement & Action	**Ministry of Infra-structure**	**Swedish Energy Agency**	**Vinnova**	**Swedish Energy Markets Inspectorate**	**Nord Pool**	**Power generators**	**Retailers**	**Svenska Kraftnät**	**Ellevio, Vattenfall Eldistribu-tion, E.ON Energidistri-bution & co.**	**New actors (aggre-gators)**	**Consumers**
Creation of a stable and encouraging policy framework for direct and indirect electrification	✔	✔	✔								
Adopt a national/regional action plan for end-use sector decarbonisation, including the deployment of renewable power-to-X	✔	✔	✔	✔				✔			✔
Adapt roles and responsibilities of system operators		✔		✔				✔	✔		
Increase the time granularity of electricity markets	✔	✔		✔		✔		✔			
Mandate new ancillary services	✔	✔		✔							
Define technical criteria for new ancillary services	✔	✔		✔		✔		✔	✔		
Define remuneration mechanisms for new ancillary services		✔		✔				✔			
Participate in the ancillary service market						✔					✔
Evaluate the costs, complexity and benefits of the proposed solution		✔	✔	✔		✔		✔			

Note: *Proposed actions for the four solutions are not meant to be treated in isolation, but could be done simultaneously and in co-ordination with two or more parties.*

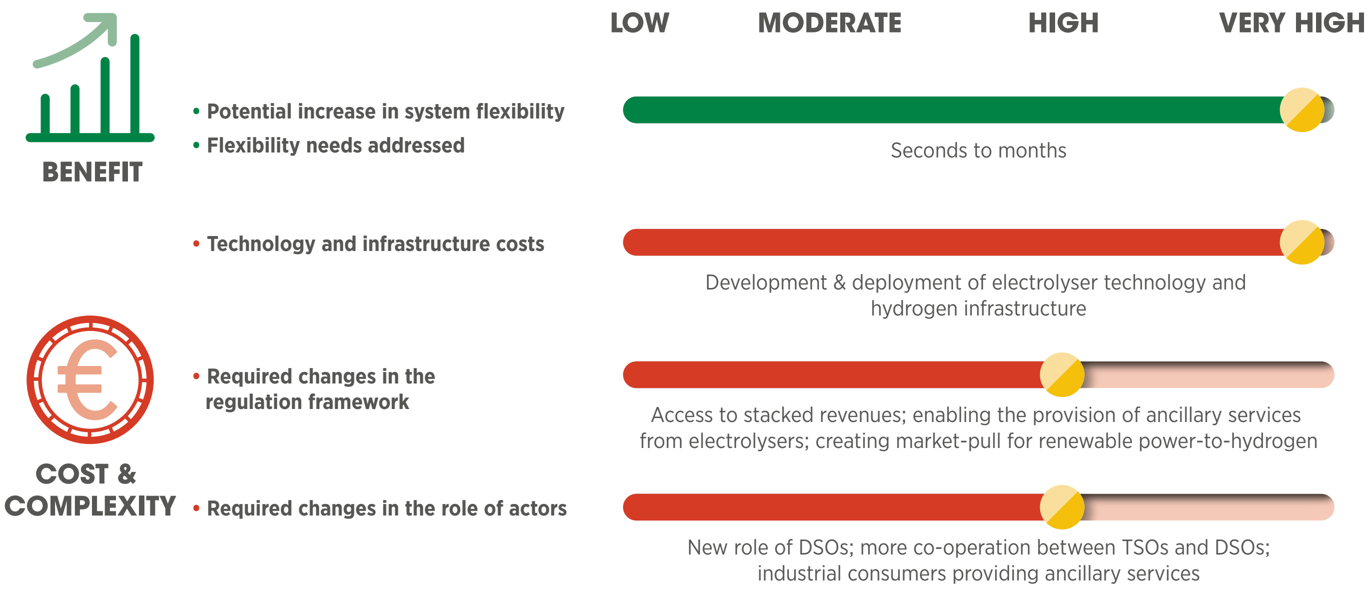
Implementing a systemic innovative solution requires a systemic approach that leverages and harnesses synergies among innovations across multiple components of the power system. For Solution IV, this implies the creation of synergies between VRE generation and the decarbonisation of end-use sectors, coupled with adaptations in market design and in the roles and duties of system operators.

Because Solution IV is based to a large extent on power-to-X enabling technologies, for which achieving scale-up and cost reductions remain critical (and still-to-be-solved) challenges, its implementation requires costly and risky investments. Moreover, producing hydrogen from low-cost VRE generation through electrolysis is only a fraction of the solution, as using the hydrogen in other applications, including the decarbonisation of end-use sectors, requires the development of adequate infrastructure and operational procedures, in addition to the changing roles of existing actors in the power sector with the emergence of new responsibilities.

Nonetheless, if implemented adequately and in co-ordination with all stakeholders, the solution may provide a very high level of flexibility to the system, from seconds to months. As with Solution II (Pan-European electricity market as flexibility provider), this solution also provides seasonal flexibility. However, it is the only solution unlocking opportunities for sector coupling, and thus has the potential to unlock significant benefits for the power system in the long term.

Moreover, beyond the power sector, similar to the case of Australia (Gielen *et al.*, forthcoming), Sweden is well positioned to produce "green" iron with very low emissions, and to export it, given the country's abundant renewable energy resources and the environmental and economic importance of the iron and steel industries, thereby reaping more benefits from the energy transition.

Figure 26: Estimated benefits, costs and complexity for the implementation of Solution IV



Note: *The benefits, costs and degree of complexity are indicative for each solution and were provided following an expert-based estimation, by comparing the four solutions to each other.*

7. RECOMMENDATIONS FOR POLICY MAKERS

Future innovation policies and measures must be tailored to meet the targets contained in Sweden's 2016 Energy Agreement. The Energy Agreement is a national roadmap to an entirely renewable power system and a net zero carbon economy, supported by a large majority in the Swedish parliament. The recommendations that follow, while primarily addressing policy makers and stakeholders in Sweden, may be broadly applicable for any country exploring high ambitions in renewable power.

Innovation challenges, such as increasing power system flexibility to accommodate larger shares of VRE for a 100% renewable-powered future by 2040, demand an adequate policy environment in which innovative solutions can flourish. Since neither technology nor policy silver bullets exist for greater power system flexibility, the systemic approach to innovation also calls for a systemic approach to power system regulation and development.

Effectively translating current VRE integration and power flexibility challenges in Sweden into concrete "innovation missions", driving disruptive innovations across multiple sectors and dimensions, could be key to setting the direction of change and fulfilling national and international decarbonisation and climate ambitions.

A. Align innovation efforts to systemic power sector transformation

VRE integration challenges need to be considered from a systemic point of view (IRENA, 2019b). Therefore, innovative solutions such as the ones proposed in this study, in which innovation directly responds to and serves to solve key VRE integration challenges, are required. For the development and implementation of such solutions, future policies in Sweden would need to provide clearly defined strategic directions for innovation to achieve a 100% renewable-based power system, and more widely to achieve decarbonisation of other end-use sectors. **The preparation of the forthcoming National Energy Research and Innovation Programme Bill offers the opportunity to formulate such "innovation missions" and to align these to the goal of achieving a 100% renewable-powered system by 2040.**

In this context, coherent and realistic time scales with regular monitoring to adapt and refine objectives are needed. Combining a "mission-oriented" policy framework with systemic innovation concepts could truly contribute in forging a long-term innovation policy agenda for VRE integration into the power system. The resulting framework could also draw on Sweden's current strengths in science, innovation and technology while being broad enough to catalyse a wide array of stakeholders.

Sweden could build a 100% renewable power system by 2040 through the integration of progressively higher shares of solar and wind energy

B. Explore synergies among energy, climate and innovation policies

Meeting the very ambitious policy goal of achieving 100% renewable power by 2040 with high shares of VRE is achievable. This is shown by experiences from countries such as Costa Rica and Uruguay, which in 2019 were already operating power systems with very high shares of renewables (98–100%). However, meeting such an objective requires co-ordinated efforts to explore synergies among energy, climate and innovation policies.

National institutions, such as the Ministry of Infrastructure, the Swedish Energy Agency and Vinnova, could strengthen the co-ordination of efforts to promote innovations for the power sector transformation towards achieving the goal of 100% renewable power in the coming two decades. For example, as stated by the European Commission's assessment of Sweden's draft National Energy and Climate Plan for the 2021–2030 period, specific objectives and funding targets for research, innovation and competitiveness would be welcome (EC, 2019a).

In a similar vein, future policies could not only consider synergies among energy, climate and innovation ambitions but also explore and leverage synergies among different innovations and enabling technologies, innovative business models, new regulations in terms of market design and new system operation practices, which may lead to lower overall investments and higher welfare benefits for power consumers and society as a whole.

C. Pursue innovation efforts strategically at different levels

As one of the world leaders in sustainable energy development, Sweden is well placed to continue pursuing innovation, renewable energy and climate policy ambitions in a strategic manner at the national, European and international levels. **Further dialogue needs to be encouraged among various stakeholder groups, encompassing academia, system operators, regulators, innovators, civil society and international organisations.** At the same time, exchanging experiences and encouraging cross-border collaboration across the Nordic and European regions and wider global community, including policy makers and regulators, needs to remain a priority. Coupling innovation with such an open, co-operative and inclusive approach may truly result in a shared vision, which could turn ambitions into actions, eventually turning the goal of 100% renewable power into reality.

National co-ordination

Systemic innovative solutions to integrate VRE into the Swedish power system, such as the ones proposed in this study, could provide the starting point for discussion on the duties and responsibilities that different stakeholders would be required to undertake to accelerate the implementation of these solutions. In-depth quantitative assessments could be conducted to evaluate the techno-economic feasibility, complexity, costs and benefits of each proposed solution from the angle of achieving a 100% renewable-powered system by 2040. This would provide more evidence of the advantages of implementing different solutions while quantifying their impact and actions required for the increase in power system flexibility to accommodate larger shares of VRE, and especially wind power.

Drawing on the quantitative assessments of the proposed solutions and in consultation with the various stakeholders in the power sector, policy makers could define clearer security of supply standards as well as define clearer roles and responsibilities for actors across the power supply chain – including the transmission and distribution system operators and the power generators – to meet these standards. The lack of clearly defined standards, roles and responsibilities could hamper the energy transition (Svenska Kraftnät, 2017). Moreover, co-operation among transmission system operators within the same region can be encouraged and is expected to be strengthened via mandatory participation in regional co-ordination centres (RCCs) established by EU Regulation 2019/943 of 5 June 2019 on the internal market for electricity, whose tasks include the contribution to 2030 and 2050 climate and energy objectives (European Parliament, 2019).

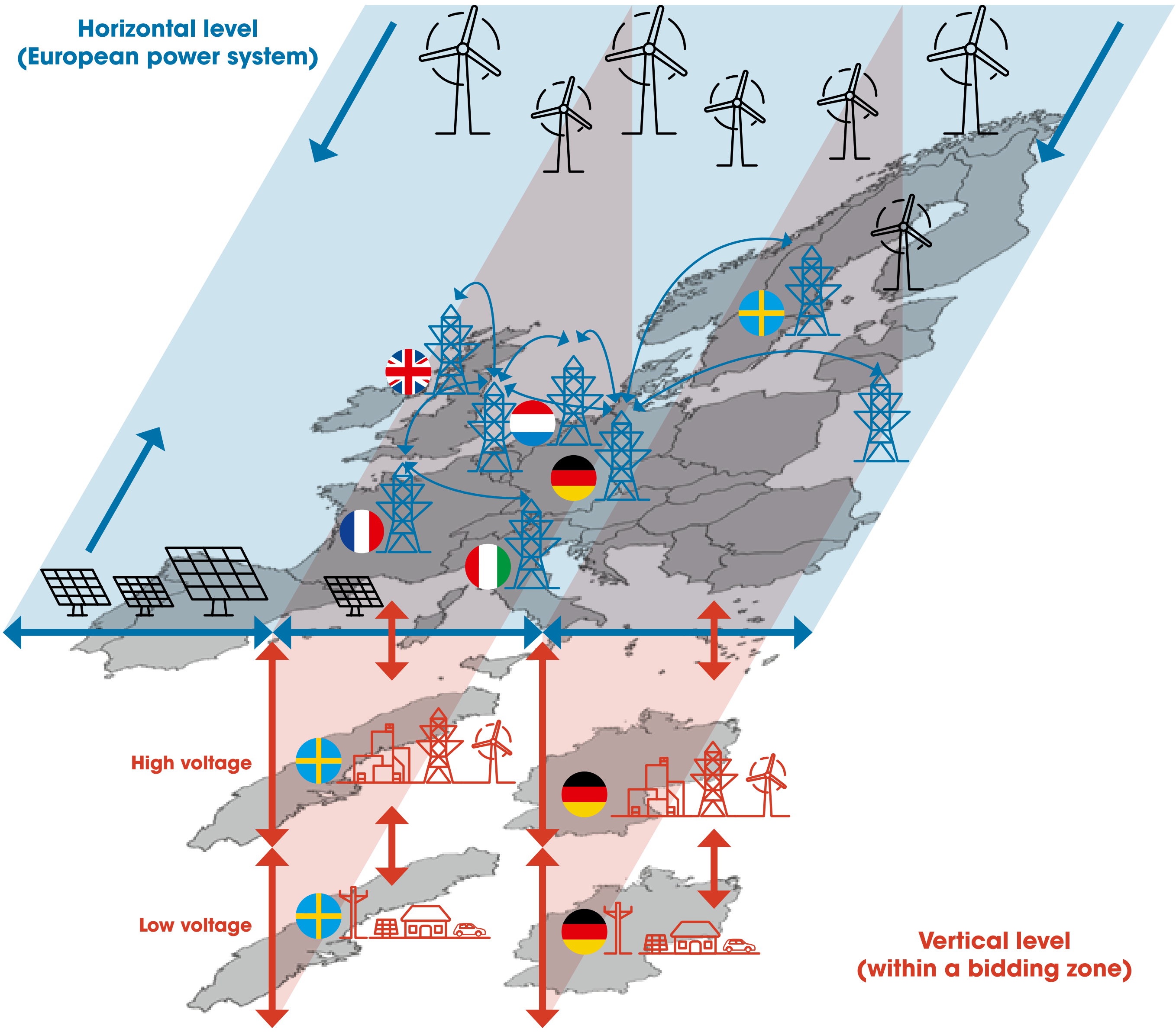
To foster, advance and implement innovative solutions, adequate regulatory space is needed to allow for experimentation to assess the combination of different innovations. Creating regulatory sandboxes, for instance, may be fruitful to allow innovators, research institutes and other power sector stakeholders, including the transmission and distribution system operators, to test pilot programmes without being restricted by the regulatory environment or suffering negative consequences if test results are unsuccessful. Providing the space for practical experimentation could be done by providing flexibility, such as temporary relaxation of some rules, in a confined area of the system, as long as it is in the public interest and certain system security thresholds are respected.

European co-operation

Co-operation between transmission and distribution system operators could be strengthened on both the national and European levels. Robust regulations would ensure more transparent collaboration between these operators. This is particularly essential for the well-functioning of the internal pan-European electricity market, including the efficient procurement of ancillary services in the context of an increasing number of connected distributed energy resources. For example, EVs resulting from the electrification of the transport sector are expected to be increasingly connected to the grid at both the national and EU scale.

From a broader European perspective, encouraging, mandating and monitoring the co-operation between European transmission system operators (including Svenska Kraftnät) within ENTSO-E, as well the co-operation of transmission system operators with European distribution system operators within the soon-to-be established entity of distribution system operators in the EU (the so-called EU DSO entity as per EU Regulation 2019/943), would engender considerable benefits. Integrated approaches with clear roles and effective co-ordination between transmission and distribution system operators, with distinct actors delivering services at different levels, are truly needed to solve the challenges of the European power system. Co-ordination is required both among stakeholders in different EU member countries (*i.e.*, in the horizontal dimension depicted in Figure 27) and between the national transmission and distribution system operators (*i.e.*, in the vertical dimension).

Figure 27: Horizontal and vertical challenges in the interconnected European power system



Source: Adapted from IEA-ISGAN, 2019

Disclaimer: Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

European and national generation adequacy assessments with a regional scope are further needed to maximise social welfare benefits and to fully benefit from the complementarity of diverse power generating resources available in the wider geographical area surrounding Sweden. Such assessments could inform decisions about whether formal requirements are necessary by 2040 for power producers to ensure that generation is available in the longer term. This could be done in co-ordination with the responsible government agencies, energy regulators, the transmission system operator and other regional stakeholders, including neighbouring transmission system operators and other European transmission system operators within the collaboration framework of ENTSO-E.

According to a recent report by the Agency for the Cooperation of Energy Regulators (ACER), mid-term adequacy forecast results for 2018 indicate that seven EU member states[18], including Sweden, that have introduced or are planning to introduce capacity mechanisms[19] will be unlikely to face adequacy problems in either 2020 or 2025, which raises the question of the need for such capacity mechanisms at the national level. However, Sweden recently introduced a means to account for interconnectors' contribution to security of supply in national adequacy methodologies, which can be considered an improvement (ACER, 2019).

More generally, implementing and overseeing the effective and timely implementation of EU regulations and directives from the Clean Energy for All Europeans legislative package is of utmost importance for all EU member states, including Sweden.

This is essential in order to reap more welfare benefits from an expanded pan-European regional electricity market, including the provision of higher flexibility of the current transmission system for more VRE integration, as well as sharing balancing resources cost-efficiently across national borders. Key legislation contained in this package includes EU regulations and directives containing legally binding rules referring to grid codes for the internal electricity market, including balancing, system operation, as well as governance rules on the Energy Union, whose ultimate goal is to meet the EU's 2030 energy and climate goals, as well as the EU's long-term commitment to reducing greenhouse gas emissions, in line with the Paris Agreement.

Wider international co-operation

Co-operating at the international level within existent networks and organisations (including IRENA) can greatly facilitate the exchange of knowledge about the latest market developments, the most disruptive technologies, as well as the best practices and lessons from projects trialled worldwide. Such exchanges can help to promote the adoption of renewable energy on a global scale. In the new paradigm of the power sector based on renewables, such collaboration efforts could be shaped in various forms, including international working groups, expert groups, workshops, conferences or research projects, all targeted to specific stakeholder groups, such as policy makers, regulators, system operators, innovators, public-private exchanges and research communities, to name some examples.

Co-operating at the international level within existent networks and organisations can greatly facilitate the exchange of knowledge, best practices and lessons from projects trialled worldwide

18 Germany, Latvia, Lithuania, Poland, Portugal, Spain and Sweden.

19 Sweden established a mechanism of strategic reserves in 2004. Its gradual phase-out has been postponed to 2025.

D. Ensure public acceptance through an inclusive transformation of the energy system

The prognosis on the development of the Swedish electricity system contains a considerable expansion of cost-competitive wind generation capacity. Additionally, extension of the transmission network is likely to be key in many parts of the country, due both to new installed generation capacity and to new consumption centres. **To successfully implement innovative solutions for a 100% renewable-powered future, consultation with all relevant stakeholders involved in the power sector is essential. Such engagement could include individuals living close to renewable-based generation sites, as well as wider civil society.** Achieving an inclusive energy transition with a successful, transparent and democratic upgrading of the power system will depend on addressing challenges related to the broader society and public acceptance, including local social acceptance of new wind power plants and new network expansion projects.

Local social acceptance is important for two main reasons. First, every new wind power plant requires approval from the municipality in which the wind park is planned. Currently, one of the main barriers to the construction of new wind parks is the denial of permits by local municipalities. Second, local social acceptance is required for the expansion of the power grid, which is crucial to meet the goal of 100% renewable power by 2040. The fact that power generating resources in northern Sweden are mostly owned and operated by large utilities presents challenges in terms of reaping local socio-economic benefits, such as the creation of new jobs in local communities.

The Swedish Energy Agency can contribute to the success of power system upgrades by continuing to fund projects aimed at helping municipalities to mobilise local companies in the construction and maintenance of new wind power or network expansion projects (with services including hotels, catering, electricians, etc.). Such activities would stimulate local economies and increase local welfare benefits.

While debate continues in Sweden about the distribution between global, national and local benefits of wind power, continued dialogue in which citizens are informed about new developments, as well as encouraged to provide their views on the social robustness of such undertakings, is required to further strengthen public acceptance. This could ultimately empower citizens, making them an integral part of Sweden's transition to 100% renewable power, especially in light of recent trends that are changing the passive power consumer into an active and engaged prosumer. In this context, local "energy communities", including "citizen energy communities" and "renewable energy communities", which were introduced in the recent Clean Energy for All Europeans package, could play a significant role in the next two decades (EC, 2019b).

Broad public acceptance is essential to achieve an inclusive energy transition that benefits all of society

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ANNEX 1 – METHODOLOGY

OBJECTIVE OF THE STUDY

The objective of this study is to consider how systemic innovations for power system integration of high shares of renewables (including from variable sources) – such as those identified in IRENA's report *Innovation landscape for a renewable-powered future* – can contribute to achieving very high levels of renewable power in Sweden in order to meet the country's ambitious policy target of 100% renewable electricity by 2040. This analysis includes an assessment of the likely impacts of those innovative solutions, as well as recommendations on actions needed.

The Swedish country-level innovation study is further informed by the outcomes of the activities performed under workstream 1 of this project, which refers to the *Experience-sharing programme on innovative solutions for very high shares of renewable power by mid-century* (see Figure 28). As part of this programme, IRENA member countries have been invited to join discussions and networking events for the international exchange of perspectives, plans and good practices in working towards very high levels of renewable power by mid-century.

IRENA'S SYSTEMIC INNOVATION APPROACH

The study's analysis to identify systemic innovative solutions for VRE integration is captured in a framework following a systemic approach, which is illustrated schematically in Figure 29. This step-wise analysis may be further used in any country as a starting point to better comprehend challenges and devise solutions for VRE integration from a systemic innovation perspective. The following section therefore provides an overview of the methodology and explains each analytical step, on which this study's findings are grounded.

Figure 28: Project overview

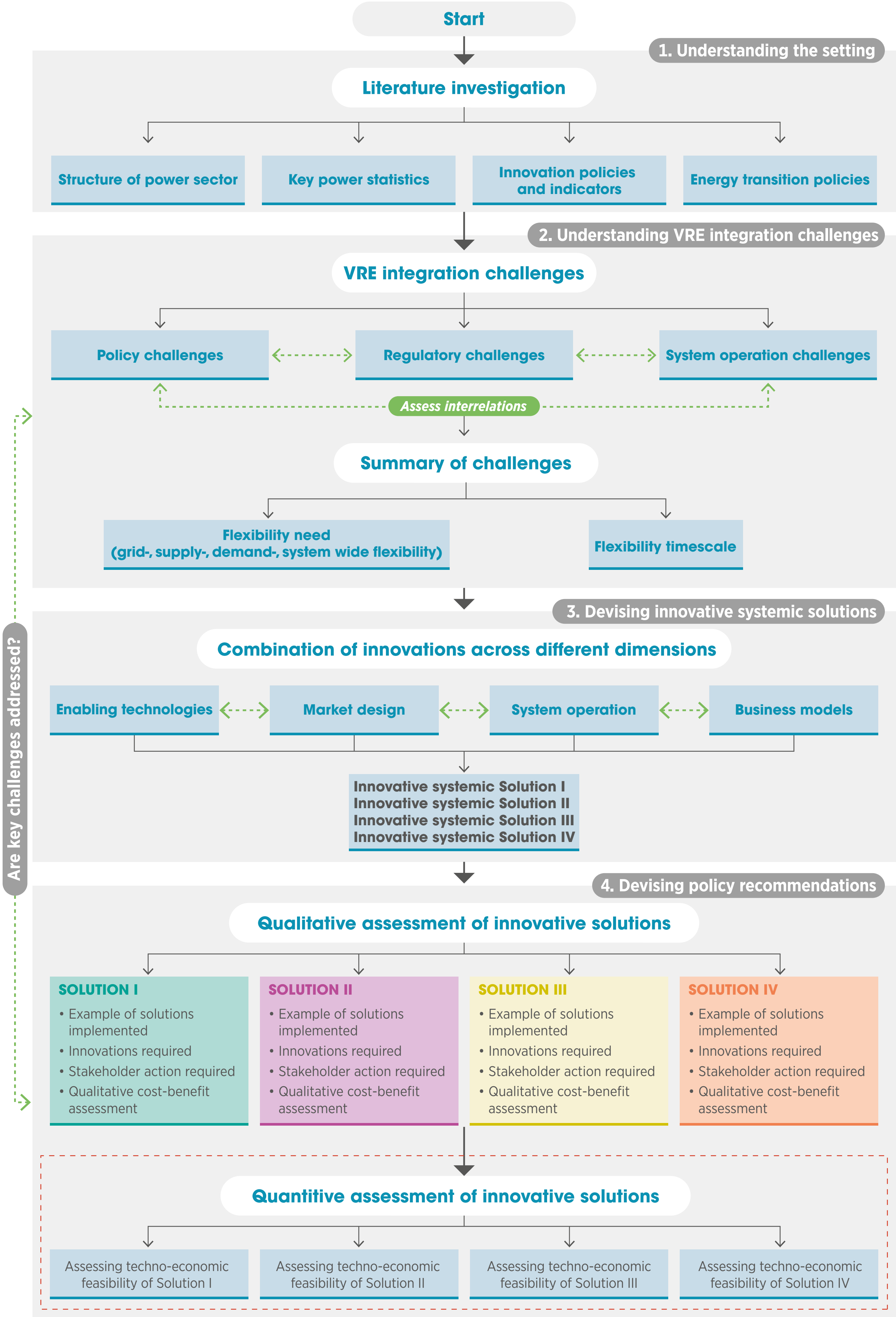
WORKSTREAM 1: CONNECTING COUNTRIES WITH TARGETS FOR HIGH SHARES OF RENEWABLE POWER

ACTIVITY	→	INPUT	→	OUTPUT	→	OUTCOME
• Engagement with member countries having similar policy targets • Engagement with experts, academia and private sector		• IRENA's 160 member countries • IRENA's analytical tools and knowledge base (IITC, KPFC)		• Online and offline engagement (regional workshops, online workshops)		• Strengthened links on innovation between countries with high renewable power targets • Outlook for future international collaboration on this topic

WORKSTREAM 2: SWEDISH COUNTRY-LEVEL INNOVATION STUDY

ACTIVITY	→	INPUT	→	OUTPUT	→	OUTCOME
• Internal IRENA (IITC, KPFC) engagement • Engagement with member countries under experience-sharing programme • Engagement with key stakeholders in Sweden		• National circumstances, including approaches to innovation, as well as challenges & opportunities for a decarbonised power system by 2040 • Qualitative analysis of disruptive innovations • Power sector insights		• Knowledge creation (published in a report) • Outreach and dissimination of knowledge in member country, as well as other interested member countries		• Informed decision-makers in Sweden • Informed decision-makers in other member countries participating in the project

Figure 29: Methodology for the identification of innovative solutions following a systemic approach



Note: *The green arrows on the figure indicate the iterative analytical process, while the red box indicates the quantitative analysis, which is out of the scope of the present report but could be used as a basis for a follow-up study.*

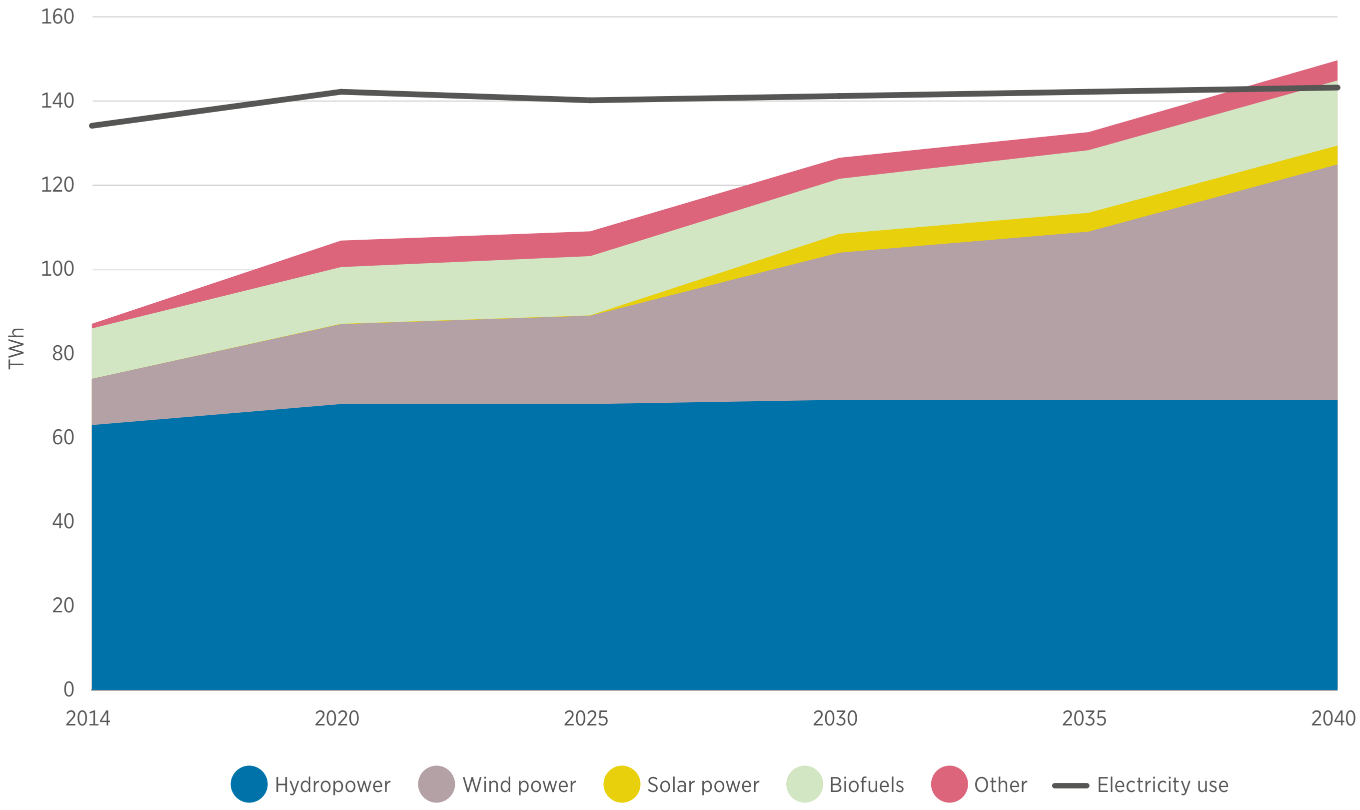
UNDERSTANDING THE SETTING

Firstly, a thorough literature review is fundamental to understand the power system and policy framework of the studied national or regional context. Therefore, as a first step, extensive literature on the structure, policies and role of innovation in the Swedish power sector has been surveyed. In particular, best practices of Swedish legislation in the power sector with a focus on renewable energy sources, where integrated approaches have been developed, were analysed. Information on key power statistics (*i.e.*, electricity mix, installed renewable energy capacity, etc.) as well as on policies for the energy transition were further collected.

Moreover, the assumption has been made that, in order to meet Sweden's renewable power targets by 2040, the share of VRE would need to exceed 45% of total generation. This assumption is based on the reference scenario of Sweden's Draft Integrated National Energy and Climate Plan (NECP)[20], which is grounded on one of the Swedish Energy Agency's 2016 climate scenarios[21] (SEA, 2017).

The reference scenario is based on current Swedish policies and targets as well as on assumptions by the European Commission on future fossil fuel prices and EU emission trading scheme allowances (Ministry of Infrastructure, 2018).

Figure 30: Renewable power generation and total power use from the Swedish Energy Agency's reference scenario, 2005–2040 (TWh)



Note: *"Other" refers to small shares of thermal generation (i.e., natural gas, coke and blast furnace gas) used in industry and district heating.*

Source: Ministry of Infrastructure, 2018

20 According to EU Regulation 2018/1999 on the governance of the Energy Union and Climate, which entered into force on 24 December 2018, EU countries are required, among others, to develop integrated NECPs that cover the five dimensions of the Energy Union for the period 2021 to 2030, and every subsequent 10-year period, based on a common template. The five dimensions are: 1) energy security, solidarity and trust; 2) a fully integrated internal energy market, 3) energy efficiency, 4) climate action, decarbonising the economy and 5) research, innovation and competitiveness.

21 More recent climate scenarios published in 2018 are available in Swedish at: https://energimyndigheten.a-w2m.se/Home.mvc?ResourceId=133529.

According to the Swedish Energy Agency (2016), growth in renewable power generation is mainly provided by wind and solar PV sources, while the share of dispatchable non-variable hydropower generation is assumed to remain stable by 2040 at around 69 TWh. Possibilities to further expand hydropower capacity in Sweden are restricted due to current regulations and permits aiming to limit environmental impacts (Flood, 2014). To address the challenge of maintaining power system stability and reliability with a 45% VRE generation share, flexibility solutions would be needed both on the supply and demand sides, as well as system-wide solutions.

UNDERSTANDING VRE INTEGRATION CHALLENGES

The literature review should pave the way for an analysis mapping key challenges and flexibility needs across the power system related to the integration of very high shares of VRE. In the case of Sweden, key challenges have been identified from a diversity of sources, including extensive reports from the Swedish Energy Agency, from Sweden's transmission system operator Svenska Kraftnät and from information collected following engagement with key stakeholders in Sweden and from workshops conducted as part of the *Experience-sharing programme on innovative solutions for very high shares of renewable power by mid-century*.

The discerned challenges have been broken down into policy, regulatory and system operation challenges.

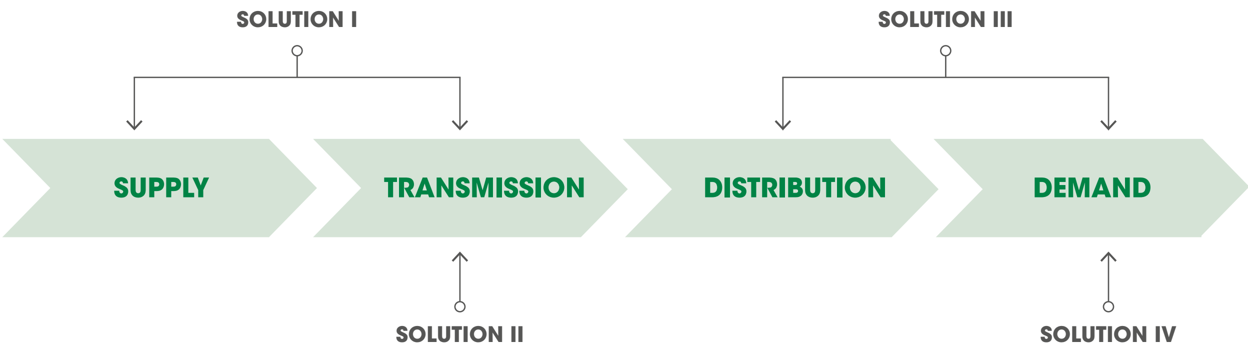
For a systems approach and to summarise the identified challenges in different categories, interrelations need to be assessed. Subsequently, flexibility needs across the power system value chain (supply, demand, grid, system-wide flexibility) and flexibility time scales (for example, seconds-to-minutes or minutes-to-hours) should be determined and analysed.

DEVISING INNOVATIVE SYSTEMIC SOLUTIONS

Based on flexibility needs at different time scales identified across the value chain of the power system, innovations from IRENA's *Innovation landscape for a renewable-powered future* report (2019) can be selected in the next analytical step. For a systemic innovation approach, innovations across at least two of the four innovation dimensions – which entail **1) enabling technologies**, **2) business models**, **3) market design** and **4) system operation** – should be chosen and combined to form a solution to each key challenge.

As there is no "one-size-fits-all" solution for the integration of high shares of VRE, the four solutions proposed in this study are tailored to the Swedish context. Each solution further targets a different part of the value chain of the Swedish power system to present different strategies for increasing flexibility in the system (Figure 31). Some solutions target one or more segments of the power sector value chain.

Figure 31: Solutions along the value chain of the Swedish power system



DEVISING POLICY RECOMMENDATIONS

Assessing the proposed innovative systemic solutions is necessary to identify policy requirements for the implementation of these solutions as well as to delineate the roles and responsibilities that different stakeholders would need to assume. In this study, a standardised template has been used for a qualitative assessment for each solution, which contains the following information: **a) challenge addressed**, **b) innovations required, c) description of the solution, d) examples of ongoing initiatives or similar pilot projects** from Sweden, the Nordic/European region or from other international experience, **e) stakeholders action required**, and **f) a qualitative cost-benefit assessment** of the implementation of the solution in Sweden, assessed in relation to other solutions proposed.

As a next step, although out of the scope of the current study, a quantitative assessment could further assess the techno-economic feasibility of each developed solution, for example by using the solutions' narratives for different energy scenarios, to better quantify the impact of proposed solutions, including the potential increase in power system flexibility. This may be particularly useful to evaluate more thoroughly country-specific variables as well as the technical and economic aspects of a given system, including its built-in flexibility capacity, grid infrastructure, demand profiles, spatial availability of VRE resources, etc.

ANNEX 2 – KEY CONCEPTS IN SYSTEMIC INNOVATION

In February 2019, IRENA launched the report *Innovation landscape for a renewable-powered future* (IRENA, 2019b). This study maps and categorises the many examples of emerging innovations and innovative solutions, supporting the integration of VRE. The report, containing over 200 real-world examples of projects, aims to provide decision makers with a clear, easily navigable guide to the diversity of innovations currently under development, or in some cases already implemented, in different settings across the globe.

INCREASING SYSTEM FLEXIBILITY FOR THE INTEGRATION OF VRE

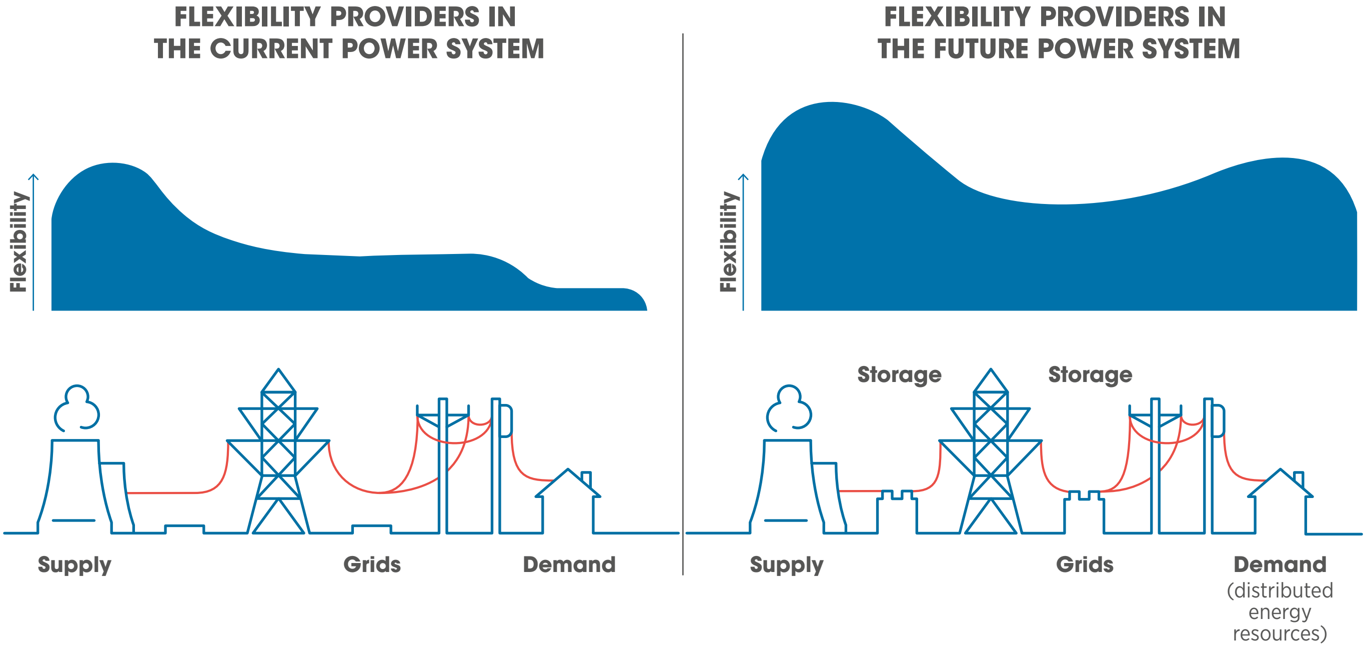
In an era of low-cost renewable power generation, and given the variability and uncertainty of wind and solar energy sources, innovative solutions are needed to provide the necessary flexibility and adequacy to power systems. In this context, flexibility is defined as the capability of a power system to cope with the variability and uncertainty that VRE generation introduces into the system at different time scales, from the very short term to the long term, avoiding curtailment of VRE and reliably supplying all of the demanded energy to customers (IRENA, 2018b).

Nevertheless, under certain market circumstances, it might be more cost effective to curtail the additional VRE generation, instead of adopting more costly measures, such as procuring balancing reserves or introducing capacity payments, which is why the reduction or complete avoidance of VRE curtailment is not a pre-requisite for a 100% renewable-powered system.

Insufficient flexibility could lead to load shedding, if the system cannot ramp up sufficient firm capacity during periods of low VRE generation, or to VRE curtailment, if the system cannot ramp down during periods of high VRE production. Insufficient flexibility leads to reduced operational value of additional installed VRE capacity and to increased operational costs due to the need for additional firm capacity to provide reserves or meet peak demand.

Traditionally, in conventional power systems, the supply side provided flexibility by adjusting the generation to follow demand. The demand side provided very little flexibility because it was largely unresponsive. Emerging innovations not only further increase supply-side flexibility, but also enable flexibility in all segments of the power system. Figure 32 illustrates the transition from a system in which generation is the only flexibility source towards a power system in which all components represent flexibility providers.

Figure 32: Illustrative representation of new flexibility options across the power sector unlocked by innovation



Source: *IRENA, 2019b*

- **Supply-side flexibility:** Higher flexibility from the supply side needs to be further incentivised, with more flexible behaviour both from existing conventional plants and from renewable energy generators (to the extent of their capabilities).

- **Grid flexibility:** Grid flexibility is provided by greater network capacity and by the establishment of regional markets, which allows electricity to be transported more readily within a larger balancing area, across several control areas or even on a continental scale. Thus, a wider geographic diversity of resources and a lower time granularity in existent markets can be used to balance supply and demand by taking advantage of weather and resource diversity. Management of distribution grid capacity is equally important for integrating more renewable energy, which is connected at the distribution grid.

- **Demand-side flexibility:** On the demand side, the emergence of distributed energy resources, which are small and medium-sized power sources located at low- to medium-voltage networks, such as distributed generation (rooftop solar PV, micro wind turbines, etc.), behind-the-meter-batteries and controllable loads such as EVs, heat pumps or electric boilers, have the potential to greatly increase system flexibility by becoming active participants in the electricity network. Peak shaving and load shifting are in this case the main strategies (IRENA, 2019b).

- **System-wide storage flexibility:** Energy storage technologies are flexibility providers across the energy sector that have huge potential to enable high VRE shares in the system. On the supply side, utility-scale batteries and power-to-X applications (for example, renewable power-to-heat and renewable power-to-hydrogen) can increase flexibility when connected to a VRE plant and storing its surplus power generation. On the demand side, direct or indirect electrification of end-use sectors can provide significant flexibility options via storage solutions, if the load is well managed. Storage could help increase grid flexibility and reduce network congestion when connected to the grid for such purposes.

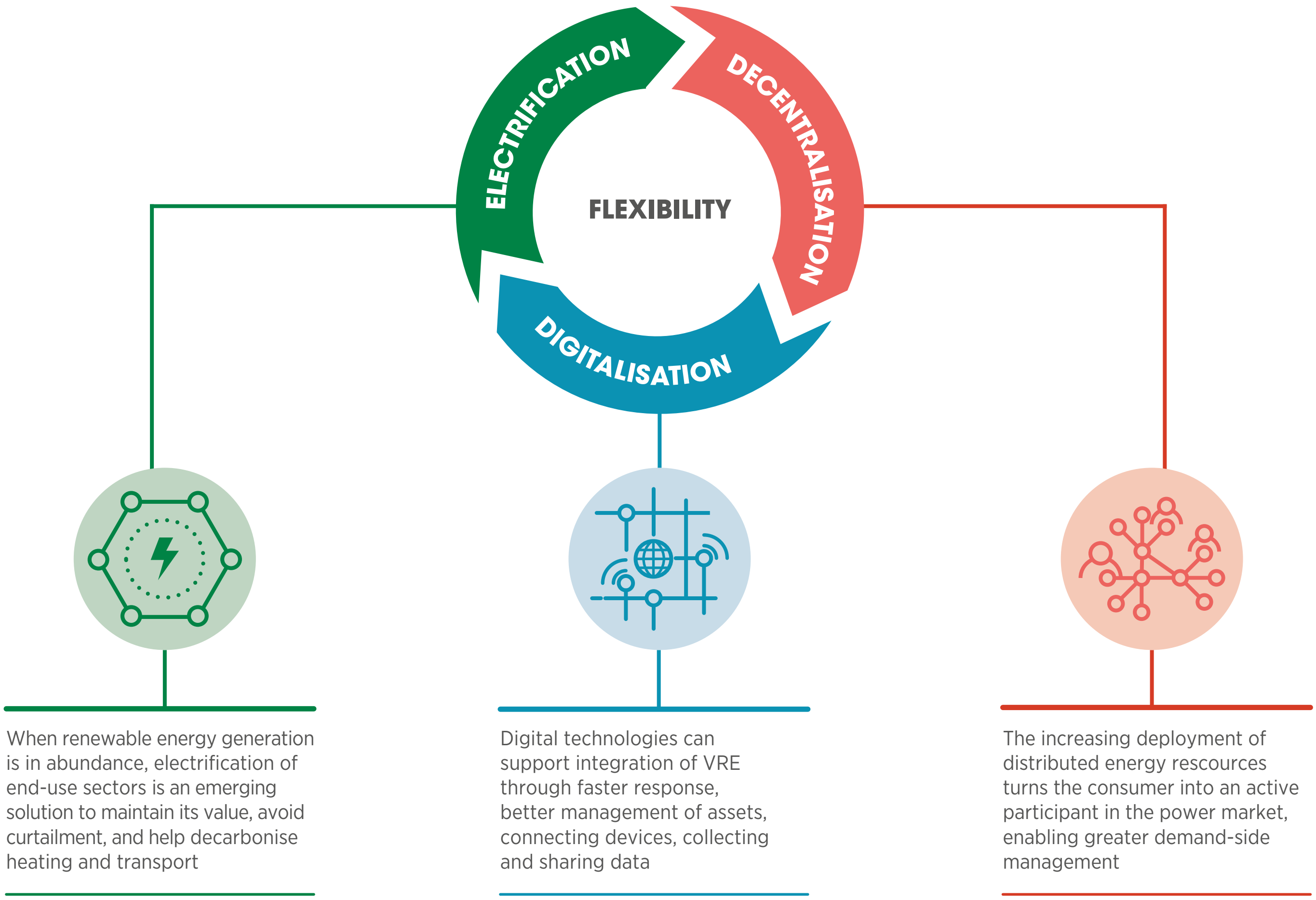
Between 2015 and 2050, investments similar to those needed for additional renewable energy generation technologies could be required for grid infrastructure reinforcement and other flexibility options for VRE integration. Investment needed in grid infrastructure and power system flexibility for this period would rise from USD 9 trillion in IRENA's baseline scenario to around USD 13 trillion in IRENA's scenario compliant with the Paris Agreement (IRENA, 2019a). These investments underline the importance of putting greater effort into addressing flexibility, in order to avoid a situation in which VRE grid integration becomes the technical or economic bottleneck of the global energy sector transformation.

ELECTRIFICATION, DECENTRALISATION AND DIGITALISATION

Policy frameworks for VRE need to combine present needs (for deployment) with future needs (for integrating VRE into the energy system at scale). Real trade-offs exist between quick wins and long-term strategies. In targeting high levels of renewable energy deployment and integration, policy makers should not focus too ardently on quick wins, but rather adopt a forward-looking analysis to a time when renewable energy deployment has already been successful. Markets and systems should therefore be designed around this long-term vision and a new power sector paradigm.

The ongoing power sector transformation is accelerated by three main innovation trends: 1) digitalisation, 2) decentralisation and 3) electrification. These trends are changing paradigms and unlocking power system flexibility for a high share of VRE penetration. At the same time, these trends are changing the roles and responsibilities of actors and opening doors to new entrants in the sector.

Figure 33: Innovation trends driving the power sector transformation



Source: *IRENA, 2019b*

Electrification of end-use sectors

Electrification with renewable power constitutes a cornerstone of decarbonising end-use sectors, including transport, buildings and industry. Consequently, new electricity loads (for example, EVs, heat pumps, electric boilers, etc.) are being connected to power systems at a larger scale, mainly at the distribution level. If not well managed, these new loads can create the need for additional power capacity and may strain the grid, leading to additional investment required for power infrastructure reinforcements.

Conversely, if done in a smart way, these new loads can themselves become a source of flexibility through demand-side management strategies. Many of these new loads are inherently flexible, as (a) they include batteries (for example, EV batteries) or thermal storage (for example, heat pumps or electric boilers with hot water tanks), and (b) their use can be shifted in time, which helps smooth out the demand pattern to match the availability of generation and the capacity of the distribution grid. This optimal contribution to system flexibility will happen only if the integration of these new loads is properly managed and if customers accept that their consumption patterns are not solely their personal choice, but also have benefits for the power system that could be valued and remunerated, for example via automated demand-side response mechanisms.

Decentralisation of power systems

The emergence of distributed energy resources connected at the consumer end is, in effect, decentralising the power system. Distributed energy resources include rooftop solar PV, micro wind turbines, behind-the-meter battery energy storage systems, heat pumps and plug-in EVs. Decentralisation based on distributed energy resources can be an important source of flexibility at the distribution level through, for example, demand response measures and aggregator business models. Active energy consumers, frequently called prosumers because they both consume and produce electricity, are changing the dynamics of the sector, with great potential to unlock demand-side flexibility.

Digitalisation of the power sector

The application of digital monitoring and control technologies in the power generation and transmission domains has been an important trend for several decades and has recently started penetrating deeper into power systems. Wider usage of smart meters and sensors, the application of the Internet of Things and the use of large amounts of data with artificial intelligence have created opportunities to provide new services to the system. Digital technologies support the transformation of the power sector in several ways, including: better monitoring of assets and their performance; more refined operations and control closer to real time; implementation of new market designs; and the emergence of new business models. Digitalisation is a key amplifier of the energy transformation, enabling the management of large amounts of data and optimising systems with many small generation units.

The growing relevance of digitalisation is also related to advancements in decentralisation and electrification. Decentralisation results in a large number of new small generators, mainly rooftop PV. Electrification of transport and heat involves large quantities of new loads, such as EVs, heat pumps and electric boilers. All of these new assets on the supply side, due to decentralisation, and on the demand side, due to electrification, have an impact on power systems, making monitoring, management and control crucial for the success of the energy transformation.

SYSTEMIC INNOVATION

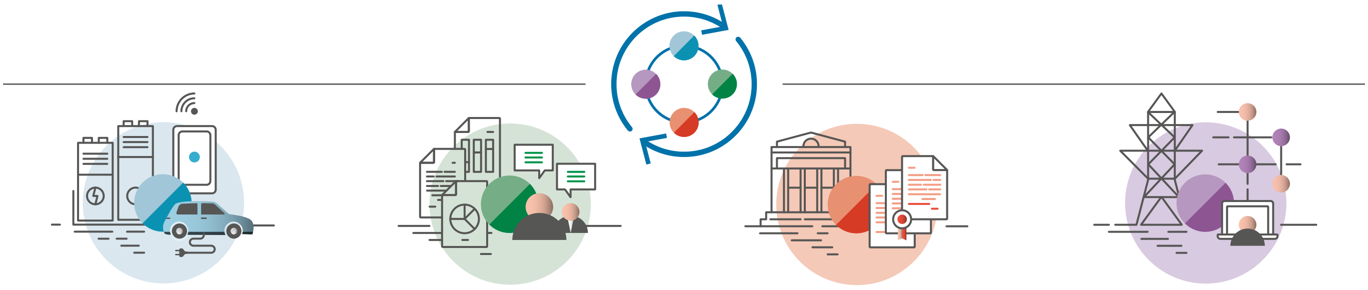
In the report *Innovation landscape for a renewable-powered future*, IRENA investigated the landscape of innovations to facilitate the integration of high shares of VRE. The innovations are categorised into 30 innovation types across 4 dimensions: enabling technologies, business models, market design and system operation (see Figure 34).

Enabling technologies for infrastructure development play an important role in facilitating the integration of renewable energy. Battery storage, together with digital technologies, is changing power sector paradigms and opening doors to various new applications unlocking system flexibility. The electrification of end-use sectors, if done smartly, can emerge not only as a new market for renewables, but also as a flexible demand.

Business models are essential to monetise the new value created by these technologies and hence enable their deployment. Given the deployment of distributed energy resources, several innovative business models emerge at the consumer end, along with innovative schemes enabling renewable energy supply in areas with limited possibilities, such as off-grid or densely populated areas.

Innovation in regulation, such as changes in grid codes, and **market design** is needed, but there should be a balance between stable and predictable regulation that can ensure private sector investments, and flexible regulation that enables innovation. Simultaneously, the speed of regulatory innovation needs to be aligned with the speed of business model and technology innovation. Adapting the market design to new premises becomes crucial to accelerate the energy transition while enabling value creation and adequate revenue streams. Innovation in both wholesale (including ancillary services) and retail markets is required to unlock more of the flexibility potential that already exists in power systems.

Figure 34: IRENA's landscape of innovations for integration of variable renewable energy



ENABLING TECHNOLOGIES

1 Utility-scale batteries
2 Behind-the-meter batteries
3 Electric-vehicle smart charging
4 Renewable power-to-heat
5 Renewable power-to-hydrogen
6 Internet of Things
7 Artificial intelligence and big data
8 Blockchain
9 Renewable mini-grids
10 Supergrids
11 Flexibility in conventional power plants

BUSINESS MODELS

12 Aggregators
13 Peer-to-peer electricity trading
14 Energy-as-a-service
15 Community-ownership models
16 Pay-as-you-go models

MARKET DESIGN

17 Increasing time granularity in electricity markets
18 Increasing space granularity in electricity markets
19 Innovative ancillary services
20 Re-designing capacity markets
21 Regional markets
22 Time-of-use-tariffs
23 Market integration of distributed energy resources
24 Net billing schemes

SYSTEM OPERATION

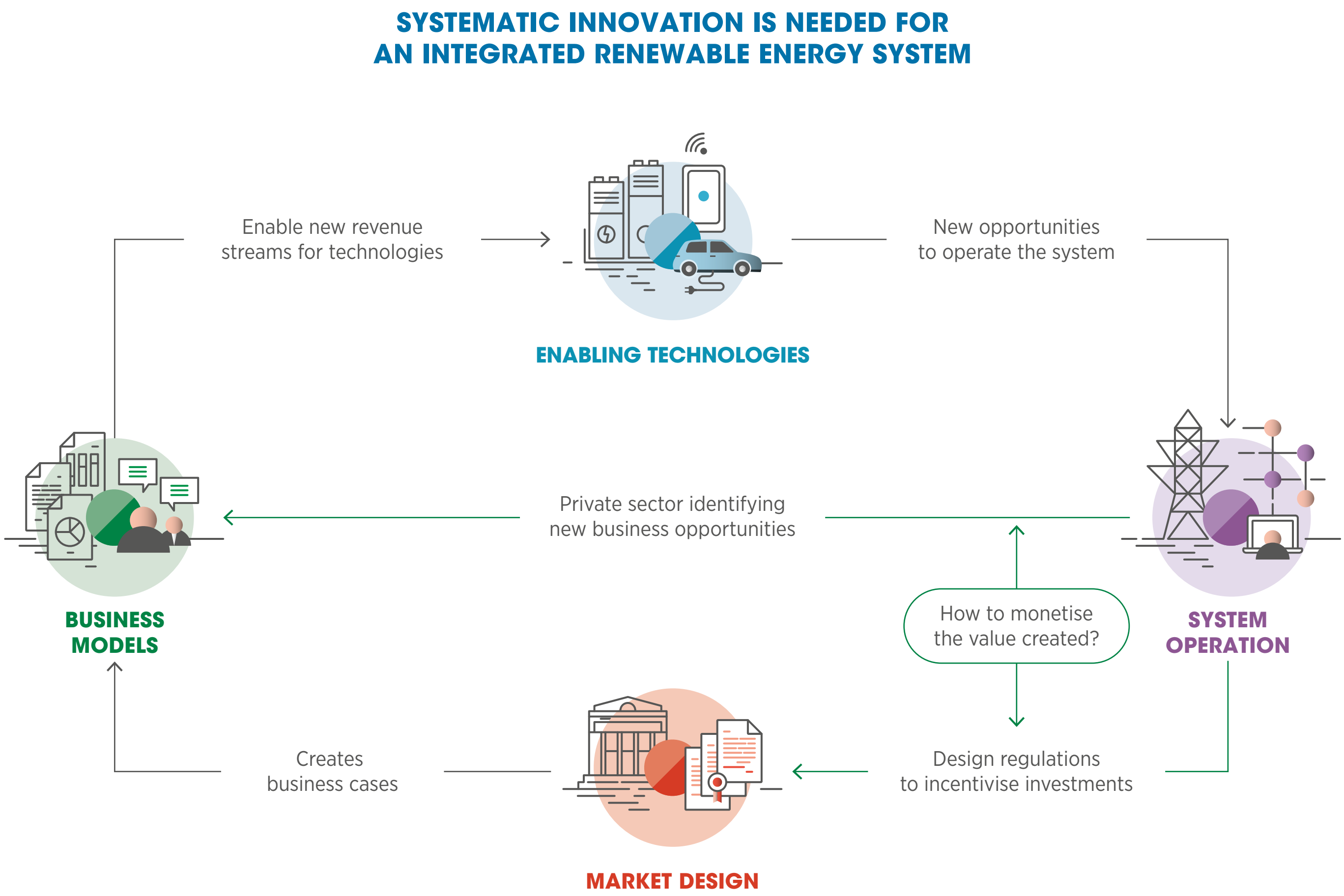
25 Future role of distribution system operators
26 Co-operation between transmission and distribution system operators
27 Advanced forecasting of variable renewable power generation
28 Innovative operation of pumped hydropower storage
29 Virtual power lines
30 Dynamic line rating

Source: *IRENA, 2019b*

With new technologies and a sound market design in place, innovations in **system operation** practices are increasingly emerging in response to the integration of higher shares of VRE into the grid. These include new operational procedures that enhance electricity system flexibility and reduce VRE curtailment with better grid congestion management. Also, distributed generation deployment requires new ways of operating the distribution grid and market facilitation for distributed generation.

Innovations are, therefore, not implemented in isolation. Innovative solutions for VRE integration emerge instead from matching and leveraging synergies among various innovations across all four dimensions: technology, business models, markets and system operation. Without a proper business model, innovations in technologies do not have a real impact. In a similar vein, adapting regulations is necessary for the creation of a framework that enables remuneration mechanisms and new business models for the new technologies. Leveraging synergies among innovations in multiple components of the power system to formulate solutions for a renewable-powered system is called "systemic innovation", as illustrated by Figure 35.

Figure 35: Systemic innovation for power sector transformation



Source: *IRENA, 2019b*

Because a "one-size-fits-all" solution for the penetration of significant shares of VRE does not exist, the design of an optimal strategy for integrating high shares of VRE and the implementation of different innovations depend on the country context and country-specific variables, such as the technical and economic aspects of a given power system. Moreover, different solutions offer increased flexibility in different segments of the power system, from generators to consumers.

The systemic perspective is imperative to harness the benefits and synergies of emerging innovations in complex and increasingly interconnected energy systems

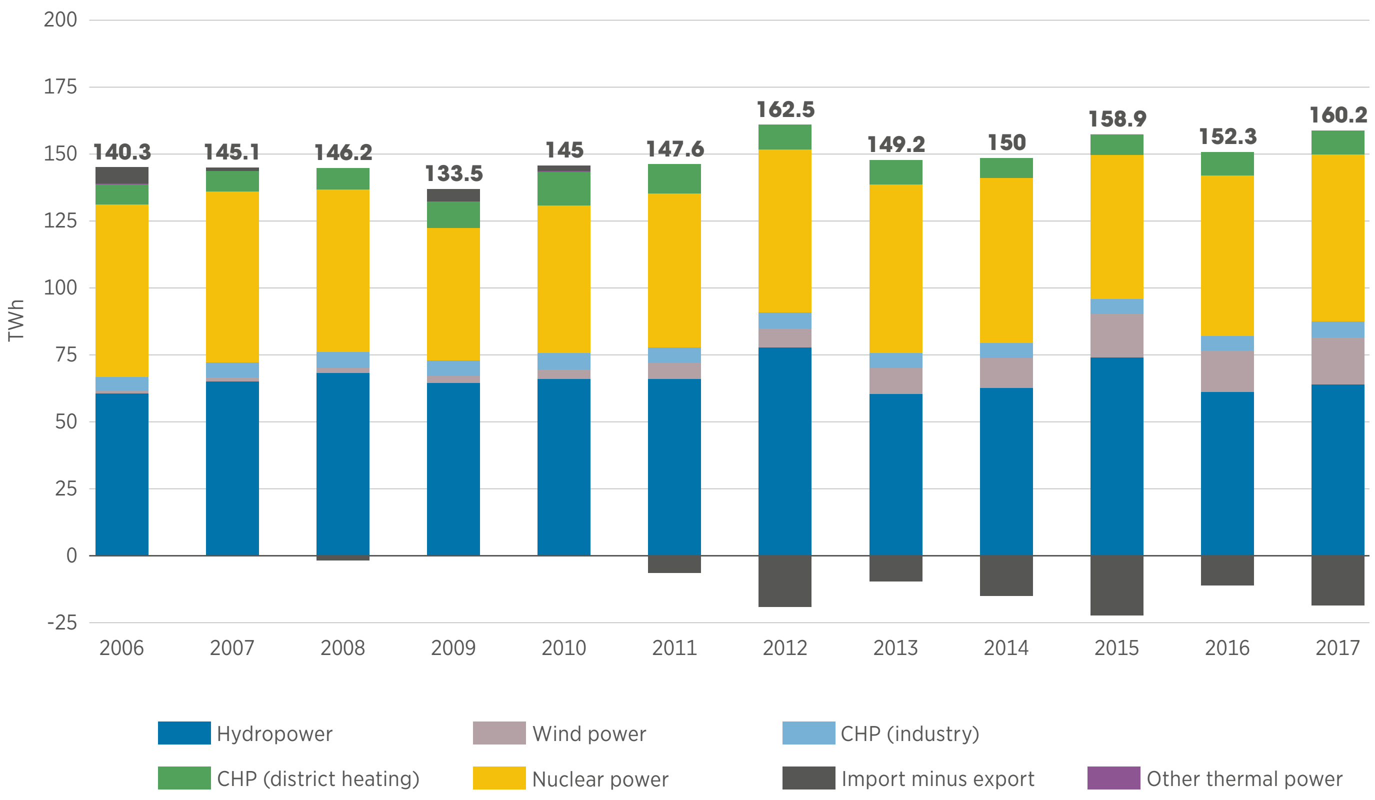
ANNEX 3 – OVERVIEW OF THE SWEDISH POWER SECTOR

KEY POWER STATISTICS

Sweden has an almost fully decarbonised electricity generation system, which since the 1980s has been based on hydropower as well as nuclear power. The share of wind power has been growing rapidly in the past decade as a result of renewables-supporting policies such as the electricity certificate system. In 2017, electricity generation totalled 164.2 TWh, of which 95.1 TWh (or 57.9%) was from renewable electricity (IEA, 2019c).

The rising share of wind generation is a key factor that has made Sweden a constant net exporter of electricity since 2011 (Figure 36). In 2017, net exports amounted to almost 12% of total generation (SEA, 2019a).

Figure 36: Net electricity production in Sweden, 2006–2017 (TWh)



Source: *IRENA based on* SEA, 2019a

The major change in Sweden's installed electricity capacity in the last decade has been the accelerated expansion of wind power (Table 11).

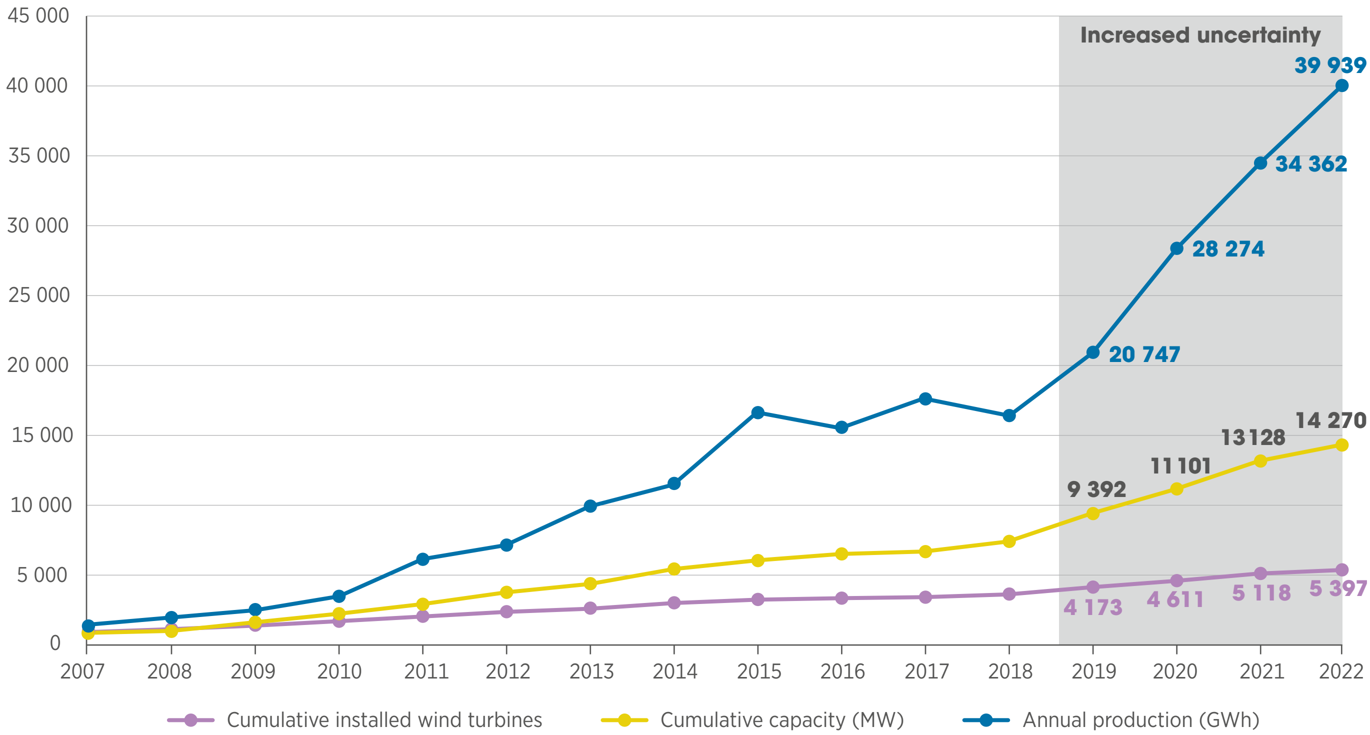
Current forecasts indicate continuously increasing wind power capacity beyond 2020 (Figure 37).

Table 11: Installed renewable energy capacity in Sweden, 2009–2018 (MW)

YEAR	HYDROPOWER	WIND POWER	BIOENERGY	SOLAR POWER	TOTAL
2009	16 652	1 448	4 014	9	22 123
2010	16 732	2 019	4 055	11	22 817
2011	16 577	2 769	4 215	12	23 573
2012	16 414	3 607	4 348	24	24 393
2013	16 494	4 194	4 013	43	24 744
2014	15 996	5 097	4 483	60	25 636
2015	16 329	5 840	4 716	104	26 989
2016	16 466	6 434	4 850	153	27 903
2017	16 502	6 611	4 822	291	28 226
2018	16 506	7 318	4 822	421	29 067

Source: IRENA, 2019h

Figure 37: Actual and forecasted growth in wind power capacity, base case scenario, 2007–2022



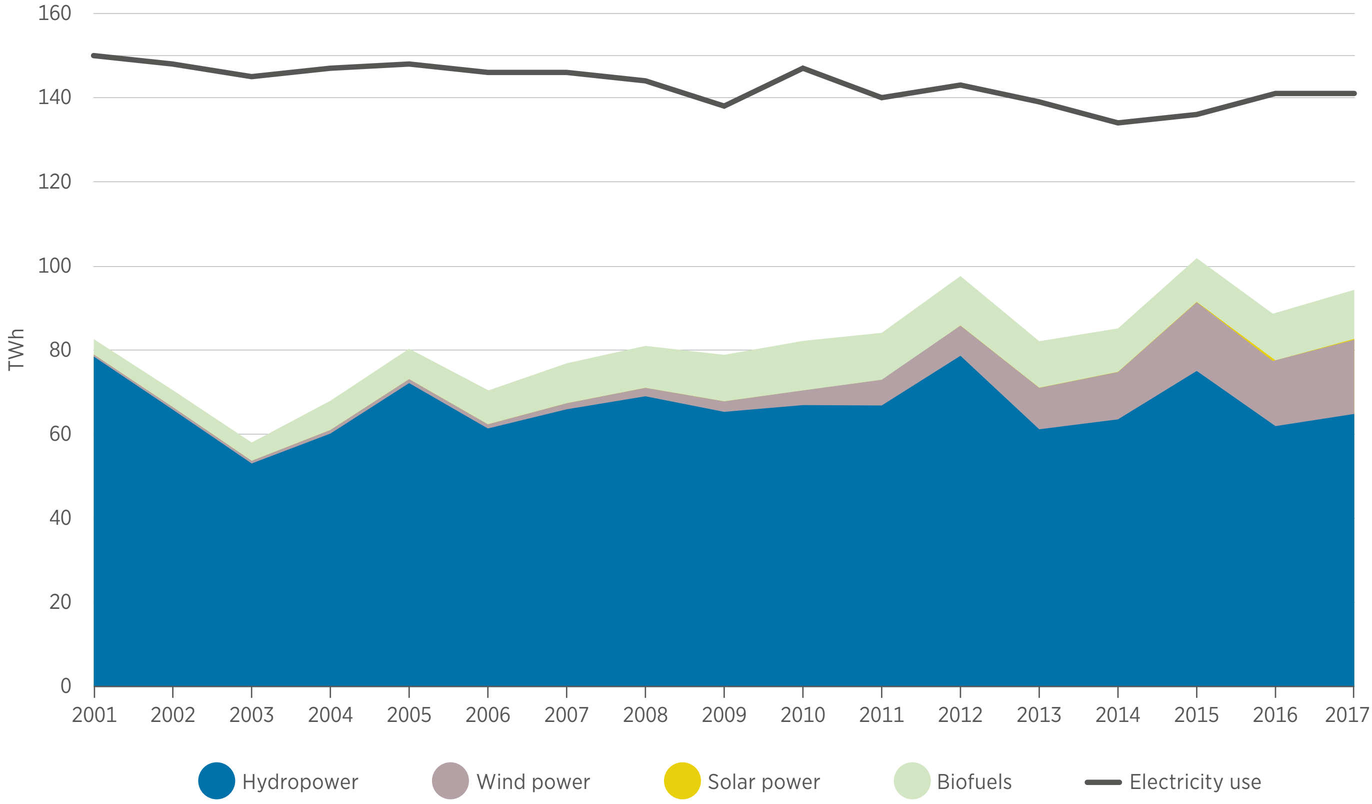
Note: *The "base case" scenario is considered by Svensk Vindenergi (Swedish Wind Energy Association) to be the most realistic.*

Source: Svensk Vindenergi, 2019

Sweden is a very electricity-intensive nation, with among the highest per capita electricity usage worldwide at more than 13 MWh per person per year. This is due mainly to Sweden's electricity-intensive heavy industry, to the extensive use of electric heating and to low electricity prices (Sarasini, 2009; IEA, 2019c).

Electricity consumption (Figure 38) has remained fairly stable over the past decade, thanks largely to shifts from direct electric heating to more efficient heat pumps, while generation from renewable sources is increasing. Demand varies on a yearly basis depending on temperature variations and business cycles of the industrial sector (Ministry of Infrastructure, 2018). However, in different scenarios the electricity demand is expected to remain relatively stable due to energy efficiency.

Figure 38: Electricity consumption and renewable electricity generation, 2001–2017 (TWh)



Source: *SEA, 2019b*

RENEWABLES POLICY IN SWEDEN

In 2019, Sweden was the EU innovation leader (EC, 2019c). With regard to innovation and technology-led climate change mitigation, the country is frequently characterised as a "forerunner" in its energy policies, reflecting Sweden's ambition to "lead by example" (Pettersson and Söderholm, 2009).

Sweden's early-mover strategy is grounded in the adoption of many policy instruments that were unique at their time of implementation. Renewable power was already an agenda item and received massive subsidies in the Energy Research Program (1975–1978), and Sweden passed the world's first carbon tax in 1991 (Uba, 2010). The electricity market was further liberalised with the establishment of the Nordic electricity market in 1994, and following the adoption of the Energy Act (2002) a system for green electricity trading (green certificates) was introduced. Sweden's current status reflects its long-term and historical commitment to renewables. The wide availability of natural resources for renewable energy is a crucial enabling factor.

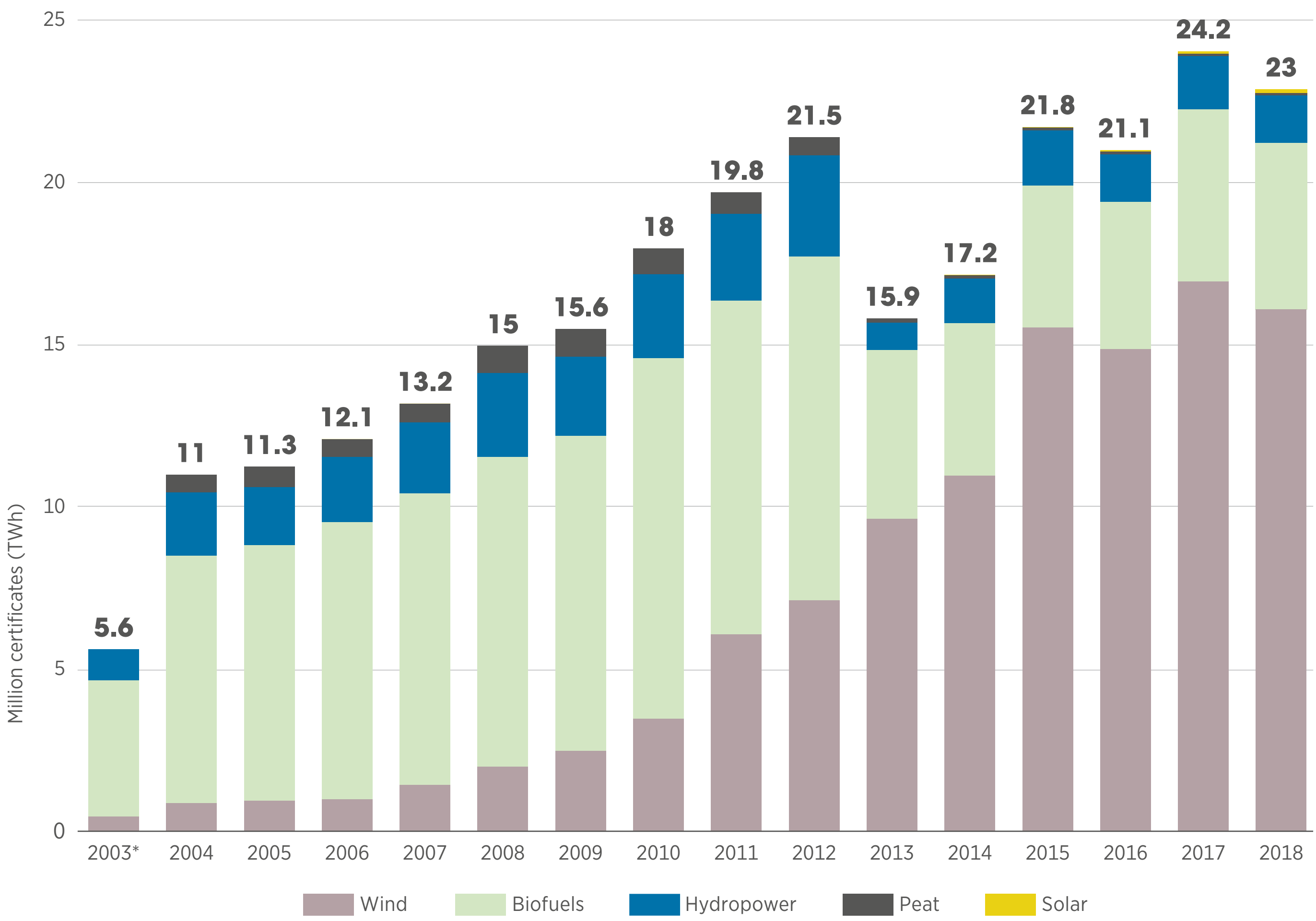
The green electricity quota system (*elcertifikatsystemet*) was introduced in Sweden in 2003 through a mechanism of electricity certificate trading as a support scheme for renewable power. The first quotas were set to increase renewable electricity production by 10 TWh by 2010 and subsequently 25 TWh by 2020, relative to 2002 levels (SEA, 2012).

The quota system is Sweden's fundamental policy instrument to support renewable electricity. Generators receive from the state one "green certificate" for each MWh of renewable electricity produced, over a maximum of 15 years. Consequently, generators sell these certificates to suppliers or industrial consumers that are legally required to cover a proportion of their electricity consumption ("quota obligation") using certified renewable electricity (Fridolfsson and Tangerås, 2013). Renewable electricity generators thus receive revenues from selling both electricity and green certificates, which consequently stimulates production and investments in renewable power generation. Sources entitled to allocation of certificates include power from wind, solar, geothermal, biofuels, wave and certain types of hydro (Figure 39).

Norway joined the quota system in 2012, and a common Swedish-Norwegian target was established of 28.4 TWh by 2020, from a 2012 baseline; this collaboration is due to end by 2036. The Swedish parliament has set a new domestic target of an additional 18 TWh by 2030 (Ministry of Infrastructure, 2018). However, the quota system will be obsolete because more renewable power is actually produced than the target. The overall common Swedish-Norwegian target of 46.4 TWh by 2030 will be met already by 2021 at the latest. Therefore, the prices for the certificates are approaching zero, illustrating the reality that wind power is already cost-competitive today in Sweden without this support mechanism (SEA, 2019b).

Sweden is well placed to continue pursuing innovation, renewable energy and climate policy ambitions at multiple levels

Figure 39: Yearly green electricity certificates allocation by energy source, 2004–2017 (TWh)



* Data for May-December

Source: IEA, 2019c

Note: *The decrease in electricity certificates issued in 2013 is explained by the fact that plants commissioned prior to the implementation of the system were only eligible for certification until the end of 2012 and due to the introduction of more stringent rules for hydropower plants (SEA, 2012).*

CURRENT POLICIES IN SUPPORT OF THE ENERGY TRANSITION

Sweden has traditionally aimed at more ambitious climate and energy targets than what is prescribed in EU directives and regulations. This is exemplified when comparing some EU and Swedish goals by 2020 (Table 12), of which Sweden already fulfilled the first two.

Sweden's long-term energy policy is stipulated in the 2016 Framework Agreement on Energy Policy, which is supported and was adopted in 2018 by a majority of political parties. Before that, the Swedish parliament ratified the Climate Policy Framework in 2017.

Targets from both bills are contained in Sweden's draft integrated NECP, as presented in Table 13 (Ministry of Infrastructure, 2018).

Table 12: EU targets compared to Swedish climate and energy targets by 2020

TYPE OF TARGET	EU	SWEDEN
Share of renewable energy in total energy consumption	20%	50%
Share of renewable energy in transport	10%	20%
Reduction of greenhouse gas emissions (from 1990 levels)	20%	40%

Source: SEA, 2019a

Table 13: Overview of main climate and energy targets in Sweden

TYPE OF TARGET	BASE YEAR	TARGET YEAR	TARGET
Share of renewable energy in gross final energy consumption		2020	50%
Emission reduction from sectors outside the EU Emission Trading Scheme (EU-ETS)	1990	2020	40%
Emission reduction from sectors outside EU-ETS	1990	2030	63%
Emission reduction from sectors outside EU-ETS	1990	2040	75%
Emission reduction from domestic transport	2010	2030	70%
Energy efficiency	2005	2030	50% more efficient energy use
Share of renewable electricity production		2040	100%
No net emissions of greenhouse gases and negative emissions thereafter	1990	2045	100%*

Source: Ministry of Infrastructure, 2018

* The objective is to achieve 85% of this target from domestic reductions. The remaining 15% can be achieved by so-called complementary measures, such as bioenergy with carbon capture and storage and offset measures from non-domestic emission reductions (Naturvårdsverket, 2019).

STRUCTURE OF THE POWER SECTOR

A liberalised electricity market

The Swedish electricity sector has been fully deregulated and liberalised since January 1996, and its legal building blocks were laid out in the 1997 Electricity Act, which has been frequently revised to conform with subsequent EU directives. Liberalising the power sector enabled end-users not only to freely select electricity suppliers but also to directly influence electricity generation by increasingly demanding renewable electricity.

Simultaneously, the liberalisation process engendered a trend of mergers and acquisitions and a dominance of the largest utilities. Currently, the three largest electricity generators – state-owned Vattenfall and private utilities Fortum and Uniper – generate over 70% of total electricity (IEA, 2019c).

To impede cross-subsidisation, power transmission and supply are partitioned through ownership unbundling, and network operations cannot be pursued by the same legal entity generating or trading electricity. Therefore, although electricity generation, distribution and trade frequently are performed within the same corporate body, activities must be separated into distinct legal entities.

In accordance with EU Directive 2009/72/EC, distribution system operators with over 100 000 customers are also functionally unbundled from power trade and generation activities. The Swedish electricity network is operated as a regulated monopoly where the Swedish Energy Markets Inspectorate (the national regulatory authority) regulates network tariffs and supervises the wholesale power market, while the Swedish Competition Authority ensures fair competition (Energimarknadsinspektionen, 2019).

Key power sector institutions

The key institutions in the Swedish power sector are:

- *Ministry of Infrastructure (formerly known as Ministry of Environment and Energy):* the ministry responsible for energy and climate policy;

- *Swedish Energy Agency:* the government agency that funds research and development (R&D), oversees the implementation of policies, provides energy projections and statistics, and administers the electricity certificate system;

- *Svenska Kraftnät:* Sweden's transmission system operator, which operates and owns the high-voltage power grid and is also in charge of the electricity system's short-term balance;

- *Swedish Energy Markets Inspectorate* (EI): the national regulatory authority for electricity, natural gas and district heating markets; and

- *Vinnova:* Sweden's governmental innovation agency, promoting research and development and sustainability.

Regional co-operation

Sweden's electricity market has been praised as a role model for both market liberalisation and regional co-operation. Sweden's electricity wholesale market is part of the common Nordic and Baltic[22] electricity market (operated by Nord Pool) and is fully integrated into the pan-European wholesale electricity market. For example, Sweden's electricity wholesale market is part of the pan-European single day-ahead coupling (SDAC) system, spanning 25 European countries,[23] as well as pan-European single intraday coupling (SIDC) spanning 21 European countries.[24]

22 The Nordic-Baltic market refers to Denmark, Estonia, Finland, Latvia, Lithuania, Norway, Poland and Sweden.

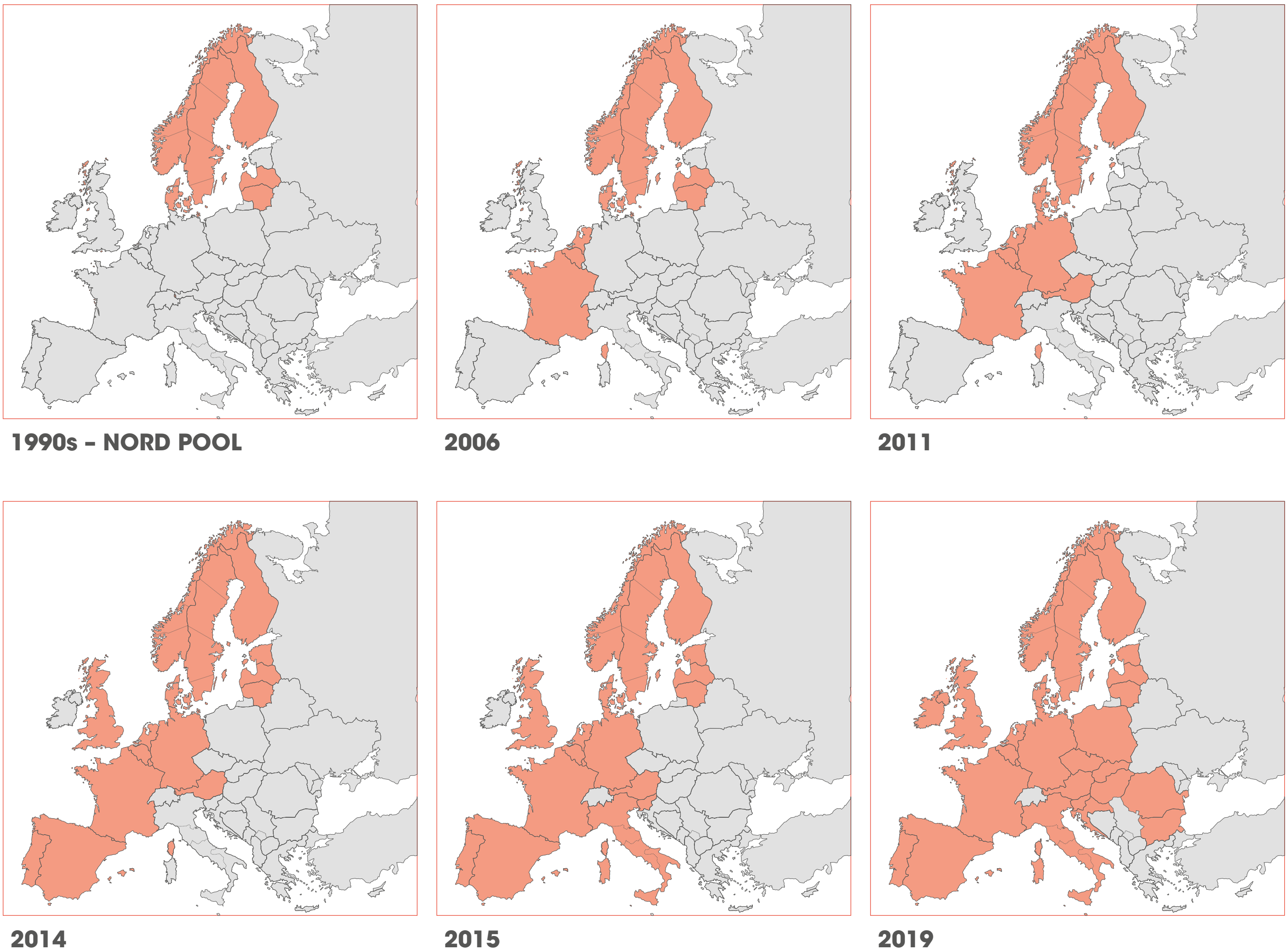
23 The SDAC covers Austria, Belgium, Croatia, the Czech Republic, Germany, Denmark, Estonia, Finland, France, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, the Netherlands, Norway, Poland, Portugal, Romania, the Slovak Republic, Slovenia, Spain, Sweden and the UK.

24 The SIDC covers Austria, Belgium, Bulgaria, Croatia, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Hungary, Latvia, Lithuania, Norway, the Netherlands, Poland, Portugal, Romania, Slovenia, Spain and Sweden.

As shown in Figure 40, the integration of the wholesale market across the EU was a gradual process that started in this region. Moreover, the Nordic electricity market (Eastern Denmark, Finland, Sweden and Norway) now constitutes a single synchronised zone based on mutually shared rules and principles (Bredesen, 2016), while Sweden is also interconnected to the Baltic markets, Germany and Poland, as shown in Figure 41.

During the summit of the Nordic Council of Ministers that took place on 25 January 2019, the prime ministers and ministers responsible for climate in Denmark, Finland, Iceland, Norway and Sweden agreed to strengthen Nordic climate co-operation and adopted a declaration on carbon neutrality, thereby taking a leading role in global efforts to fight climate change (Nordic Co-operation, 2019). The Swedish power system must therefore be considered within the entire regional market.

Figure 40: Gradual integration of the European regional wholesale market (day-ahead time frame)



Source: *Adapted from* ENTSO-E, 2019

Disclaimer: Maps in this report, including the present appendix, do not imply any official endorsement or acceptance by IRENA in regard to country names, borders, territorial claims or sovereignty.

Figure 41: The regional Nordic-Baltic grid

Source: Svenska Kraftnät, 2017

Disclaimer: Maps in this report, including the present appendix, do not imply any official endorsement or acceptance by IRENA in regard to country names, borders, territorial claims or sovereignty.

Within this market, Sweden is a net exporter of electricity and is expected to remain so in the coming decades. The nation's export capacity is 10 575 MW, while the import capacity amounts to 9 645 MW (Table 14).

Table 15 provides an overview of planned network extension and grid development projects in Sweden.

Table 14: Swedish cross-border electricity connections in 2017 (MW)

To	AC (MW)	DC (MW)
Finland	1 500	1 200
Norway	3 995	N/A
Denmark	1 300	680
Germany	–	600
Poland	–	600
Lithuania	–	700

From	AC (MW)	DC (MW)
Finland	110	1 200
Norway	3 995	–
Denmark	1 700	740
Germany	–	600
Poland	–	600
Lithuania	–	700

Source: IEA, 2019c

Table 15: Planned grid developments in Sweden

NAME	AREAS CONCERNED	TYPE	EXPECTED COMMISSIONING
Hansa PowerBridge	Sweden (Hurva) Germany (Güstrow)	700 MW DC cable	2026
Ekhyddan – Nybro	South-eastern Sweden	400 kV AC overhead line	2023
Nybro – Hemsjö	South-eastern Sweden	400 kV AC overhead line	2023
Skogssäter – Stenkullen	Trollhättan and Lerum municipality (south-eastern Sweden)	400 kV AC overhead line	2023
SouthWest Link	Central to south-western Sweden	Part I: 400 kV AC overhead line; Part II: DC connection with a transfer capacity (overhead and underground) of 2 * 600 MW	2015 (Part I) 2020 (Part II)
Storfinnforsen – Midskog	Northern/Central Sweden	400 kV overhead AC line	2021
Öresund cables	Sweden (Kristinelund) Denmark (Skibstrupgård)	400 kV cable connections	2020
Långbjörn – Storfinnforsen	Northern Sweden	400 kV AC overhead line	2020
Lindbacka – Östansjö	Örebro and Hallsbergs municipality (central to southern Sweden)	400 kV overhead AC line replacing old 220 kV line	2021
Messaure – Keminmaa	Sweden (Messaure) Finland (Keminmaa)	400 kV AC interconnection	2025
Anneberg – Skanstull (City Link Phase 2)	Southern Stockholm	400 kV AC cables in a tunnel	2023
Örby – Snösätra (City Link Phase 3)	Southern Stockholm	400 kV AC connection	2021
Snösätra – Ekudden (City Link Phase 4)	Southern Stockholm	400 kV AC connection	2021

Note: *AC = alternating current; DC = direct current*

Source: Svenska Kraftnät, 2019

Wholesale market design

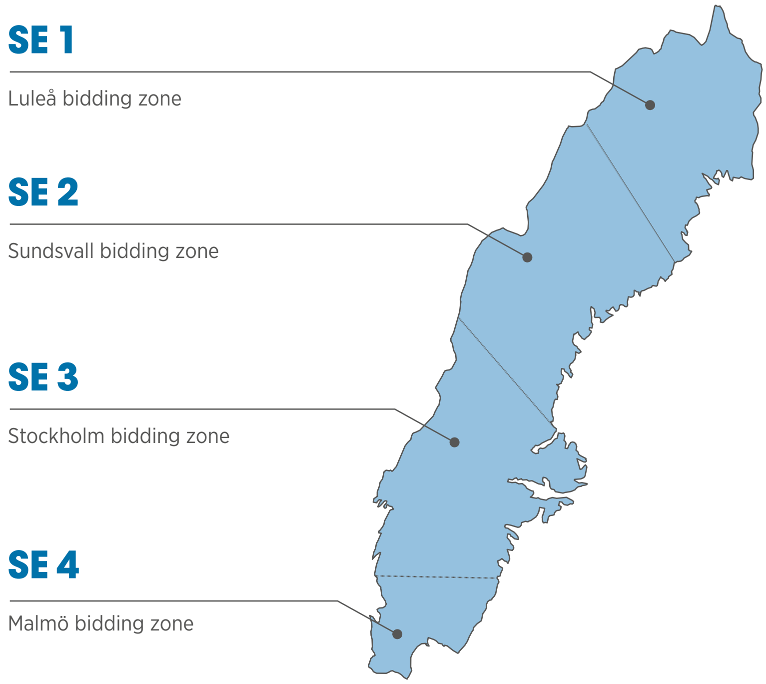
Regulations across all EU member countries are harmonised to ensure the well-functioning of the internal electricity market.

Over 95% of the electricity trading for physical supply in Sweden happens through Nord Pool[25], a regional power exchange encompassing the Nordic-Baltic market and more recently also other markets in the Central-Western European region (Austria, Belgium, France, Germany, Luxembourg, the Netherlands), as well as Poland. Besides Nord Pool, which has been designated as the Nominated Electricity Market Operator (NEMO) in Denmark, Sweden and Finland, a second NEMO, namely EPEX SPOT, intends to offer services for the single day-ahead and single intraday coupling in the Nordic area and whose request was approved by the respective national energy regulators.

Nord Pool operates two types of power markets, the day-ahead Elspot and the intraday Elbas markets. Most trading occurs in the Elspot day-ahead market (387.3 TWh in 2017), although the intraday volume (6.7 TWh in 2017) is increasing. Until the trading gate closure, which is currently limited to one hour before real-time delivery, Nord Pool is in charge of the power market. Following gate closure, responsibility for the Swedish grid is transferred to the transmission system operator (Swedish Smartgrid, 2019a).

To manage transmission congestion more effectively, the Nordic market is split into different price zones, while the national wholesale market in Sweden is split into four bidding zones, as shown in Figure 42.

Figure 42: Bidding zones in Sweden



Source: ENTSO-E, 2015

25 The Nordic and Baltic day-ahead market operated by Nord Pool registered a record 396 TWh of exchanged power in 2018 (Nord Pool, 2019).

With the current market design, cross-zonal transmission capacity should be used in the "right economic direction", *i.e.*, from low- to high-price bidding zones, in the presence of a price differential across a given border between two zones. Because a price differential illustrates congestion, zonal pricing provides both price signalling of electricity's marginal value and investment incentives, while reducing the need for transmission system operators to manage congestion by re-dispatching or countertrading (ACER, 2018). Most price differences occur between the southern price areas (SE3 and SE4) and the northern zones (SE1 and SE2) (Svenska Kraftnät, 2017).

Despite these price differences, wholesale electricity prices in the Nordic region have remained fairly low in recent years, with day-ahead prices ranging between EUR 20 and EUR 40 (USD 22 and USD 45) per MWh, which can be explained in Sweden mainly by its surplus capacity, stagnating demand and low-cost resources. With an additional 23 GW of wind capacity expected in the Nordic market by 2025, more power system flexibility is needed in neighbouring countries as well, which has motivated Nordic transmission system operators to provide joint balancing services, to combine balance settlement processes and to develop a Nordic capacity market for automatic as well as manual frequency restoration reserves (Statnett, 2017b). Nord Pool allows negative prices as a price signal on the electricity wholesale market when inflexible power generation meets low demand.

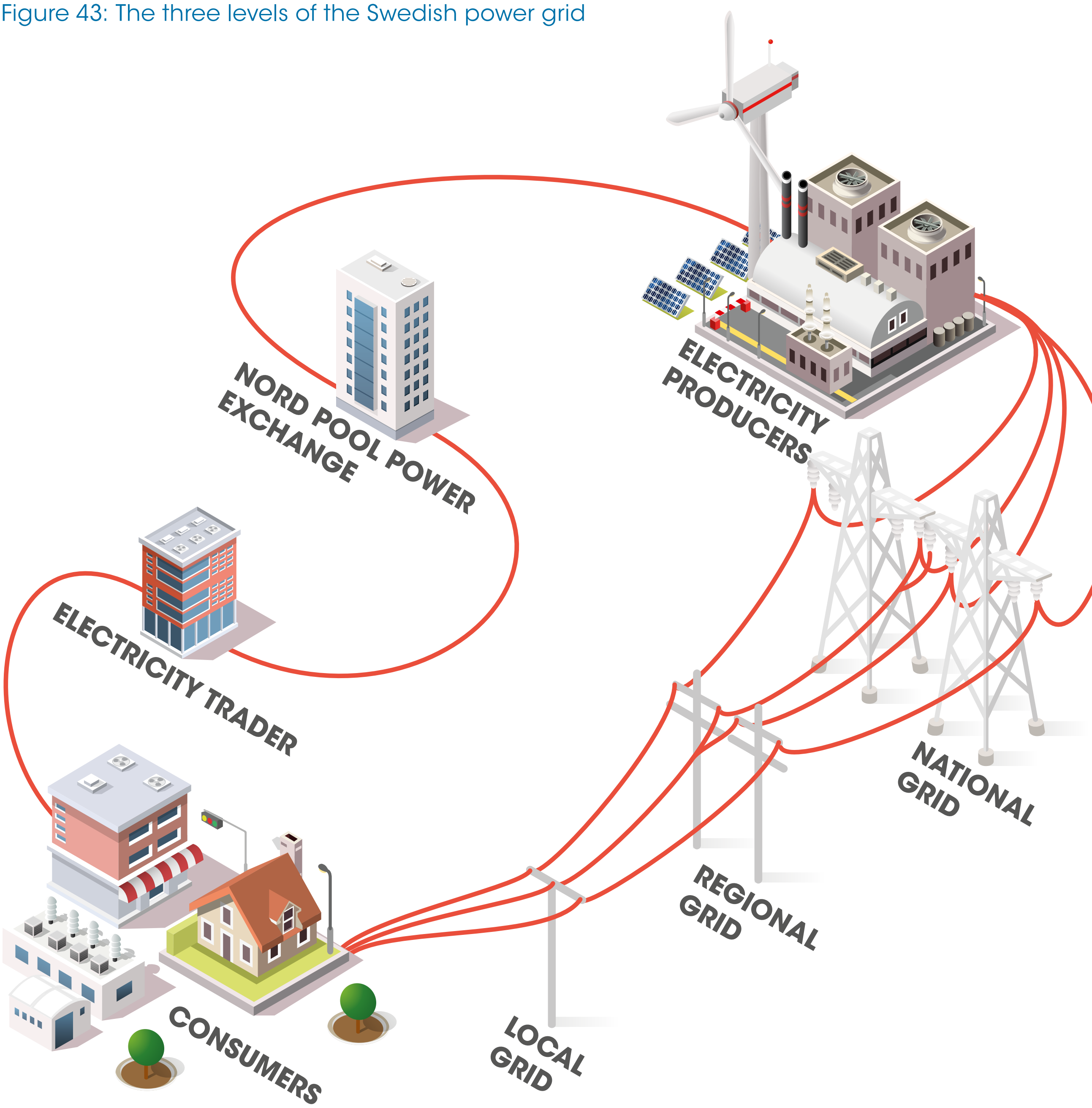
Over 95% of the electricity trading for physical supply in Sweden happens through Nord Pool

Transmission and distribution networks

The Swedish network is divided into three levels: the national transmission network operated by Svenska Kraftnät, as well as the regional and local grids which are both classified as distribution networks. These three grids have different voltages and are owned by distinct grid operators (Swedish Smartgrid, 2019a). Sweden's high-voltage transmission network is owned and operated by the state-owned transmission system operator Svenska Kraftnät, which is entirely unbundled from other activities in the power sector. The transmission network spans from the north (where most of Sweden's hydropower and wind power is produced) to the consumption hubs in the south and consists of 220 kV and 400 kV cables (SEI, 2015).

The regional grid connects to the national grid via converters and has a lower voltage, *i.e.*, 40–130 kV (SEI, 2015). The three largest distribution operators, which own and manage most of the regional network and each have over 800 000 customers, are Ellevio, state-owned Vattenfall Eldistribution and E.ON Energidistribution (Swedish Smartgrid, 2019a). The local grids with voltage levels of 20 kV or lower are, also via converters, connected to the regional grid. In distribution zones, electricity is transformed to low voltage (400/230 volts) and transported to the end-consumers (SEI, 2015). Power generated by small-scale electricity generation is further directly fed into the local grids. Overall, more than 170 distribution system operators manage local grids in Sweden and these are owned either by the state, the municipality or economic associations, while there is a strong municipal ownership (SEA, 2019a).

Figure 43: The three levels of the Swedish power grid



Source: SEI, 2015

Retail market design

Sweden's 5.4 million electricity customers are served by over 120 suppliers, with the three largest (Vattenfall, E.ON and Fortum) supplying around 40% of all power consumers; this leads regulators to characterise market competition as fair (Energimarknadsinspektionen, 2018).

Thanks to 100% penetration of smart meters, dynamic price tariffs are becoming increasingly common. As in other Nordic nations, Sweden is leaning towards a centralised information exchange system in which all metering data are concentrated in the so-called data hub. Both Svenska Kraftnät and Swedish Energy Markets Inspectorate are in charge of the data hub's development, which is expected to facilitate the aggregation of demand-side response capacity. Once the data hub is operational (expected by 2022 at the earliest), Svenska Kraftnät will be in charge of operating it (Svenska Kraftnät, 2018b).

ENERGY INNOVATION IN SWEDEN

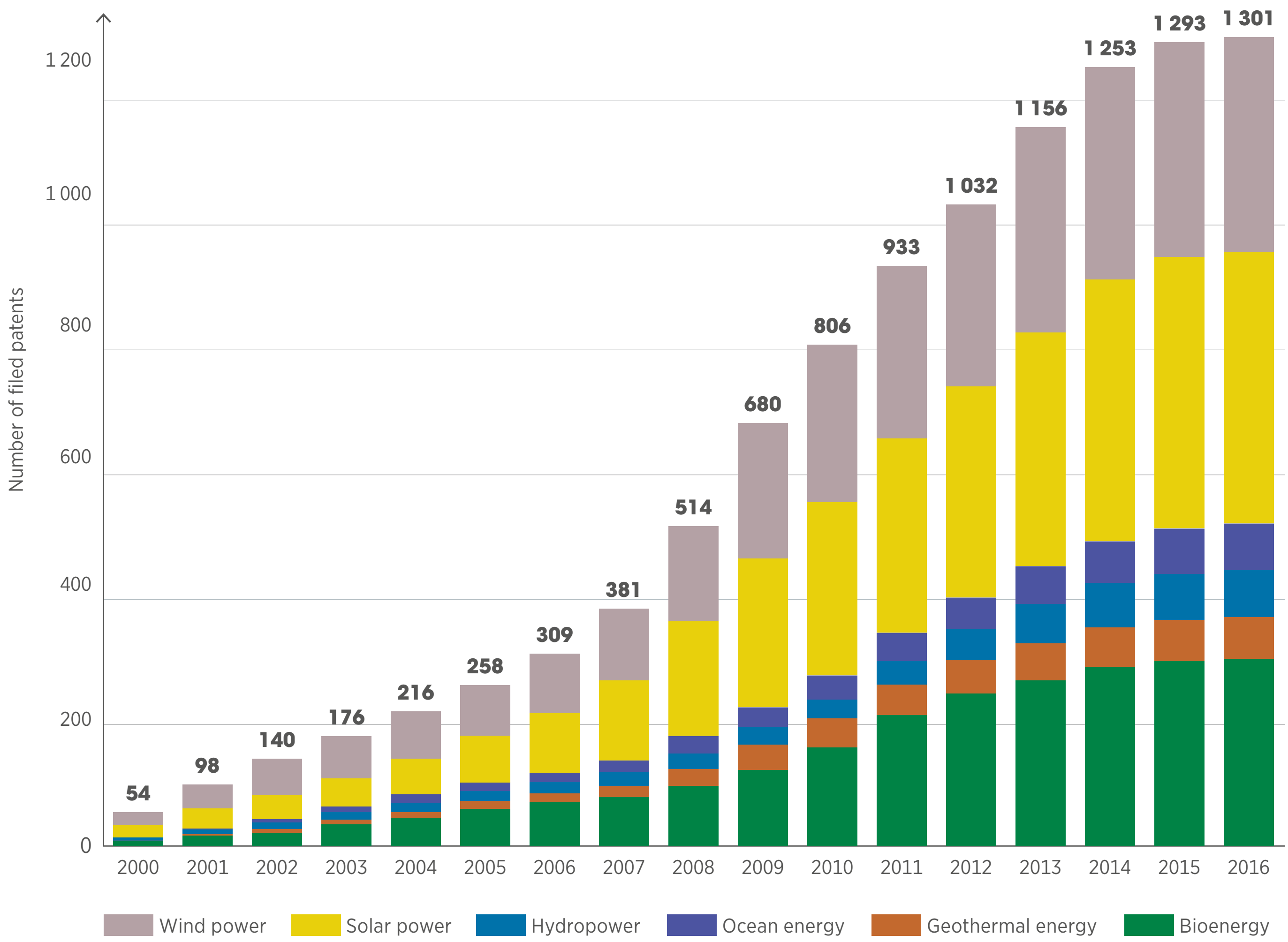
Public spending on research and innovation

Sweden's commitment to renewable power is not only backed up by specific policy instruments, such as electricity certificates, but also demonstrated via strong support for R&D for renewable energy technologies. This is true for most Nordic nations, in which R&D expenditures are more than 0.7% greater than the EU average of around 2% of GDP.

Nordic R&D spending has increased greatly in recent years, particularly thanks to research programmes and initiatives focused on achieving carbon neutrality targets (IEA, 2016). By accounting for around 6% of total revenues and employment in the Nordic region, energy innovation is an essential economic activity. Moreover, exports of energy technology and related equipment represent up to 9% of industrial exports (Irandoust, 2018).

Shortly after the oil crisis in 1972, Sweden drew its attention to many domains of low-carbon energy research, with a strong focus on energy efficiency, solar, wind and bioenergy (Nordic Energy Research, 2015). This is further exemplified by the increasing number of patents filed in these categories (Figure 44).

Figure 44: Evolution of patents for renewable technologies (cumulative annual data) in Sweden



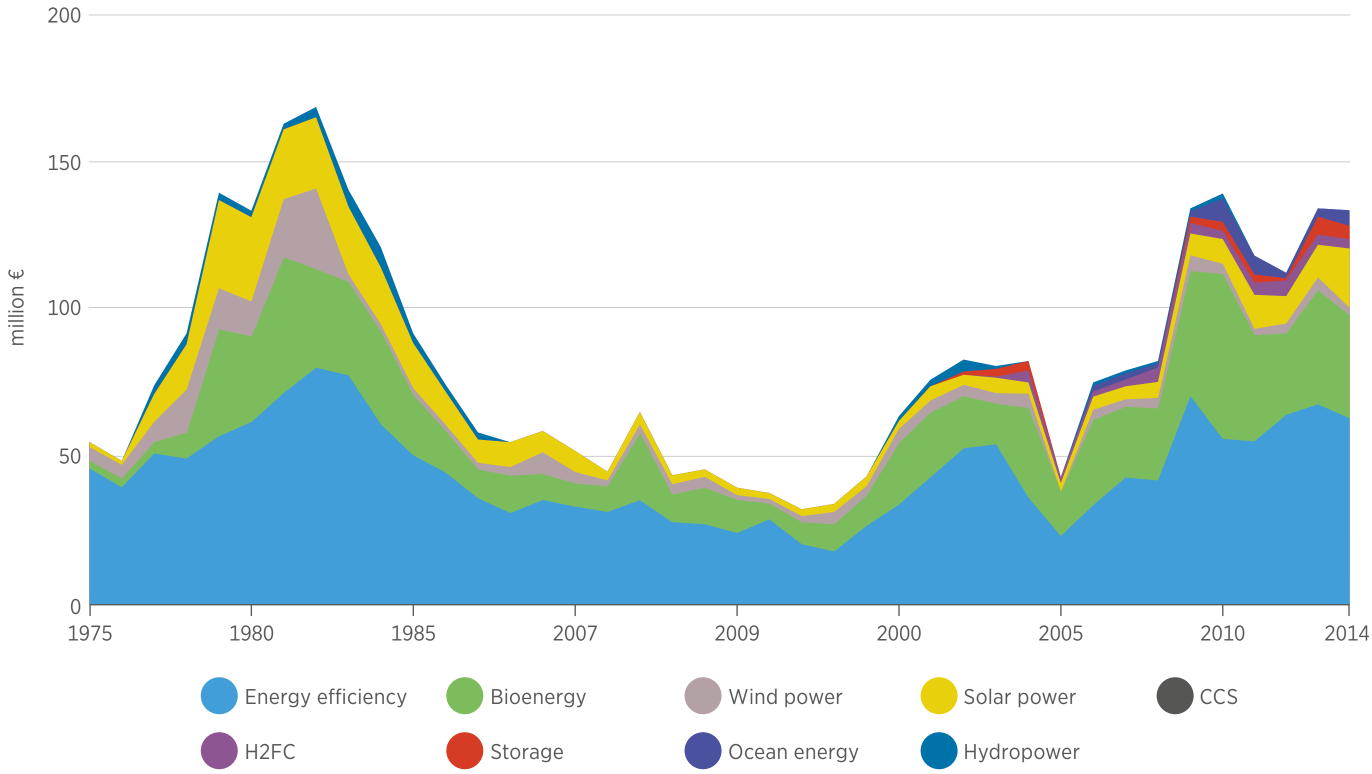
Source: IRENA-INSPIRE, 2019

In the Nordic region, Sweden ranks second after Norway in R&D spending, with around 3.5% of its GDP spent on general R&D. Although government spending on low-carbon R&D is lower than it was in the 1980s, recent trends – with an increasing focus in innovative areas of energy research, including ocean energy and energy storage as well as in other enabling technologies such as electromobility and EV smart charging – suggest that similar high levels will be achieved in the near future (Figure 45) (Nordic Energy Research, 2015).

This is further demonstrated by the Swedish Energy Agency's rapidly increasing funding for research and innovation in recent years and the positive trend in patents filed in enabling technologies (Figure 46).

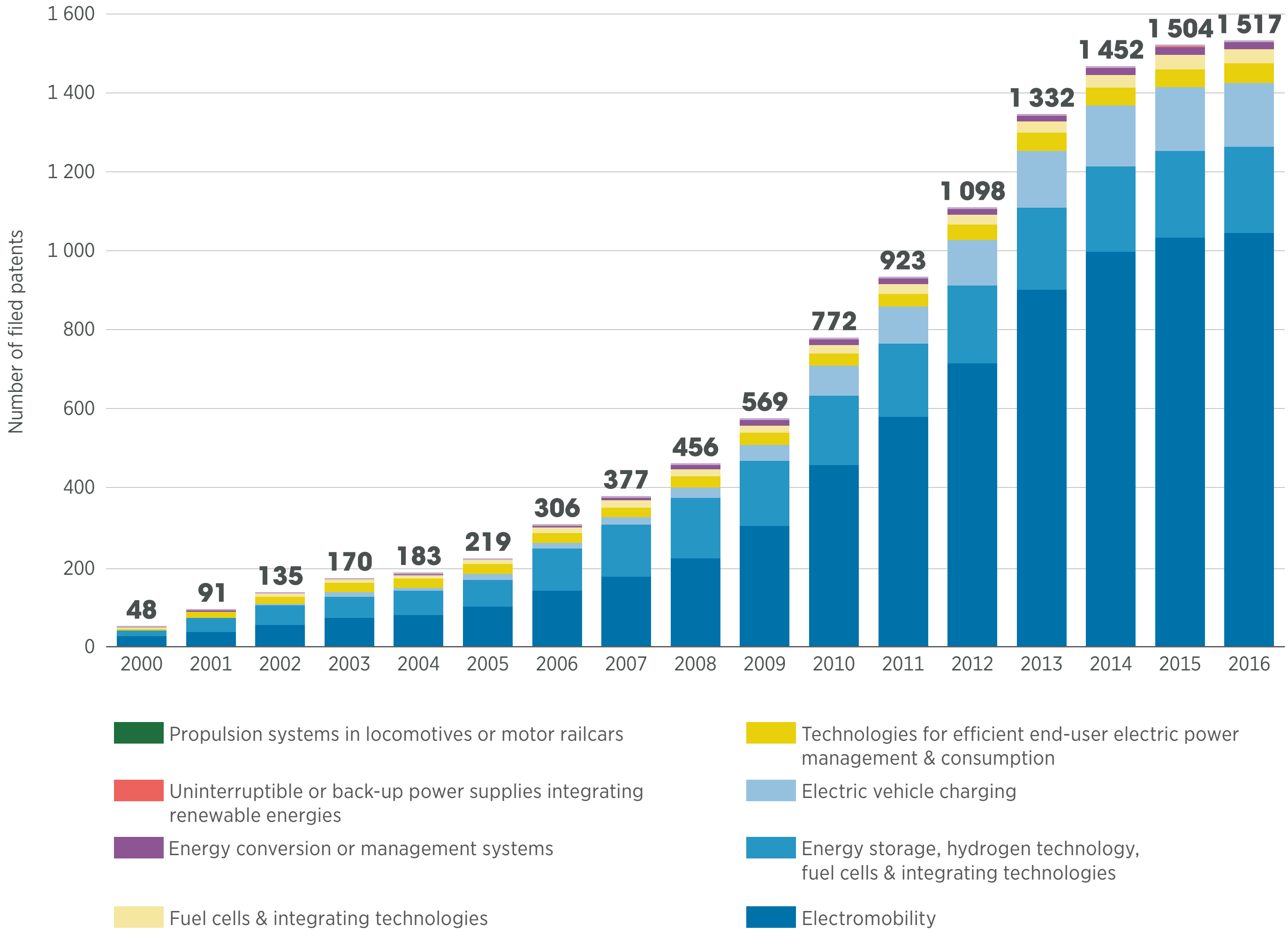
As can be seen in these figures, a correlation is apparent between R&D spending and accelerated innovation growth in certain areas.

Figure 45: Government R&D spending on low-carbon energy in Sweden



Source: Nordic Energy Research, 2015

Figure 46: Patents filed in enabling technologies by category in Sweden, 2000–2016



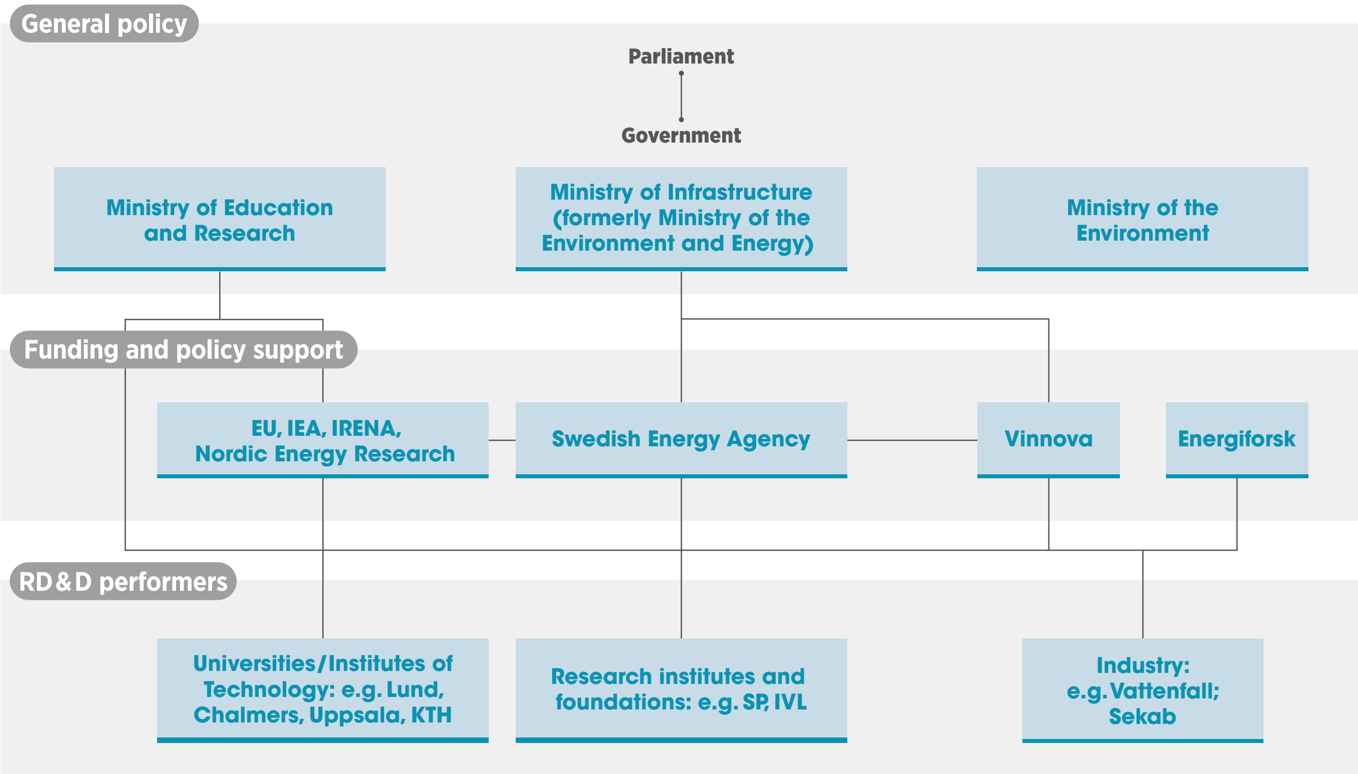
Source: IRENA-INSPIRE, 2019

Key innovation institutions

Efforts in energy research and innovation are primarily co-ordinated through the Swedish Energy Agency and the government innovation agency Vinnova. Additionally, Energiforsk (former Elforsk) is a research institute initiated by the Swedish power sector, which, together with the publicly funded Swedish Energy Agency, invests in R&D in several strategic areas. The main R&D institutions in Sweden are shown in Figure 47.

Collaboration among various actors and sectors, from industry and research institutions to local authorities and citizens, is actively stimulated to enable a more holistic and dynamic approach to innovation. Therefore, energy research not only focuses on technological development but also targets market design, infrastructure and business models as well as behavioural considerations (Mission Innovation, 2019). Sweden's systemic innovation approach, which cuts across sectors and disciplines to encourage co-operation and interaction, is expected to help accelerate the transition towards a completely renewable energy system (Ministry of Infrastructure, 2018).

Figure 47: Swedish R&D institutions



Source: *Nordic Energy Research, 2013*

Research and innovation ambitions

Sweden's energy research and innovation programme is based on the 2017 Act on Energy Research and Innovation for Ecological Sustainability, Competitiveness and Security of Supply. Innovation is thus an integral component of both Sweden's research and energy policy. Moreover, innovation is perceived as a significant means to meet the goals of 100% renewable power by 2040 and net zero carbon emissions by 2045 in a cost-effective manner (Mission Innovation, 2019).

More specifically, as highlighted in the country's draft NECP, Sweden's ambitions in energy research and innovation should encourage interdisciplinary collaboration and interaction in the energy system to accelerate the transition towards renewable-powered energy systems, among others (Ministry of Infrastructure, 2018).

The Swedish government initiates actions under the National Energy Research and Innovation Programme, which aims to address all value chains in the energy system. Between 2017 and 2020, with the intention to span entire innovation systems, the programme covers and enables innovation efforts in nine thematic areas (Ministry of Infrastructure, 2018): 1) transport system, 2) bioenergy, 3) buildings in the energy system, 4) electricity generation and power system, 5) industry, 6) sustainable society, 7) general energy systems studies, 8) business development and commercialisation, and 9) international co-operation.

Examples of innovation initiatives for renewable energy

In addition to the National Energy Research and Innovation Programme, Sweden has implemented many other innovation initiatives at the national, regional and international levels.

At the national level, the Swedish government has planned the Industrial Leap, under which SEK 300 million (USD 32 million) will be invested annually from 2018 to 2040 to reduce industrial process-related greenhouse gas emissions (SEA, 2019a). In addition, a 10-year national climate research programme administrated by Formas, Sweden's research council for sustainable development, is encouraging intersectoral research and innovation to achieve Sweden's goal to evolve into a fossil-free society. Around SEK 130 million (USD 14 million) is to be spent on this programme yearly between 2019 and 2026 (Formas, 2018). In another noteworthy example, the Swedish Smart Grid Forum has been appointed to develop measures aiming to increase flexibility in power systems using smart grids (Swedish Smartgrid, 2019b).

Sweden actively collaborates with Nordic countries on energy research and innovation as part of the Nordic Energy Research Programme (Ministry of Infrastructure, 2018).

The programme finances and organises cross-border energy research that is of mutual interest to stakeholders in the Nordic region, such as the Flex4RES project that assesses how to integrate higher shares of VRE through energy market coupling across the Nordic and Baltic regions (Nordic Energy Research, 2019).

Finally, Sweden's energy research is prominent in the international research community, with the country leading and engaging in long-term inter-governmental co-operation and campaigns via Mission Innovation, the EU's Horizon 2020 and Strategic Energy Technology Plan, and the Clean Energy Ministerial. Within the Mission Innovation initiative, of which Sweden was a founding participant, the Swedish government recently decided to double allocated budgets for transformative long-term energy research and innovation projects, which have been initiated bottom-up from academia and/or industry (Mission Innovation, 2019).

Overall, Sweden's innovation policy framework, with clear visions and objectives, highlights that research and innovation not only are perceived as fundamental for meeting energy and climate targets but also are of strategic significance, with a strong focus on fostering competitiveness, international co-operation, and scientific and technological leadership.

Table 16: Examples of Swedish energy innovation collaborations and/or initiatives at different levels

INTERNATIONAL LEVEL
Mission Innovation – Clean Energy Ministerial
EU LEVEL
Horizon 2020 – Strategic Energy Technology Plan
REGIONAL LEVEL
Nordic Energy Research Programme
NATIONAL LEVEL
Industrial Leap – Swedish Smart Grid Forum – National Energy Research and Innovation Programme – National Climate Research Programme

International Renewable Energy Agency

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