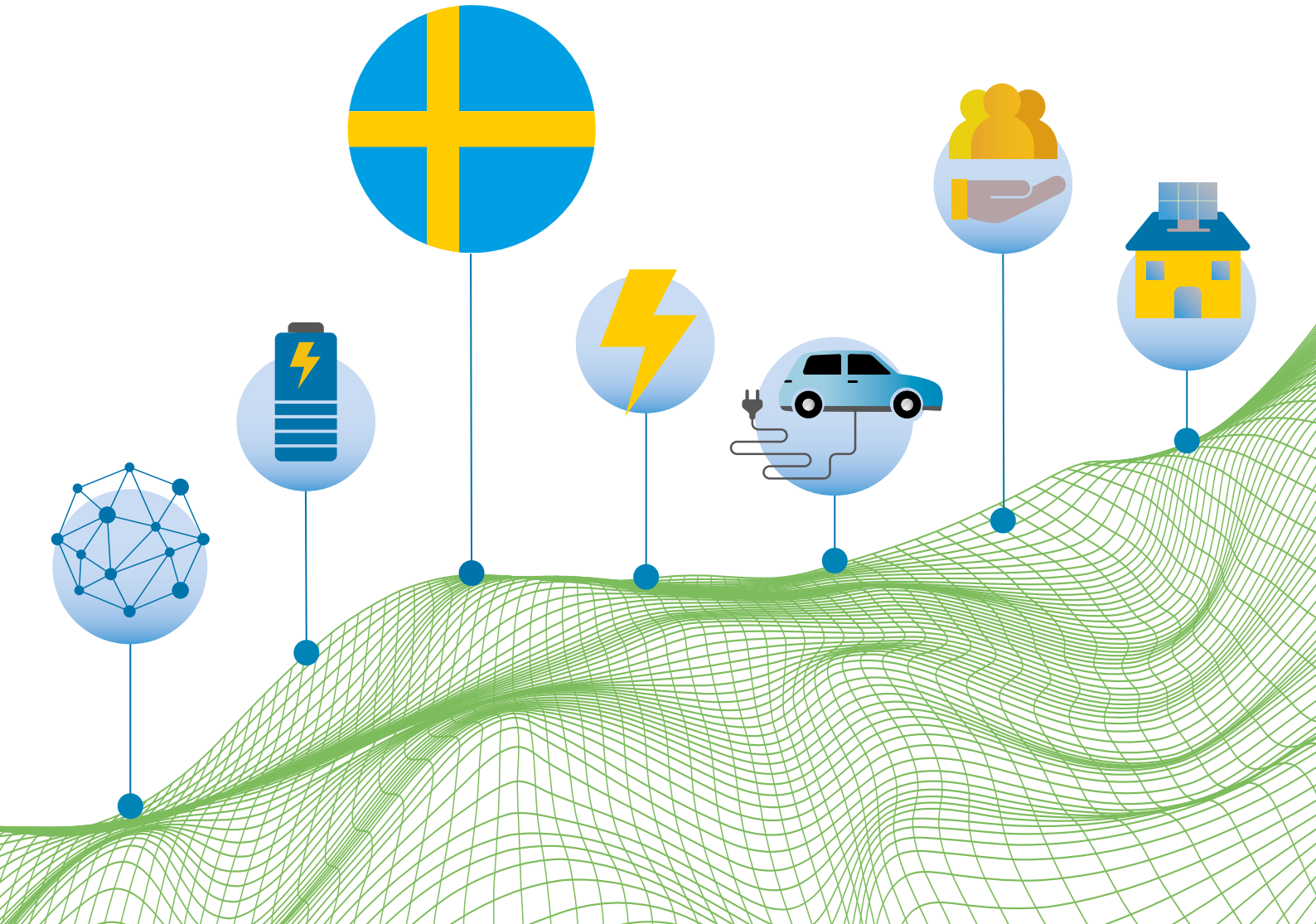
IRENA
International Renewable Energy Agency

INNOVATIVE SOLUTIONS FOR 100% RENEWABLE POWER IN SWEDEN

SUMMARY FOR POLICY MAKERS



This document summarises 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**

Disclaimer

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.

Figure 1 outlines eight key interrelated challenges, while **Table 1** looks at these challenges in more detail and highlights the need for flexibility in the time scale for addressing them.

Figure 1: Challenges for 100% renewable power in Sweden

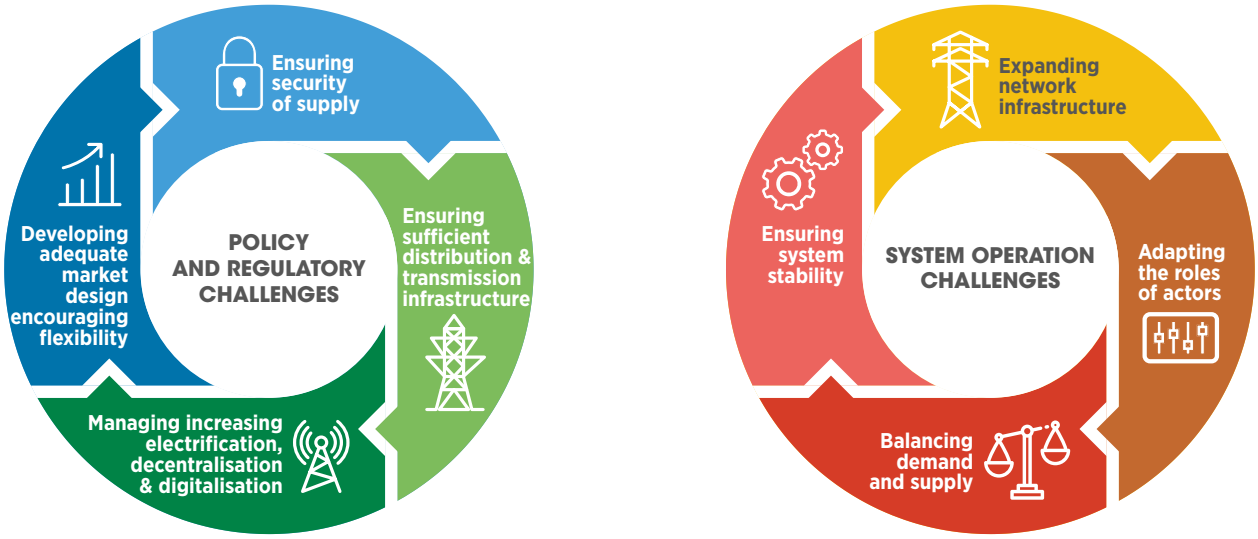


Table 1: Timescale flexibility needs across the value chain of the power system

POLICY AND REGULATORY CHALLENGES	SYSTEM OPERATION CHALLENGES	FLEXIBILITY TIMESCALE NEEDED	FLEXIBILITY NEED IN THE POWER SYSTEM VALUE CHAIN
Developing an adequate market design encouraging flexibility	Ensuring system security and stability and accessing adequate ancillary services	Seconds to minutes	Supply side flexibility solutions
Developing an adequate market design encouraging flexibility	Ensuring system security and stability and accessing adequate ancillary services	Seconds to hours	Grid flexibility solutions
Managing increasing decentralisation and digitalisation	Division of responsibilities to effectively manage the system	Seconds to hours	Grid flexibility solutions
Ensuring security of supply	Daily balancing of supply and demand in the context of wind shortage or surplus	Minutes to days	Demand flexibility solutions
Ensuring adequate grid infrastructure	Network congestions and long lead times for new networks projects to be implemented	Minutes to hours	Demand side flexibility solutions
Ensuring security of supply	Daily balancing of supply and demand in the context of wind shortage or surplus	Seconds to months	Demand side flexibility solutions

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.

Innovative solutions combining innovations in enabling technologies, business models, market design and system operation tackle different challenges at various points in the value chain

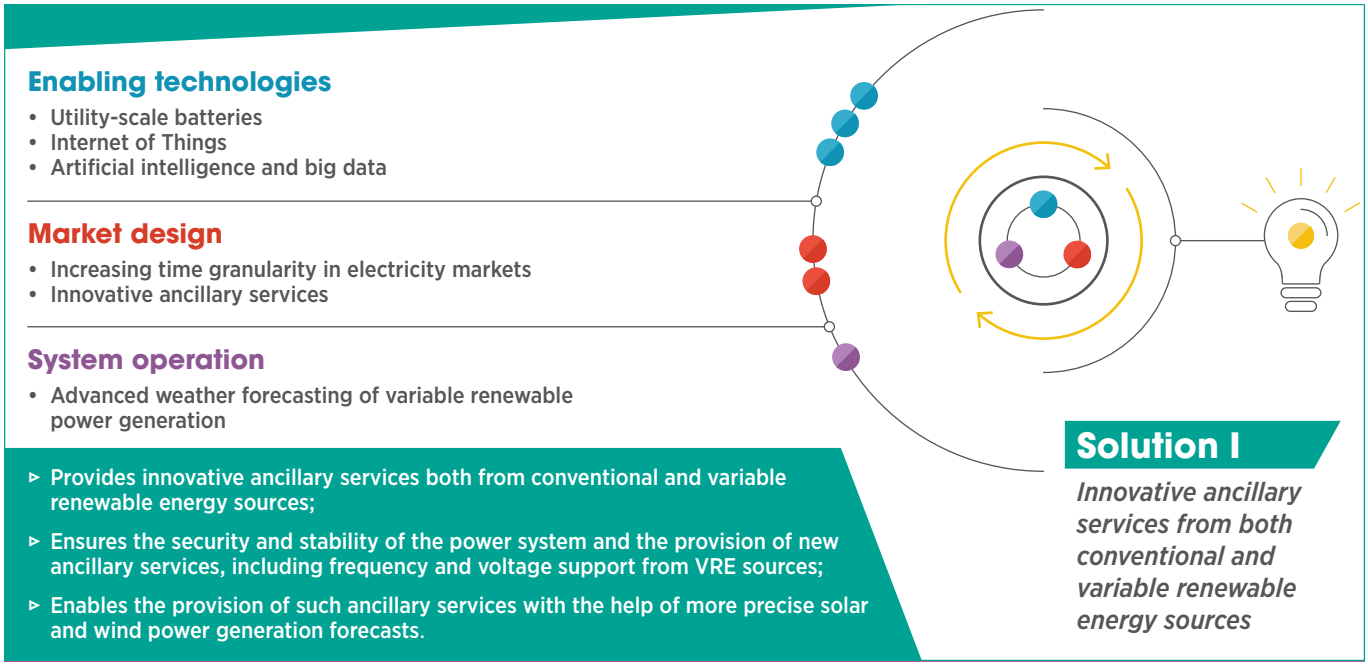
TAILOR-MADE, SYSTEM-WIDE, INNOVATIVE SOLUTIONS

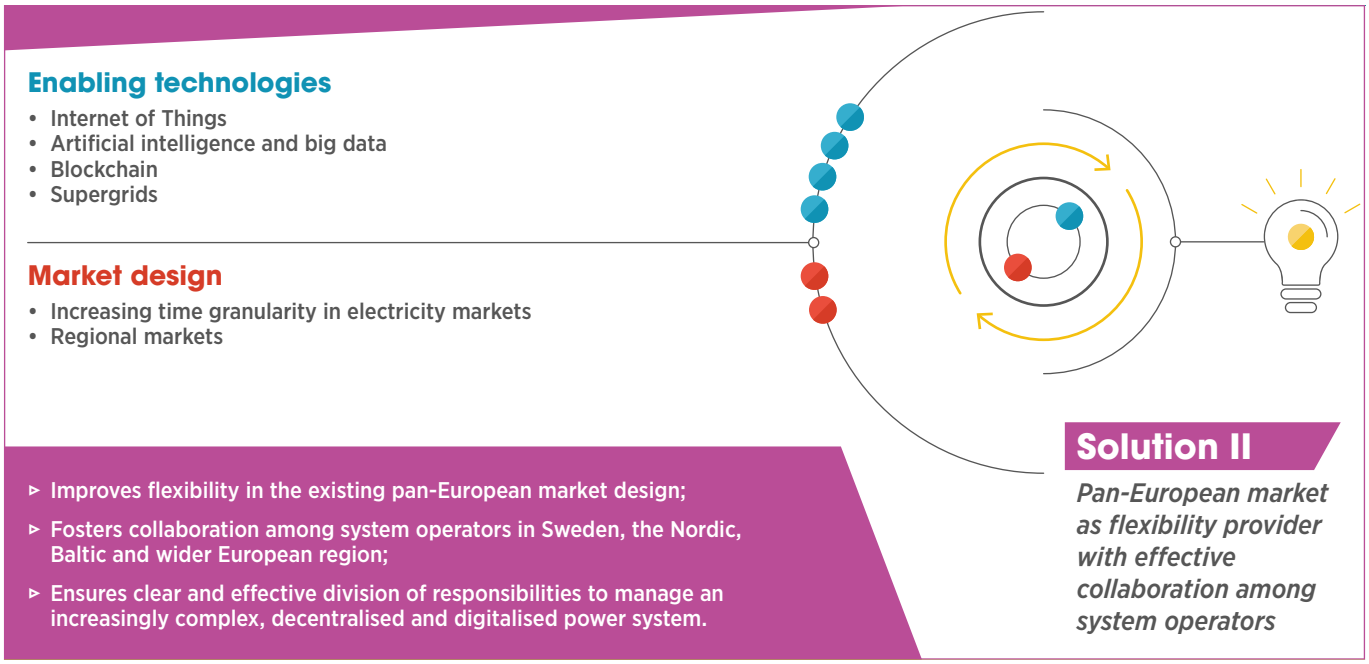
Sweden needs innovative solutions to meet its ambitious policy goal of 100% renewable power by 2040. IRENA, in consultation with the Swedish Energy Agency (Energimyndigheten), has therefore proposed four tailor-made solutions based on a systemic approach to address the country's specific challenges in scaling up VRE. These four innovative solutions are described in **Figure 2**.

Estimated costs, complexity and the expected benefits of each innovation are all taken into account in assessing the suitability of each solution in the Swedish context.

Figure 2 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 3**).

Figure 2: Four innovative solutions for Sweden's power system





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

Enabling technologies

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

Business models

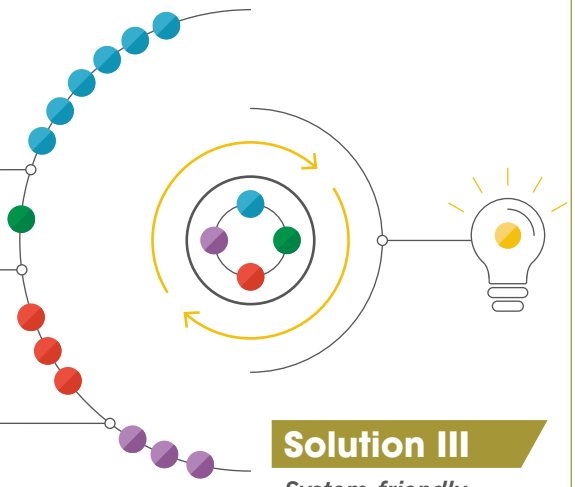
- Aggregators

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

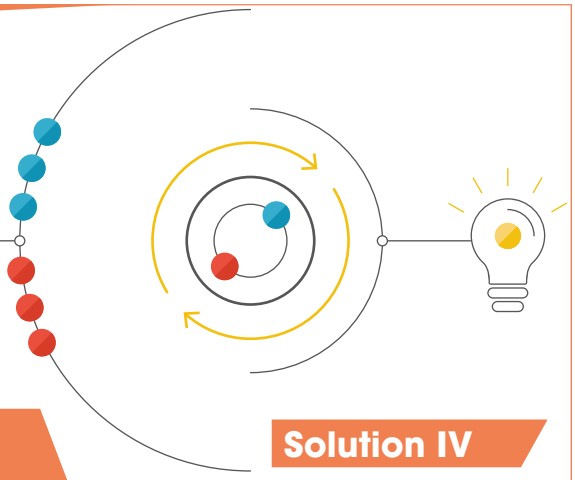
- ▹ Aggregates distributed energy resources to optimise distribution system operation;
- ▹ Balances supply and demand daily;
- ▹ Manages network congestion at the distribution level in the context of wind shortage/surplus in the short term, until transmission projects with long lead times are implemented.

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



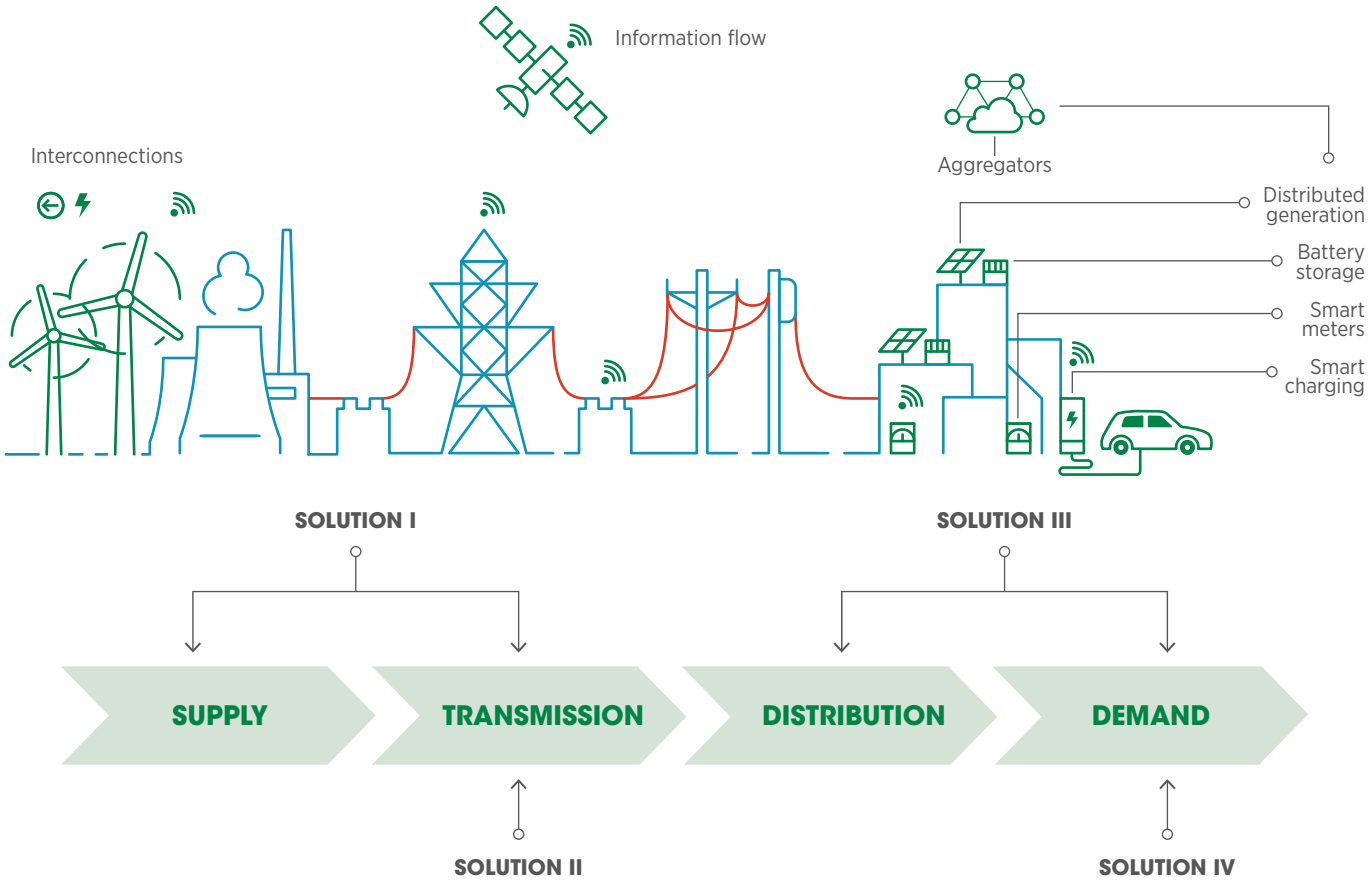
Solution IV

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.

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

Figure 3: 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 4**. 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:

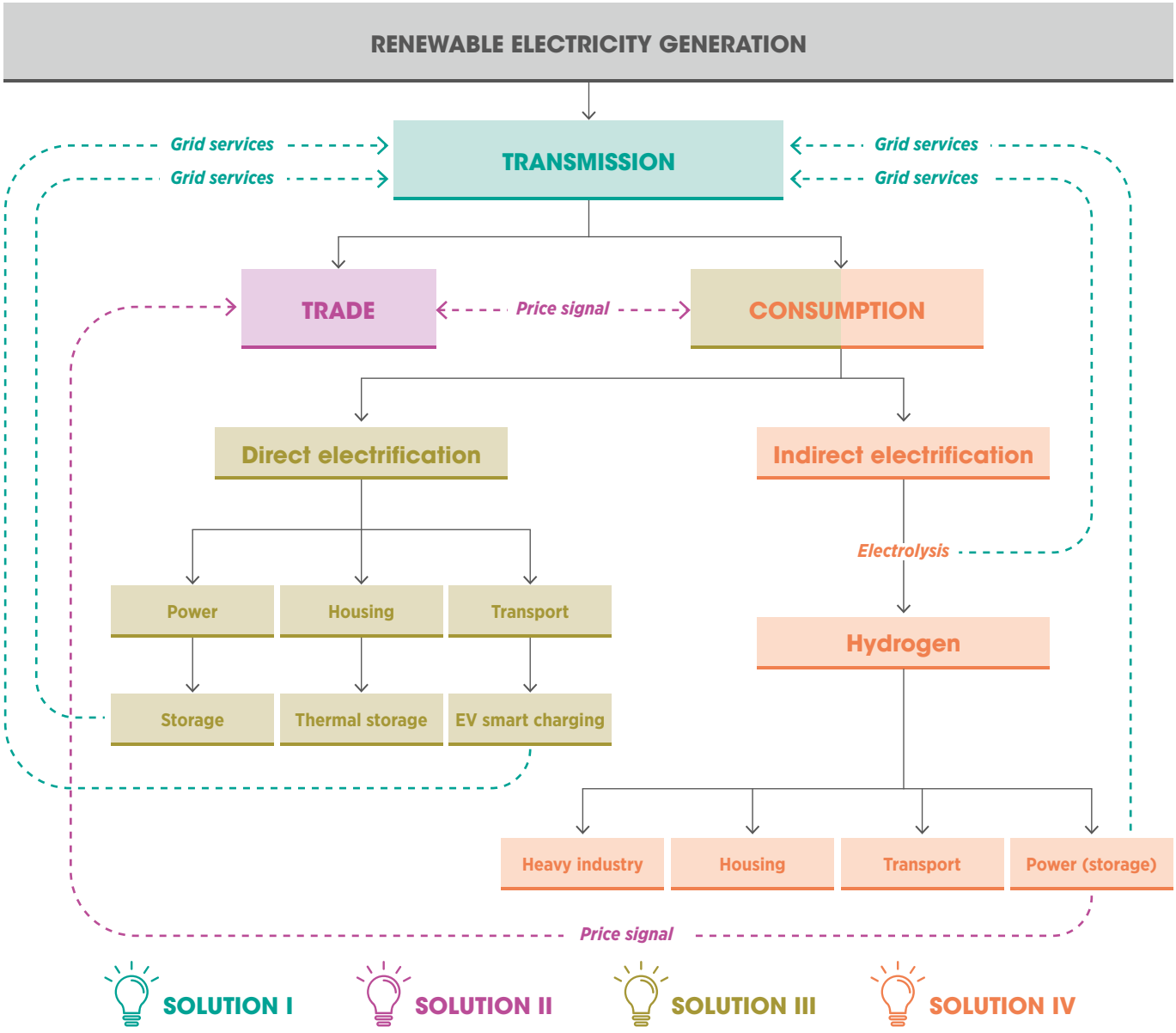
» **Direct electricity use**, including in heating and cooling or transport. This in turn opens the door to electricity and heat storage, as well as smart charging for electric vehicles (EVs). See **Solution III**.

» **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 4: 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.

Achieving a 100% renewable power system with an increasingly higher shares of variable renewable energy sources in Sweden is possible by 2040

RECOMMENDATIONS

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.

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, 2019).

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 the national and supra-national 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.

1. 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 the 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).

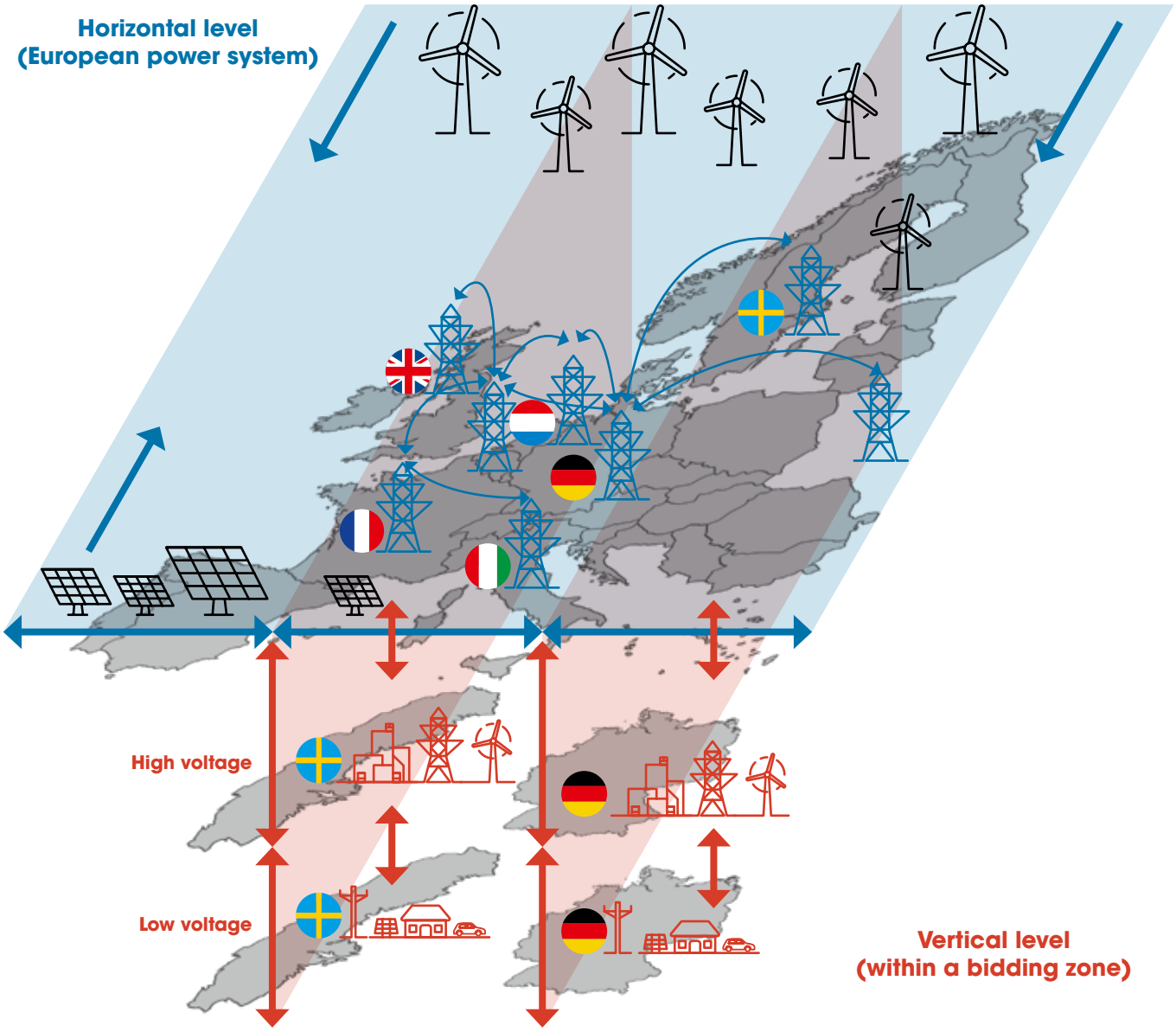
To foster, advance and implement innovative solutions, adequate regulatory space is needed to allow for experimentation to assess the combination of different innovations. Creating regulatory sandboxes, for instance, may be fruitful to allow innovators, research institutes and other power sector stakeholders, 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.

2. 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 5**) and between the national transmission and distribution system operators (i.e., in the vertical dimension).

Figure 5: Horizontal and vertical challenges in the interconnected European power system



Source: Adapted from IEA-ISGAN 2019

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, including Sweden, that have introduced or are planning to introduce capacity mechanisms 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.

3. 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.

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

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

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, 2019).

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