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Driving the Energy Revolution

An index for grid edge need and readiness

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Content

Executive summary

The world's relationship with energy is transitioning as we attempt to mitigate the impact of climate change. In the energy systems of the future, residential, commercial, and industrial consumers will no longer be passive. They may own generation sources, such as solar panels; they may be able to offer a service, such as giving flexibility for when energy may be used; or they may make lifestyle choices which have an impact on their energy consumption. Because of this, the interface between the grid and these distributed end-users will only grow in importance. This interface is called the grid edge.

The grid edge encompasses a wide range of technologies and services, from electric vehicles to heat pumps, solar panels to home batteries, and smart meters to building controls. To maximize the impact of grid edge technology roll-out, knowledge of both the need for and readiness for grid edge technologies in a specific geography can be extremely valuable for companies and governments alike.

This report presents a novel index to characterize the need and readiness for grid edge technologies of a region. To achieve this, factors which affect the need or readiness are included through an extensive range of indicators – 99 in total. Indicators for need are categorized based on those that contribute to current and to future need for system flexibility. There are four components of grid edge readiness: political, economic, social, and technical. Each indicator influencing each of these components has been weighted based on its importance following expert advice. For example, the introduction of a carbon price is considered to have a substantial impact on a region's readiness for grid edge, as it incentivizes renewables and could be used as a key policy tool. By applying this hierarchical weighting scheme to data collected about various locations, grid edge need and readiness scores can be calculated for each region.

Five regions form the focus of the report; these are Finland, Germany, Singapore, the United Kingdom (UK), and California in the US. These focus regions were selected as locations which have historically been among those leading in developing and adopting modern energy-related technologies. Of these focus regions, Finland is the country with highest readiness, in part due to its plans for a flexibility market and high carbon price, while California has the highest need, in part due to significant solar panel penetration. Germany and the UK follow closely behind with the UK displaying high political ambition but slightly less need and readiness. Singapore, although exhibiting high readiness for grid edge, presents a lower need, which is due to its present dependence on dispatchable fossil-fueled generation and more moderate ambitions for introducing renewable energy generation into the future energy mix.

To position these focus regions within a global context, the index is also applied to a broader range of locations, with the caveat that due to data gaps there is an aspect of uncertainty. Figure 1 shows the relative grid edge need and readiness of selected regions.

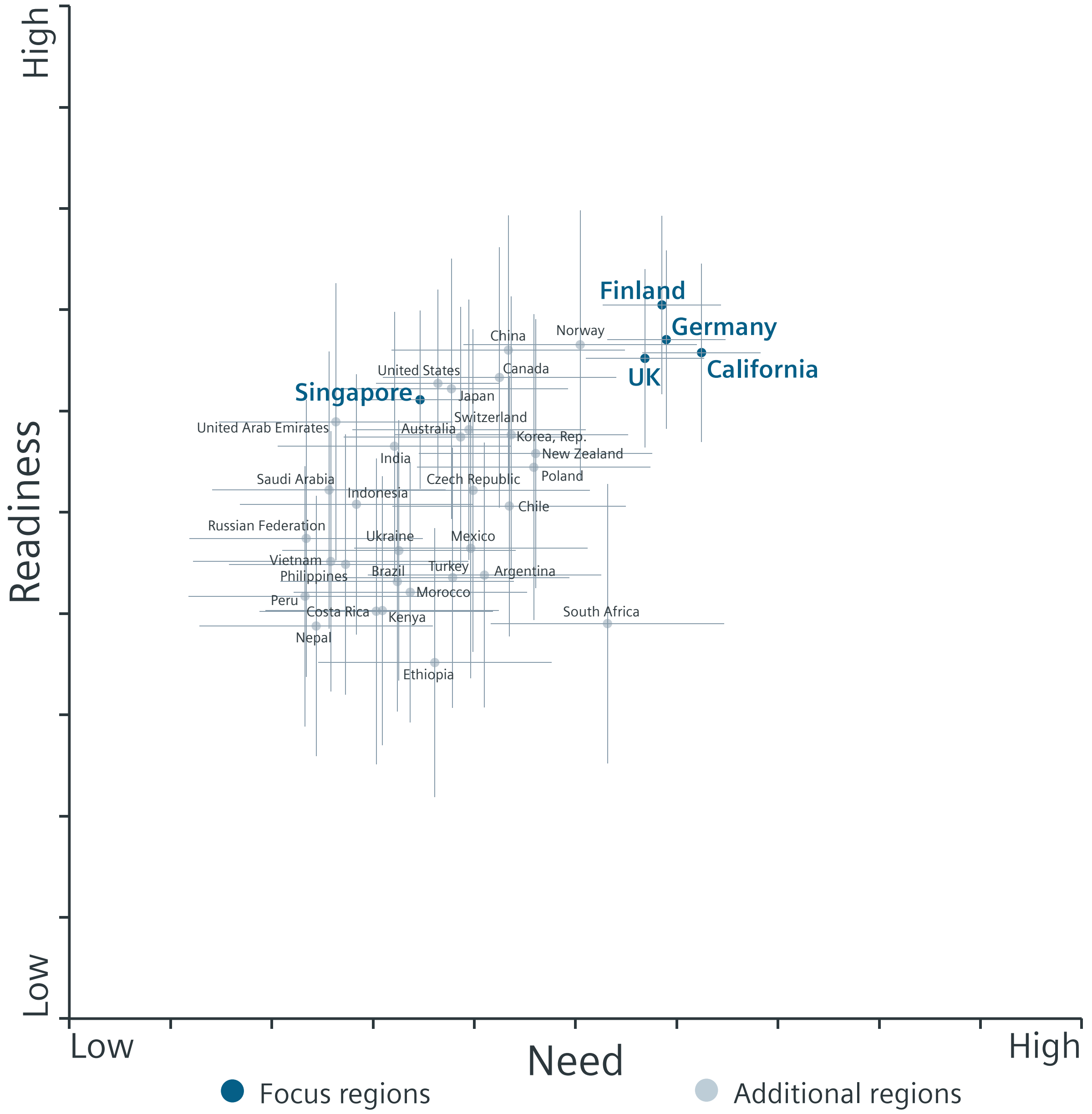


Figure 1:

Relative grid edge need and readiness for selected regions, where error bars represent uncertainty

Although the focus regions of Finland, Germany, UK, and California are the regions with greatest need and readiness, Norway, China, and Canada exhibit the next highest need and readiness, making them promising candidates for further attention. Another country to highlight is South Africa, which has relatively high need but low readiness. This is a country where grid edge technology could make a difference, and where policy could be employed to improve readiness.

Three key policy levers to improve a region's readiness for grid edge are identified. These include introducing incentives for clean energy technologies; introducing flexibility and carbon markets; and developing policy pathways to provide reliable and secure communications infrastructure to all domestic citizens.

1 Introduction

Grid edge technologies are increasingly important tools to facilitate higher penetrations of renewable energy and to mitigate climate change. However, many factors influence whether and which grid edge solutions are appropriate for a particular location or how ready that location is to deploy them at scale.

This white paper proposes an index to assess a country or region's relative need and readiness for grid edge solutions. The overall index scores can be used to identify particular locations of interest, while index components can yield insights into opportunities and barriers in a specific country or region.

Human activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels. Global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate [1]. Decarbonization of the energy, transport, and industry sectors will help to reduce this increase, but continues to present a major challenge. A credible path to fight climate change in the energy sector has become evident with a sharp decline in the cost of renewables and a dramatic increase in their uptake. In addition to efficiency gains, higher penetration of low emissions sources is a central requirement for a clean transition. Increasing consumer awareness and decreasing costs have led to higher adoption of behind-the-meter resources such as solar panels, combined heat and power plants, home batteries, and electric vehicles. These changes mean that residential, commercial, and industrial consumers are moving from being passive users of energy and now represent a largely untapped resource that can help accelerate the clean transition through the grid edge revolution.

The concept of grid edge refers to the interface of distributed energy demand and distributed energy supply with the electricity grid. There is significant innovation in both hardware and software components of the grid edge to support the rapidly changing electricity system which is moving away from the centralized paradigm to a more decentralized and bidirectional one.

Transitioning to a low carbon electricity system involves challenges on both the supply side and the demand side. On the supply side, one major challenge is the intermittency and inflexibility of renewable energy sources. On the demand side there is increasing demand from electrification of heating and mobility infrastructure. To balance this mismatch between supply and demand, a low carbon future will require the ability to shift energy both in time and through space.

A previous white paper "The grid edge revolution" [2] examined the developments at the grid edge and their impact on the transition to a net-zero system. The paper showcased how innovations at the grid edge help decarbonize the energy system. It focused on the social implications of this change and the technologies and business models involved. Grid edge technologies have the ability not just to maintain energy service provision, but also to improve the availability of choices to customers while providing them with a sense of control and ownership. The analysis concluded that such technologies are vital for the transition and that there is a clear need, a market opportunity, and the political will for grid edge innovation.

The current white paper builds on that work by evaluating location-specific need and readiness for grid edge solutions. It proposes a framework to identify the key factors that influence the need and readiness for adoption of grid edge technologies in different locations. It provides an insight into which regions will benefit the most from the grid edge (i.e. those with highest need), and which are most likely to be able to engage with the grid edge (i.e. those with highest readiness). Through the process of identifying a region's need or readiness for grid edge, it identifies characteristics which improve a region's need or readiness and highlights what needs to be done to improve a region's position.

The index is split into two parts: need for grid edge technologies and readiness of the region to deploy them. The need represents the imminent requirement for grid edge technologies because the region's aspirations necessitate its roll out. The readiness represents the suitability of conditions in the region to deploy grid edge technologies.

Policymakers could use the index scores to assess their relative strengths or barriers, which could inform future policy directions to address specific needs or improve readiness for grid edge deployment. The index scores could also be used to assess which locations might be more in need of certain technologies or more ready for others. Because the index scores only yield a relative position, the index should be used only to indicate a region or policy is worthy of further study, rather than to inform specific decisions.

Regions which are ahead of others in terms of need or readiness can be useful examples from which others can learn, or can serve as benchmarks with regards to the clean energy transition. Evaluating the grid edge potential of different locations will, to some extent, indicate the current status of a country's clean energy transition while highlighting any potential to improve. In this regard, the results of this paper help to identify the relationship between the need and readiness for grid edge technologies, which can be used for policy recommendations.

1.1 Research objective

The aim of this white paper is the development of an index to understand two things:

Need for grid edge technologies

Readiness for grid edge technologies

The specific objective of the paper is to identify the key factors that influence the adoption of grid edge technologies and to develop a grid edge index which can be used to assess different regions. The index enables identification of a region's strengths and potential areas of improvement and can inform policy making and identify market potential.

These research objectives are achieved by the following methodology. First, factors that influence grid edge need or readiness are translated into quantifiable metrics. Next, the indicators are combined using a weighting scheme which considers their relative importance and impact on the need or readiness for grid edge solutions. The final output incorporates all of the indicators to provide scores for a region's need and readiness for grid edge solutions. The approach uses comprehensive data collection, synthesis, and expert interviews to determine the indicators and appropriate weights. The index is first applied to a carefully selected set of focus regions and then expanded to a wider range of countries.

1.2 Definitions

Grid edge refers to the interface of distributed energy demand and distributed energy supply with the electricity grid. Grid edge solutions include the many connected technologies and services which exist at this interface.

Readiness for grid edge solutions is the state of having the necessary economic, political, technical, and social preconditions for the effective deployment of related technologies and services at scale.

Need for grid edge solutions is the extent to which grid edge solutions can support the clean energy transition and enable a region's future aspirations. The need for grid edge solutions includes both existing needs for flexibility and potential future needs for flexibility, driven by changes in the electricity system.

1.3 Scope

The focus regions were chosen by creating a shortlist of regions which have historically been leading in developing and adopting modern energy-related technologies. From this shortlist, the five focus regions were selected with the aim of covering a range of geographies, economics, social structures, and political characteristics. The five focus regions are:

Finland: a country with relatively cold weather and increasingly high penetrations of biomass

Germany: one of the initial leaders of the renewable energy revolution

Singapore: a small tropical island and autonomous city state, with a highly reliable electricity infrastructure

United Kingdom (UK): a larger island and the first country to set a legally binding net-zero target

California: a state administration under the larger central administration of the United States with significant renewable resources*

The resulting scores for need and readiness have value only relative to other location's scores. Rather than an absolute need for grid edge or readiness, results must be interpreted in the relative context among analyzed countries. However, the methodology was developed in a way that allows extension to more focus areas as more data becomes available.

*California was selected in preference to the whole US because the structural, political, and climatic diversity of different states makes it valuable to understand different states separately.

2 Index development

Index development is an iterative process involving choices about which factors to include and how to combine them into a suitable score.

The grid edge index has two dimensions: the need for grid edge solutions and the readiness to deploy them at scale, both defined in Section 1.2. These dimensions are measured separately, with distinct scores for grid edge need and grid edge readiness for each location.

The index was then developed based on factors which influence the need and readiness for grid edge technologies. The need for grid edge solutions is driven by the need for flexibility in the electricity system because grid edge solutions can be used to enable this flexibility. Electricity systems with high penetrations of variable renewables need more flexibility due to the inflexible power generation. Therefore, regions with significant renewable generation, or with ambitious climate change mitigation policies which would require more renewables, have greater need for grid edge solutions.

For any new technology, whether a location is ready to deploy or scale up that technology is influenced by policies, regulations, markets, and social structures, in addition to whether the technology itself is fully developed and compatible with existing systems. Therefore the grid edge readiness score is composed of the technical readiness, political readiness, social readiness, and economic readiness for grid edge solutions.

Because the need or readiness for grid edge cannot be directly measured, a hierarchical framework of factors which influence these two dimensions was developed, as covered in Section 2.1. These factors are assigned weights corresponding to their influence on the need or readiness for grid edge solutions. For each of the influencing factors, measurable indicators are chosen as inputs.

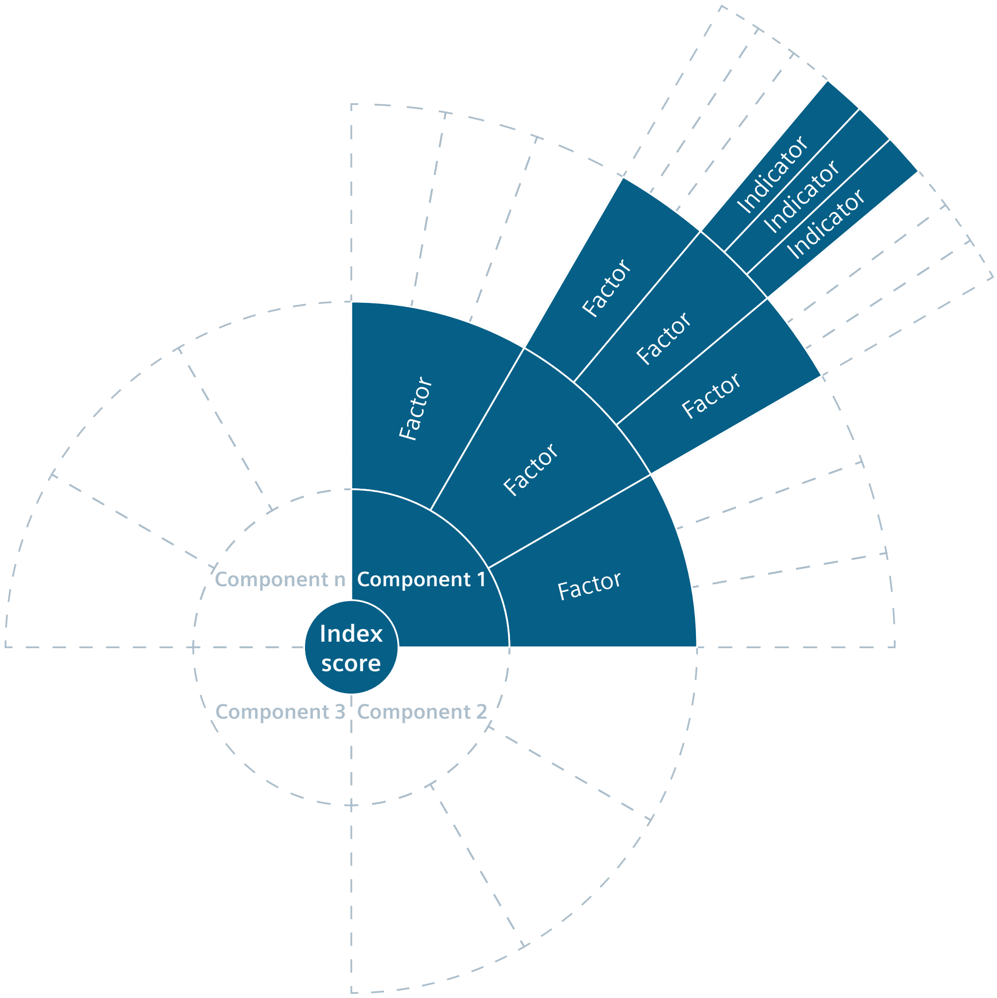
The data acquisition process is described in Section 2.2. Where possible, data was gathered from publicly accessible data sources for multiple locations. Grid edge index scores were only calculated for locations where enough data was available to calculate a credible score. For those locations, for the remaining indicators where data was not publicly available, values were replaced with a best estimate or neutral score, described in Section 2.2. Although this introduces additional uncertainty into the final scores, applying the index to more locations can help identify regions of potential interest for deeper analysis or further data collection. To ensure comparability across locations, some of these indicators were scaled by population or GDP where appropriate.

2.1 Hierarchy and weighting

Following a top-down procedure, the scores for grid edge need and readiness are based on a hierarchical index structure, which allows for a structured evaluation of complex relationships. The need and readiness were broken into different components which influence the final scores.

Figure 2:

Example hierarchical index structure



For each *component* of the index, as shown in Figure 2, influencing *factors* were identified and for each of these, measurable *indicators* were selected. Weights were determined based on the relative influence of each branch on the final score; and this weighting scheme was developed in consultation with industry experts. The detailed data processing is elaborated in the Appendix.

Figures 3 and 4 show the hierarchical structures for both grid edge need and readiness.

The overall scores for grid edge readiness and need are the sum of all individual final indicator scores multiplied by the weights of those nodes. A list of measurable indicators, processing details, and associated sources can be found in the Appendix.

Figure 3:

Weighted hierarchy of grid edge need index

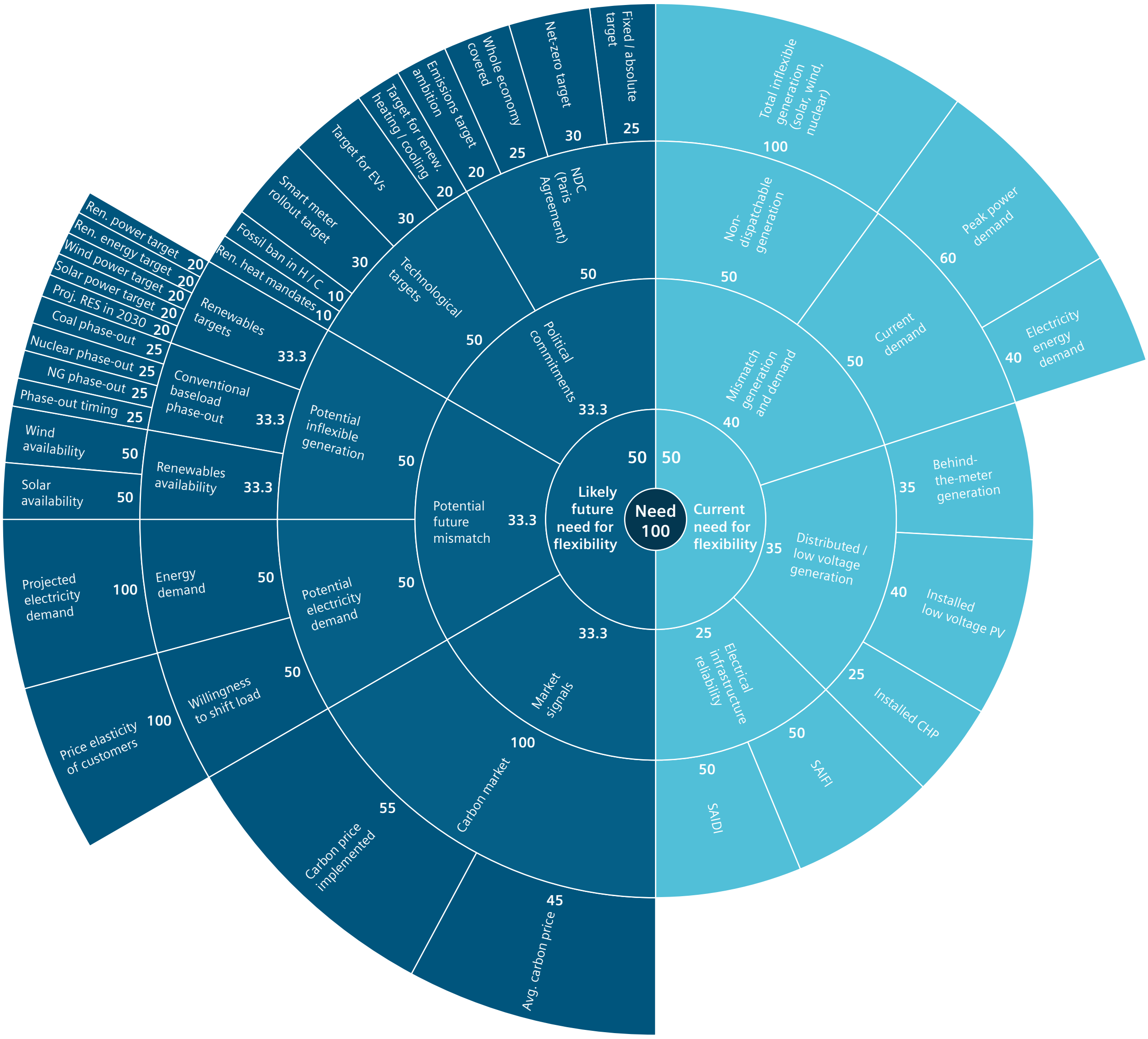
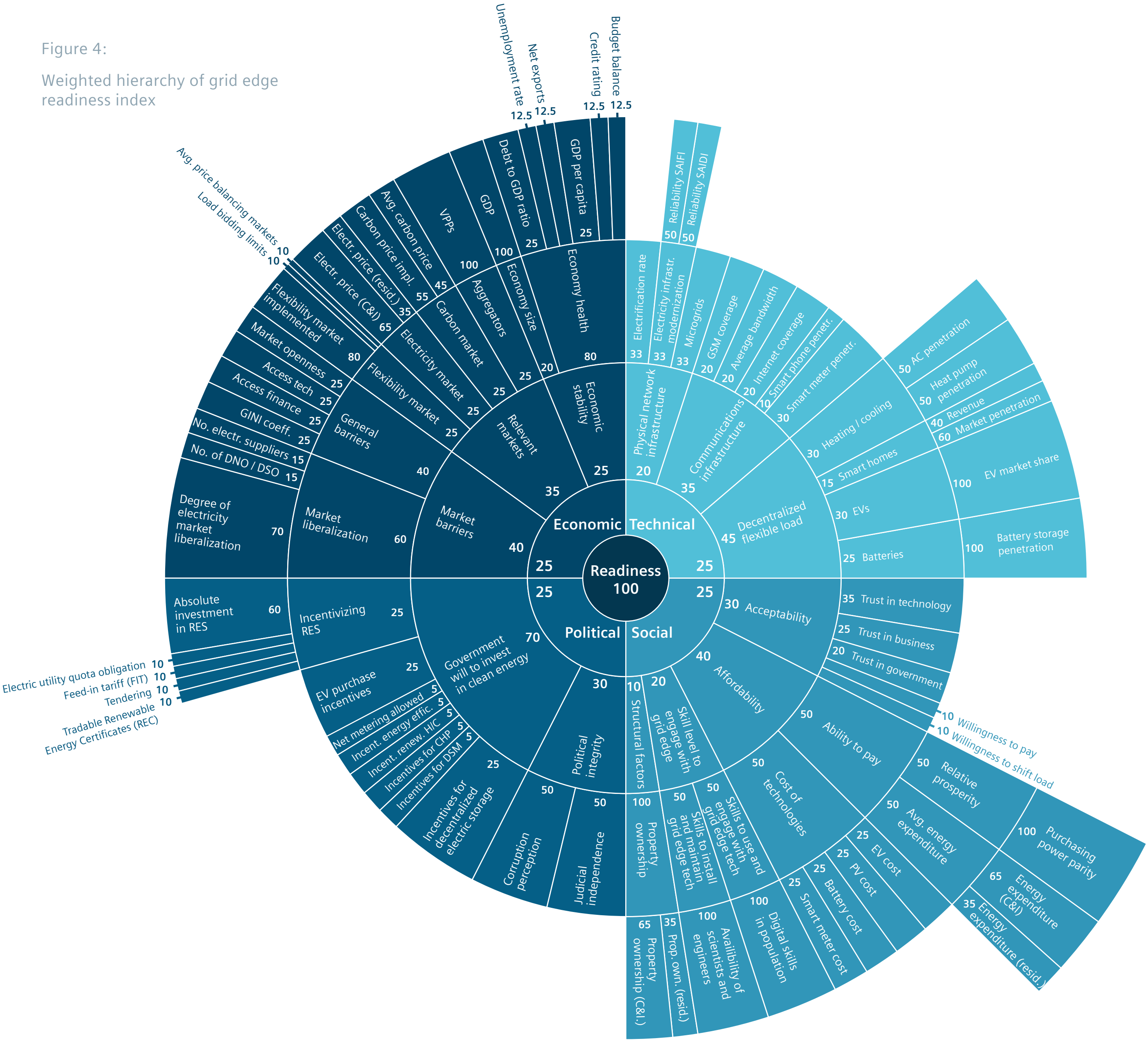


Figure 4:

Weighted hierarchy of grid edge readiness index



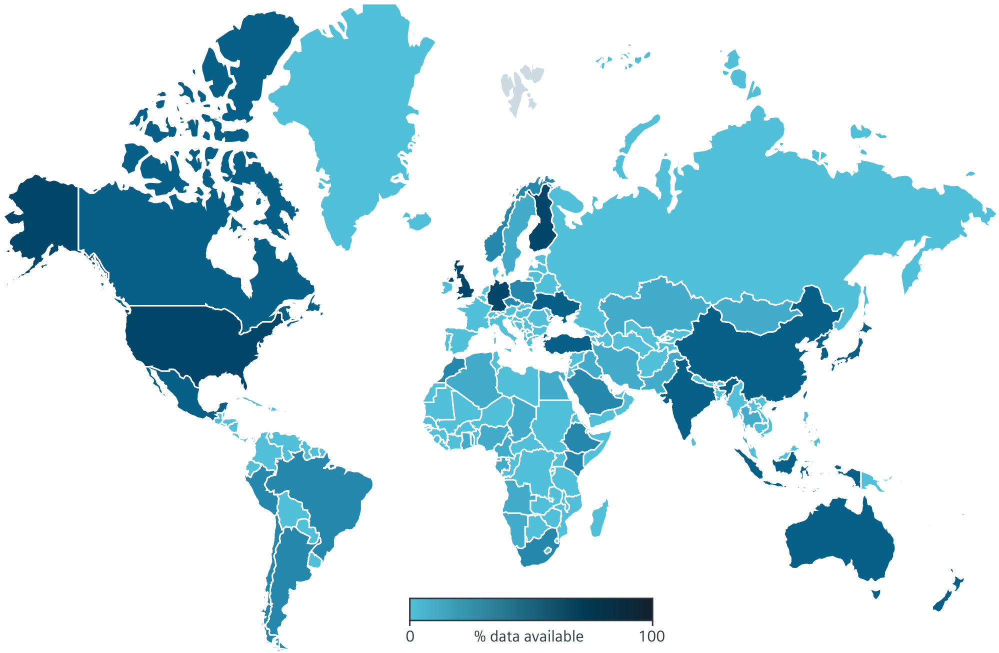
2.2 Data

Data was collected from a wide variety of publicly available sources. These include in particular, the World Bank Group, International Renewable Energy Agency, International Energy Agency, Climate Action Tracker, REN 21, US Energy Information Administration, International Monetary Fund, European Commission, Transparency International, Standard & Poor's Financial Services LLC, and the relevant government databases. A comprehensible list of sources and associated indicators can be found in the Appendix.

Final index scores were only computed for locations where enough data was available to calculate credible scores. Figure 5 shows the availability of data for relevant input indicators.

Figure 5:

Global grid edge indicator data availability



Values of indicators differ from each other in type and in magnitude. Binary indicators were directly used as model inputs; they were not processed any further. The continuous indicators needed to be normalized before they could be combined into a single index. First, to compare numbers which had large absolute values from different contexts, they were divided by location specific parameters such as population, number of households, or total generation capacity. The conversion of absolute numbers to specific ratios is common practice in the benchmarking of indices. By doing so, scale effects of most indicators are reduced. Instances where data was not available were either filled with regional replacements or neutral values. A more detailed description on chosen replacement values is given in the Appendix.

Next, the outliers were removed on the upper and lower end. This is done by defining an outlier as a data point that is located outside 1.5 times the interquartile range above the upper quartile and below the lower quartile.

Finally, the data was linearly scaled to between zero and one, with the minimum equal to zero and the maximum equal to one. Therefore, the final scores show the relative need and relative readiness of a particular location, compared to other locations worldwide. After all processing, the final index scores were scaled to yield values between 0 and 100.

The index has been designed to accommodate data gaps, which can occur when data is not recorded or exists but is not accessible (e.g. behind a pay-wall). Data gaps are commonplace in a system as complex as the energy system, where there are a multitude of different players. Where data gaps do exist for a certain indicator, the use of the index will introduce an aspect of uncertainty. Nevertheless, it can be valuable to apply the index to indicate which locations are promising with regards to grid edge need and readiness.

Where there are data gaps, the application of the index is achieved by using a neutral replacement value of 0.5 for each indicator where data is missing. Because the final index scores are between zero and one, using this value should minimize distortion of results for the specific region in a particular direction.

To indicate the uncertainty in the values, error bars are shown for these data points. These are calculated by considering the different scores which would be achieved if the indicators affected by data gaps were filled with a full value of 1 or a value of 0, instead of the neutral value of 0.5.

3 Results

The index was applied to five carefully selected focus regions: Finland, Germany, Singapore, United Kingdom (UK), and California. Choosing these locations enables the comparison of the need and readiness for grid edge technologies in locations with differing energy use patterns, social attitudes, and economic and political systems. Furthermore, these regions were selected as they are considered by industry experts to be among those leading the way in decarbonization, digitalization, and decentralization which makes them of interest for deployment of grid edge technology.

To apply the index and calculate scores, data was gathered for the input nodes shown in Figure 3 and Figure 4 for each region. The results for all five regions are shown in Figure 6, with the need on the horizontal axis and the readiness on the vertical axis. As has been mentioned before, these values are not absolute and must only be considered in relation to one another. In addition to the results, Figures 8, 12, 16, 20, and 24 provide context by comparing the relative sizes of indicators relevant for market opportunities.

Figure 6:

Relative grid edge need and readiness for selected regions

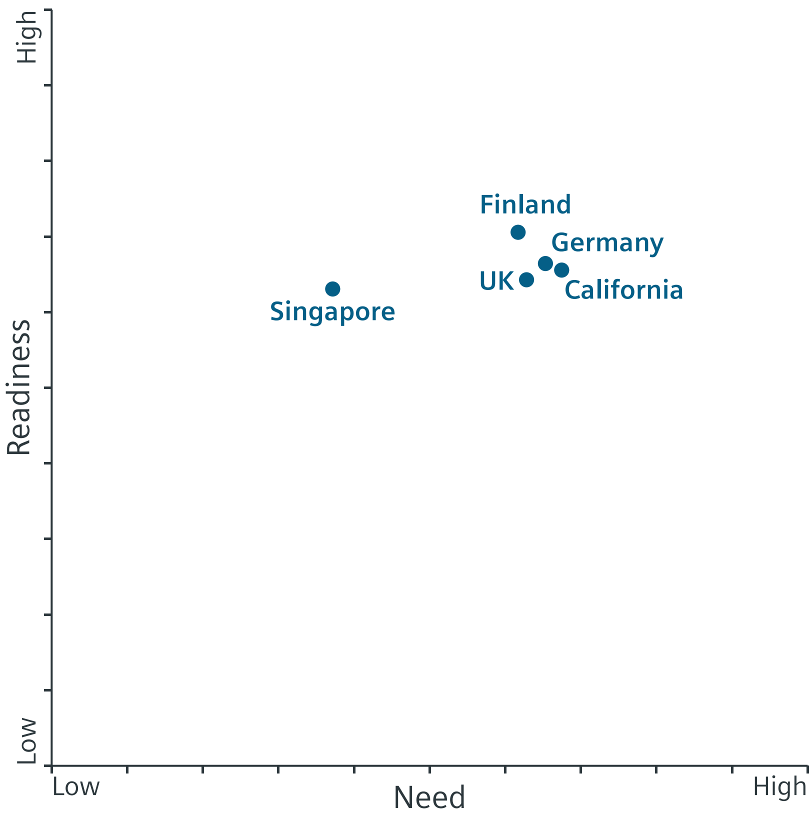


Figure 6 shows Finland as the country with highest readiness to engage with grid edge technologies, while California has the highest need for grid edge technologies. Singapore, although still relatively ready for grid edge technology, is currently less in need of grid edge technology.

The reasons for the differences between these focus regions is considered in detail in the following sections.

3.1 Finland
In depth analysis

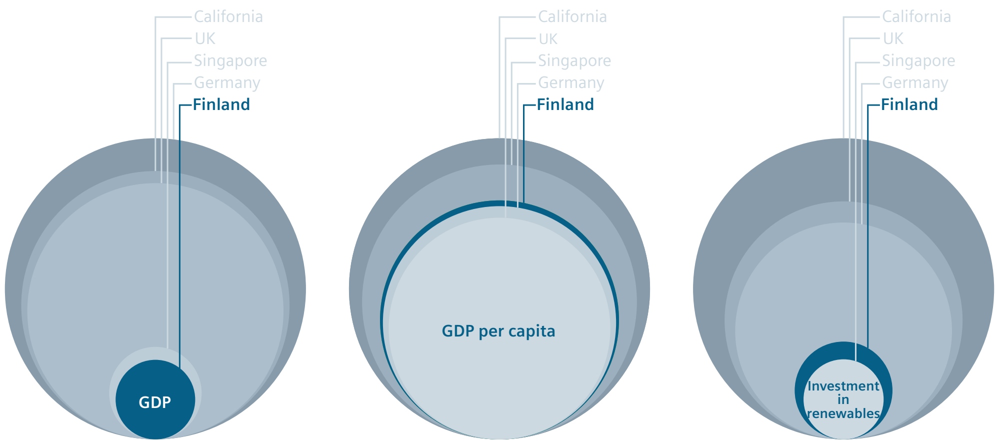
Figure 7:

Finland: grid edge need and readiness score

Finland has shown its willingness to drive towards a clean energy transition through its commitments and goals laid out in the Integrated Energy and Climate Plan from December 2019 by the Finnish Ministry of Economic Affairs and Employment [3]. Therefore, it does not come as a huge surprise that Finland ranks highly in terms of grid edge readiness and grid edge need, leading all examined regions in readiness, as depicted in Figure 7.

Figure 8:

Finland: Relative market opportunity indicators



Regarding readiness for grid edge innovations, Finland demonstrates a rather balanced readiness across all four dimensions, with higher political and technical readiness compared to the other focus regions – as shown in Figure 9.

On the social side, Finland shows high acceptability, trailing only Singapore. This could be due to the Finnish people's high trust in technology, businesses, and their government. However, Finland lags behind other focus regions regarding EV costs. Affordability in Finland can still be considered quite high, benefiting from having a generally high purchasing power parity. Similar to Germany and the UK, Finland has relatively higher energy expenditures among focus regions, limiting society's ability to pay. Finland is nonetheless well prepared when it comes to the skills required to engage with grid edge solutions. They lead all focus regions in digital skills in the population, as well as availability of scientists and engineers.

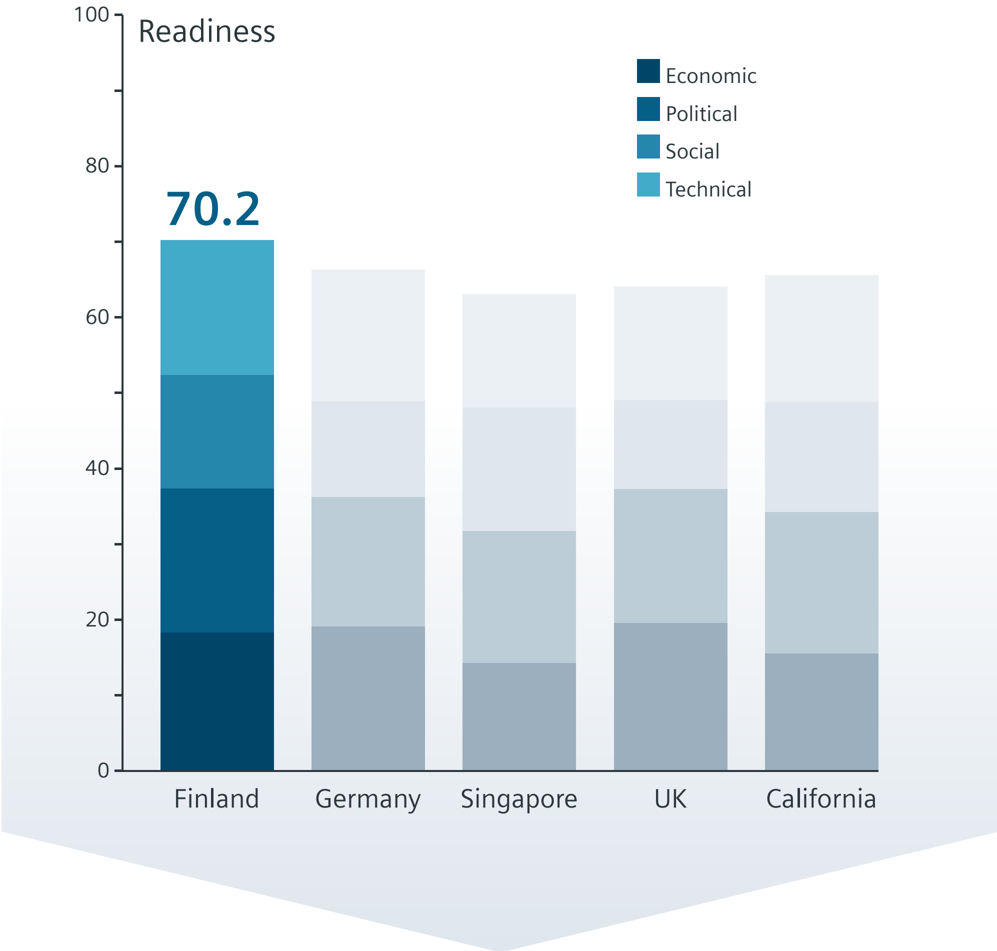
For technical readiness, Finland, similarly to all other focus regions, shows great potential for including grid edge solutions in terms of the existing physical network infrastructure due to very high reliability and electrification rates. Where Finland stands out, however, is in its communications infrastructure. It shows outstanding smartphone penetration as well as solid internet and GSM coverage, though lacking in terms of average bandwidth, similar to the UK and Germany. Most significantly, and in contrast to almost all focus regions except Singapore, Finland has made significant progress in smart meter penetration after intensifying its roll out following 2009's Governmental Decree on Determination of Electricity Supply and Metering (66/2009) [4] and reaching a penetration level of 97.6% in 2017 [5]. Finland is also already planning the roll out of second generation smart meters [6] while other countries are still struggling to roll out smart meters in the first place. Since smart meters are an important precondition for efficient load management and shifting, the integration of smart meters will have to play a vital role in the clean energy transition and the implementation of grid edge technologies and Finland is at the forefront there.

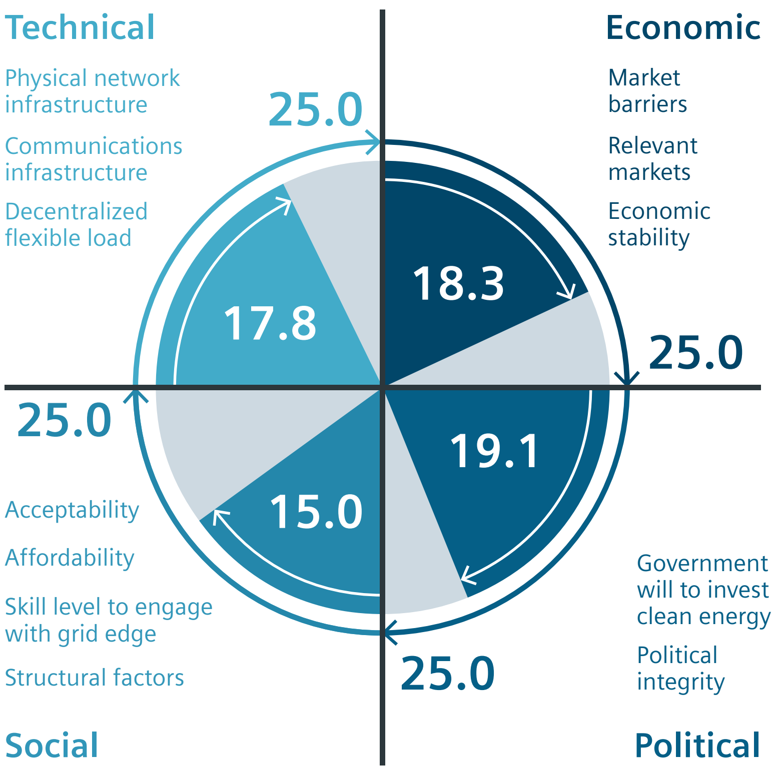
Economically, Finland has advanced readiness for grid edge solutions, especially in regards to relevant markets, by having a plan for a flexibility market [7] and pricing carbon as high as 69.5 USD/tCO2e [8] – only trailing Switzerland in this regard. Unsurprisingly, and as is the case for all of the focus regions, Finland also demonstrates a comparably high economic stability, making it a favorable location to invest in deploying or scaling up grid edge technologies.

Politically, Finland scores slightly higher compared to the other focus regions, because it is a generally stable country politically and scores high marks in judiciary independence and corruption perception indices. Finland is the only of the focus regions that does not incentivize CHPs after the corresponding feed-in tariffs were phased out in 2017 [3] and thus is showing a lower grid edge readiness. Finland also does not have a renewable portfolio standard specifically and there is no net metering, both of those lowering the grid edge readiness. This does not necessarily mean that Finland lags far behind in efforts for a clean energy transition, but it does leave room for improvement. Despite these deficits Finland is still comparably well prepared politically, leading all focus regions in the percentage of GDP invested in renewables and having incentives into EVs and energy efficiency as well as building efficiency.

Figure 9:

Grid edge readiness score: Finland





Finland also comes in quite high in regards to its grid edge need, trailing California and Germany and the UK by a bit but experiencing considerably higher need than Singapore – see Figure 10. This is mainly due to Finland showing a considerably greater future need for flexibility whilst having a more modest current need for flexibility. This future need mainly arises from Finland's high carbon price which indicates a push for a shift towards renewable energy sources and electrification of different sectors. This ambition is also mirrored in Finland's political commitments having defined targets for renewable energy as well as renewable heating and cooling and renewable power, and allowing tendering and trade on renewable energy certificates (REC). Noticeably, despite both Finland and Germany being integrated in the EU, Finland has shown greater ambition mainly in regards to their NDC targets. In line with these findings, Finland also has a comparably high projected share of renewable generation with 57% in 2030 [9], only trailing the UK and California of the case study locations (64.4% and 60% respectively [9]).

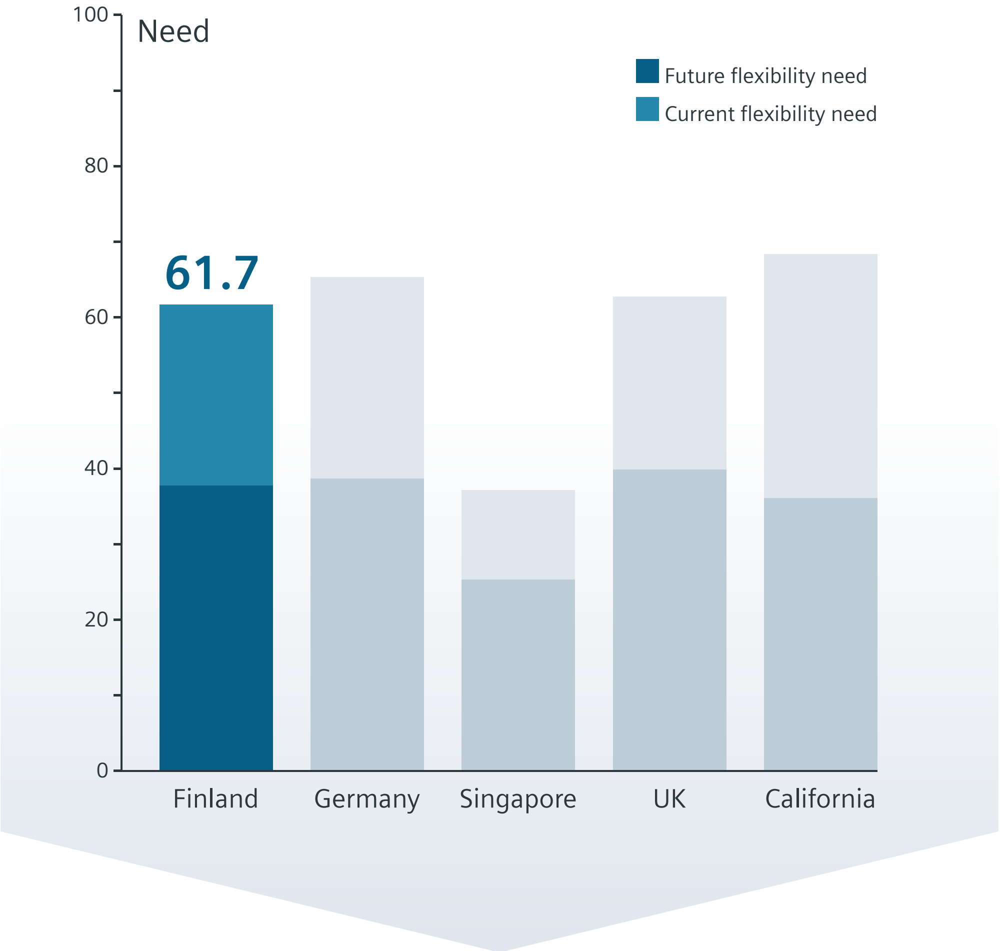
Despite these ambitions and targets, as with other examined regions, Finland's current need for flexibility is noticeably lower than its future need. Finland has a significantly higher peak power demand and, compared to all other examined regions, also has comparably high amounts of non-dispatchable wind and nuclear power. Overall Finland shows less pure non-dispatchable generation than other focus regions – largely due to less non-dispatchable solar PV. Nonetheless, Finland potentially has a high mismatch between generation and demand and because of this has a higher current need for grid edge technologies.

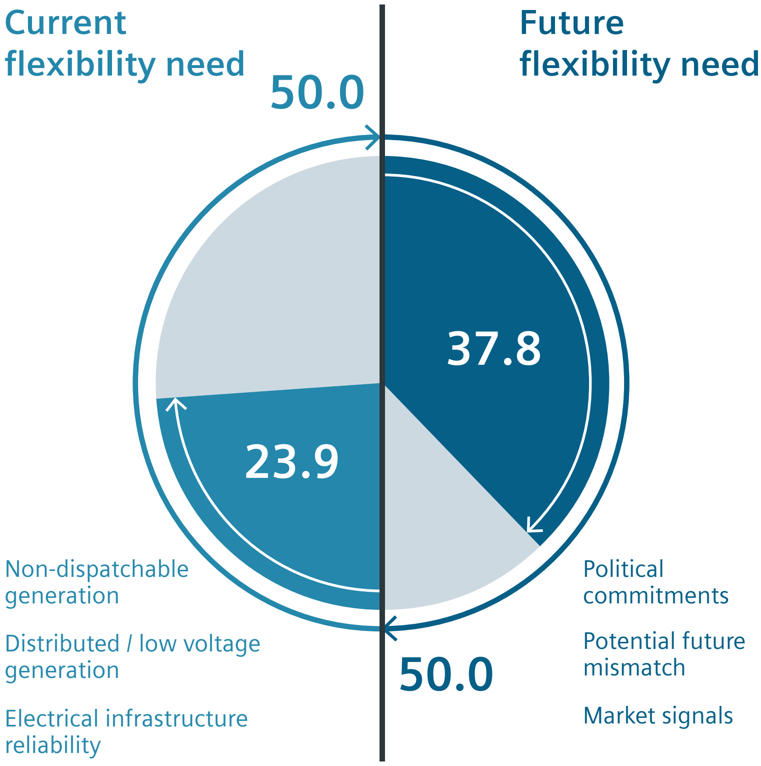
Taking a deeper look at the structure of the Finnish renewable energy mix yields more differentiated insights into the origin of this potential mismatch between renewable generation and demand. The Finnish Ministry of Economic Affairs and Employment projects for 2020 that about 79% of the total renewable gross final energy consumption will come from bioenergy sources compared to a combined 6% of solar and wind – mainly due to great amounts of heating with biofuels and biowaste from Finland's forests [3]. And at the same time, according to data from the IEA, most renewable electricity generated stems from hydro and biosources [10]. This is predicted not to change significantly, as the Finnish Ministry of Economic Affairs and Employment projects only a small rise in wind power and just a slight rise in solar energy [3].

Finland provides quite an unusual case in terms of flexibility, with a high renewable energy generation share, but less non-dispatchable solar and wind energy sources. Finland's mismatch between generation and demand mainly arises due to it having a considerable share of installed CHP on the distributed level using renewable biowaste; however, this may be only of limited dispatchability because electricity generation will be in parts dependent on heating demand. This yields a considerable amount of distributed low voltage generation overall and therefore an increased need for grid edge solutions to support this. This could be typical for countries which have considerable availability of biomass resources or biowaste and which also in particular experience a great demand for heating.

Figure 10:

Grid edge need score: Finland

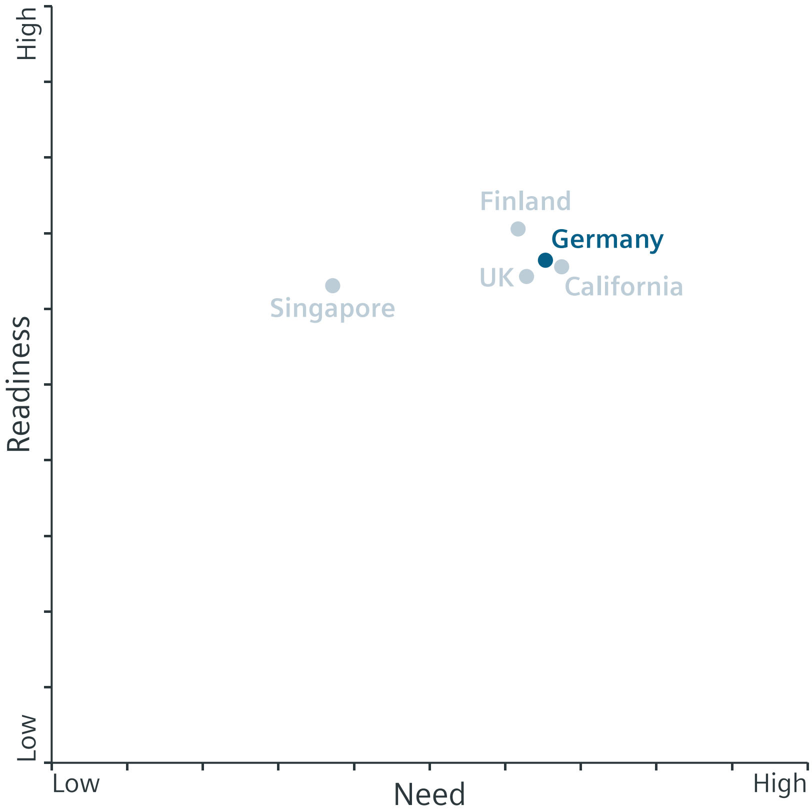




3.2 Germany
In depth analysis

Figure 11:

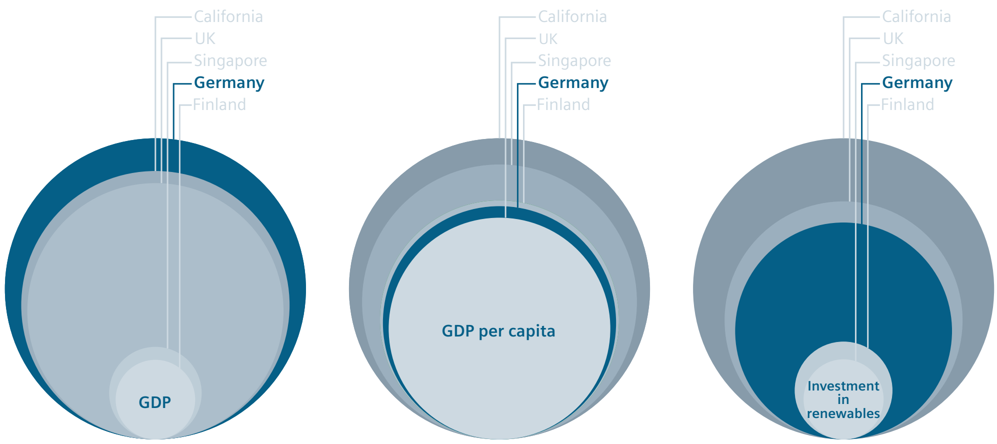
Germany: focus region overview



Once a pioneer of renewable energy deployment, Germany has lacked ambition in recent years in the expansion of renewable energy as well as related measures for effective decarbonization of the economy. Germany still is, however, among the leading countries of grid edge readiness and need, as depicted in Figure 11.

Figure 12:

Germany: Relative market opportunity indicators



Regarding Germany's readiness for grid edge innovation as shown in Figure 13, there are some infrastructural deficits in comparison to the other focus regions. Germany still lags behind in smart meter deployment, since it was only with the market declaration of January 31, 2020, that the Federal Office for Information Security (BSI) gave the go-ahead for the smart meter rollout in Germany [11]. As part of this process, smaller consumers with an annual energy consumption of more than 6,000 kWh are now to be successively equipped with a smart meter in the next decade [12]. Smart meters are an important precondition for efficient load management and shifting. Another factor is that the average internet bandwidth only occupies a middle position among target locations, which is needed for reliable data transmission in a future smart electrical grid. The German electrical grid infrastructure is associated with high reliability, which positively affects grid edge readiness.

Decentralized flexible loads are also very important for the integration of grid edge technologies. With a low but increasing market penetration of heat pumps [13] and EVs [14], Germany has moderately growing amounts of decentralized flexible loads. This is also reflected in low to average smart home penetration and revenue rates, as compared to target locations. Due to the temperate central European climate, Germany has a very low AC penetration, which could be a potential source for significant flexible load in a warming world.

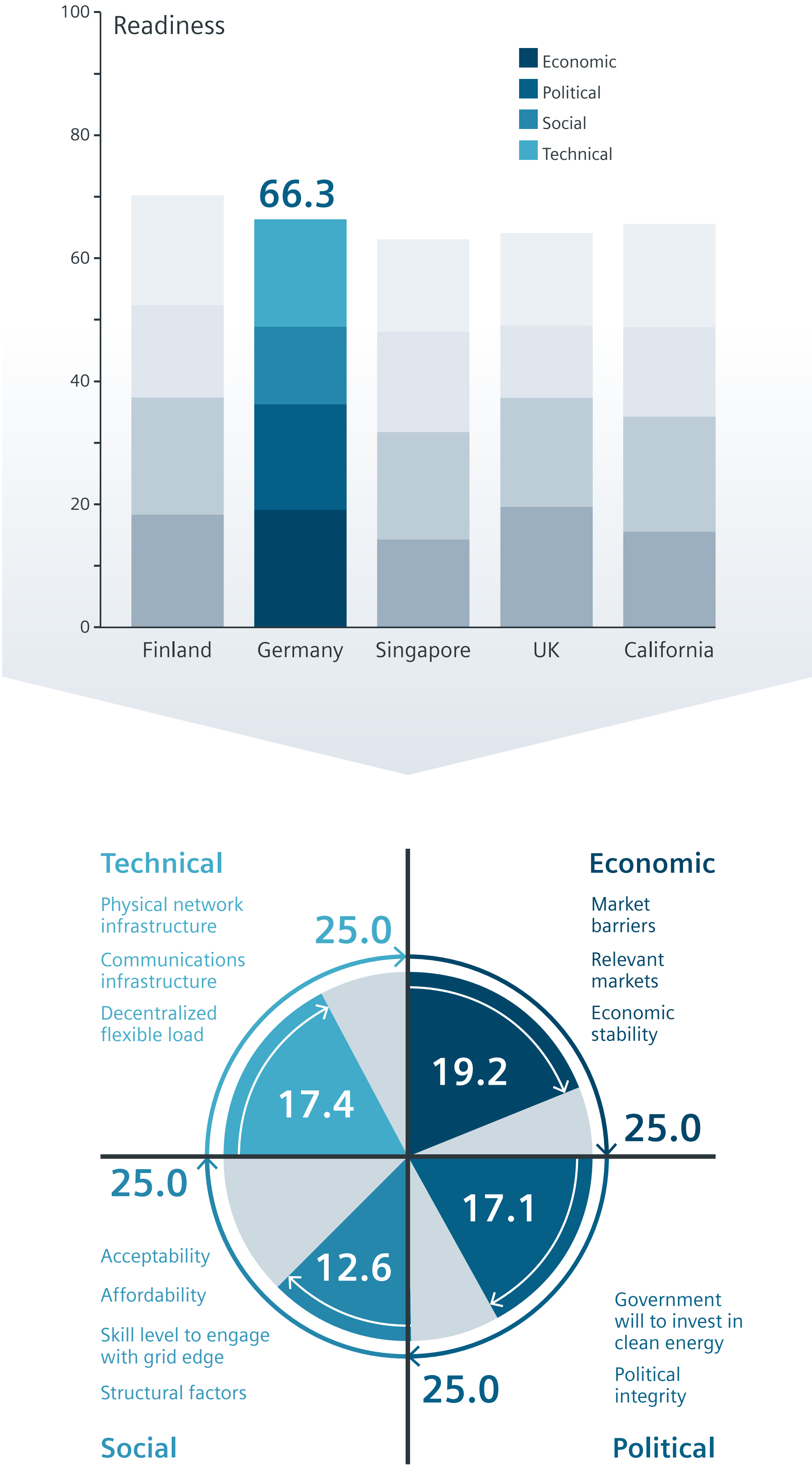
Despite the previously mentioned lower ambition in emissions reduction targets in recent years, Germany provides multiple incentives for renewable energy deployment (feed-in tariff, tendering, trade renewable energy certificates and others), which positively affects the expansion of renewable energies and efficiency measures and thus the political readiness for grid edge innovation.

On a global scale, Germany has a healthy economy and exhibits sound economic fundamentals and low market barriers, with a decent GDP per capita and purchasing power parity internationally as well as among target locations. Furthermore, Germany has a high degree of electricity market liberalization and a competitive electricity supplier environment, which can trigger innovative services, once attractive business models exist. In terms of relevant markets, however, Germany lags behind in flexibility markets, as market design is still in the research stage [15], in contrast to the UK, Singapore, and Finland.

Socially, Germany reveals minor deficits in acceptability of new grid edge technology among the five focus regions, based on its scores in trust in technology, trust in business, and trust in government. Furthermore, Germany is among the most expensive countries for energy expenditure, decreasing the ability to pay for grid edge solutions within society. At the same time, EV costs are relatively low in Germany which could prove favorable to furthering the clean transition and implementing grid edge technologies.

Figure 13:

Grid edge readiness score: Germany

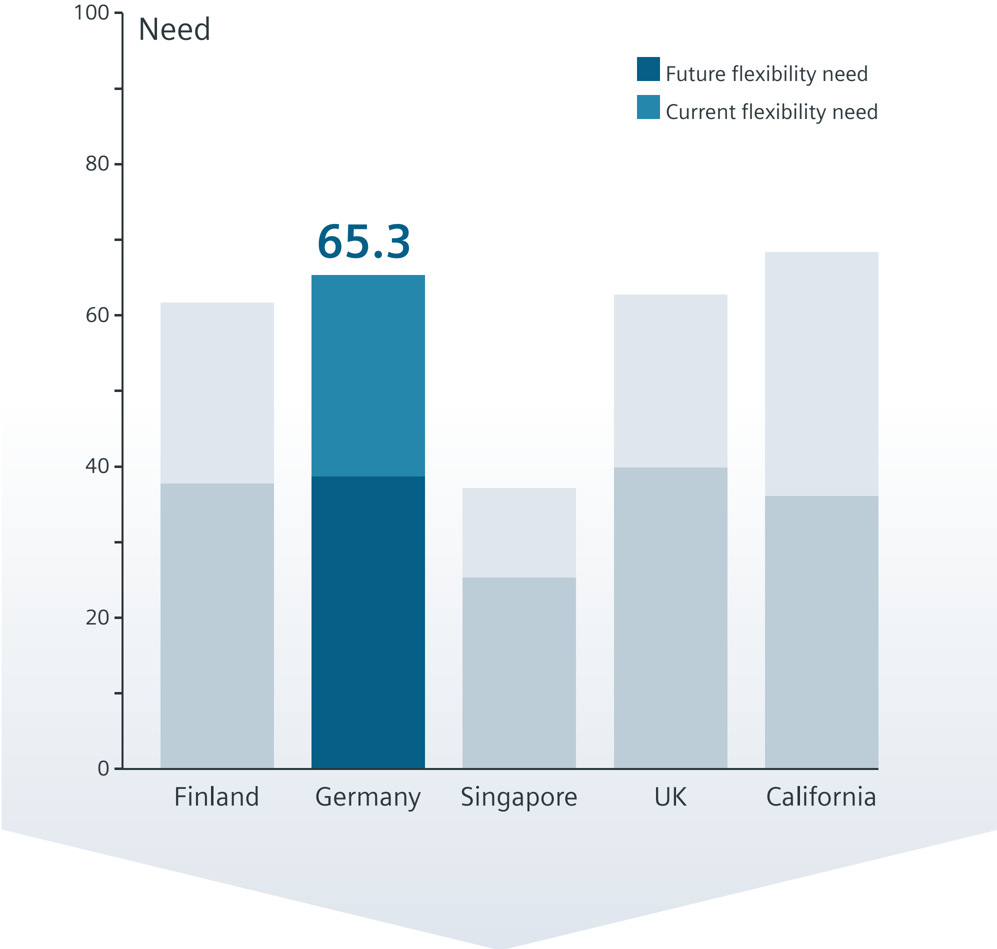


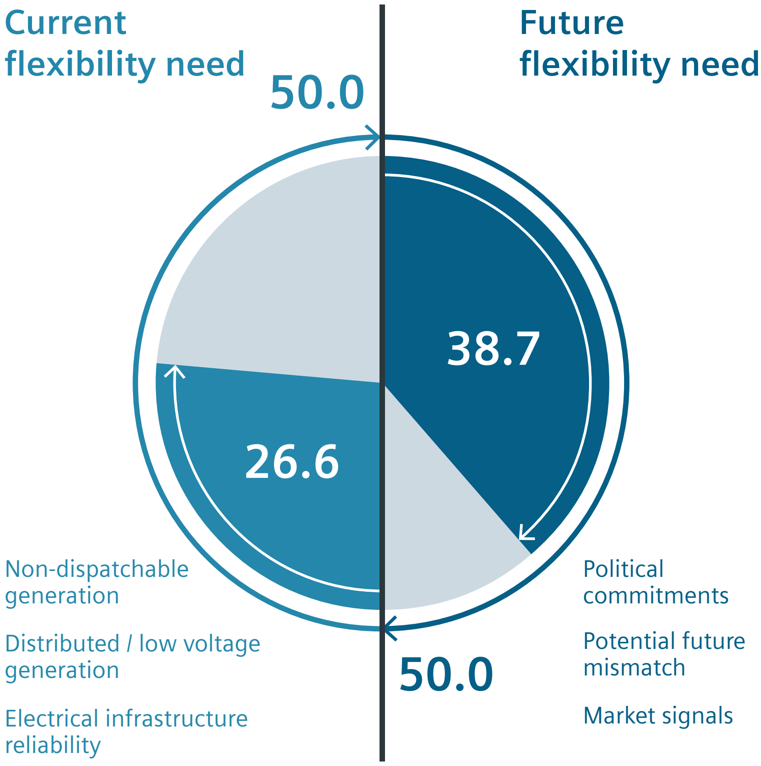
Regarding Germany's need for grid edge innovation as shown in Figure 14, Germany exhibits significant need for flexibility both now and in the future. The current high reliability of the electrical grid indicates that innovations are not immediately necessary. Further, Germany reveals a comparably low peak power demand per installed generation, which indicates that the infrastructure is currently well able to supply electricity demand even at peak times. Despite limited renewable potentials of solar and wind, Germany exhibits a relatively high share of installed wind power as well as solar PV. Respective investments in renewable energy systems are significant. High investments and high shares of renewable energies increase the current need for flexibility and thus for grid edge innovation.

There is still room for improvement regarding binding political commitments of climate protection, which would have an enhancing effect on future flexibility needs. Germany's decision to phase out nuclear in the short term and to phase out coal in the mid- to long-term, as well as renewable heat and EV targets, do drive future flexibility needs and a future mismatch of supply and demand. As a potentially accompanying market signal, the carbon dioxide emission trading system (ETS) for carbon dioxide within Europe, as well as the planned domestic carbon price in Germany, have low prices and thus only exert slight pressure on the direction of a low carbon transformation.

Figure 14:

Grid edge need score: Germany

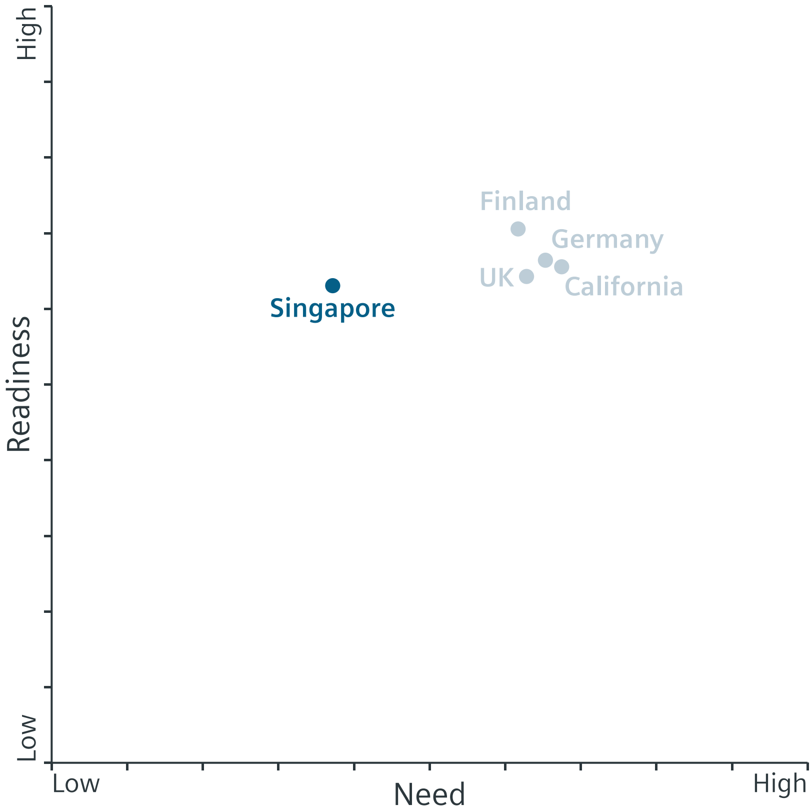




3.3 Singapore
In depth analysis

Figure 15:

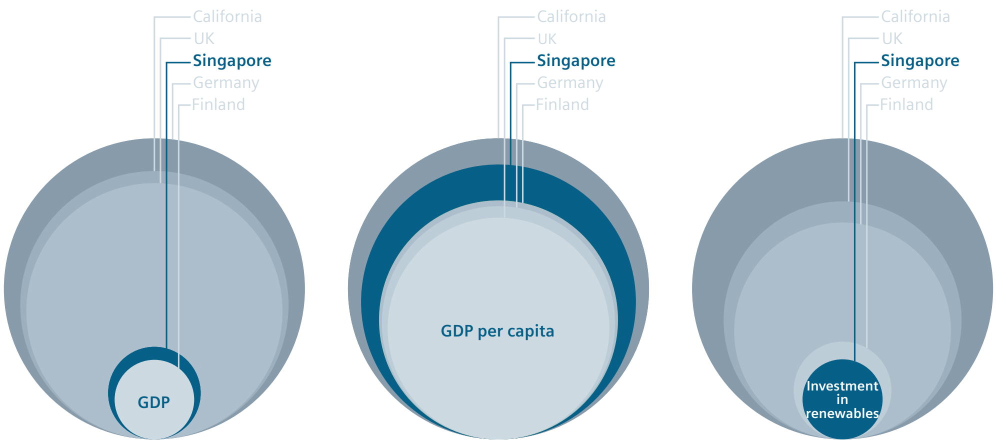
Singapore: grid edge need and readiness score



Although Singapore exhibits the lowest need for grid edge solutions of the five focus regions, it still exhibits a similar level of readiness to deploy grid edge technologies as depicted in Figure 15. Singapore's need for grid edge solutions might not be as high right now, but it can still serve as an example in terms of readiness for similar regions.

Figure 16:

Singapore: Relative market opportunity indicators



Singapore's readiness to deploy grid edge solutions is very similar to the other focus regions as shown in Figure 17, and above average globally.

Economically, Singapore scores lowest of the focus regions. It has a less liberal energy market and higher general market barriers, potentially related to its relatively small market size. However, the existence of a flexibility market shows it is beginning the market transformations necessary to fully realize the potential of grid edge solutions.

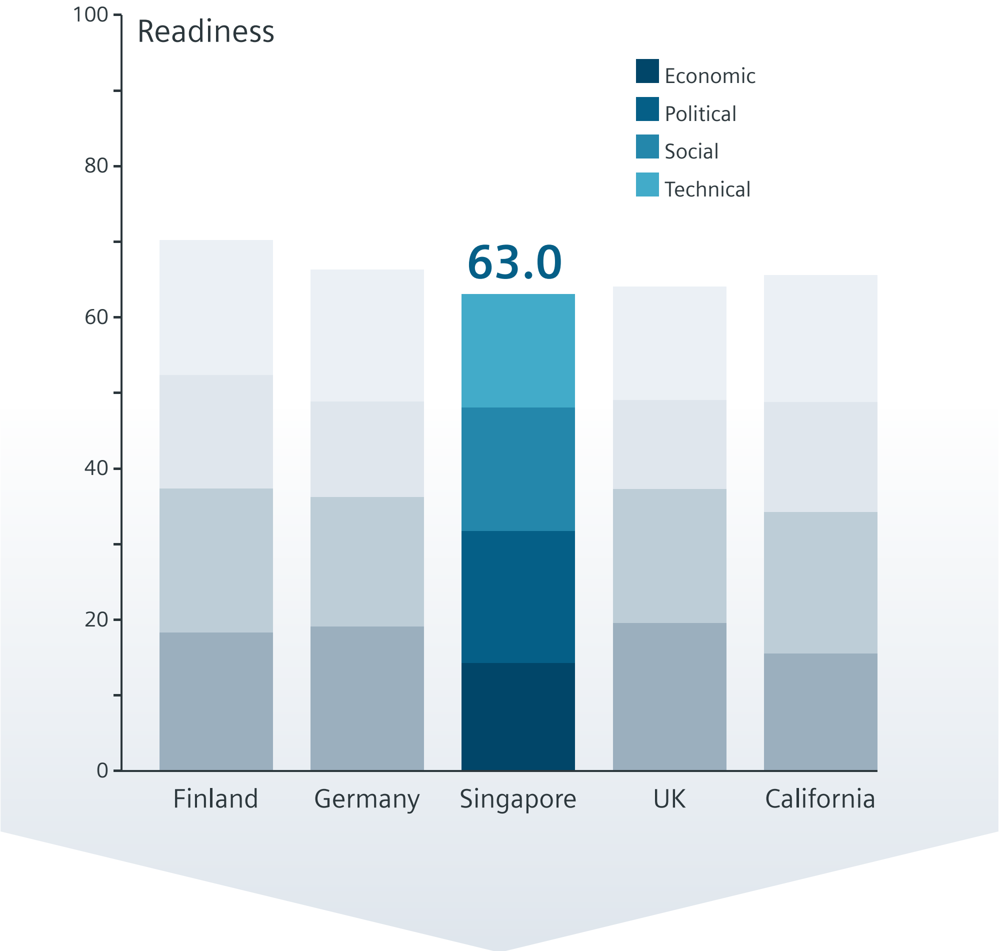
Politically, Singapore's strong institutions and governance make it a favorable location for investors considering deploying or scaling up grid edge technologies. However, most investment in renewable energy, flexibility, and grid edge technology is driven by the private market. Of the focus regions, Singapore has the fewest government incentives to support a clean energy transition.

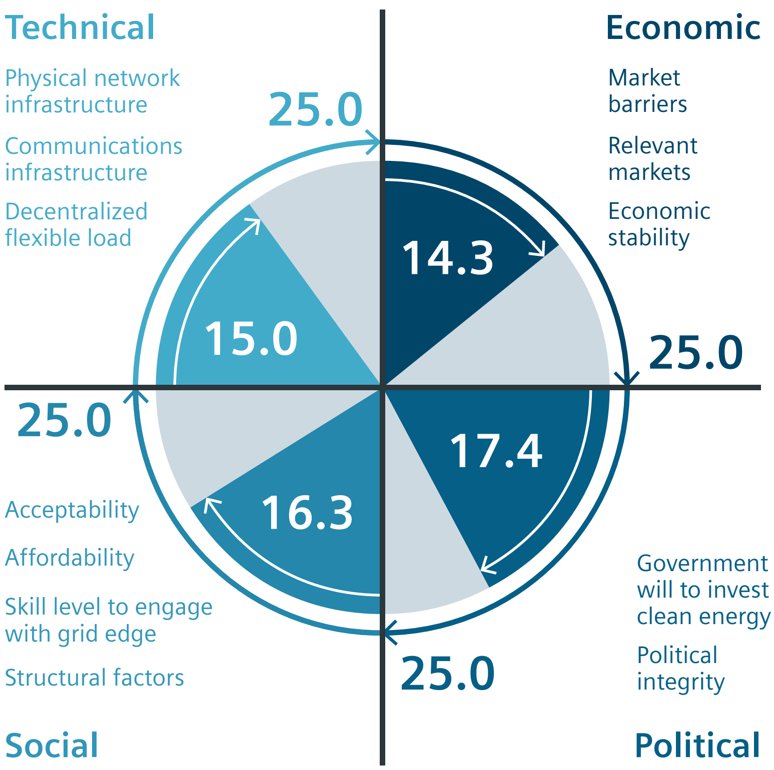
Socially, Singaporean society is well prepared for deployment of grid edge solutions. Its high levels of trust in technology, business, and the government, mean that Singaporean citizens are some of the most open to the technological shifts related to grid edge deployment. With high education levels and technical skills in the population, Singapore has a workforce ready to install and maintain grid edge solutions and an educated population who can quickly learn to engage with grid edge technologies. Singapore is relatively affluent, but the potential readiness gains here are offset by relatively high inequality and expensive technology costs.

Technically, Singapore's robust and reliable electricity and communications infrastructure will enable it to deploy and scale up a variety of grid edge technologies. Alongside Finland, it leads in smart meter penetration. However, it currently has very low levels of decentralized flexible load relative to the other focus regions. More decentralized flexible load in the future could increase the opportunities and need for grid edge technologies.

Figure 17:

Grid edge readiness score: Singapore





Like the other focus regions, Singapore's need for grid edge solutions is driven more by potential future flexibility requirements than by those of today. However, both the current and potential future need for flexibility in Singapore are lower than the other locations analyzed here.

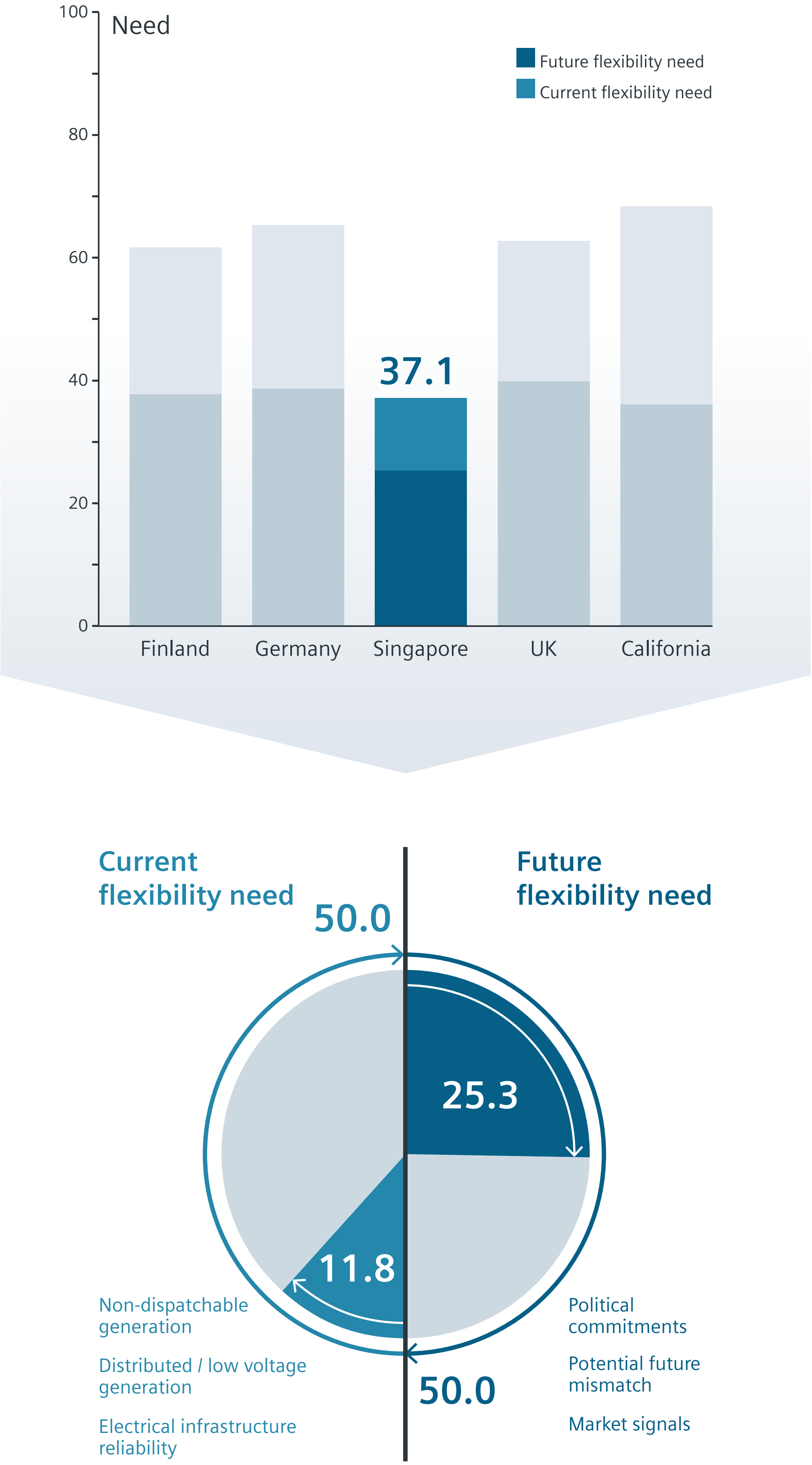
The lower current need for flexibility is driven by infrastructure. The electricity system currently relies almost exclusively on dispatchable generation, resulting in low demand for additional flexibility which could be provided by grid edge solutions. Singapore's highly reliable electricity infrastructure increases its readiness for grid edge deployment, but means it does not need grid edge solutions to help cope with a less reliable system.

The future need for flexibility is more complex. Singapore has made several political commitments and introduced regulations which could increase its future share of renewables and therefore the future need for flexibility. While these increase the potential need for future flexibility, and mean Singapore may need some more grid edge solutions in the future, these are not as ambitious as in other focus regions and still leave room to improve Singapore's efforts towards a clean energy transition. For example, although it has a carbon price, Singapore's carbon price is not as high as in other focus regions and therefore may not incentivize renewables as much compared to fossil fuels. Similarly, Singapore's plan for cleaner transportation includes a target to phase out internal combustion engine vehicles by 2040 [16]. This could lead to a greater share of electric vehicles, which could increase demand and need for grid edge solutions. However, there is not a specific electric vehicle target, making the effect on the electricity system and need for grid edge less certain.

Additionally, due to its small area, Singapore has little scope for large scale renewable generation. As long as Singapore continues to rely on dispatchable energy sources and interconnectors, it may not require as much flexibility enabled by grid edge as the other focus regions.

Figure 18:

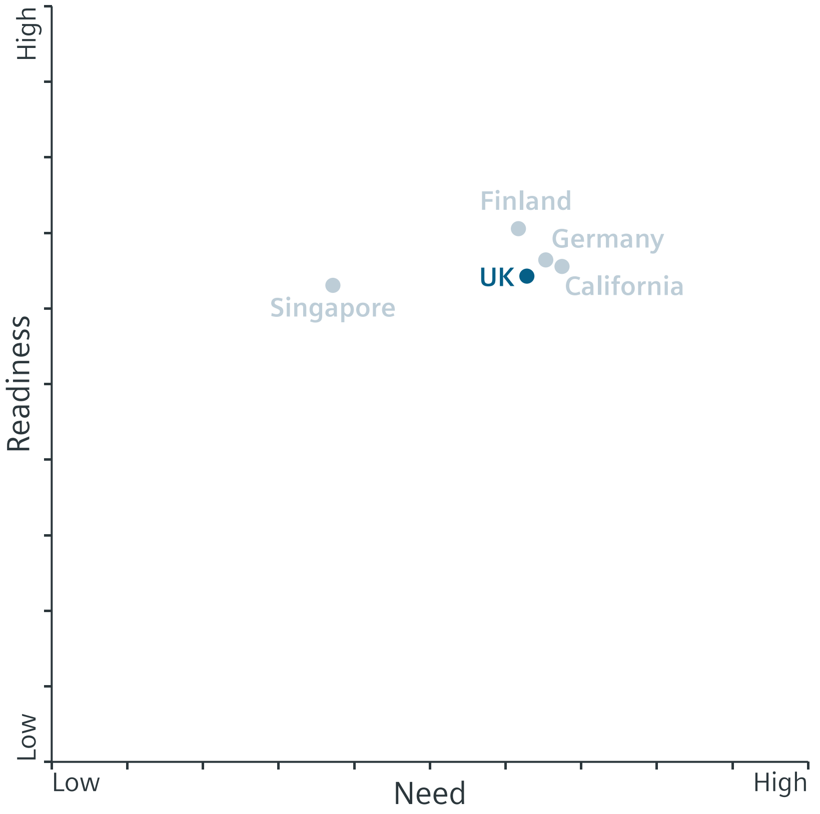
Grid edge need score: Singapore



3.4 United Kingdom
In depth analysis

Figure 19:

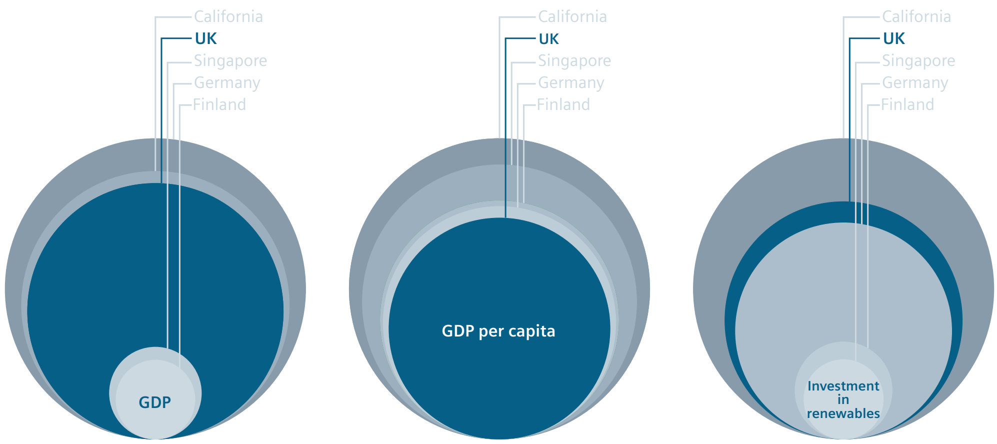
United Kingdom: grid edge need and readiness score



The UK was the first major economy to pass a net-zero emissions law [17]. The new target requires all greenhouse gas emissions to be brought to net zero by 2050, a step up in ambition from the previous target of at least 80% emission reduction from 1990 levels. 'Clean growth' is at the core of the UK's industrial strategy, with approximately 45% reduction in greenhouse gas emissions by 2019 from 1990 levels [18]. This places the UK among the leaders in both readiness and need for grid edge technologies, as depicted in Figure 19. The UK's high readiness level is reflective of the high political and economic readiness. The UK has high government willingness to invest, behind only California, and a high degree of market liberalization.

Figure 20:

United Kingdom: Relative market opportunity indicators



Economically, the UK's readiness for grid edge, as shown in Figure 21, is favored by the presence of aggregators, existence of a carbon price, and availability of incentives for electrification of different services.

On the social aspects, the UK has relatively low energy affordability, with around 10% of households considered fuel poor in 2018 [19] and a lower prosperity compared to other focus regions. Even though this lowers the ability to buy and install grid edge solutions, it is still within the range of most of the other focus regions. Where the UK scores lowest of focus regions, however, is in skills to install and maintain grid edge technologies as well as to use and engage grid edge technologies. Here, the UK lags behind on both the availability of scientists and engineers and the digital skills of the population. The UK has the lowest acceptability of new technologies among the focus regions, with low trust in government, business, and technology, making it less ready for the scaling up of grid edge solutions.

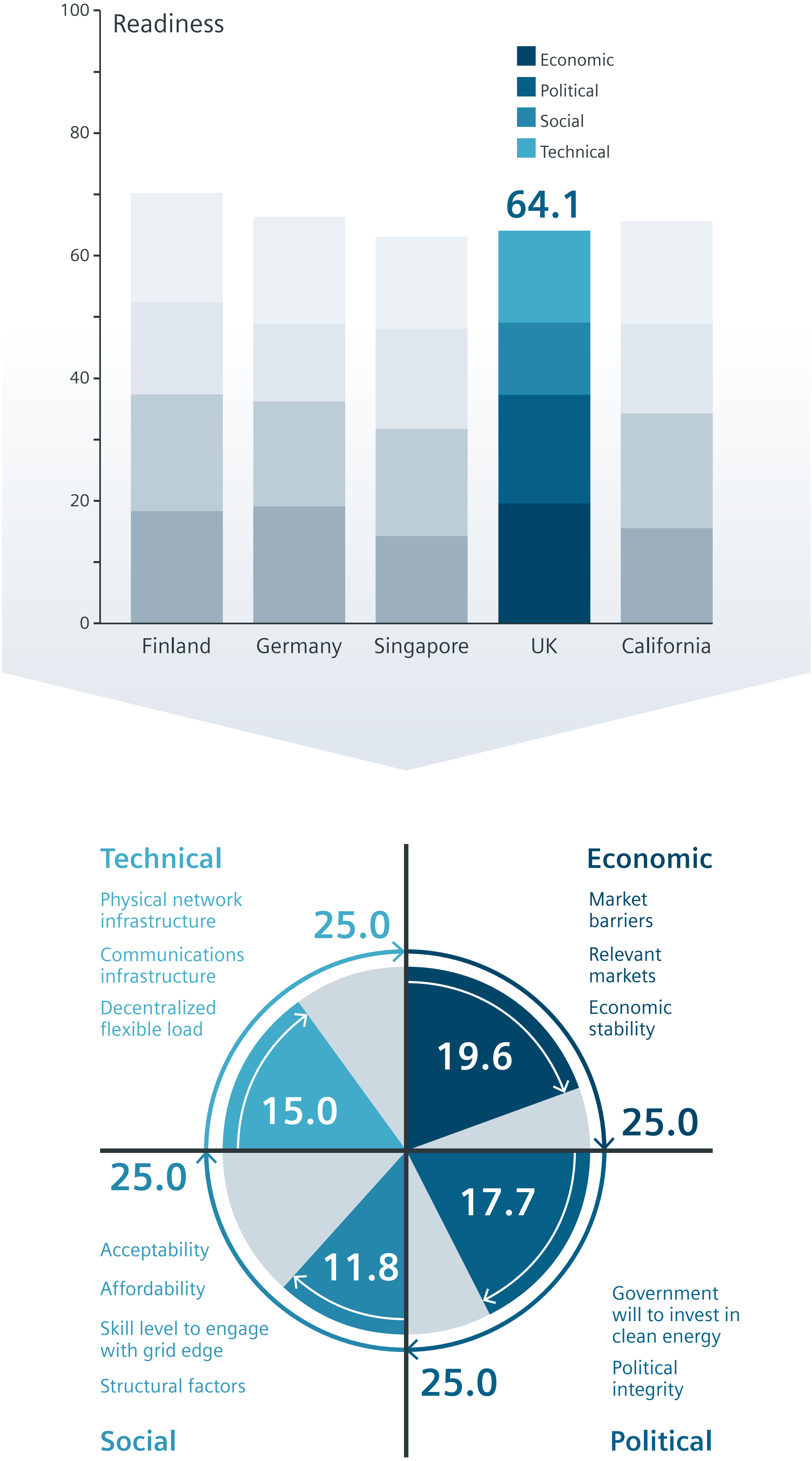
On the policy front, the UK government has high willingness to invest in clean energy, next only to California. The installation of PV systems were favored through feed-in tariff systems in the beginning of the energy system transition in 2010; however, the scheme is no longer available for new entrants [20]. Though this reduces the incentives for households to install PV systems, the significant reduction in the cost of PV systems is expected to compensate for it. The UK also has incentives for purchase of battery electric vehicles, improvement of energy efficiency, and CHP. There are incentives available to improve home energy efficiency and also plans to improve energy efficiency as a key element in the future investment cycles.

In technical aspects indicating the readiness of the country, the UK and Singapore have similar readiness levels. The UK has relatively lower scores in decentralized flexible loads and communication infrastructure among the focus regions. Though the UK has high coverage of internet, GSM and smartphones, the penetration of smart meters and average bandwidth of internet connection are among the lowest of the focus regions. Less than 30% of households have smart meters and installations are way behind the target dates [21].

The readiness of a region to adopt grid edge is higher if the amount of existing decentralized flexible load is higher. The UK currently has very low heat pump penetration; however, there are significant incentives to install more heat pumps especially in houses that are off the gas grid. The penetration of air conditioners is also low owing to the relatively cool weather in summer. The electrification of other assets in the UK, especially heating, is adversely affected by the cheap per unit cost of gas when compared to electricity – which is almost one-third of the cost [22]. However, the removal of feed-in tariff has increased the self-consumption of PV generation, resulting in an increased number of domestic batteries being installed. This trend is expected to continue, increasing the future readiness of the country for grid edge. This serves as an example for reverse measures at times being a means to furthering the implementation of grid edge solutions and the clean energy transition.

Figure 21:

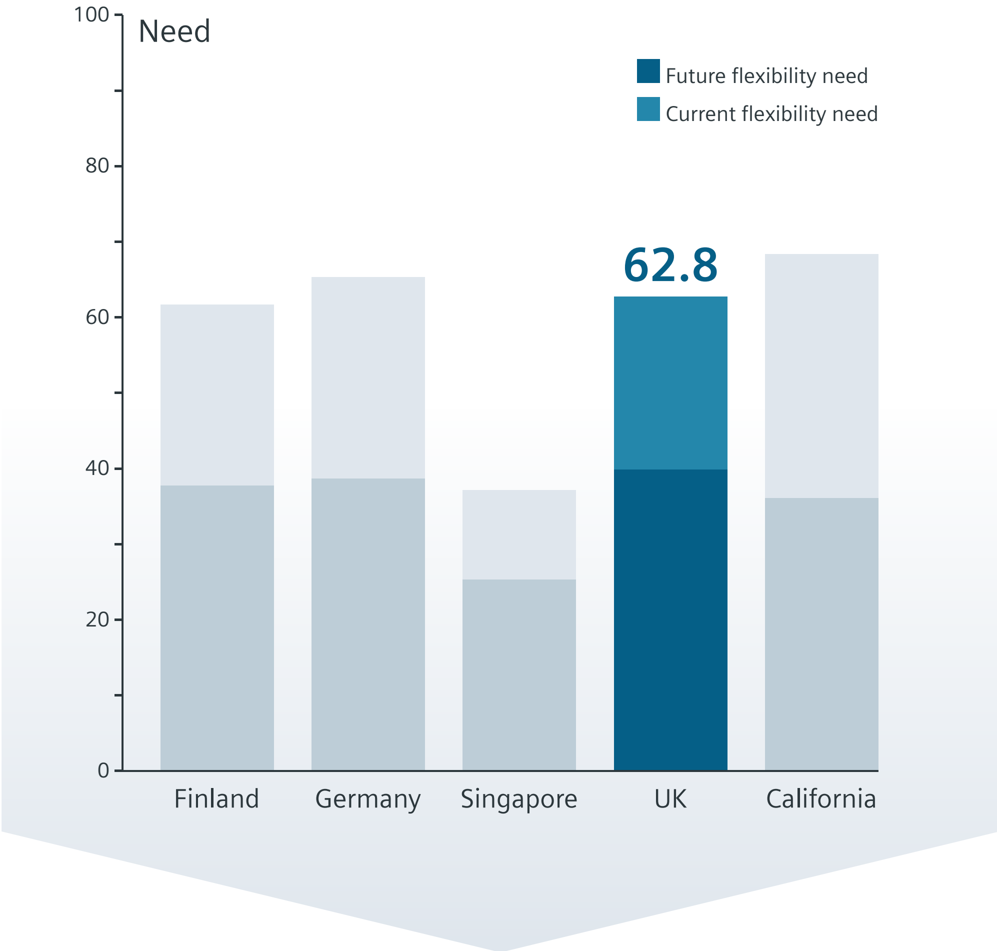
Grid edge readiness score: United Kingdom

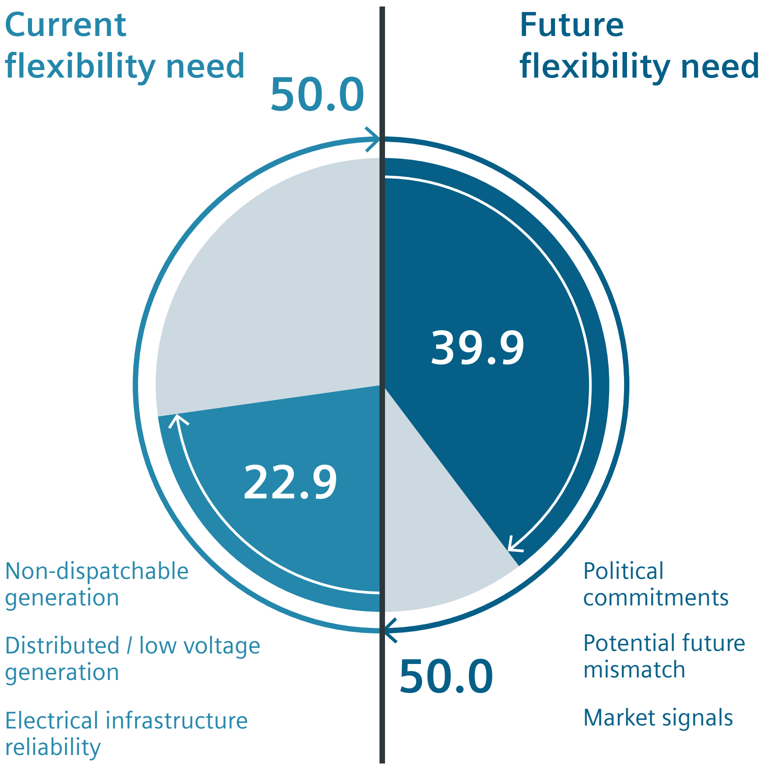


The UK has the highest future flexibility need among the focus areas and low current flexibility need as shown in Figure 22. The higher the reliability of the existing electricity network, the lower is the need for current flexibility. The current UK network has high reliability next only to Singapore among the focus regions. Though the UK has relatively high current demand for electricity, the availability of non-dispatchable loads is among the lowest, next only to Singapore, resulting in less imminent and current need. The future need is fueled by the legally binding target for net-zero emissions by 2050 and the target ban on fossil fuels and internal combustion engine vehicles, which results in the highest political commitment among the focus areas. The presence of market signals in the UK is next only to Finland, which was to be expected from a country that was the first major economy to pass a net-zero emissions law.

Figure 22:

Grid edge need score: United Kingdom

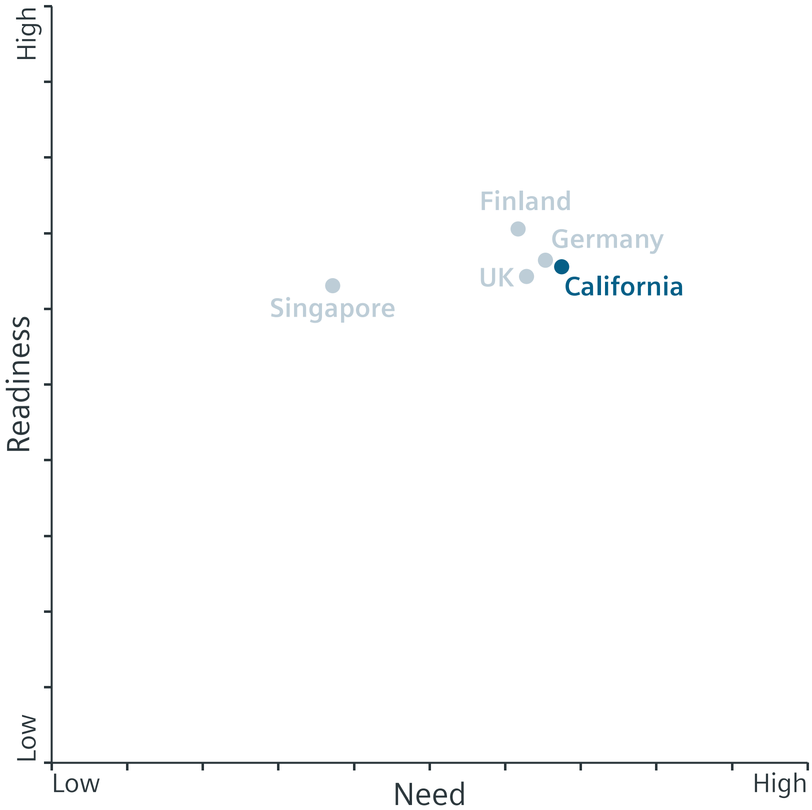




3.5 California, United States
In depth analysis

Figure 23:

California: grid edge need and readiness score

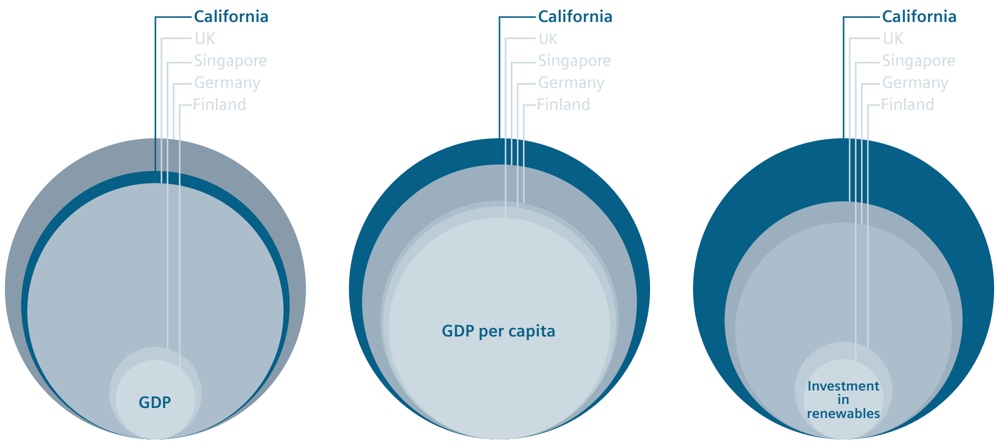


California exhibits the highest need of all focus regions, as shown in Figure 23, but is also relatively ready for grid edge solutions, so it is well placed to address these needs.

California is also one of the most progressive focus regions in terms of energy policy, passing multiple laws related to renewable generation [23], [24] and making substantial investments in solar power. Most prominently it has set its sights on a zero-carbon energy future by the year 2045 – and grid edge technologies will be essential in achieving this.

Figure 24:

California: Relative market opportunity indicators



The readiness to roll out these grid edge technologies is most influenced by electric vehicles, market liberalization and trust in technology (in order of importance). In California, EV market share is roughly 1.5%, but the absolute cost of an EV is high. Considering that California is also rated highly in terms of purchasing power parity, this higher EV cost should not be a deterrent in the future. The degree of market liberalization in California does not favor grid edge technologies, but a relatively large number of electricity suppliers will encourage innovation and, in turn, grid edge technologies. Although California is home to some of the largest tech companies in the world, trust in technology is lower than other focus regions. This can be attributed to a general sense that technology companies are going to remove more jobs than they create and also that they are under regulated.

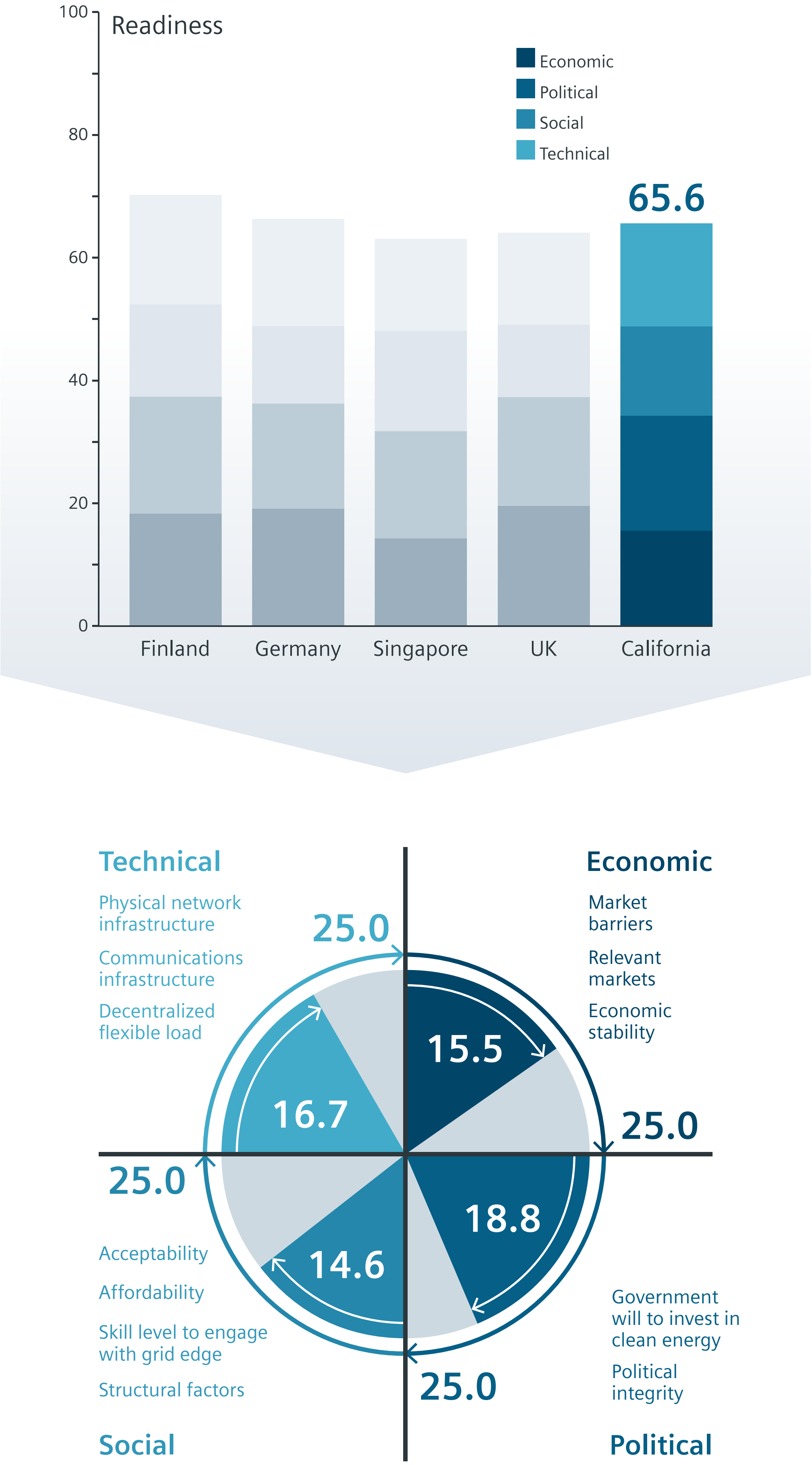
Technical factors which play a major role in deciding whether a region is ready for grid edge are investment in renewables, penetration levels of battery storage, smart meters, and electricity grid coverage. California scores highly with regards to all four of those factors.

Non-technical factors also play a significant role in grid edge readiness. California has healthy scores in terms of judicial independence, corruption perception, and digital skills in the population. A high availability of scientists and engineers in the workforce means that California can handle an increase in grid edge penetration. As many smart homes have already been adopted, with the ability to switch over to smart grids, this will prove vital when transitioning to more and more distributed generation.

California is relatively advanced in terms of energy policy and is publicly committed to upholding the goals set in the Paris Agreement, despite the US's 2017 decision to leave [25]. This can be demonstrated by the numerous targets for renewable energy, incentives for efficiency, combined heat and power, and renewable heating and cooling. This, along with the large number of virtual power plants, makes California an attractive region in terms of grid edge readiness as shown in Figure 25.

Figure 25:

Grid edge readiness score: California



California has the highest levels of low voltage PV in the focus regions. The level of low voltage PV is crucial when discussing the need for grid edge – as increasing levels of low voltage PV are likely to cause stability issues. These can, however, be countered through the use of grid edge resources. In California the difference between demand and renewable generation will become a major issue, as large fluctuations in PV can require expensive power plants to be dispatched. Thus, in addition to security reasons, there is a significant cost incentive to deploying grid edge technologies in this region.

Wind accounts for 6 GW [26] and solar for 27 GW [27] of California's installed generation capacity, but capacity in this region has to increase on a massive scale to achieve California's target of a 100% renewable electricity grid by 2045. This will be supported by a relatively high amount of solar and wind availability. High levels of inflexible nuclear power can cause problems in some regions, but with nuclear capacity at around 2.24 GW [28], which is low in relation to the size of California, this is not expected to be an issue.

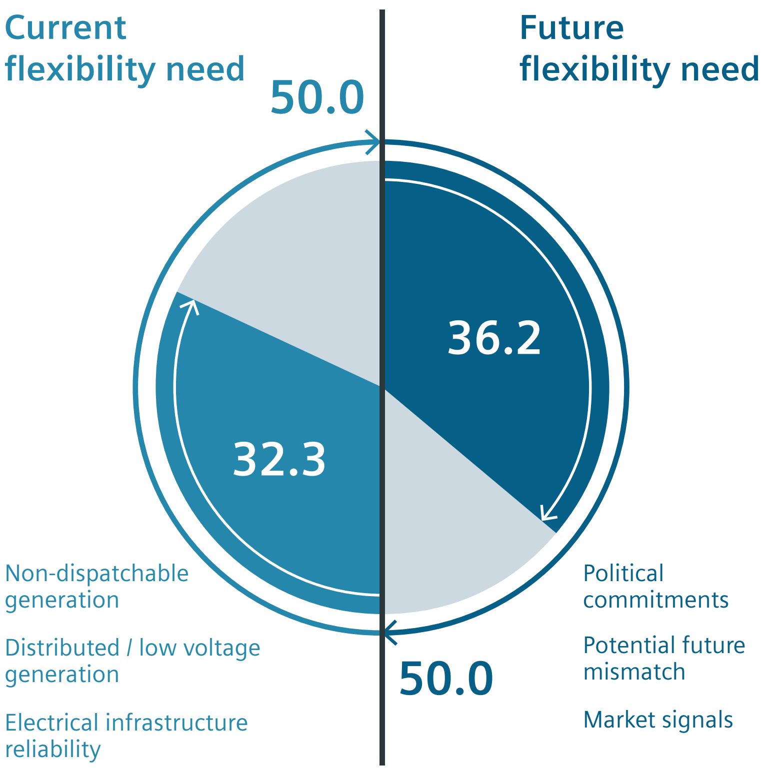
In California, there are some important trends in terms of reliability. Although the average number of interruptions is low, the average interruption duration is the highest among the focus areas. This means that although the frequency of outages is low, if they do happen, they can last for extended periods. This can be attributed to California being affected by forest fires and natural disasters which force the system operator to take parts of the grid offline. Grid edge technologies, especially microgrids and distributed generation, would definitely improve this situation.

Targets related to electric vehicles and an emission reduction of 40% in the next ten years [29] are likely to require grid edge technologies to be deployed. For example, uncontrolled electric vehicle charging can lead to a large number of vehicles switching themselves on en masse, which will require a scheduling or coordination mechanism to be put in place to prevent this happening. The emission reduction target also puts more pressure on increasing renewable capacity since it places a palpable short-term target in addition to the long-term vision of a net zero electricity system.

California represents a region that is going to need increasing amounts of grid edge penetration in the coming years, as it is among the leaders of locations moving to a clean energy system. It is, however, well placed to facilitate this transition because of the high level of grid edge readiness as shown in Figure 26.

Figure 26:

Grid edge need score: California



3.6 Application of index to multiple regions

Figure 27:

Relative grid edge need and readiness for selected regions, where error bars represent uncertainty

Application of the index to a broader set of regions places the focus regions in a global context and offers insight into the status of a variety of other geographies, including identifying locations which may be of interest for further analysis.

The need and readiness for the additional regions are shown in gray in Figure 27. The original five regions are shown in blue to highlight their comparative location.

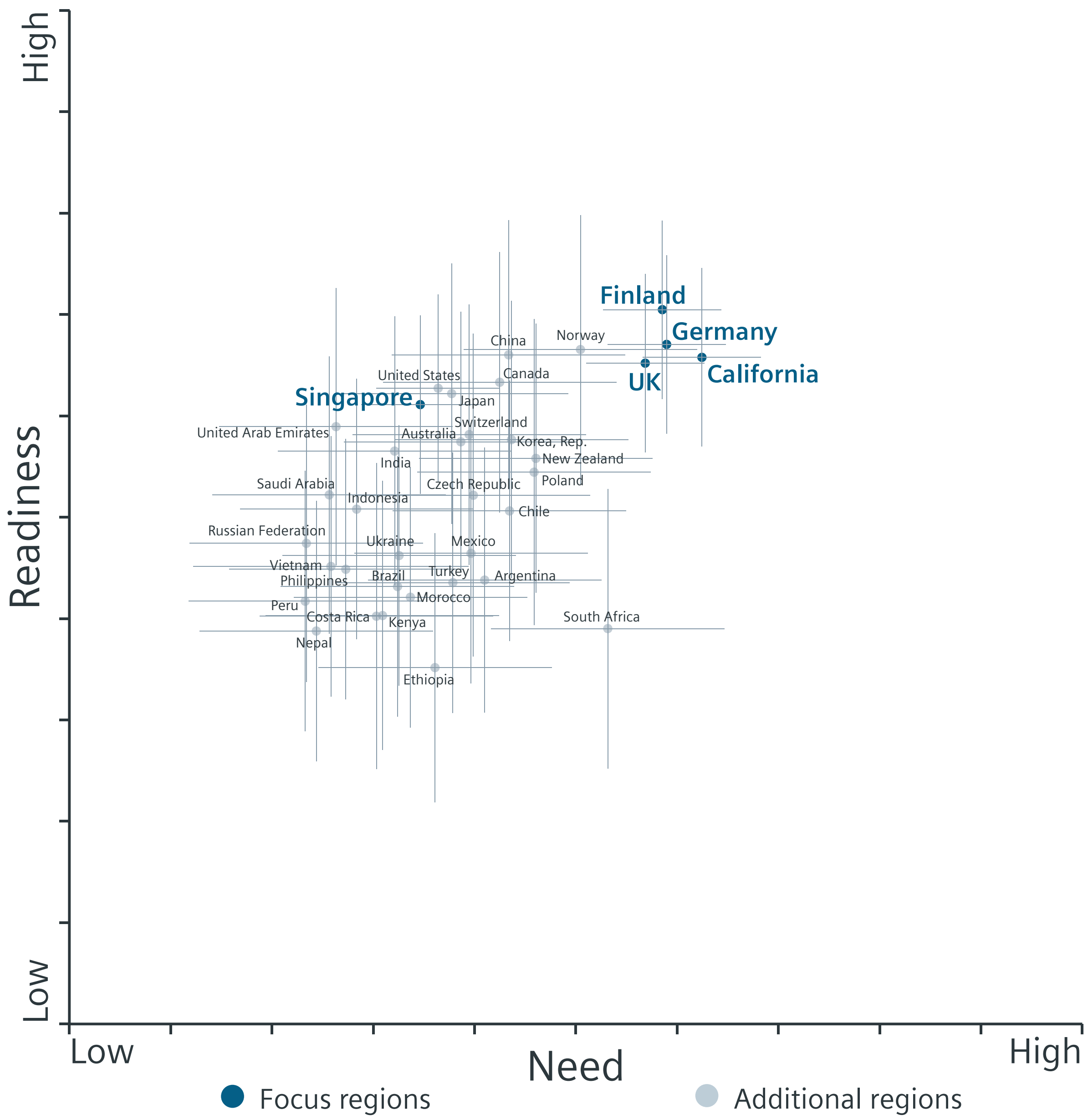


Figure 27 shows that of the additional regions, Norway has the highest readiness and South Korea has the greatest need for grid edge technology.

Outside of the focus regions and Norway, China and Canada are also reported to have high readiness for grid edge technologies, whereas Ethiopia, Nepal, and South Africa are among the least ready. In addition to several of the focus regions, the countries with the greatest need for grid edge technologies include Norway, South Korea, and South Africa. In contrast, Russia, Peru and Nepal are seen to have the least need, at present.

Exhibiting both a high need and readiness for grid edge innovation, Norway, China, and Canada can be highlighted as promising candidates for further research and detailed analysis.

It must be noted that all conclusions are drawn based on a snap-shot in time and in relation to the other regions considered.

4 Key policy levers

For many countries that do not currently score high on need or readiness for grid edge solutions, governments and stakeholders in the energy sector might ask what could cause the need for grid edge solutions to increase, how they could improve grid edge readiness in this location, or how to address existing needs for grid edge solutions. Policy makers may ask these questions so that they can act to meet their targets; clean energy companies will want to know so that they can lower barriers, implement technology, and work with the government; and industry would want to understand the changes ahead so they can diversify their business and remain relevant.

The need for grid edge technology is heavily influenced by the region's requirement for flexibility in the energy system. This need for flexibility evolves from the increasing presence of renewable energy generation. Incentivizing renewable energy generation capacity and committing to mitigate climate change could increase a region's need for grid edge solutions.

Unlike fossil fuel power stations, some renewable generation can be inflexible, constrained by natural resources and weather conditions. Therefore, energy systems must adapt and become more flexible. The results of international research in recent years explicitly identify the ability of the demand side to react flexibly to fluctuating power generation as an important element in the successful clean energy transition [30]. Flexible demand can come in many forms, such as batteries, demand side management and operational flexibility for industrial and commercial consumers, adaptive consumer behavior, or smart charging an electric vehicle. Infrastructure can also play an important role in increasing flexibility, through interconnections and grid expansion, microgrids, and distribution network connected assets. Much of this flexibility is enabled by grid edge technology, hence the high need for grid edge solutions in systems more dependent on renewable energy generation. Increased renewable generation comes hand-in-hand with meeting greenhouse gas emission targets. Policies that encourage either or both will see a significant impact on the need for grid edge.

Improving a region's grid edge readiness is especially pertinent in places where there is high need and low readiness, such as South Africa. In places where a higher need for grid edge is identified, grid edge should be able to make a positive difference to the energy system; however, the lack of readiness acts as a barrier.

Three key policy levers to improve a region’s readiness for grid edge technology are to:

Introduce incentives for clean energy technologies.

Placing funds from the public purse behind clean energy technologies improves political, social, and technical readiness by showing political support, improving social acceptance and consumers’ (residential, commercial, and industrial) ability to pay, and by potentially increasing decentralized flexible load. Through these incentives, the economic barrier is reduced, enabling business models which otherwise would not be viable, and leading to an increase in technology adoption. This in turn results in potential economies of scale and cost reductions in technology, such as with rooftop solar. Alongside this, as technology becomes commonplace, society becomes more familiar and accepting of it. This can result in a positive feedback loop and rapid adoption of a technology, commonly seen as an S-curve in emerging markets.

Introduce flexibility and carbon markets.

These markets work to improve economic readiness. Giving flexibility (e.g. shifting consumer energy demand in time) a value will encourage residential, commercial, and industrial actors to invest in the technologies and assets necessary to provide flexibility of services. Many of these solutions will operate at the grid edge. The existence of a carbon market improves the economic viability of grid edge solutions compared to their respective fossil-fuel based counterparts. For the system as a whole, the existence of a carbon market is considered to hold significant importance for economic readiness.

Develop policy pathways to provide reliable and secure communications infrastructure to all residents.

The presence of widespread, reliable communications infrastructure improves a region’s technical readiness. Robust communications infrastructure will be required to coordinate and enable the network of decentralized and distributed actors at the grid edge. Smart meters will play a vital role in understanding demand and enabling flexibility.

5 Conclusion

In this white paper, an index is defined that assesses the need and readiness for grid edge technologies across a portfolio of regions. Grid edge solutions are a crucial component to help integrate renewable energy sources into the energy system and mitigate climate change. This index is designed for use by policy-makers and corporations to aid them in (i) identifying the need and readiness status of a region at present, which is useful in targeting where to roll-out technology, and (ii) to highlight what action can be taken to improve a region’s readiness for grid edge technology. This is especially important for regions in need of grid edge but hindered by a lack of readiness for it. Key policy levers for improving a region’s readiness are identified as incentives for clean technologies, the introduction of flexibility markets and carbon markets, and developing policy pathways for reliable and secure communications infrastructure.

The index was applied to 36 locations. Of the five focus regions, Finland is identified as the country most ready for grid edge, while California is the region most in need. The UK and Germany follow close behind with Germany having a slightly higher readiness and need than the UK. In addition to these locations, countries such as China, Canada, and Norway appear promising locations for roll-out of grid technology. South Africa offers a prime example of a country that is in great need of grid edge technology, but not yet ready for it. Locations such as this will benefit from considering the policy levers identified.

6 Appendix

Table 1 includes all indicators which are included in the grid edge index for need and readiness, whether they are positively or negatively correlated with the final index scores, how data was processed, and the data sources for each indicator. As described in Section 2.2, some indicators were processed so that they could be better compared across different locations. Where not enough data was found to enable credible comparison between regions, the data could not be included and sources are listed as "N/A". These missing values were replaced with a neutral value of 0.5, except in cases where additional available information yielded better estimates as noted in the corresponding footnotes below.

Table 1: Grid edge index indicators

Indicator	Grid edge dimension	Direction of influence	Processing details	Sources
Availability solar	Need	Positive	None	[31], [32]
Availability wind	Need	Positive	None	[33]
Behind the meter generation	Need	Positive	None	N/A
Carbon price	Need	Positive	None	[8]
Carbon price implemented	Need	Positive	None	[8]
Electricity energy demand	Need	Positive	Divide by total energy demand	[34], [35]
Emissions target ambition	Need	Positive	None	[29], [36]–[40]
Installed CHP	Need	Positive	Divide by total installed generation capacity	[41]–[45]
Installed low voltage PV	Need	Positive	Divide by total installed generation capacity	[34], [46]–[49]
Installed nuclear	Need	Positive	Sum with other inflexible loads, then divide by total installed generation capacity to yield non dispatchable generation	[50], [51]
Installed solar PV	Need	Positive	Sum with other inflexible loads, then divide by total installed generation capacity to yield non dispatchable generation	[27], [51]
Installed solar CSP	Need	Positive	Sum with other inflexible loads, then divide by total installed generation capacity to yield non dispatchable generation[1]	[46], [52]–[56]
Installed wind	Need	Positive	Sum with other inflexible loads, then divide by total installed generation capacity to yield non dispatchable generation	[26], [51]
NDC fixed target	Need	Positive	None	[29], [36], [57], [58], [59]
NDC net zero target	Need	Positive	None	[36], [60]–[65]
NDC whole economy	Need	Positive	None	[29], [36], [57]
Peak power demand	Need	Positive	Divide by total installed generation capacity	[66]–[72]
Price elasticity of consumers	Need	Negative	None	N/A
Projected electricity demand	Need	Positive	Scale regional change in electricity demand by population[2]	[73]

1 Missing values for installed solar CSP were replaced with zero since absence of public domain information about this uncommon generation type was considered to indicate an absence of such assets.
2 Missing values for projected electricity demand were calculated by scaling regional projections by the population of the location divided by the population of the region.

Indicator	Grid edge dimension	Direction of influence	Processing details	Sources
Reliability SAIDI	Need	Positive	None	[74], [75]
Reliability SAIFI	Need	Positive	None	[76], [74]
Renewables projected share of generation	Need	Positive	None	[9], [77]
Target EVs	Need	Positive	None	[78], [9]
Target ban fossil fuels buildings/industry	Need	Positive	None	[9]
Target buildings renewable heat	Need	Positive	None	[9]
Target coal exit	Need	Positive	None	[79], [32], [80], [81], [82], [83], [10], [84], [85], [86]
Target for natural gas exit	Need	Positive	None	N/A
Target nuclear exit	Need	Positive	None[3]	[87], [88]
Target renewables energy	Need	Positive	None	[9], [89]
Target renewables heating or cooling	Need	Positive	None	[9], [90]
Target renewables power	Need	Positive	None	[9], [89]
Target smart meters	Need	Positive	None	[91]–[93]
Target solar installed	Need	Positive	None[4]	[9], [94]
Target wind installed	Need	Positive	None[4]	[95], [9]
Timing of phase outs	Need	Positive	None	N/A
AC penetration	Readiness	Positive	Divide by households, where number of households is calculated from population and average household size	[96]
Access to electricity	Readiness	Positive	None	[97]
Availability of scientists and engineers	Readiness	Positive	Divide by max index score	[98]
Average balancing market price	Readiness	Positive	None	N/A
Average bandwidth	Readiness	Positive	None	[99]
Battery costs	Readiness	Negative	Convert to USD, scale by PPP	N/A
Battery storage penetration	Readiness	Positive	Scale regional total GWh proportionally by population[5]	[100]
Budget balance stable	Readiness	Positive	None	[101]
Carbon price	Readiness	Positive	None	[8]
Carbon price implemented	Readiness	Positive	None	[8]
Corruption perceptions index	Readiness	Positive	Divide by max index score	[102]
Credit rating	Readiness	Positive	Assign linear score, where AAA = 1 and SD = 0	[101], [103]
Debt to GDP ratio	Readiness	Negative	None	[104]
Degree of electricity market liberalization	Readiness	Negative	Divide by max index score	[105]

3 Nuclear phase out was set to the neutral value for locations which do not have nuclear power as this is irrelevant for them and it is very unlikely that they will face a nuclear phase-out in the coming decade.
4 Replacement values of 0 were used for target solar installed and target wind installed because very few countries had targets for specific generation types rather than renewable generation more generally.
5 Missing values for battery storage penetration were calculated by scaling regional battery penetration figures by the population of the location divided by the population of the region.

Indicator	Grid edge dimension	Direction of influence	Processing details	Sources
Digital skills in population	Readiness	Positive	Divide by max index score	[106]
EV cost	Readiness	Negative	Convert to USD, scale by PPP	[107]–[111]
EV market share	Readiness	Positive	None	[112], [78]
Electric utility quota / Renewable portfolio standard	Readiness	Positive	None	[9], [113]
Electricity price C&I	Readiness	Neutral	Replace with neutral value because effects in both directions[6]	[34], [114], [115]
Electricity price residential	Readiness	Neutral	Replace with neutral value because effects in both directions[6]	[34], [114], [115]
Energy expenditure (C&I)	Readiness	Negative	None	N/A
Energy expenditure (residential)	Readiness	Negative	None	N/A
Feed in tariff / premium payment	Readiness	Positive	None	[9], [116]
Flexibility market (or plan)	Readiness	Positive	None	[117], [118], [119], [120], [121]
GDP	Readiness	Positive	None	[122]
GDP per capita	Readiness	Positive	None	[123]
GINI coefficient	Readiness	Negative	Divide by max index score	[124], [125]
GSM coverage	Readiness	Positive	None	[126]
Heat pump penetration	Readiness	Positive	Divide by households, where number of households is calculated from population and average household size	[127]–[130]
Imports	Readiness	Positive	None[7]	[131]
Incentives CHP	Readiness	Positive	None	[132], [133], [134], [135], [136]
Incentives EVs	Readiness	Positive	None	[78]
Incentives building renewable heat / cooling	Readiness	Positive	Divide by 24, because made up of 24 binary values for 24 separate incentives policies	[9]
Incentives efficiency	Readiness	Positive	None[8]	[137], [138], [139], [140], [141]
Incentives for DSM	Readiness	Positive	None	N/A
Incentives for decentralized storage	Readiness	Positive	None	N/A
International Investment Liabilities	Readiness	Positive	None	[142]
Internet coverage	Readiness	Positive	None	[143]
Investment renewables	Readiness	Positive	Divide by GDP	[144], [145]
Judicial independence index	Readiness	Positive	Divide by max index score	[98]
Load bidding limits	Readiness	Positive	None	N/A
Microgrids	Readiness	Positive	Divide by total installed generation capacity	N/A
Net exports	Readiness	Positive	None	[101]

6 Electricity price for all types of consumers (residential and commercial and industrial) was replaced by neutral value due to competing influences on grid edge readiness. Higher grid electricity prices may discourage electrification of different sectors, but may also encourage self-generation with renewable energy sources.
7 Any conclusions or analyses based on IDB and CTS data are accompanied by a disclaimer stating that they are the responsibility of the authors and do not necessarily represent the opinion of the WTO.
8 Missing values were replaced with 1 because the overwhelming majority of the countries researched had this.

Indicator	Grid edge dimension	Direction of influence	Processing details	Sources
Net metering	Readiness	Positive	None	[9]
Number of DNO/DSO	Readiness	Positive	Divide by population	N/A
Openness to new entrants	Readiness	Negative	None	[146]
PV costs	Readiness	Negative	Convert to USD, scale by PPP	N/A
Players electricity suppliers	Readiness	Positive	None	[147]–[151]
Virtual power plants (VPP)	Readiness	Positive	None	[152]
Property owners (C&I)	Readiness	Positive	None	N/A
Property owners (residential)	Readiness	Positive	None	N/A
Purchasing power parity	Readiness	Positive	None	[153]
Reliability SAIDI	Readiness	Negative	None	[75], [74]
Reliability SAIFI	Readiness	Negative	None	[76], [74]
Smart homes market penetration	Readiness	Positive	None	[154]
Smart homes revenue	Readiness	Positive	Divide by GDP	[154]
Smart meter costs	Readiness	Negative	Convert to USD, scale by PPP	N/A
Smart meter penetration	Readiness	Positive	None	[5]
Smartphone penetration	Readiness	Positive	None	[155]–[159]
Tendering	Readiness	Positive	None	[160], [9]
Trade Renewable Energy Certificates	Readiness	Positive	None	[161], [9]
Trust in business	Readiness	Positive	Divide by max index score	[162]
Trust in government	Readiness	Positive	None	[163]
Trust in tech	Readiness	Positive	Divide by max index score	[164]
Unemployment rate	Readiness	Negative	None	[101]
Willingness to pay	Readiness	Positive	Scale by PPP	N/A
Willingness to shift load	Readiness	Positive	None	N/A
Population	N/A	N/A	Used to process other indicators	[165]
Energy demand	N/A	N/A	Used to process other indicators	[169]
Average household size	N/A	N/A	Used to process other indicators	[166]–[168]

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