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Energy and Security: new challenges of the transition to a low-carbon economy

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Abstract

In order to combat climate change, countries across the globe have set up plans to reduce their carbon emissions in the upcoming decades. This effort requires a wide-ranging transformation, which will influence the structure of energy systems, the related markets, as well as inter-country relations. As a result of the energy system reconfiguration, countries are confronted with the question of how to ensure secure and affordable energy supply in future low-carbon energy systems: policy makers and corporate investors need to address new challenges, especially at the nexus between energy and security. In the context of energy systems, security stretches beyond technical dimensions, as it includes also economic and political considerations due to the paramount importance of energy for economic well-being and prosperity of nations.

In this dissertation I show that the transformation of our energy systems imposes new security challenges. While the transition to a low-carbon economy can contribute to a more secure energy world, many pitfalls could arise along the way. Energy systems are challenged by the intermittency of renewables, but also by the wide-ranging reconfiguration of value chains. With changes to the global energy system, the geopolitical importance of countries is recalibrated, and governments strive to be among the winners of this transition process. This, in turn, also affects the way governments structure and regulate energy markets. In this dissertation, I aim to provide policy makers, as well as corporate investors with the means to navigate a new energy world of cooperation and conflicts, as well as to take informed decisions on policy instruments, energy governance and long-term investments in energy infrastructure.

While the first essay investigates potential security of supply risks that stem from multi-year weather fluctuations, the second essay examines national conflicts, which may arise from the integration of energy systems within Europe and analyzes the impact of different national security of supply strategies on system cost, security levels and the allocation of capacity. The third essay addresses the shifts in energy-related geopolitical influence within European Economic Area, the role of the energy transition in political power rebalancing and implications for energy market governance. Finally, the fourth essay sketches the global market structure of renewable hydrogen and investigates, how the adoption of renewable hydrogen might influence energy trade and relationships between nations.

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1.1 Background and motivation

Climate change is arguably one of the largest challenges of the 21st century. The effects of global warming are becoming increasingly apparent to nearly everyone on the planet: melting polar caps result in rising sea levels and the increasing number of extreme weather phenomena affects the lives of millions of people. Three out of the top five risks in the 2019 'Global Risk Report' by the World Economic Forum are related to climate change. Extreme weather events, natural disasters, and failure to mitigate and adapt to climate change are listed amongst the risks that are most likely to occur in the next ten years with significant impact on our planet. In fact, environmental risks dominated the risk assessment in the last three years, while none of these risks were part of the top list ten years ago (World Economic Forum, 2019b).

To counteract the adverse impact of climate change, the global community started to increase its efforts to limit global warming. A universal and legally-binding climate agreement was reached for the first time at the 2015 United Nations Climate Change Conference in Paris[1]. In the final resolution of this conference the participating countries stated their intention to limit the increase of the global average temperature to 2° Celsius (UNFCCC, 2015a). In order to reach this goal countries committed to reduce their greenhouse gas emissions. A key debate, however, centered around the question of how much each individual county needs to contribute towards the global emission reduction efforts; or in other words: how are the efforts and costs of global carbon emission reduction shared within the global community? As economies are dependent on energy to foster prosperity and economic well-being, countries tend to be reluctant to implement significant changes to their energy system. In addition to that, some countries have diverging interests when it comes to the speed of the transition, the technologies employed and distribution of costs. However, this is not a new phenomenon. Due to its economic and political importance, energy has been a focal point of numerous discussions that caused controversy and conflicts.

[1] The previous climate agreement reached in Kyoto 1997 did not include the two largest emitters: the United States and China

Therefore, it can be expected that also the emerging energy transition is paved with competing goals and conflicting interests of parties involved.

One of the key reasons for the success of the Paris climate conference is the fact that countries were given the utmost freedom to determine their national greenhouse gas emission reduction targets. This way potential conflicts and heated discussions around the contribution of each state to the global target were avoided. Instead of a global coherent definition of emission reduction targets e.g., based on historical emission levels or national wealth, countries set their own reduction ambitions in the 'Intended Nationally Determined Contributions' (INDCs). As a result, INDCs reflect national interests and countries attempt to protect economic prosperity, employment and energy security. Moreover, this bottom-up approach has resulted in a situation, in which the commitments stay far behind the required emission reduction level: the combined contribution of all INDCs submitted would result in a forecasted temperature increase of approx. 2.7°C by 2100 (UNFCCC, 2015b) —significantly above the pledged 2°C target. Figure 1.1 depicts the projections of global warming until 2100 (based on Climate Action Tracker (2019)).

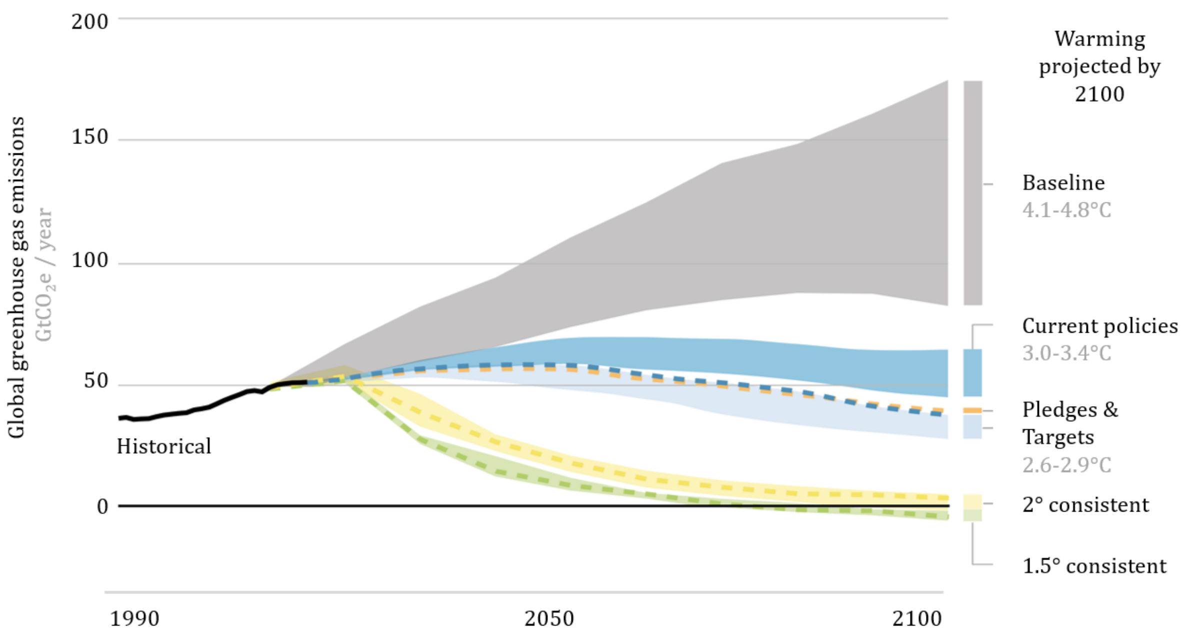
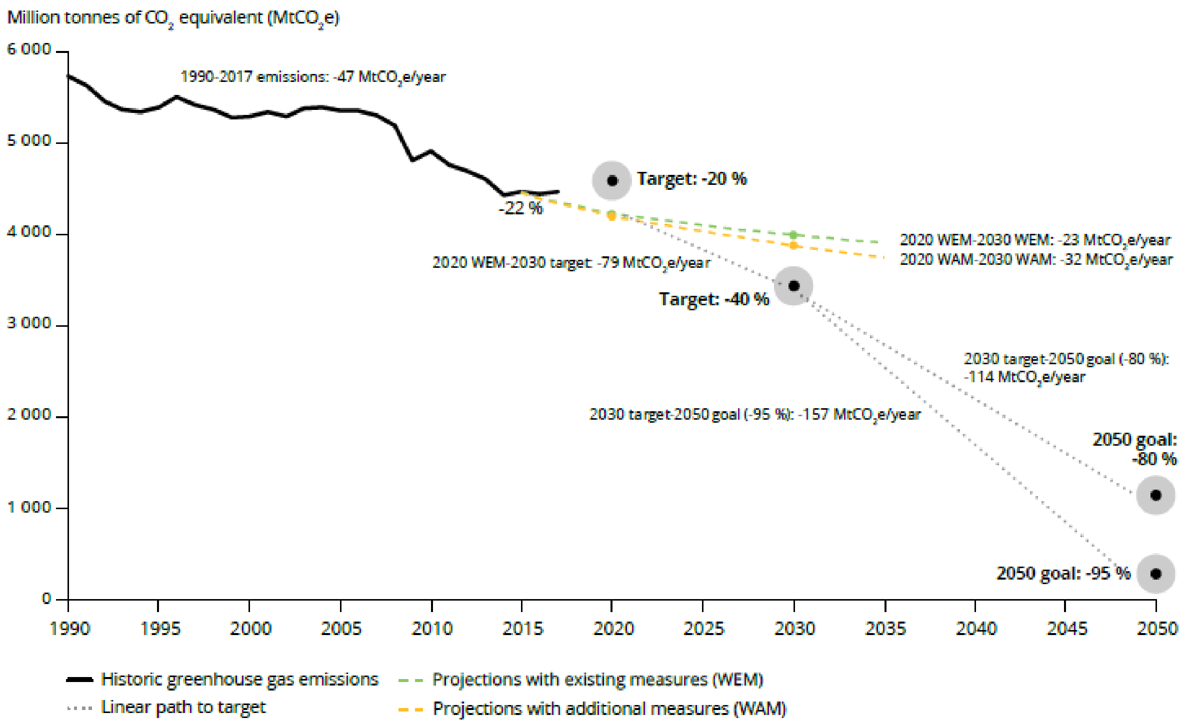


Figure 1.1 Global warming projections until 2100 based on pledges and current policies

All eyes on Europe

Even though the European Union (EU) accounts for only 9% of total global greenhouse gas emissions (UNFCCC, 2017) —a share, which is likely to shrink in the foreseeable future due to strong economic growth in other parts of the world fueled by increased energy consumption— the EU sees itself as a moral leader of the global climate protection efforts and takes a leading role in accelerating the emission reduction efforts. Thus, Europe needs to showcase that decarbonization is feasible without harming welfare, economic growth and security before other countries might follow. The EU member states have set particularly ambitious emission reduction targets in their INDCs in line with existing EU climate policy. The EU has agreed to cut domestic greenhouse gas emissions by at least 40% by 2030 and plans to eliminate 80-95% of all greenhouse gas emissions by 2050; that is illustrated in figure 1.2 (EEA, 2018). In a new pledge the European Commission even formulates the ambition to become climate-neutral by 2050 (European Comission, 2019).



Notes: The GHG emission trends, projections and target calculations include emissions from international aviation, and exclude emissions and removals from the LULUCF sector. The WEM scenario reflects existing policies and measures, whereas the WAM scenario considers the additional effects of planned measures reported by Member States.

Figure 1.2 Greenhouse gas emissions in the European Union and emission reduction path

While these efforts are certainly driven by environmental concerns, the European Union follows two additional, more short-term policy goals: a primary objective is to reduce the dependence on energy imports, especially from Russia, as part of the security of supply strategy. A second objective is to establish European companies as technological and economic leaders in the emerging market for low-carbon technologies (European Comission, 2015b).

Despite its ambitions, the European Union is not on track to deliver on its commitments, as not all member states are achieving their emission reduction targets for 2020, including economic giants, such as Germany and France. Despite this mixed track record, the European Union remains in focus of academic research, as it serves as an ‘energy transition laboratory’ for the rest of the world. Thus, researchers study the case of Europe to examine the impact of new policy instruments, the challenges of the transition to new technologies, as well as resulting social and economic tensions. Learnings from the European example can guide countries in other parts of the world on their transition paths.

Decarbonization pathways for Europe

In order to achieve the targeted levels of decarbonization, a wide-ranging transformation of the energy system is required. This transformation needs to span across all emitting sectors: power, buildings, transport, industry and agriculture sector.

The *power sector* has been in focus of policy makers and researchers, as it is critical to achieve the ambitious emission reduction targets. Fossil-fuel based power generation can be directly replaced by large-scale deployment of renewable energy sources (RES), such as solar Photovoltaics (PV) and wind power. Especially, the rapid phase-out of high-emission hard coal and lignite plants is a key lever to lower emissions. The United Kingdom already announced a plan to completely phase-out their coal generation until 2025; Germany’s coal plants will end operations until 2038 (BEIS, 2018; BMWi, 2019). In the future, innovation and commercialization of low-carbon technologies are expected to further increase economic viability of renewables and lead to further deployment.

Moreover, the power sector is essential for enabling the decarbonization of the remaining energy sectors through sector coupling. Electrification of buildings and transport sector can lower emissions by utilizing electricity generated by renewable. Besides the efforts to couple sectors, energy efficiency is another key lever to reduce the emissions in the *buildings sector*. Improved insulation of buildings could significantly reduce the energy consumption and together with low-carbon technologies, such as heat pumps or hydrogen furnaces, emissions of the building sector could be brought down to zero (Meggers et al., 2012).The *transport sector* could be decarbonized using two strategies: increased deployment of electric vehicles or a wider usage of renewable fuels e.g., biofuels. The *industrial sector* is most challenging to decarbonize, as its energy consumption is driven by high-temperature heat furnaces, which cannot be easily electrified, and by processing of carbon-based feedstock. However, new technologies, such as carbon capture or Power-to-X, could facilitate the decarbonization efforts in this sector. Finally, the *agriculture sector* can be decarbonized, for instance, by using synthetic carbon-free fertilizers.

Challenges of the energy transition

The wide-ranging transformation of our energy system will have a profound impact on the structure of the current carbon-intensive energy landscape and the players within it. The challenges of the transformation are mainly linked to the characteristics of the renewable generation technologies. While existing generation capacity, such as coal, gas and nuclear power, can be dispatched based on load requirements, the dominant renewable energy sources in Europe, solar PV and wind power, have intermittent generation profiles. This poses a challenge to the power system, as electricity supply and demand need to be balanced at any point in time to ensure the smooth operations of the electricity system. Even small interruptions of electricity supply could cause serious adverse effects on industrial production: supply gaps could lead to breakdown of machinery, which may take hours to restart, or even result in the shut-down of entire supply chains. In order to avoid these shortcomings, future electricity systems need to be resistant against incidents, when the majority of renewable load is unavailable over a comparably long time period (for instance, during winter days with little wind and even less sunshine). Flexibility options need to be in place that counterbalance the shortfall in renewable generation. While demand-side management can help to increase flexibility for short periods of time (minutes to hours), hydrogen storage could help to smooth seasonal or even inter-annual fluctuations.

Besides the intermittency of renewables, a further challenge of the transition to low-carbon technologies is the wide-ranging reconfiguration of energy value chains. During this process —which is the most fundamental change to our energy system of the last century— all energy market players will need to review and adopt their business models. Utility companies in Europe were among the first ones to experience the transformative impact of the transition to low-carbon technologies, when renewables with zero variable cost entered the market, which resulted in significant deterioration of electricity wholesale prices. Furthermore, the shift to renewables turned parts of the existing fossil fuel infrastructure into stranded assets. In an attempt to adjust to the new energy realities, legacy utilities started to compete for investments into sustainable projects, which, in turn, drove down profitability. Similar shifts are foreseeable in the transport sector: tightening car fleet emission regulations on European level (ICCT, 2014) and the announcement of bans for petrol and diesel cars in several countries including Norway (2025), Netherlands (2030), France (2040) and the United Kingdom (2050) question the business model of legacy car manufacturers (Coren, 2018). Technological leaders of green mobility, such as Tesla, exploit the resistance to change of established manufactures and gain market share. Similarly, players in the upstream energy value chain are affected: oil and gas companies, like Shell and BP, cannot solely rely on oil and gas exploration and extraction in the future. In order to stay in business, production needs to shift to low-emission fuels, while existing gasoline fueling infrastructure possibly needs to be replaced with charging infrastructure for electric battery vehicles and fuel-cell electric cars.

Nexus between energy and politics

Previous evolutions of the energy system were mainly caused by economic and technical considerations, nowadays environmental concerns spur the shift to renewable energy. Therefore, the renewable agenda has become an important part of current political debates. While governments aim at reducing carbon emissions, they are at the same time highly interested to ensure that energy costs do not rise too high. Major increases could not only threaten the competitiveness of the domestic industry but may also lead to social protest and unrest. The movement of 'Gilets jaunes' in France illustrates how sensitive a society may react to energy price changes (Cigainero, 2018). Furthermore, unemployment caused by the phase out of conventional energy sources needs be adequately addressed, especially because conventional power plants are often located in structurally less developed regions. At the same time, the changes to the energy system should not affect security of supply levels.

Such competing objectives of governments are often referred to as the energy trilemma: energy should be provided at affordable prices, from sustainable energy sources, while ensuring uninterrupted and secure supply (Ang, Choong, & T.S.Ng, 2015). Historically, policy makers and researchers used to be focused on the first two dimensions, whereas security of supply was a rather minor topic. In a conventional energy system security of supply was usually only affected by technical failures of the grid infrastructure or by supply cut-offs through exporters. However, with a growing share of renewable intermittent generation and global reconfiguration of the energy supply chain, security of supply comes to the forefront.

The International Energy Agency defines security of supply as *"the welfare impact of either the physical unavailability of energy, or prices that are not competitive or overly volatile"* (International Energy Agency, 2007, p. 12). The intermittency of renewable generation can have influence on both components of this definition: without enough backup capacities or flexibility instruments interruptions might occur. In addition, steep ramps of renewable generation may lead to erratic wholesale price fluctuations.

However, the security notion of most countries typically stretches beyond these rather technical dimensions. Due to the paramount importance of energy for economic well-being and prosperity of nations, energy is often considered a key strategic resource. Furthermore, countries with greater energy resources tend to have more weight in the foreign policy arena and are able to influence other states, which are dependent on energy imports. As a result, the reconfiguration of energy systems raises the question of how nations will ensure the secure access to energy in the future. With changes to the global energy system, the geopolitical importance of countries is recalibrated, and governments strive to be among the winners of this transition process —or at least avoid being on the losing side. This, in turn, also affects the way governments structure and regulate energy markets.

This dissertation examines new challenges of the transition to a low carbon economy with regard to energy and security. While the first essay addresses security of supply concerns that stem from multi-year weather fluctuations, the second essay investigates national conflicts, which arise from the integration of energy systems across Europe and analyses the impact of different national security of supply strategies on total system cost, security levels and the allocation of capacity. The third essay addresses the shifts in energy-related geopolitical influence within European Economic Area and the role of the energy transition in political power rebalancing. Finally, the fourth essay outlines characteristics of a potential future global market of renewable hydrogen and examines how such a market structure might influence energy trade and inter-country relationships.

1.2. Research objectives and methodology

This dissertation explores research questions at the intersection of energy and security. This overarching topic is addressed with four distinctive research projects, which resulted in different essays (Essays I-IV). The following chapter provides an overview of the research objectives of each essay and the applied research methodologies.

The first essay examines the influence of multi-year weather variability on future power systems with a particular focus on its impact on security of supply. As outlined in the previous chapter, the intermittency of renewables is one of the key challenges of the transition to low-carbon technologies. The intermittency can be observed over different timescales that range from days and weeks (Ueckerdt, Brecha, & Luderer, 2015) to several years (S. Collins, Deane, Gallochóir, Pfenninger, & Staffel, 2018; Staffel & Pfenninger, 2018a). As fluctuations in generation can have severe impact on the stability of power systems, the large-scale deployment of renewable energy sources (RES) raises security of supply concerns.

Existing research has focused on the variability of specific renewable generation types over different timescales and spatial distribution (Alonzo et al., 2017; Ela, Diakov, Ibanez, & Heaney, 2013; Gutiérrez, Gaertner, Peripinán, Gallardo, & Sánchez, 2017). However, these studies are limited to only one aspect of the power system (e.g., a specific type of generation). Moreover, integrated power models often neglect the multi-year dimension, as computational constraints limit the model's time horizon; therefore a time horizon of one year is usually chosen (Egerer, 2016; Østergaard, 2015). However, without considering a longer horizon the existing research does not adequately capture the true impact of multi-year weather fluctuations on security of supply (Staffel & Pfenninger, 2018a). This lays the ground for the research question of the first essay: how does multi-year weather variability impact the security of supply in highly renewable power systems?

This research projects provides insights on the magnitude of multi-year weather fluctuations and improves the understanding of how various energy transition scenarios affect security of supply based on a case study for Germany. The scenarios are developed along three dimensions, which can (directly and indirectly) impact the resilience of a power system to fluctuations in variable renewable generation: the enforced CO_2 regime (and thus the availability of fossil-fuel peaker capacity), the grid infrastructure and the cost of storage technologies. Varying assumptions for these three dimensions result in six distinct energy transition scenarios that are subsequently modeled.

The six scenarios are implemented in a novel power model, which incorporates most components of a power system with a high spatial and temporal resolution. It uses extensive time series of fluctuating wind and solar PV generation profiles to model multi-year weather variability (drawing on weather data in the period of 2000-2016). The model is calibrated to the German power system, and its technology-specific input parameters reflect a 2050 perspective. The model is comprised of two optimization steps: first, the cost-optimal portfolio of renewable and storage capacity is derived based on one reference year, in line with the existing literature. Second, synthetic RES generation profiles of the years 2000 until 2016 are applied to the capacity park derived in the first step. Both optimization steps are performed for each of the six scenarios. Security of supply is studied by lifting the common assumption of full demand fulfillment and instead explicitly modelling the welfare loss of unfulfilled demand as macro-economic opportunity cost. In addition, the model introduces the valuation of stored energy at the end of the optimization period as a possibility to derive more realistic renewable and storage capacity estimations when modelling only one year of weather data.

The essay focuses on Germany, as it has become a leading country with respect to the introduction of RES over the last two decades and can only rely on highly weather-dependent RES due to its geography and climate. Nevertheless, the results are of general interest for other countries with increasing share of intermittent renewable energy sources.

The second essay analyses how different levels of cooperation among countries may influence electricity prices, security levels and spatial allocation of capacity. Cooperation among countries is getting increasingly important, as electricity market integration is seen as one of the most promising approaches to smooth renewable electricity generation over time (Brown, Schlachtberger, Kies, Schramm, & Greiner, 2018). The European Union (EU) facilitates this by proposing to substantially increase cross-border interconnector capacity to 15 percent of installed generation capacity by 2030 as part of the European Target Electricity Model (Commission Expert Group on electricity interconnection targets, 2017).

However, increased interconnectedness may conflict with prevailing national security of supply strategies, with which member states ensure security of supply in their own jurisdictions. As countries have no control over generation capacities in adjacent markets, national governments tend to prefer domestic generation over foreign supply (Newbery & Grubb, 2014). National governments are particularly cautious with regard to their long-term electricity security strategy, as energy infrastructure decisions are hard to reverse: they are often associated with high upfront investments, long investment cycles and limited potential to replace supply in crisis.

Existing literature addresses the economic benefits and technological aspects of market integration, as well as implications of specific policy instruments, such as capacity mechanisms (Cepeda, 2018; Newbery, Strbac, & Viehoff, 2016; Schlachtberger, Brown, Schramm, & Greiner, 2017). However, only few studies examine potential tension and conflicts that could arise from increased cooperation among the member states (Hawker, Bell, & Gill, 2017; Leiren, Rayner, Szulecki, & Banet, 2019; Mastropietro, Rodilla, & Batlle, 2015). As a result, the existing literature falls short in systematically identifying potential roadblocks that could prevent countries from agreeing to a more cooperative electricity system, in particular with regard to security of supply. In addition, studies that rely on energy market models only implicitly include assumptions on countries' willingness to cooperate. This leads to the research question of the second essay: how do different national security of supply strategies influence the future European electricity system in terms of electricity cost, security levels and spatial distribution of capacity?

This essay aims at (1) developing a conceptual framework for security of supply strategies (2) investigating and quantifying the benefits of cooperation and (3) identifying potential roadblocks for countries to agree to a more cooperative security of supply strategy. These three aspects have direct implications on EU energy policy making: assessing the collective benefits, as well as identifying 'winners and losers' of tighter cooperation can fuel the political debate on energy market integration within Europe.

Drawing from theories of International Relations, four archetypes of security of supply strategies along two dimensions (the trust in reciprocal security and the willingness to depend on electricity imports) are developed. Figure 1.3 summarizes these four archetypes and provides an overview of energy policy instruments that correspond to the respective security of supply strategy.

Willingness to depend on electricity imports	**Trust in reciprocal security: Low**	**Trust in reciprocal security: High**
High	**Moderate integration** The benefits of market integration are acknowledged, yet policy makers are concerned that foreign generation capacity might be not available to provide capacity in times of supply shortages. Limited control in foreign jurisdictions is perceived as a barrier to trust in reciprocal security *Related policy instruments: capacity mechanism for domestic generation, establishment of a 'strategic reserve'*	**Collective security** Security of supply is perceived as cross-national task, which can be most effectively tackled with a multilateral approach. Policy makers strive for full integration of electricity markets within a collective security of supply framework *Related policy instruments: collective capacity mechanism, facilitation of investments in grid infrastructure/ interconnectors, open feed-in tariffs to foreign generation*
Low	**National Autarky** Policy makers share a strong mistrust in availability of foreign generation capacity in times of shortage and fear import dependency. Influence of foreign policy makers and companies is perceived as a threat to national security *Related policy instruments: (partly-) nationalized electricity sector, central planning of generation adequacy, regulated electricity tariffs, high regulatory requirements for foreign companies to enter the national market*	**Import independence** Mutual interdependence ensures trust; security of supply is achieved collectively via cooperation. However, as energy infrastructure decisions are long-term and hard to reverse, critical infrastructure and capabilities should be kept domestically. In order to avoid vulnerability, the energy trade-balance should not be one-sided, hence significant dependence on foreign capacity is avoided *Related policy instruments: collective capacity mechanism, protection/creation of 'national champions', tax exemption for domestic generation, national feed-in tariffs*

Figure 1.3 Conceptual framework for security of supply strategies

These four different strategies are implemented in a Pan-European investment and dispatch model, which derives the cost-optimal system design given the strategy-dependent constraints on security of supply. The model is calibrated to represent a future European power system that is heavily reliant on renewable generation. All technology-specific input parameters, as well as the demand pattern reflect a 2050 perspective.

The third essay addresses the shifts in energy-related geopolitical influence within European Economic Area, the role of the energy transition in political power rebalancing and implications for energy market governance. The shift towards renewable sources leads to significant changes of employed technologies, spatial allocation of capacity and governance systems, thereby fundamentally affecting the structure and the dynamics of the energy markets. In Europe the first signs of these changes are already visible, as European countries started to reorganize their energy systems in the early 2000s. The transition process has accelerated since then and is likely to speed up further to meet the decarbonization targets in the upcoming decades (IRENA, 2019c). The profound changes of the energy system also impose new challenges for governments and regulators: welfare and influence will be redistributed among the countries and will potentially result in winners and losers of the energy transition (Scholten, Sattich, & Ydersbond, 2014). Due to the vital importance of energy for economic prosperity and national security, developments in the energy sector always have a strategic and geopolitical dimension. Moreover, geopolitical factors are often at top of minds of investors when deciding on energy infrastructure and technology investments.

The existing literature mainly addresses the geopolitics of fossil-based energy (Bradshaw, Graaf, & Connolly, 2019; Jong, Auping, & Govers, 2014; Tagliapietra, 2019) and only few studies started to examine the impact of the energy transition on country relationships and power structures (Criekemans, 2019; IRENA, 2019b; Paltsev, 2016). Furthermore, the existing literature mainly relies on narratives and anecdotal studies backed up with limited empirical research. As a result, the existing literature does not follow a systematic approach to describe the formation of energy-related geopolitical influence in the context of the energy transition. Europe is a pivotal point to study the formation of energy-related geopolitical influence, as it is governed by a complex set of inter-country relationships and at the same time a frontrunner in the transition to low-carbon technologies. Hence, the resulting research questions are: (1) What is the current ability of countries to exercise energy-related geopolitical influence within Europe? (2) How will the transition to low-carbon technologies affect the energy-related geopolitical influence of countries within Europe?

This research project develops a novel theoretical model that explains the formation of energy-related geopolitical influence incorporating both conventional and the renewable energy. Furthermore, based on empirical data the essay illustrates how influence shifted in the European Economic Area since the early 2000s and outlines, how the transition to low-carbon technologies could influence the power balance going forward. In addition, the purpose of this research project is to explain how the energy transformation is rewriting the relationship between investment decisions and geopolitics. Historically, political actions of energy-producing states have impacted global energy prices and thus investment decisions. Therefore, equilibrating energy-related geopolitical influence through the energy transition may increase resilience of financial markets, and shield investors from the erratic shifts induced by geopolitical volatility (Royal, 2016).

A novel index is introduced as a more rigorous and structured approach to assess the implications of the energy transition on energy-related geopolitical influence. The proposed methodology allows to bridge conceptual studies of geopolitics and established literature on indexes that systematically map the strengths and weaknesses of countries. Assessing geopolitical strength is at the core of geopolitical research, as it studies a country' ability to influence world politics and to pursue its interests vis-à-vis other nations with potentially conflicting agendas. Indexes, especially composite indicators that integrate various sub-indicators in one comprehensive metric, are increasingly recognized as a useful tool to guide policy analysis. As a result, the number of studies using indicators has been growing over the past years. Indicators are used to analyze and illustrate complicated and sometimes elusive topics in wide-ranging fields, such as economy, environment, society or technological development (OECD, 2008). Indexes and indicators are well equipped to analyze complex, multi-dimensional realities that usually cannot be captured by traditional methodologies in social science (Saisana & Tarantola, 2009). In this essay the energy-related geopolitical influence is measured over time with a set of 12 indicators that reflect geopolitical strength, including classical indicators, such as fossil fuel reserves, as well as novel factors, such as the access to technology and control over connecting infrastructure.

The fourth essay explores the general principles of how hydrogen may reshape the structure of global energy markets and the geopolitical game between countries. Renewable hydrogen, with its variety of potential applications, is emerging as a flexible option for decarbonization, and its presence is rapidly expanding in policies and projects around the world. It is drawing increased attention, as deep decarbonization of all sectors of the energy system (power, mobility, buildings, and industry) likely requires clean energy carriers beyond electricity, such as renewable hydrogen. In order to take full advantage of the current political and business momentum of renewable hydrogen, adoption of technologies at global scale, significant cost reduction, deployment of enabling infrastructure, and definition of appropriate policies and market structures will be required.

Due to its versatility, hydrogen is sometimes described as the "missing link" in global decarbonization. Renewable hydrogen can be used both in mobility and in stationary applications; as sustainable mobility energy carrier, it can be used to power fuel-cell electric vehicles (FCEV), as well as be the basis for synthetic fuels. Furthermore, it can be used as a means for storing renewable energy both at utility scale in stationary applications and also off grid. In this way, it can provide backup power to buffer the intermittency of RES and serve as a carbon-free source for heating.

Existing literature on renewable hydrogen mainly focuses on technical advancements (Kuang et al., 2019), economic viability and use cases of renewable hydrogen (Ozturk & Dincer, 2020), as well as the role of renewable hydrogen as long-term storage in future power systems (Colbertaldo, Agustin, Campanari, & Brouwer, 2019). While studies concerning first opportunities for site specific applications are highly relevant for understanding pathways to spur adoption, it is similarly relevant for policy makers and investors to understand, what energy markets would look like, in which renewable hydrogen production and infrastructure is deployed at scale. Recent publications by the IEA (2019a) and IRENA (2019a) highlight first implications of large-scale adoption, further invigorating the global conversation. Nevertheless, a comprehensive analysis of market structure and geopolitical implications of renewable hydrogen deployment at scale is currently lacking. Key variables dictating the future of renewable hydrogen include technology, infrastructure, global markets structures and geopolitics. This essay, co-authored with Dr. Nicola de Blasio, provides a methodological framework to address both the challenges of these variables and the opportunities they offer. Thus, these considerations pose the research question: what are the potential geopolitical and market implications of renewable hydrogen? In other words: how might renewable hydrogen influence energy trade and energy-related relationships?

The study is based on the assumption of a low-carbon energy world, solely powered by renewable energy sources (mainly solar and wind power due to their large-scale potential and favorable cost structures). According to the IRENA, more than 50 countries have already committed to 100% renewable energy targets (IRENA coalition for action, 2019). For instance, the European Commission published its long-term vision to achieve climate neutrality by 2050 (European Comission, 2019). Renewable hydrogen is assumed to be a relevant component of this low-carbon energy world, widely adopted as a result of technological innovation and active national decarbonization policies.

This essay aims at providing policy makers, investors and other stakeholders with a comprehensive overview of the potential dynamics of a future renewable hydrogen market. It outlines the implications of large-scale adoption of renewable hydrogen for the global energy systems —which has been governed by a complex set of relationships among fossil fuel exporting and importing nations— and highlights policy and commercial options, on how to embrace the potential of renewable hydrogen. Policy makers and corporate investors around the world need to be equipped with a better understanding of these issues to guide effective national and international policy design and investment decisions.

1.3. Findings and contribution

The results of the **first essay**, which investigates the impact of multi-year weather variability on security of supply, show that renewable generation fluctuates significantly over multi-year timescales. The simulations for the German power system of 2050 show that renewable generation output varies significantly between the most windy/sunny year and the calmest/dullest year with annual fluctuation margins up to 71.2 TWh, which equals to 13.9% of total electricity demand. These results contribute to the evolving literature on multi-year variability of renewables (Staffel & Pfenninger, 2018a) by highlighting the impact of multi-year weather variability on power systems: without appropriate counter-measures and flexibility instruments, the multi-year weather variability can threaten the security of supply of highly-renewable power systems, such as the one envisioned for Germany. Thus, the multi-year variability of intermittent renewable energy cannot be neglected in power system models with high shares of intermittent renewables. Yet, forward-looking studies of the German power system typically forecast required RES capacity based on only one reference year (German Advisory Council on the Environment, 2011; Lunz et al., 2016). However, this underestimates the capacity required to balance electricity supply and demand over the long-term. The simulations of the presented essay underpin this argument by showing that the supply gaps are larger, interruption times are longer and more frequent in the multi-year horizon compared to the reference period, if only one reference year is selected for deriving capacity requirements. The simulations also indicate that not only the total generation output of the renewable sources matters, but also does the shape of the weather profiles: even in considerably ‘good’ weather years supply shortfalls may occur, as the power system optimized for one specific reference year is not able to withstand varying shapes of weather profiles.

These results strongly suggest that energy research should move towards multi-year analysis, when modelling power system with high shares of intermittent renewables. Otherwise, the intermittency risk of variable renewable energy sources (VRES) and their impact on security of supply might be underrated. If a multi-year analysis is not possible, at least a deliberate choice regarding the reference year should be made. Studies that attempt to calculate average system costs may choose a year with ‘normal’ weather conditions, while studies focusing on security of supply should use a year with rather unfavorable weather conditions as reference to ensure supply fulfillment also in adverse circumstances.

When optimizations are limited to one year, incorporating a fair valuation of stored energy at the end of the optimization period (in this essay valued with the levelized avoided cost of electricity) can help to achieve greater power system robustness against multi-year fluctuations of intermittent renewables. By doing so, the economic value of stored energy for future periods is reflected, which results in the build-up of more ('expensive') long-term storage conversion capacities. The increased conversion capacities can be then used to store excess electricity that would otherwise be curtailed, which ultimately increases flexibility of the power system.

Furthermore, the findings raise the question if —in light of soaring renewable investment— the current set of policy instruments can sufficiently address the security of supply risks that stem from high shares of intermittent renewables, or if further market interventions (such as capacity remuneration) are required. Previous research by Coester, Hofkes, and Papyrakis (2018) already showed that energy shortages might occur in a future German electricity system due to the shut-down of conventional power plants. The results of the first research project of this doctoral thesis indicate that keeping some of the conventional plants as 'security reserve' significantly reduces the security of supply risk, while at the same time not jeopardizing the greenhouse emission reduction targets. In contrast, adjustments to the speed of grid extensions influence security of supply only to a small degree. In addition, the results suggest that the deployment of long-term storage (in this essay Power-to-Gas was modelled) is suitable for smoothing renewable generation profiles over several years. While long-term storage, such as Power-to-Gas, is currently mainly discussed with regard to seasonal storage (Blanco & Faaij, 2018), this finding points to its wider application as multi-year storage, which is not yet fully explored.

The **second essay** examines how different national security of supply strategies influence the future electricity system within the European Economic Area in terms of electricity cost, security levels and spatial distribution of capacity. The results suggest that with regard to electricity costs and prices, clear winners and losers of market integration can be identified: countries with very low generation cost, e.g. Norway and Switzerland, lose from increased cooperation compared to a national autarky strategy. A more cooperative strategy leads to increased exports to adjacent countries, which in turn results in higher spot prices in the exporting states. For example, the two aforementioned countries are exposed to 83% and 16% higher spot prices in the collective security strategy compared to national autarky. In addition, the benefits of integration are unevenly distributed among the 'winning' countries. While Belgium, Netherlands, Slovenia and Italy experience a significant reduction in the electricity nodal spot prices of more than 40%, nodal spot prices in Greece and Spain drop by only 8% when comparing collective security to national autarky.

Nevertheless, the economic advantages of market integration are unequivocal on collective European level. The average electricity price of the collective security strategy is lower than the one of the three other security of supply strategies, as system costs are minimized. The system cost advantage of the collective security strategy, and thus the value of a European security of supply strategy, is between 7-42bn EUR per year (3-16% of total annual system cost) compared to the moderate integration strategy and national autarky strategy.

Similar to the disparities in electricity prices, discrepancies among the member states exist with regard to the security levels: while on European system level all outlined strategies achieve low supply interruptions, the level of supply security of each individual member state varies depending on the applied security of supply strategy. The moderate integration strategy, which assumes a significant build-up of national backup capacities, is very effective for all countries in preventing supply deficiencies, whereas the level of electricity shortages varies among countries in the collective security strategy: while the supply of most countries is not interrupted at all, a few countries (mainly Bulgaria and Croatia) face significant supply deficiencies. This is the result of market-based adequacy derivation in combination with price clearing in integrated electricity markets. Countries with high economic electricity productivity and resulting higher willingness-to-pay ensure their security of supply by being able to import electricity from countries with lower productivity in times of domestic shortage (only constrained by the available grid capacity). Hence, countries with higher electricity productivity benefit more from market integration than low-productivity countries.

Lastly, each of the four security of supply strategies requires different levels of commitment to renewable build-up by the member states: in the collective security strategy a few countries with the most favorable weather and geographical conditions need to deliver most of the total European build-up of wind capacity (mainly United Kingdom, France, Finland and Spain) and solar PV (mainly France, Spain, Italy, Greece). It remains unclear how these countries should be compensated for building up renewables and grid infrastructure at scale, significantly beyond of what is required to supply their domestic demand. On the contrary, other countries need to focus solely on replacement investments without increasing the capacity beyond current levels, which partly conflicts with national renewable extension plans and self-perceptions as renewable pioneers, e.g. in Germany. Hence, early alignment on European level could facilitate the efficient allocation of capacities across Europe in the future.

While the economic benefits of market integration and a truly European security of supply strategy are tangible, the resulting consequences of such a collective security might sometimes conflict with national interests of some member states. This study clearly indicates that national perspectives on the often-proclaimed target of collective security within the EU play a vital role in the success of the integration process and are not yet fully understood. This essay contributes to the ongoing political debate on the 'Energy Union' by outlining potential obstacles that may appear on the way towards a truly European security of supply strategy.

Furthermore, the study results indicate that the current policy framework within the European Union is unlikely to be strong enough to ensure system development towards collective security. Further alignment and member states' commitments would be required to achieve this. A potential way forward could be the further completion of the European Energy Union, which would allow central steering and harmonized energy regulation across all member states. However, irrespective of the policy instruments in focus, this essay strongly suggests that a wide-ranging political debate both on the EU, as well as on member state level, is required. In order to avoid internal conflicts, which in turn could jeopardize the energy market integration, a transparent and fair set of regulations need to be established, that is complemented by a consistent and long-reaching political commitment of all European countries.

At the core of **Essay III** is a newly developed theoretical model that describes how energy-related geopolitical influence is formed. Furthermore, a novel index is proposed to measure this influence. In the previous decades geopolitical strength in the energy space used to be closely linked to fossil-fuel reserves. Thus, measuring the reserves of combustible fuel, mainly oil and gas, already resulted in a clear representation of the power imbalance among countries. In a low-carbon energy world, however, additional factors, such as access to technology, power lines, rare earth materials and storage influence the geopolitical strength, as pointed out by Paltsev (2016). This essay builds on his conceptualization of relevant additional factors and further extends it in a systematic way. For this purpose, a two-stage theoretical model is developed, which conceptualizes the formation of energy-related geopolitical influence: the first stage captures geopolitical foundations and in the second stage the transformative capacity is introduced as a prerequisite to exercise power. The theoretical model is depicted in figure 1.4.

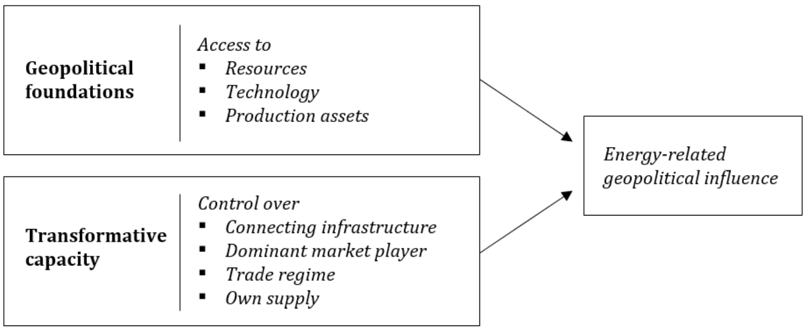


Figure 1.4 Theoretical model of energy-related geopolitical influence

The geopolitical foundations are comprised of the access to resources, including conventionals as well as renewables, the access to technologies to be able to exploit the resources, and access to production assets to transform the energy potential in energy carriers, such as electricity, heat, and/or fuels. These foundations need to be combined with means to shape the interactions with other countries; otherwise nations lack the ability to turn geopolitical foundations into influence. These means are grouped under the transformative capacity: a frequently mentioned example is control over connecting infrastructure, such as pipelines or power interconnectors (Paltsev, 2016). Other relevant factors include the control over relevant market players as means to pursue national interests in foreign jurisdictions, the ability to shape the trade regime, as well as vulnerability due to energy import dependence (control over own supply).

The results show that energy-related geopolitical influence was centered in five Northern European countries (Germany, France, Netherlands, Norway and the United Kingdom) in the early 2000s, however their hegemony has deteriorated in the following two decades, because Southern and Eastern European countries have caught up. The energy transition may impact the energy-related geopolitical influence within the European Economic Area further: Southern and Eastern European countries are potentially going to be among the winners of the geopolitical rebalancing in Europe. However, despite the universal access to renewable energy sources, countries differ significantly in their ability to become self-sufficient: countries with high energy consumption and limited renewable resources, such as Belgium and the Netherlands, are likely to experience 'resource scarcity', while on the contrary, countries, such as Spain and Norway, could develop themselves into renewable energy exporters in the future due to their renewable 'resource abundance'.

In addition, in contrast to what is usually assumed, countries with the greatest decarbonization efforts are not necessarily the sole winners of the transition. The results rather suggest that countries in pivotal geographical positions, such as France, can still preserve their leading position irrespective of their decarbonization ambition. Lastly, increasing interdependence of the countries in Europe and reduced dependence on fossil imports from outside of the EU could lead to a convergence of interests, which ultimately could help to further integrate the European Union.

This essay contributes to the ongoing academic discussion on the geopolitical implications of the energy transition. It provides a ground for further debate and helps to refine narratives about the geopolitical implications that have been presented by scholars in the past. This enables policy makers and other stakeholders to navigate in a new world of energy conflicts and cooperation and assist policy makers to address potential conflicts of interests early on. Policy makers need to keep energy security concerns in mind when building new energy market structures and setting up energy governance in order to reach a low-carbon energy system in a cost-effective way.

Furthermore, without a deep understanding of the geopolitical and historical context, the evolution and functioning of financial markets related to energy cannot be explained accurately. Geopolitical considerations have been and continue to be one of the most important concerns of investors, when they are confronted with decision on energy investments, infrastructure and technology financing. This research project equips investors with a deeper understanding of geopolitical factors that should be taken into account for assessing investments in energy technologies and infrastructure in light of the energy transition.

The **fourth essay** analyses the global dynamics of a future renewable hydrogen market and explores the implications for inter-country trade and relationships. The role a country could play in the envisioned future renewable hydrogen market will depend on its national ability to produce and distribute renewable hydrogen cost competitively and at scale. Producing renewable hydrogen through electrolysis requires renewable energy resources and freshwater resources, while its distribution requires infrastructure capabilities. Thus, three parameters are considered for the analysis of a country's renewable hydrogen potential: (1) renewable energy resource (RES) endowment; (2) renewable freshwater resource endowment; and (3) infrastructure potential, defined as a nation's capacity to build and operate renewable hydrogen production, transportation and distribution infrastructure.

The analysis shows that countries are likely to assume specific roles in future renewable hydrogen systems and can be clustered in five groups. Countries with large renewable and freshwater resource endowment, as well as high infrastructure potential are well-positioned to emerge as "export champions" in future renewable hydrogen markets (Group 1). Group 2 countries have abundant renewable energy resources, but limited freshwater resources, which decreases their likelihood of becoming relevant hydrogen exporters. Countries in Group 3 will need to import renewable hydrogen due to their limited renewables potential and/or land availability. Most countries in this group —including Japan and parts of the EU— are already dependent on energy imports today. Hence, energy dependencies of these countries might perpetuate also in the future. Countries in Group 4 have the renewable and freshwater resource potential to satisfy their local renewable hydrogen demand through domestic production. While these countries are potentially self-sufficient, they may still complement domestic production with imports due to cost considerations. Hence, nations in Group 4 are typically faced with a make-or-buy decision. Countries in Group 5 have vast access to renewable resources but are unlikely to be able to build the required infrastructure for the production, transmission and distribution of renewable hydrogen. The greater the landmass, the more complex and costly it is to deploy a cohesive national infrastructure. Therefore, a likely alternative for these countries is hydrogen production at smaller off-grid sites. A detailed country classification is depicted in figure 1.5.

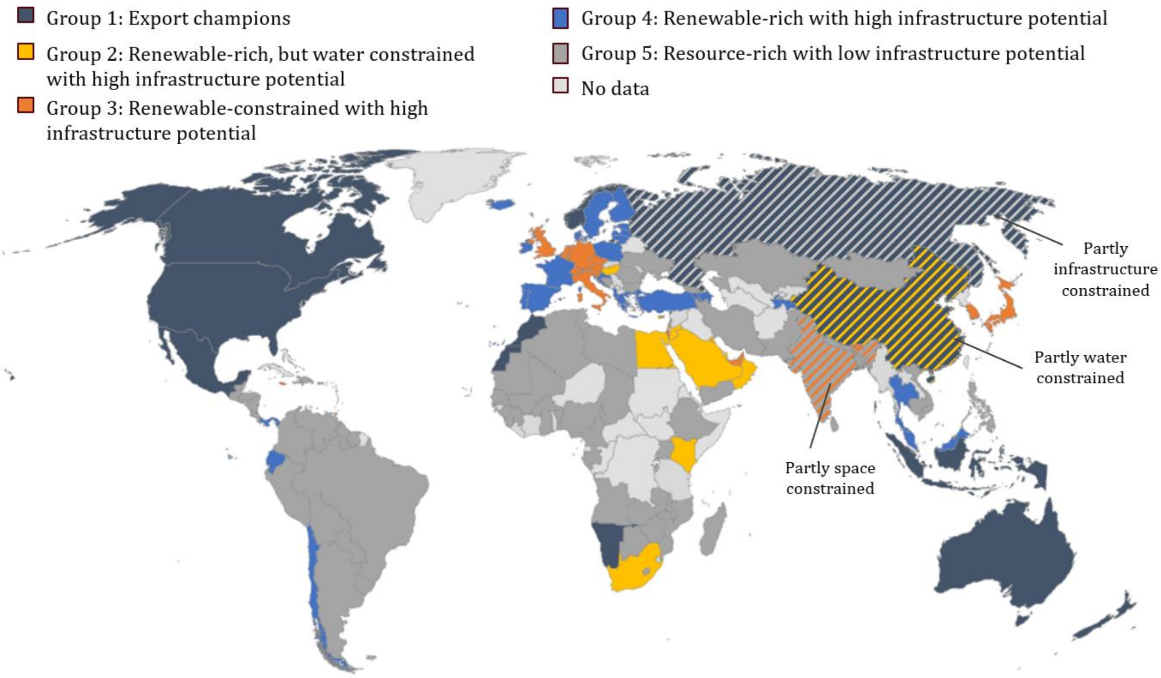


Figure 1.5 The future renewable hydrogen market map

With regard to future trade relationships, the essay points out that future geopolitical realities of resource-poor countries in Europe and Southeast Asia might be very similar to today's situation, as energy import dependencies may continue. There could be also new energy export champions emerging, such as Australia and Morocco, due to their superior cost positions and access to large import markets. Potential "export champion" nations may set policies to trigger innovation and infrastructure investments thus paving the way for dominant positioning in global future hydrogen markets. However, sustaining high renewable deployment rates will be key to achieve the needed scale. On the other hand, importing countries should facilitate cooperation with exporting countries to establish international standards for renewable hydrogen production, transportation and use. In order to increase their energy security, governments of importing countries would also need to define long-term hydrogen strategies, including options to diversify hydrogen supply.

In addition, the results of the project suggest that it is almost certain that the Middle East would play a less prominent role in renewable hydrogen markets than it does in today's oil markets. As a result, international political interest in the region could deteriorate and is likely to shift to regions like North Africa.

The results further illustrate that a global transition to low-carbon technologies may not change the geopolitical position of importing countries, given that reliance on foreign fossil fuels may simply be replaced with reliance on foreign renewable energy supplies. Thus, for these nations the energy sector may not yield the geopolitical gains suggested by some scholars, who advocate that renewable electricity may reduce geopolitical tensions due to the reciprocity of trade. With increasing interconnector capacity and the subsequent build-up of a regional electric supergrid, countries are becoming increasingly codependent. Electricity interconnection is especially beneficial for neighboring countries, whose generation profiles of the electricity sources are complementary. Coupling such markets is economically appealing for both sides, but such extensive cooperation can result in strong codependence. This trade reciprocity may ultimately reduce the risk of geopolitical power plays by any of the participants. However, this equitable dynamic could prove different for renewable hydrogen: if hydrogen is produced where costs are the cheapest and resources are most abundant, the supply flow could become one-sided, characterizing countries as either importers or exporters. Under these circumstances, the geopolitics of energy may continue to revolve around access to resources, security of supply, supplier rents and transportation disputes.

Policymakers, investors and other stakeholder need to assess the economic, environmental, and geopolitical implications of renewable hydrogen and examine courses of action. A deeper understanding of these nascent dynamics is needed, so that policy makers and investors can better navigate the challenges and opportunities of a low carbon economy without falling into the traps and inefficiencies of the past.

1.4. Dissertation structure and overview

The next parts of this dissertation are structured as follows: chapter 2 presents the first essay on the security of supply implications of multi-year weather variability. Chapter 3 consists of the second essay, which investigates how national security of supply strategies influence the design of a future European power system. Chapter 4 proceeds with the third essay on the formation of energy-related geopolitical influence and the implications of the energy transition thereon. Chapter 5 consists of the fourth essay on geopolitical and market implications of renewable hydrogen. Finally, chapter 6 provides an overarching conclusion of all research projects presented in this dissertation, summarizes the practical and political implications and outlines avenues for further research. Supplementary information on input variables, detailed optimization results and methodological notes can be found in the appendix at the end of this dissertation.

2 | The impact of multi-year weather variability on the security of supply in highly renewable power systems: a case study for Germany[2]

by Fridolin Pflugmann

This essay introduces a new power model that incorporates most components of a highly renewable power system with a high spatial and temporal resolution as well as extensive time series of fluctuating wind and solar PV generation profiles to model multi-year weather variability. The model is calibrated to the German power system. Its technology-specific input parameters reflect a 2050 perspective. Security of supply is studied by lifting the common assumption of full demand fulfillment and instead explicitly modelling the welfare loss of unfulfilled demand as macro-economic opportunity cost. In addition, this essay introduces the valuation of stored energy at the end of the optimization period as a way to derive more realistic renewable and storage capacity estimations (when modelling only one weather year). The results show that multi-year variability of wind and solar PV generation is severe and consequently cannot be neglected when modelling power systems with high shares of intermittent renewables. Otherwise, the intermittency risk of variable renewable energy sources might be not appropriately reflected, and capacity requirements underestimated. Weather variability poses a risk to security of supply in power systems that mainly depend on wind and solar PV generation, such as the one envisioned for Germany.

Key words: *Multi-year weather variability, security of supply, value of stored energy, intermittent renewables*

[2] This essay was presented and discussed at the 13th International Conference on Energy Economics and Technology 2019. An adapted version of this abstract has been published in the conference proceedings.

2.1 Introduction

Countries across the globe are determined to reduce greenhouse gas (GHG) emissions in order to fight climate change. The European Union has defined particularly ambitious emission reduction targets; it aims at lowering emissions by at least 80% until 2050 (European Comission, 2011). Significant efforts across all major GHG emitting sectors (power, buildings, industry, transportation and agriculture & forestry) are required to achieve this target, however the power sector plays a crucial role in the integration of renewable generation and sector coupling (Federal Enviornment Ministry, 2017). As a result, the power sector has been the departing point for the energy transition and continues to be in focus of policy makers and researchers.

In recent years the efforts to reduce emissions have led to unprecedented build-up of renewable energy sources (RES). In 2015 global capacity additions of renewables overtook conventional power generation technologies for the first time (International Energy Agency, 2016), while renewable power generation cost continue to fall, being now competitive to conventional generation (IRENA, 2018c). In Germany significant policy support under the feed-in-law triggered large-scale build-up of renewables (Wüstenhagen & Bilharz, 2006). Installed renewable capacity has almost tripled in Germany from 38.6 GW to 113.1 GW between 2008 and 2017. Due to the geographical and climate conditions in Germany, large-scale renewable capacity build-up is mainly comprised of wind (+33.1 GW) and solar energy (+36.3 GW) (IRENA, 2018a). While offshore wind made up only a small part of the capacity additions in the past (5.4 GW offshore versus 27.7 GW onshore), significant offshore capacity additions are planned in the next decades reaching an installed base of around 32 GW by 2035 (Bundesamt für Seeschifffahrt und Hydrographie, 2017a, 2017b). Available grid capacity constrains the integration of large amounts of renewable energy (esp. offshore wind) into the energy system. Therefore, Germany plans to construct new transmission lines spanning from the North to high-consumption regions in Western and Southern Germany and connect the offshore wind parks to the mainland through large-scale transmission lines (50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, & TransnetBW GmbH, 2017b; Steinbach, 2013).

Renewable are expected to contribute 65% of electricity generation in 2030, while at the same time conventional capacity is gradually reduced due to the complete phaseout of nuclear power until the end of 2022 as well as the reduction of coal-fired generation until 2038 (German Federal Government, 2019). As a result, the German power system will mainly rely on wind and solar power in the mid-to-long term. Lunz et al. (2016) project that the share of wind and solar photovoltaic (PV) power will be in the range of 42-122% of load[3] in Germany in 2050 (see Lunz et al. (2016) for a comprehensive overview of various model results for 2050).

In contrast to conventional generation technologies, wind and solar power are dependent on weather conditions and thus have an intermittent generation profile. The variability in generation can be observed on different timescales ranging from days and weeks (Ueckerdt et al., 2015) to several years (S. Collins et al., 2018; Staffel & Pfenninger, 2018a). This intermittency challenges the stability of the power system and raises security of supply concerns.

While existing research has focused mainly on short-term variability within one year, only few studies looked at multi-year variability. Without considering the multi-year horizon the existing research does not adequately capture the true impact of weather fluctuations on security of supply (Staffel & Pfenninger, 2018a). This lays the ground for the research question of the first essay: How does multi-year weather variability impact the security of supply in highly renewable power systems?

The aim of this essay is to provide a framework for quantifying the impact of multi-year variability on security of supply in a highly renewable power system. Drawing on weather data from Germany in the period of 2000-2016, the presented essay aims to extend the understanding of multi-year RES variability in power systems and in particular its implications on security of supply. Although this study focuses on Germany, the results are of general interest for countries with increasing share of variable renewable energy sources (VRES). This study focuses on Germany as it has become a leading country with respect to the introduction of RES over the last two decades and can only rely on highly weather-dependent RES due to its geography and climate.

The results of this research project show that renewable energy sources fluctuate significantly over multi-year timescales. The simulations for the German power system in 2050 demonstrate that renewable generation output fluctuates significantly between the most windy/sunny year and the calmest/dullest year with fluctuations margins up to 71.2 TWh (which equals 13.9% of total electricity demand). These results add to the evolving literature on multi-year variability of renewables by highlighting the impact on power systems: Without appropriate counter-measures and flexibility instruments, the multi-year weather variability can threaten the security of supply of highly-renewable power systems, such as the one envisioned for Germany.

Relying on one reference year underestimates the required capacity to balance electricity supply and demand over the long-term. The simulations of this study underpin this by showing that the supply gaps are larger, interruption times longer and more frequent in the multi-year horizon

[3] The authors explicitly include one scenario in which RES generation is significantly higher than required load (resulting in 122%)

compared to the reference period if models rely only on one reference year for deriving capacity requirements. These results strongly suggest that energy research should move towards multi-year analysis, when modelling power system with high shares of intermittent renewables. Furthermore, the findings raise the question if —in light of soaring renewable investment— the current set of instruments can sufficiently address the security of supply risks stemming from high shares of intermittent renewables or if further policy instruments (such as capacity remuneration) are required.

The remainder of this essay is structured as follows. Section 2 gives an overview of existing literature; followed by introducing the security of supply concept in section 3. Section 4 details the model methodology and section 5 contains the model results. Section 6 highlights policy implications of the results, followed by a discussion and conclusion in section 7 and 8, respectively.

2.2 Background

With rising deployment rates of renewables, it becomes increasingly important to understand the impact of weather-driven RES variability on the security of supply. Recent work already focused on the variability of wind over different timescales (Alonzo et al., 2017) and spatial distribution (Karagali et al., 2013). Similar research exists for solar (Ela et al., 2013; Gutiérrez et al., 2017). Recent studies also started looking into the weather impact on demand (Staffel & Pfenninger, 2018a). However, these studies are typically limited to only one aspect of the power system.

Integrated power models on the other hand run detailed simulations, but are often limited to a time horizon of one year due to computational constraints (Egerer, 2016; Østergaard, 2015). For example, high-profile studies modelling a 100% RES system for Germany rely on a single reference year to forecast required RES capacity (German Advisory Council on the Environment, 2011; Lunz et al., 2016). While this approach can serve as a first estimate of capacity requirements, omitting long-time series for renewable generation underestimates the required capacity to balance electricity supply and demand over the long-term.

The few studies that address this shortcoming mainly focus on countries in which the predominant renewable energy sources are hydro power (run-of-river, hydro reservoirs and/or pumped storage) and geothermal power (Duenas et al., 2018; Mason, Page, & Williamson, 2013). Comparable studies on highly renewable power systems that rely on wind and solar PV power are currently lacking. Long-time series for renewable generation are rather studied in the context of storage requirements (Fattori, Anglani, Staffell, & Pfenninger, 2017; Schill & Zerrahn, 2018) and not security of supply.

Studies with an explicit security of supply perspective typically follow traditional approaches calculating firm capacity (Agora Energiewende, 2017) or simulate more near-term scenarios (e.g., for the year 2030 for Germany as in Grave, Paulus, and Lindenberger (2012)). In studies with a longer perspective up to 2050 security of supply is not explicitly captured as often an assumption of full demand fulfillment is applied (i.e. assuming the in-existence of security of supply issues).

One additional shortcoming of several studies that model power systems based on one reference year is the inadequate representation of value of stored energy at the end of the modelled time period (e.g., Zerrahn and Schill (2017)). Energy that is stored at the end of the modelling period can be used in the subsequent period and consequently may reduce the required future cost for generation (and/or storage). Storing energy entails a value from a multi-period perspective.

To summarize, this essay contributes to the existing literature in three ways: first, it uses a comprehensive power model together with multi-year weather data sets, which allows to study the impact of multi-year RES variability on power systems, especially focusing on wind and solar PV generation. Second, the commonly used assumption of full demand fulfillment is replaced by explicitly modelling the opportunity cost of unfilled demand. By doing so, this essay enables the analysis of security of supply in future power systems. Third, it includes the valuation of stored energy at the end of the optimization period. This allows a more realistic derivation of required renewable and storage capacities in future power system (even when modeling only one year of weather data).

2.3 The concept of security of supply

Security of supply has always been a fundamental objective of energy policy. The European Union defined security of supply as a key energy policy goal besides competitiveness and environmental protection (European Comission, 1995). Similar policies exist on EU level. Despite the frequent use in policy documents and research, the term is rather poorly defined, and its interpretation differs significantly depending on the context. As pointed out by Johansson (2013), relevant aspects of security of supply can range from critical infrastructure protection to demand-supply matching. According to the definition of the International Energy Agency (IEA) energy insecurity *"is the welfare impact of either the physical unavailability of energy, or prices that are not competitive or overly volatile"* (International Energy Agency, 2007, p. 12). Therefore, security of supply is comprised of a physical and pricing dimensions. In this essay physical unavailability is measured in the three most common technical dimensions: extent of supply interruptions, their duration and frequency (Röpke, 2013). Adapted from the definitions of the Council of European

Energy Regulators (CEER, 2008) the extent of supply interruptions is measured with Energy Not Supplied (ENS) in MWh

$$ENS = \sum_{i} E_i$$

where E_i is the energy not supplied at each incident (i).

The duration of interruption is measured as the Average Interruption Time (AIT) in hours

$$AIT = \frac{\sum_i E_i}{P_T}$$

where P_T is the average hourly power supplied in the system and E_i is the energy not supplied at each incident.

The frequency is measured with Average Interruption Frequency (AIF)

$$AIF = \frac{\sum_i P_i}{P_T}$$

where P_T is the average hourly power supplied in the system and P_i is the power interrupted at each incident (in MW).

Similar metrics for the pricing dimension of the IEA definition are less common. As argued by Löschel, Moslener, and Rübbelke (2010) the terms 'not competitive' and 'overly volatile' are vague and remain unclear. Similar issues arise with other definitions of the pricing dimension (Bohi & Toman, 1996; European Comission, 2010). For the purpose of this essay, it is therefore assumed that only prices, which exceed the welfare loss associated with the unavailability of energy fall into the definition of the IEA. This assumes that demand is inelastic up to the point where the electricity price is higher than the benefits from receiving the corresponding amount of electricity.

This welfare impact will be explicitly modelled with the value of lost load (VoLL) i.e. maximum electricity price that customers are willing to pay to avoid an outage (European Comission, 2017). Several approaches exist to determine the VoLL. Some models, e.g. Egerer (2016), use the technical price cap of the day-ahead market in the German/Austrian grid zone, which is currently fixed at 3,000 EUR/MWh (Epex Spot, 2018). More sophisticated approaches use revealed preferences, macro-economic analysis and case studies to estimate the VoLL. In recent years, macro-economic methods have been predominantly used for estimating the VoLL in Germany. However, as there exists no single definition and calculation procedures, estimation outcomes differ depending on regional and sectorial focus of the studies. Appendix A provides an overview of recent studies focusing on Germany. This essay will set the value of lost load to 12,400 EUR /

MWh which is based on CEPA (2018). Extensive sensitivity analysis on the VoLL illustrate the impact of variation of this assumption on model results.

From a system-cost perspective, the optimal level of supply security will be at the intersection of welfare loss measured with the VoLL and marginal cost of energy generation. The relationship is shown in Figure 2.1 (figure adapted from Bliem (2005)).

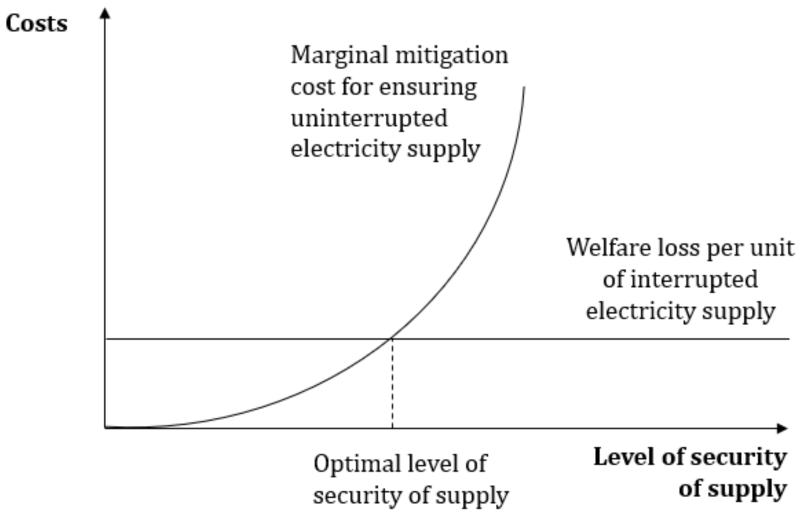


Figure 2.1 Schematic representation of macro-economic optimal level of security of supply

2.4 Methods

This section describes the applied methodology. First, an overview of the optimization procedure is provided; followed by a description of the scenarios. Finally, the model parameters and assumptions of technologies and transmission grid are presented.

2.4.1 Overview

A two-stage power model is used, which addresses the issues identified in the previous chapters: it incorporates most components of a power system with a high spatial and temporal resolution and uses extensive time series of fluctuating wind and solar PV generation profiles. The model is calibrated to the German power system with regard to its renewable and conventional technology park, demand pattern and transmission grid infrastructure. However, it can serve as a general case study for a power system with high shares of VRES. All technology-specific input parameters as well as the demand pattern reflect a 2050 perspective (Appendix B includes an overview of assumptions and data sources), while the renewable generation is modelled based on the weather data of 2000-2016.

In the first optimization stage, a power investment and dispatch model derives the cost optimal capacity and spatial distribution of solar PV, wind power generation as well as storage capacities based on a reference year with 'normal' weather conditions. The subsequent second optimization stage consists of a power dispatch model that incorporates the capacity results of the first-stage investment model and determines the cost-optimal dispatch in a multi-year setting based on synthetic RES generation profiles of the years 2000-2016.

'Normal' weather conditions are defined as average capacity factors observed in the dataset. In the dataset used (wind and solar PV capacity factors for the years 2000-2016) the capacity factors in 2012 are close to the dataset average for both solar PV and wind profiles. In addition, S. Collins et al. (2018) conclude that the year 2012 (and 1987) is the *"most representative for considering power system operation at a European level" (p.10).* Thus, 2012 serves as reference year in the first optimization stage as it can be considered representative for 'normal' weather conditions in Germany. Figure 2.2 and 2.3 depict the average yearly capacity factor for solar PV and wind power.

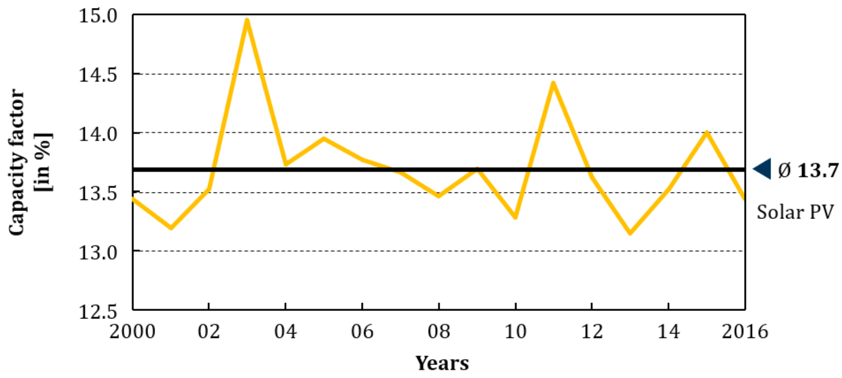


Figure 2.2 Range of yearly renewable generation capacity factors for solar PV

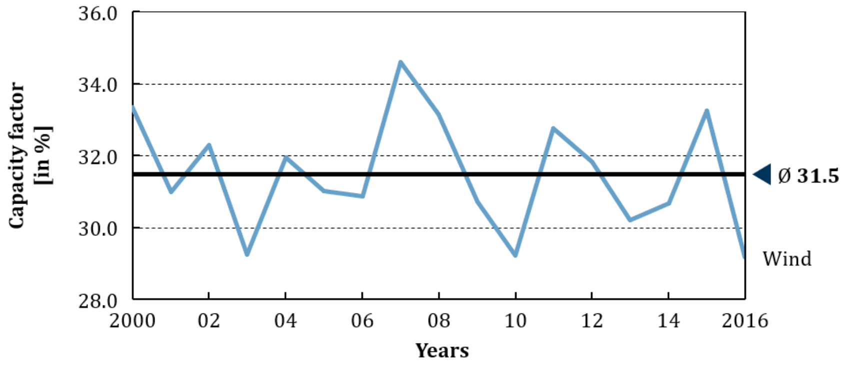


Figure 2.3 Range of yearly renewable generation capacity factors for wind power

The objective function of the model is the minimization of system cost including annualized investment, fixed (operating and maintenance) cost and variable cost for conventional generation, renewable generation, as well as power storage minus the value of stored energy. The equation below depicts the objective function to be minimized.

$$min \begin{pmatrix} \sum_{n,i} G_{n,i}\, c_i + \sum_{n,i,t} g_{n,t,i}\, mc_i + \\ \sum_{n,i} S_{i,n}\, c_i + \sum_{n,i} SC_{i,n}\, c_i - \\ \sum_{n} se_{i,T}\, VoSE \end{pmatrix}$$

The optimization is solved in blocks of one year. In the second optimization stage, inter-year continuity is accounted for by allowing the transfer of stored energy at the end of the year to the next year. The value of energy stored at the end of the optimization period (VoSE) is valued with the levelized avoided cost of electricity (LACE). The LACE is based on the concept by U.S. Energy Information Administration (2018), stating that the economic value of energy can be expressed as the cost the system would otherwise incur to provide the same amount of energy. For the purpose of this analysis, it will be assumed that the LACE is identical for all years and can be approximated by the average cost for electricity supply in the reference year. Hence, the LACE has been set to the average-scenario outcome of 62 EUR/MWh[4]. By valuing stored energy at the end of the optimization period, the impact of stored energy on the optimal capacities can be examined.

The input data –including the capacity factors for the wind and solar PV generation– is collected on granular level for each of the 457 geo locations corresponding to the nodes of the transmission grid model. Geo location data is aggregated to Dena zone level (dena, 2010). Build-up of endogenous VRES variables and storage is restricted to Dena zones that are situated in Germany (no build-up in zones covering foreign countries e.g., Austria), and exclude the two zones covering the offshore wind parks in the North and Baltic Sea. The model is implemented in Matlab and solved with the commercial solver CPLEX on hourly resolution in both stages.

Nomenclature

n	Node (country)	$g_{n,d,i}$	Electricity generated
t	time period	$s_{n,d,i}$	Electricity charged or discharged
i	Generation and storage technology	c_i	Annualized investment and fixed cost
$G_{n,i}$	Generation capacity	c_l	Annualized investment cost of interconnector
$S_{n,i}$	Storage conversion (charge/discharge) capacity	mc_i	Marginal cost
$SC_{n,i}$	Storage capacity	$VoSE$	Value of stored energy
$SL_{n,d,i}$	Storage level	se_i	Stored energy

[4] The LACE is in the range of 57.8-64.6 EUR/MWh for all six scenarios.

2.4.2 Scenarios

Three dimensions significantly influence how fluctuations in VRES generation impact power systems and thus model results: the regulatory regime or CO_2 budget (determining the availability of conventional generation), the grid infrastructure and the economic viability of storage technologies. Based on various specifications along these three dimensions the scenarios are developed.

CO_2 budget

Traditionally, system operators considered supply to be secure if available firm capacity exceeds expected peak demand (UCTE, 2009). Firm capacity can be dispatched based on load requirements and include most conventional plants, especially nuclear, lignite, coal and gas plants. In light of the emission reduction efforts, the available CO_2 budget constitutes a boundary for the dispatch of the conventional generation capacity. The EU-emission reduction targets of 80-95% until 2050 serve as cornerstones for the CO_2 budget calculations. As decarbonization targets are hard to achieve in certain 'hard-to-abate' areas (especially in the industrial sector), it it can be expected that the power sector has to overcompensate for these areas and thus need to achieve 100% RES share in 2050. Therefore, three different specifications regarding the remaining emission budget are introduced in the model: 20%, 5% and 0% (compared to 1990 levels).

Grid infrastructure

In order to integrate high shares of RES, significant grid extensions are required to balance electricity across areas with high generation potential and areas with high demand.

With rising shares of RES the geographical distance between generation and demand is increasing: while areas with high generation potential are located in the North of Germany, the main demand occurs in Western and Southern Germany (BMWi, 2017). Therefore, significant grid extensions are required to avoid supply shortages due to transmission constraints. However, Bruns, Futterlieb, Ohlhorst, and Wenzel (2012) point out that it remains a challenge for regulators and transmission system operators (TSOs) to keep up with the increasing build-up of renewables. Therefore, besides the base scenario in which the grid extensions are built as currently planned (status as of 2018), also two other scenarios are investigated:

- Investment backlog: Grid extensions are assumed to be significantly delayed, i.e. only 50% of the planned transmission line capacity is available
- Unconstrained grid: As counter-scenario to investment backlog it is assumed that capacity of all grid lines are doubled (existing and planned).

Cost of storage technologies

Finally, storage plays a major role in balancing supply and demand and ensuring security of supply in a future power system (Cebulla, Naegler, & Pohl, 2017; Zerrahn & Schill, 2017). Depending on the assumed storage cost reductions until 2050, storage capacity at scale may become economic viable. For tackling multi-year weather variability long-term storage technologies, such as Power-to-Gas, might be required. This study includes a moderate storage cost reduction path (as projected for 2050) as base case and an alternative case, in which aggressive cost reductions are assumed until 2050. Detailed techno-economic assumptions are listed in Appendix B.

Table 2.1 provides an overview of the six scenarios investigated.

Table 2.1 Overview of scenarios

	Scenario name	**CO_2 emission reduction path**	**Speed of transmission grid extension**	**Storage cost development path**
A	All green (base scenario)	Zero emission regime	Grid capacity is available as planned	As projected for 2050
B	Push for green	Reduction to 5% compared to 1990 levels	Grid capacity is available as planned	As projected for 2050
C	Minimum ambition	Reduction to 20% compared to 1990 levels	Grid capacity is available as planned	As projected for 2050
D	Grid investment backlog	Zero emission regime	Only 50% of newly planned grid capacity is available	As projected for 2050
E	Removal of grid constraints	Zero emission regime	Capacity of all grid lines are doubled (existing and planned)	As projected for 2050
F	Storage cost break-through	Zero emission regime	Grid capacity is available as planned	Aggressive storage cost reduction until 2050

2.4.3 Data input

2.4.3.1 Transmission grid

The base for modelling the transmission grid is the open-source ELMOD-DE model[5] (Egerer, 2016). In order to reflect potential grid extensions, further transmission lines have been added to the existing data set. 43 transmission grid extension projects have been identified based on the grid extensions plans published by the German Federal Network Agency (Bundesnetzagentur, 2015, 2018). These projects have been mapped with the transmission grid nodes, resulting in 126 additional transmission lines added to the model. Unless stated otherwise by the Federal Network Agency, the thermal power limits have been estimated based on the voltage level in line with the

[5] The grid model consists of 438 nodes out of which 393 nodes are substations in Germany, 22 nodes are located in neighboring countries and the remaining 23 are auxiliary nodes. The nodes are connected with 697 network lines (220 and 380 kV lines). An incidence matrix reflects the grid topology and takes the value +1 for the start node and -1 for the end node.

data provided in the ELMOD-DE model (i.e. all 380kV lines have been estimated to have a power constraint of 1,700 MW).

In addition, 5 transmission grid lines have been added to connect the offshore wind parks with the transmission grid. Based on the Federal Office of Navigation and Hydrography the entry nodes of the wind parks have been specified and the corresponding grid power capacity estimated (Bundesamt für Seeschifffahrt und Hydrographie, 2017a, 2017b). Since the currently planned grid capacity is not sufficient for the total installed offshore wind capacity in zone 1-3, it is assumed that the lines are scaled up to match the final installed capacity. The transmission grid model follows the transshipment model approach (Medjroubi, Müller, Scharf, Matke, & Kleinhans, 2017; Nygard, Ghosn, Chowdhurry, Loegering, & McCulloch, 2011) that focuses on constraining the exchange of power among zones by a net transfer capacity, neglecting physical power flow principles for simplicity. Net transfer capacity of the lines is assumed to be determined by the thermal power capacity, which is assumed to be a function of the voltage level.

2.4.3.2 Renewable capacity and capacity factors

The installed renewable capacities as of 2016 for onshore wind, offshore wind, solar PV, biomass, geothermal and run-over-river have been derived from the respective transmission system operators (50Hertz Transmission GmbH, Amprion GmbH, TransnetBW GmbH, & TenneT TSO GmbH, 2017) and validated with reports by the Federal Network Agency (Bundesnetzagentur, 2017). The renewable capacities have been mapped with the geo data of the grid nodes based on zip codes.

The capacity factors for wind and solar PV are derived from the renewables.ninja database (Staffel & Pfenninger, 2018b) with hourly resolution for the years 2000-2016. The transmission grid nodes are used as geo locations. In the model, biomass is fully dispatchable, while constant generation is assumed for geothermal and run-over-river (only restricted by availability assumptions derived from (Egerer, 2016)). The endogenous VRES capacity variables (wind onshore, wind offshore and solar PV) have been constrained based on their technical-ecological potential. See Appendix B for detailed assumptions.

2.4.3.3 Conventional generation

The conventional plants included in the model are based on the list provided by the transmission grid operator as part of the grid development plan 2030 (50Hertz Transmission GmbH, Amprion GmbH, et al., 2017b). The plant capacity as listed in 'Scenario B 2035' is used. The Scenario B is the 'medium' case (referring to the speed of deployment of RES) of the grid development plan and is projected until 2035. It is assumed that due to the environmental concerns no new power plants are added to the generation park and furthermore plants with high-carbon intensity (lignite and oil) are phased out until 2050.

The plants have been allocated to the grid nodes/zones based on neighboring zip codes. Plants which are connected to the German grid but are located in Austria and Luxemburg have been also included based on the list of the Federal Network Agency. The availability of the conventional plants has been derived from Egerer (2016) with seasonal availability factors grouped in six summer and six winter months.

2.4.3.4 Storage

The list of pumped storage plants has been derived similar to the conventional power plants (50Hertz Transmission GmbH, Amprion GmbH, et al., 2017b). Since the storage capacity is not provided, the corresponding values have been derived from Egerer (2016). The storage capacities for new pumped-storage plants have been estimated based on cubic meter storage volume and the corresponding falling height (available from plant operators). The formula for storage capacity calculation by Hartmann et al. (2012) has been applied. An efficiency of 80% is assumed for pumped storage plants.

In addition, two new storage types are introduced in a stylized manner: Lithium-Ion batteries as short-term storage and Power-to-Gas as long-term storage. For the long-term storage it is assumed that an interconnected storage across zones can be used (e.g., feed-in to the existing gas grid). The technical details are listed in Appendix B.

2.4.3.5. Demand

The total demand and the load curve is derived from Staffel and Boßmann (2015). The total annual electricity demand is 512 TWh (compared to 536 TWh in 2010) and peak load increases to 104.6 GW (compared to 82 GW in 2010).

The geographical distribution of the load on the nodes has been derived from Egerer (2016). Compared to demand pattern in recent years, the ramps are getting larger since heat pumps and electric vehicles influence the load profile. Despite this, the potential storage effect from the transport and buildings sector is not included in this paper.

2.4.3.6. Emissions and carbon price

All emission reductions are calculated against the base level as of 1990 (Federal Enviornment Ministry, 2016). This base level of emitted CO_2 equivalents has been set to 466 million tons; this amount refers to the energy industry. The carbon content per fuel type has been derived from

Umweltbundesamt (2018). The carbon price has been set to 130 EUR/ton based on the high-price scenario in Pape et al. (2014).

2.5 Results

5.1 Cost-optimal VRES and storage capacities based on one reference year (first stage)

The first optimization stage resulted in a significant build-up of onshore and offshore wind as well as solar PV capacities in all scenarios. Furthermore, in all six scenarios the long- and short-term storage capacities increased substantially, with long-term storage accounting for the largest portion of build-up. Offshore wind appears to be the most cost-efficient technology due to the high capacity factors. In almost all scenarios the maximum techno-ecological potential of 31.9 GW is reached. Only the wind offshore build-up in scenario D (28.3 GW) remains considerably below the potential due to the assumed investment backlog in grid extensions to the offshore wind parks.

The availability of conventional capacity dramatically reduces the need to build-up VRES and storage capacities in scenarios B and C. Capacity of solar PV is reduced by 57.2 GW (42.3%), while onshore wind capacities decrease by 2.8 GW (2.6%) compared to scenario A. Similarly, storage requirements fall strongly: only 57.8% of the short-term and 20.0% of the long-term storage capacity is required in scenarios B and C (compared to scenario A).

The CO_2 emission threshold does not constrain the optimal power system setup (i.e. the optimal capacities for scenario B and C are the same). Due to the favorable cost structures of VRES in 2050, it is more cost-efficient to build-up large amounts of VRES capacity rather than to increase the utilization of conventional capacities up to the defined CO_2 emission limit. The maximum CO_2 budget is used in neither of the scenarios. Therefore, further lifting the CO_2 budget from scenario B to C (5% to 20% vs. 1990 emission baseline) has no impact on the power system optimal capacity setup. In both scenarios, a RES share of 94.4% is reached (calculated as percentage of total demand).

Scenario E shows that grid upgrades beyond the current plans is likely not required as grid capacity at this point does not seem to be a major constraining factor anymore. However, a backlog in grid investment as described in scenario D significantly alters the optimal capacity park; wind capacity shifts from offshore to onshore.

As expected, the assumption of aggressive storage cost reduction in scenario F leads to a significantly larger build-up of short-term and long-term storage capacities. In addition, the VRES build-up shifts from wind onshore to solar PV capacities. Increased storage capacities allow better balancing of VRES generation, in particular short-term balancing of daily solar PV fluctuations.

For all six scenarios Table 2.2 provides an overview of the capacities for VRES and storage after the first optimization stage as well as the corresponding RES share.

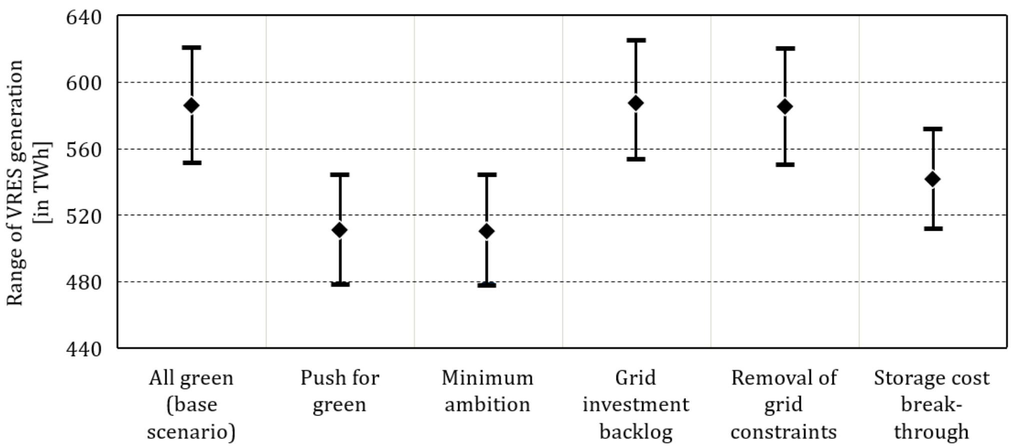
Table 2.2 Cost-optimal capacities derived in first optimization stage

Scenario	**VRES capacities (in GW)**			**Storage capacities (in GWh)**		**Storage conversion capacities (in GW)**		**RES share (in %)[a]**
	Wind onshore	Wind off-shore	Solar PV	Short-term	Long-term	Short-term	Long-term	
All green (base scenario)	106.0	31.9	135.2	223.8	20,864.6	37.4	19.3	100.0
Push for green	103.2	31.9	78.0	129.3	4,169.5	27.9	14.9	94.4
Minimum ambition	103.2	31.9	78.0	129.3	4,169.5	27.9	14.9	94.4
Grid investment backlog	112.6	28.3	138.6	226.8	21,436.7	40.4	19.2	100.0
Removal of grid constraints	105.5	31.9	135.6	224.2	20,760.5	27.4	19.3	100.0
Storage cost break-through	84.6	31.9	143.7	304.5	29,717.0	46.2	24.6	100.0

[a] RES share in relation to total electricity demand

2.5.2 RES variability in multi-year simulation (second stage)

In the multi-year simulation (second stage) great variations in VRES generation over several years are observed. Across the scenarios the fluctuation margin between the most windy/sunny year and the calmest/dullest year ranges from 60.0 to 71.2 TWh, which represents 11.7% to 13.9% of total demand. Figure 2.4 shows the VRES generation range in each scenario.



Notes: Bars indicate range of annual VRES generation. The higher value indicates the generation in most windy/sunny year, whereas the lowest value indicates the generation in the calmest/ dullest year. The diamond points to the time series average.

Figure 2.4 Range of yearly generation of weather-dependent RES in simulation 2000-2016

With fluctuation margins up to 71.2 TWh the multi-year variability is of a significant magnitude that cannot be neglected. In high-generation weather years sufficient grid and storage capacities are required to handle the increased supply while in low-generation weather years flexibility measures must be in place at scale to compensate for the shortfall in supply. For comparison: 71.2 TWh is the equivalent to approximately 12 average conventional plants (with 700 MW capacity) running full-load the entire year. Thus, studies that aim at calculating required capacity of future power systems using one reference year (Agora Energiewende, 2014; Henning & Palzer, 2014; Lunz et al., 2016; Schill & Zerrahn, 2018) are likely to underestimate the RES and storage capacity requirements, since the capacity required flexibility measures to buffer low RES generation in low-generation weather years is not accounted for.

This has a direct implication for energy research: if possible, multi-year time series should be used to capture the full impact of multi-year weather variability; or else, at least a representative year with 'normal' weather conditions should be chosen. Using a randomly chosen year or simply the most recent data may adversely affect the robustness of results.

2.5.3 Security of supply implications

The multi-year simulation examines how well the cost-optimal power system, as derived in the first optimization stage, is coping with the multi-year VRES variability. The results show that all three indicators for security of supply used in this study —Energy not supplied (ENS), Average interruption time (AIT) and Average Interruption Frequency (AIF)— reflect the reduced security due to multi-year fluctuations of VRES generation.

Even in the first optimization stage complete security of supply is not achieved, however supply gaps are relatively small: the cost-optimal solution based on one reference year results in supply gaps ranging from 0.004 TWh (0.001% of total demand) in scenario F to 0.93 TWh (0.02% of total demand) in scenario E. Achieving full demand fulfillment comes at high costs: the marginal cost for providing electricity in the last incremental hours rises substantially, as installations of more generation and storage capacities with very low utilization hours is required. Despite very high opportunity costs (12,400 EUR/MWh) it is more economical from a system-cost perspective to pay the opportunity cost of supply outages rather than to build more capacity.

While the supply gaps are comparably small in the first optimization stage, the average ENS across all simulated years in the second optimization stage is significantly higher. The average ENS across all years of scenario A is 24-times greater than the ENS in the reference year 2012. See table 2.3 for further results per scenario.

Table 2.3 Mean and standard deviation of ENS across scenarios (in TWh)

Scenario		ENS mean and standard deviation	ENS in reference year 2012
A	All green (base scenario)	2.2±2.3	0.093
B	Push for green	0.2±0.2	0.058
C	Minimum ambition	0.2±0.2	0.058
D	Grid investment backlog	2.0±2.3	0.070
E	Removal of grid constraints	2.3±2.4	0.093
F	Storage cost break-through	3.7±3.1	0.004

As shown in table 2.3, the scenarios B and C achieve significantly lower ENS than the 100% RES scenarios. While this is hardly surprising, the fact that scenario F results in higher average ENS than any other scenario is noteworthy. One may conclude, that the increased amount of available storage is not sufficient to buffer the variability of VRES over several years. In fact, the reason for the higher ENS is insufficient generation capacity, which could be used in high-generation weather years to fill the available storage. This is a result of the first optimization stage, where lowered storage cost assumptions lead to decreased onshore wind capacity.

One observation in the multi-year simulation is particularly surprising: supply gaps occur in every year across the entire 17-year time horizon and across all scenarios. Even in significantly 'better' weather years (i.e. years with higher VRES generation compared to the reference year 2012) the ENS never decreases to zero and sometimes is even significantly higher than in the reference year. Counter-intuitively 'better' weather years do not necessarily result in similar or even lower ENS than in the reference year.

The simulated power system setup cannot take full advantage of the increased VRES generation due to varying shapes of the weather profiles. The available excess electricity (compared to the reference year) is curtailed, because of a lack in available conversion and storage capacity, as the system was designed for the particular shape of the weather profile in the reference year. Higher VRES generation does not inevitably lead to a lower ENS.

In all scenarios interruption times (AIT) reach high levels. However, the extent of supply security varies significantly among and within the scenarios. Figure 2.6 presents the mean as well as the range of AIT outcomes.

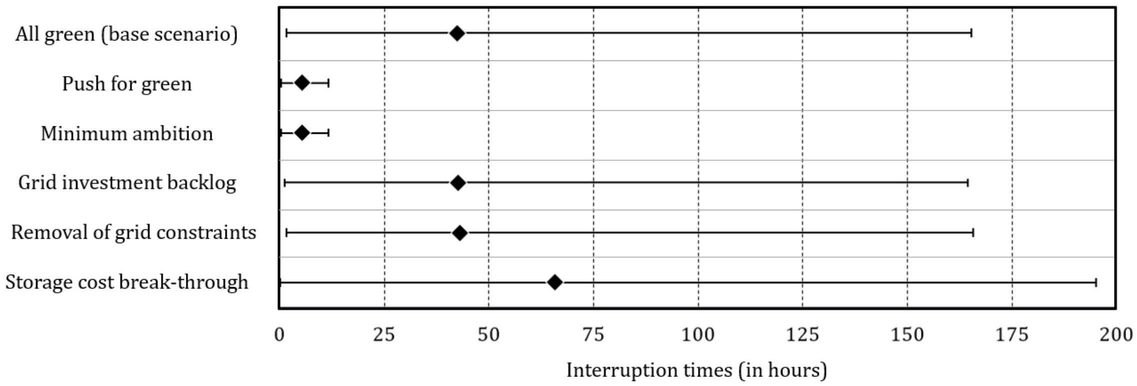


Figure 2.5 Mean, minimum and maximum AIT of each scenario in hours

Permitting the use of conventional energy in scenarios B and C results in a significant reduction of average interruption times. The available capacities of hard coal, gas and waste can be used to balance the power system significantly better than a 100% RES system (scenario A). However, although conventional back-up capacities are available, the average AIT of 4 hours in both scenarios is still at comparably high levels (compared to today).

Nevertheless, the CO_2 emission is not a constraining factor: neither in the reference year, nor in any year during the simulation period the CO_2 restrictions are reached (see table 2.4).

Table 2.4 Utilization of CO_2 budget

Scenario	Average of all years	Year with highest emission level
B Push for green	50.6%	69.8%
C Minimum ambition	12.6%	17.4%

The scenarios related to the speed of grid extensions (scenario D and E) show similar levels of interruption times as the base scenario A. Thus, the speed of grid extension has only limited impact on the level of supply insecurity stemming from multi-year variability. Furthermore, scenario D with grid investment backlog results in even lower interruption times than the unconstrainted grid scenario E. This is due to the fact that in the first optimization stage more VRES generation capacity is required to be installed to compensate for the grid extension backlog (see table 2.2).

Similar to the ENS, the AIT is higher for scenario F than for all other scenarios. A balanced build-up of both storage and generation capacities is required to withstand multi-year VRES fluctuations. Without sufficient generation in years with average and high-generation weather conditions to charge the storage, the increased storage capacity alone is not effective.

While in scenario B and C the AIT varies slightly, it varies widely in all other scenarios. Although in high-generation weather years the AIT can be reduced almost to zero, years with low-generation weather conditions result in supply gaps of more than 150 hours in scenario A, D and

E and almost 200 hours in scenario F. For comparison: 200 hours would represent almost 8 days of national power outage in Germany.

The results of the average interruption frequency also fit to the results of the ENS and AIT analysis. While the scenarios B and C result in the lowest AIF, scenario F shows the highest mean AIF of 516 incidents and the highest maximum value of 2,570 incidents.

Table 2.5 Mean, minimum and maximum frequency of supply interruptions

Scenario		Mean	Minimum	Maximum
A	All green (base scenario)	354	15	1,005
B	Push for green	51	12	103
C	Minimum ambition	53	12	120
D	Grid investment backlog	326	15	986
E	Removal of grid constraints	357	15	998
F	Storage cost break-through	516	2	2,570

5.4 Implications of valuing stored energy at the end of the optimization period

The value of energy stored at the end of the optimization period (VoSE) is valued with the LACE (set to 62 EUR/MWh). The chosen value for the VoSE has direct influence on the cost-optimal capacity mix in the first optimization stage. With rising VoSE, it becomes more economical to install more long-term storage conversion capacities. The increased conversion capacities can be used to charge excess electricity into the storage that would otherwise be curtailed. Omitting the valuation of stored energy assumes that storing excess electricity has no economic value as its potential use in the subsequent periods is not considered.

The introduction of valuation of stored energy leads to lower storage capacity requirements, which may seem counter-intuitive. However, with increased storage conversion capacities it is possible to fill the storage faster and the utilization of the storage capacities increases. A tipping point for the value of stored energy exists between 40 and 50 EUR/MWh, at which a significant change in the size of long-term storage and conversion capacities (as shown in figure 2.7) is triggered.

Due to this increased flexibility (faster charging of storage capacities) the power system's ability to cope with greater VRES generation fluctuations is improved. As a result, the capacities of VRES with a more volatile generation profile (wind onshore and offshore) expand with increasing valuation of stored energy, while the less volatile solar PV capacities slightly decrease. In addition, with rising long-term storage conversion capacities, the short-term storage and conversion capacities decline. A full overview of sensitivity results is displayed in appendix C.

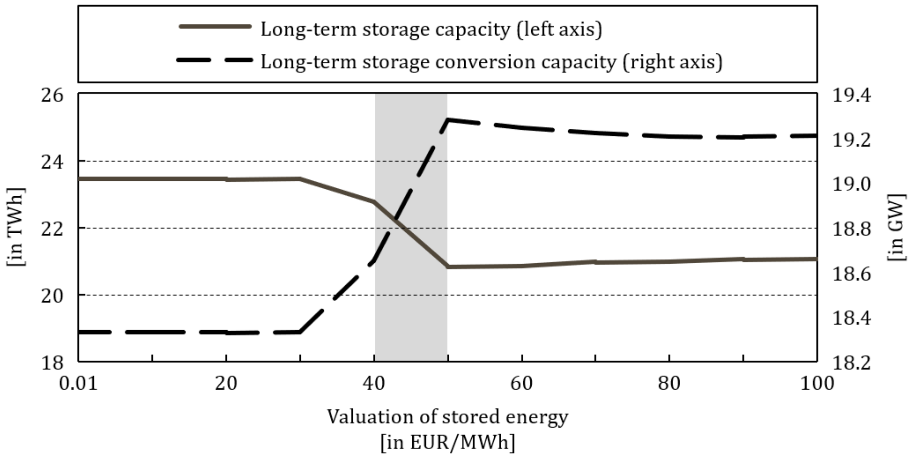


Figure 2.6 Cost-optimal size of long-term storage capacity and storage conversion capacity

Similarly, variations in the valuation of stored energy has influence on ENS, AIT and AIF in the multi-year simulations. In table 2.6 results based on a LACE of 62 EUR/MWh is compared to valuing stored energy at the end of the optimization period with 0.01 EUR/MWh[6].

Table 2.6 Sensitivities of security of supply metrics to the valuation of stored energy

Multi-year mean		**ENS (in TWh)**		**AIT (in hours)**		**AIF**	
Valuation of stored energy (in EUR/MWh)		**62**	**0.01**	**62**	**0.01**	**62**	**0.01**
A	All green (base scenario)	2.2	4.4	37.9	74.6	354	544
B	Push for green	0.2	0.2	3.8	3.9	51	52
C	Minimum ambition	0.2	0.2	3.8	3.9	53	52
D	Grid investment backlog	2.0	4.2	34.1	71.7	326	536
E	Removal of grid constraints	2.3	4.4	38.8	74.5	357	552
F	Storage cost break-through	3.7	5.8	62.5	98.4	516	611

A value close to zero leads to greater supply gaps, longer interruption times and higher frequency of interruption (except for scenario B). Omitting a valuation of stored energy at the end of the optimization period (when using one period optimization), makes the power system more vulnerable to multi-year fluctuations in VRES generation and consequently the security of supply risk increases. Hence, the robustness of the power system towards multi-year fluctuations can be improved by incorporating a fair valuation of stored energy at the end of the optimization period when relying on capacity optimization with the time horizon of one period. Nevertheless, this approach does not replace a multi-year analysis. Rather it mitigates the modelling shortcomings when relying only on one reference year.

[6] The VoSE needs to be positive to ensure that it is optimal to store excess electricity in available capacities. Otherwise curtailment would be equally cost-optimal, which may lead to distorted outcomes. Therefore, a positive value close to zero is chosen.

2.5.5 Sensitivity of model results to changes in VoLL

As described in section 2.3 several approaches to calculate the VoLL exist which result in a range of possible values for the macro-economic threshold. In order to better understand the influence of VoLL on model results, the sensitivity to VoLL changes is analyzed.

Conceptually, increasing the VoLL will lead to a greater level of security of supply as technologies with comparably high marginal mitigation cost for ensuring uninterrupted electricity supply are becoming increasingly economical. The optimal level of security of supply shifts to the right as shown in figure 2.8 (graph adapted from Bliem (2005)).

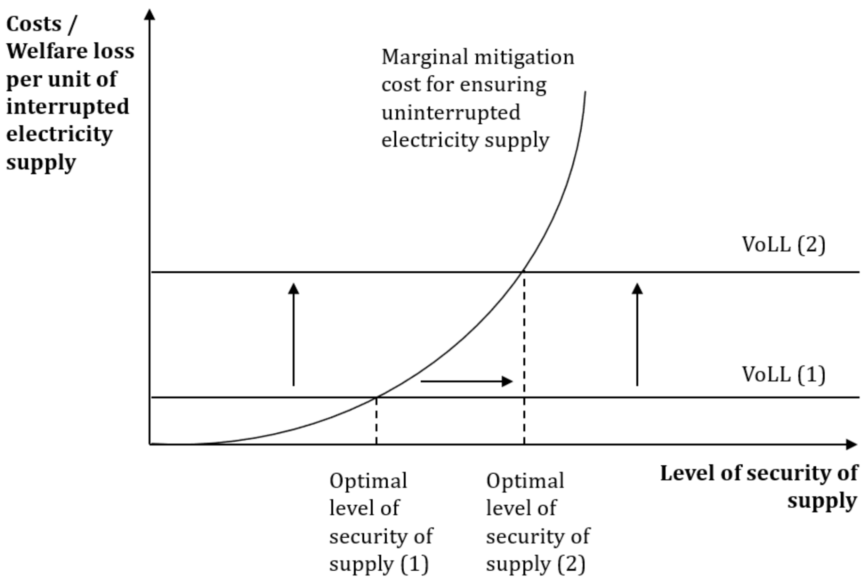


Figure 2.7 Shifting optimal level of security of supply with increasing value of lost load

Three values for the VoLL are included in the sensitivity analysis: (1) 3,000 EUR/MWh based on the technial price cap in the day-ahead market in the German/Austrian grid zone (Epex Spot, 2018), (2) 12,400 EUR/MWh based on CEPA (2018) and (3) 26,000 EUR/MWh which is according to a European Commission staff working document the upper range of VoLL estimation in European member states (European Comission, 2016). The results of the sensitivity analysis can be found in table 2.7.

As expected, the level of supply security increases with rising VoLL. It gets increasingly economical to invest in additional generation and storage capacities to reduce supply outages. However, even with very high VoLL the average ENS, AIT and AIF in the multi-year simulation remain at comparably high levels. This is explained by the fact that the increased VoLL mainly impacts the optimal capacity park in the first optimization stage (based on the reference year). Raising the VoLL threshold leads to increased VRES and storage capacity installations and thus to lower levels of supply insecurity. Nevertheless, energy market modelling based on one reference year underestimate the security of supply risk stemming from multi-year VRES variability irrespective of the chosen VoLL.

Table 2.7 Sensitivity of model results to changes in VoLL

VoLL (EUR/MWh)	3,000	12,400	26,000
Optimal VRES and storage capacity as derived in optimization stage 1			
Wind onshore (in GW)	117.6	106.0	152.2
Wind offshore (in GW)	31.9	31.9	12.6
Solar PV (in GW)	106.2	135.2	133.1
Short-term storage conversion capacity (in GW)	33.1	37.4	41.0
Short-term storage capacity (in GWh)	159.9	223.8	234.9
Long-term storage conversion capacity (in GW)	23.6	19.3	18.4
Long-term storage capacity (in GWh)	17,289.6	20,864.6	20,740.0
Security of supply indicators from multi-year analysis in optimization stage 2			
Average ENS (in TWh)	3.4	2.2	1.9
Average AIT (in hours)	58	38	32
Average AIF (in incidents)	606	354	295

2.6 Policy implications

First, interruption levels in all scenarios (and especially in the 100% renewable scenarios) are significantly higher than nowadays. Achieving very high supply security levels appears to be costly in the future power system due to the high marginal cost of ensuring security of supply. While the interruption frequency is relatively high from a security of supply perspective, the frequency is too low for plant operators to utilize their capacity economically. Similarly, the marginal profits from increasing storage sizes are too low due to low utilization and thus make investments in additional capacity unattractive.

This dilemma may represent a challenge for policy makers in future power systems as the macro-economic optimum might not be the politically desired level of supply security. If high interruption times should be avoided, additional policy intervention might be required. For example, the introduction of capacity remuneration for storage or gas plants could trigger the build-up of further capacity beyond the macro-economic equilibrium. However, deviating from the macro-economic equilibrium would represent a welfare loss, which is likely to be borne by customers in the form of increased electricity prices.

Second, the build-up of further gas plants as peakers (which can be run with synthetic or natural gas) needs to be considered beyond the build-ups currently included in the grid development plan by the Federal Network Agency. In the simulations a lack of conventional generation capacity often constrains the system (supply outages occur despite dispatch of the entire conventional generation capacity). However, it is unclear if rational investors would be willing to invest in the required capacity without further monetary incentives. Investors face a high uncertainty regarding future operating times and hence their income is very volatile. Unclear expectations regarding regulatory regimes and technology advancements might pose additional investment risks. Thus, appropriate policy instruments are required to mitigate these challenges.

Finally, a very high renewable level can be obtained without strictly enforcing a close-to-zero CO_2 regime. As seen in the scenarios B and C the build-up of RES is more economical in 2050 than utilizing more of the existing conventional capacity. As a result, the CO_2 emissions remain below the assigned CO_2 budget every year. From a security of supply perspective, it might be worthwhile to accept a limited amount of CO_2 emissions. This might not even require any further policy support, as conventional plants are only dispatched in times of very low VRES generation.

2.7 Discussion

2.7.1. Comparison of model results to literature

The recent dispute over Jacobson's work on a 100% renewable system for the United States in 2050 (Jacobson, Delucchi, Cameron, & Frew, 2015; Tsai, 2018) illustrates the complexity and factual constraints in modelling energy systems. In Germany, a significant number of energy models have been developed to address shortcomings of existing models while at the same relying on simplifying assumptions on areas outside of the core focus (Zerrahn & Schill, 2017). One key aspect is the modelling approach towards representing the spatial and temporal resolution on an acceptable level of granularity and comprehensiveness. Staffel and Pfenninger (2018a) highlight in their recent work that the multi-year variability of renewable energy sources might be currently not sufficiently represented. In order to ensure comprehensiveness, energy models need to move towards multi-year analysis. This essay contributes to the idea brought forward by Staffel and Pfenninger by exemplifying the problems when deriving optimal generation and storage capacities in a highly renewable power system based on one reference year. For the case of Germany, this essay confirms the concerns raised by in the study. Moreover, the results regarding the magnitude of VRES multi-year fluctuations are in line with existing research. Nevertheless, as this line of research is relatively new, several studies, including this one, rely on the same data sources for simulating multi-year fluctuations of wind and solar PV (S. Collins et al., 2018; Staffel & Pfenninger, 2018a).

The findings presented in section 2.5.3 suggest that multi-year VRES variability has a significant influence on security of supply and, more importantly, that insufficient representation of this variability in energy modeling greatly underestimates the associates supply risk. The results therefore contradicts the arguments put forward in several other studies that a 100% renewable system is feasible and might even increase the security of supply, e.g. due to decreased import dependency and increased decentralization of generation (Nitsch et al., 2012; Zappa, Junginger, & Broek, 2019). In addition, one common argument against security of supply concerns stemming from rising shares of RES is the observation that despite the comparably high renewable capacity and generation shares in Germany the interruption times remain at very low levels (Mormann, Reicher, & Hanna, 2015).

In line with this essay, some studies such as Coester et al. (2018) already demonstrated that energy shortages might occur in a future German electricity system due to the shut-down of conventional power plants. The authors use a dynamic simulation, in which five policy scenarios were analyzed.

The security of supply implications presented should be interpreted against the background of this emerging discussion on supply security. In particular with regard to the comparably high ENS and interruption times in the low-generation weather years, it would be too simplistic to conclude that Germany should not strive for a full decarbonization of the power sector. The quantitative results rather illustrate the shortcomings of energy market modelling based on one reference year and potential challenges of future highly renewable power systems.

2.7.1 Limitations

As the essay is taking a 2050 perspective, assumptions regarding the generation setup, demand pattern and technological input parameters are subject to uncertainty. This essay tackles this by incorporating six scenarios that address the most important areas of uncertainty: regulatory regime, speed of grid extensions and development of storage costs. Nevertheless, the results should not be interpreted as a forecast, but rather as one potential representation of a future power system.

Despite calibrating the model to the current German power market and incorporating plans regarding future developments (e.g., grid extension plans, available conventional capacity), the study focuses on the power system in the year 2050. Thus, no conclusions can be drawn regarding the path towards this state and potential intermediate development stages. Calibrating the model to the current German power market also neglects potential future geographical shifts in demand and renewable capacity within Germany.

Furthermore, this study has quantified the security of supply risk by focusing on the power sector. As explained in Zerrahn and Schill (2017) this simplification is largely justified for the majority of current power systems, however it can be argued that due to the electrification of the buildings and transport sector, the coupling of sectors will gain importance in future highly renewable energy systems. Further research could validate the results of this study by incorporating also these other sectors.

In addition, this essay studies the future German power market in isolation, neglecting the potential for smoothing VRES generation and demand across a larger geographical area. Despite ongoing efforts to integrate European power markets, it seems reasonable to restrict the geographical scope of this study, as decarbonization ambitions differ significantly across Europe (e.g., Poland's commitment to lignite versus the renewable agenda in Germany) and national governments are likely to be still interested in achieving their decarbonization and security of supply targets on their own. Nevertheless, potential geographical diversification effects from an integrated European power system would be an interesting line for future research.

Similar to other investment models, this essay simplifies and partly omits certain technical assumptions regarding generation capacity (e.g., start-up costs and minimum generation levels) and grid power flow principles. In addition, the power model mainly focuses on selected storage technologies in order to smooth load and neglects potential other future flexibility measures (e.g., demand-side management).

Despite lifting the assumption of full demand fulfillment, the study is limited as inelastic demand below the VoLL threshold is assumed. Thus, the results could be further improved by incorporating detailed demand price elasticities. In addition, an important and yet not fully developed area of research is the impact of weather on demand, which is not covered in this essay.

2.9 Conclusion

This essay analyzes the influence of multi-year weather variability on future power systems and especially its impact on security of supply. For this purpose, a new power model is introduced, which incorporates most components of a power system with a high spatial and temporal resolution and which uses extensive time series of fluctuating wind and solar PV generation profiles to model multi-year weather variability. The model is calibrated to the German power system and its technology-specific input parameters reflect a 2050 perspective.

The model is comprised of two optimization steps: first, the cost-optimal portfolio of renewable and storage capacity is derived based on one reference year. Second, synthetic RES generation profiles of the years 2000 until 2016 are applied to the capacity park derived in the first step.

Security of supply is studied by lifting the common assumption of full demand fulfillment and instead explicitly modelling the welfare loss of unfulfilled demand as macro-economic opportunity cost. In addition, the model introduces the valuation of stored energy at the end of the optimization period in order to derive more realistic renewable and storage capacity estimations even when modelling only one year of weather data.

The results show that the multi-year variability of VRES is severe and consequently cannot be neglected when power systems with high shares of intermittent renewables are modelled. For power systems that mainly depend on wind and solar PV generation, such as the one in Germany, the multi-year weather variability could impact security of supply. The results of the simulations can be summarized in the following 6 points:

1) The variability of VRES generation across several years is significant: the simulations show fluctuation margins up to 71.2 TWh (or 13.9% of total demand) between the most windy/sunny year and the calmest/dullest year
2) Even high-generation weather years with high VRES generation (compared to the average conditions) can result in increased insecurity of supply, as the power system's ability to withstand varying shapes of weather profiles is limited
3) Permitting the use of conventional energy significantly reduces the security of supply risk, while adjustments in the speed of grid extensions have a limited impact on security of supply
4) Long-term storage (in this study Power-to-Gas) can be helpful in smoothing VRES generation profiles over several years, however this is only effective in combination with sufficient VRES generation capacity
5) Increasing the value of stored energy at the end of the optimization period influences the cost-optimal capacity mix (long-term storage conversion capacity increases, while long-term storage decreases)
6) Even when modelling only one reference year, power system models that include a fair valuation of stored energy (in this essay valued with the LACE) are significantly more robust against multi-year fluctuations of VRES compared to optimizations with value of stored energy close to zero

The results show that energy research should move towards multi-year analysis, when analyzing power system with high shares of intermittent renewables. Otherwise, the risk from VRES fluctuations and its impact on security of supply might be underrated. If multi-year analysis is not possible, at least a deliberate choice regarding the reference year should be made (depending on the aim of the study e.g., a year with 'normal' weather conditions). When optimizations are limited to one year, incorporating a fair valuation of stored energy at the end of the optimization period can help to achieve greater power system robustness against multi-year fluctuations of VRES.

Moreover, the results demonstrate that with rising shares of VRES, ensuring security of supply will be of growing importance for energy policy. It needs to be assessed if the current set of instruments can address the security of supply risks stemming from high shares of intermittent renewables or if new policy instruments (such as capacity remuneration) are required.

Future work could enhance the presented model by also incorporating buildings and transport sectors to study the impact of sector coupling. Another important aspect worthwhile studying is the weather impact on demand.

3 | The value of a European security of supply strategy — trade-off between national interests and collective benefits

by Fridolin Pflugmann

Geographical integration of electricity markets is a promising approach to the renewable intermittency challenge. Nevertheless, countries tend to prefer domestic generation over foreign supply when it comes to their security of supply strategy, abandoning potential cost savings. This essay aims at (1) investigating and quantifying the benefits of cooperation and (2) identifying potential roadblocks for countries to agree to a more cooperative security of supply strategy. For this purpose, four different security of supply strategies, that range from national autarky to collective security, are outlined. These strategies are implemented in a Pan-European electricity market model. I investigate how different security of supply strategies influence a future electricity system in terms of electricity cost, security levels and spatial distribution of capacity.

The results show that clear economic benefits of a European security of supply strategy exist, estimated at annual savings of 7-42bn EUR (3-16% of total system cost). While on European system level the collective security strategy achieves low supply interruptions, security levels vary significantly among member states. Countries with high electricity productivity benefit over-proportionately from the market integration due to their ability to import electricity from countries with lower productivity at times of domestic shortages. Also, other implications of a collective security strategy might be conflicting with national interests: in terms of electricity prices, countries with very low generation cost are better off with a less cooperative security of supply strategy. Furthermore, the uneven distribution of capacity in a collective security strategy might be in conflict with national renewable expansion plans. As benefits of market integration are not equally distributed, a political debate is required to set transparent and fair rules.

Keywords: *Electricity* m*arket integration, security of supply, collective benefits, conflicting interests*

3.1 Introduction

While in the past security of electricity supply was mainly threatened by technical failures in power plants and the grid network, nowadays policy makers and researchers are increasingly concerned that security of electricity supply is at risk due to insufficient investment in generation capacity (Newbery & Grubb, 2014). Regulators therefore aim at establishing policies that trigger sufficient investment in generation, storage and network infrastructure within an appropriate timeframe to ensure that future electricity demand can be met. At the same time, electricity should be provided at affordable prices and with means that allow the reduction of greenhouse gas emissions based on the emission reduction path agreed on European level (European Comission, 2011). This set of objectives is often referred to as the energy policy trilemma, as the goals are partly conflicting (Ang et al., 2015). The most prominent example for this conflict is the large-scale deployment of renewable energy sources (RES) across Europe. While wind and solar power are considered crucial for the decarbonization of the power sector, their deployment is costly, and the intermittent generation profile poses a risk to secure supply.

Solving the intermittency challenge of renewable generation is one of the key aspects of the transition to a low carbon and secure energy system. Besides storage and sector coupling, geographical integration of electricity markets by increasing interconnector capacities is seen as one of the most promising approaches to smooth electricity generation over time (Brown et al., 2018). The European Union (EU) facilitates this by proposing to substantially increase cross-border interconnector capacity to 15 percent of installed generation capacity by 2030 as part of the European Target Electricity Model (Commission Expert Group on electricity interconnection targets, 2017).

While this effort leads to increased integration of the short-term balancing market, the long-term generation adequacy as part of the security of supply strategy continues to be decided on national level. Historically, national states ensured security of supply in their own jurisdiction, for example by defining minimum levels of back-up capacity. The implicit assumption used to be that interconnector capacity can only to a small extent contribute to national security of supply. As countries have no control over generation capacities in adjacent markets, national governments tend to prefer domestic generation over foreign supply (Newbery & Grubb, 2014). Grid operator procedures that restrict exports in times of domestic shortage and the implementation of capacity mechanisms to stimulate the build-up of domestic generation capacity exemplifies this (Hawker et al., 2017; Mastropietro et al., 2015). Yet, this idea of 'self-sufficiency' is becoming increasingly outdated as electricity markets are integrating and the economic benefits of cooperation are indisputable (Newbery et al., 2016; Schlachtberger et al., 2017). At the same time, national governments are particularly cautious with regard to their long-term electricity security strategy, as energy infrastructure decisions are hard to reverse: they are often associated with high upfront investments, long life cycles and limited potential to replace supply in crisis.

Academia has only started to understand how a government's reluctance towards relying on foreign capacity impact energy markets. Existing literature falls short in systematically identifying potential roadblocks for countries to agree to a more cooperative electricity system, in particular with regard to security of supply. To guide such an analysis, a conceptual framework that outlines relevant dimensions of cooperation and strategy archetypes is currently lacking. In addition, studies relying on energy market models only implicitly include assumptions on countries' willingness to cooperate. However, it can be expected that the security of supply strategy has significant influence on the structure and dynamics of the energy market. This leads to the research question: how do different national security of supply strategies influence the future electricity system in terms of electricity cost, security levels and spatial distribution of capacity?

To understand the underlying rationale whether countries opt for cooperation or not, it is relevant to investigate and quantify the potential benefits of increased cooperation, while it is equally important to pinpoint potential roadblocks for countries to agree to more cooperation. Elaborating on the collective benefits as well as identifying 'winner and losers' of the integration can fuel the political debate on energy market integration within Europe. The results not only provide more transparency for policy makers, but also can be used to guide the development of regulation that is more likely to be supported by all countries. Thus, this essay contributes in three ways: first, it develops a conceptual framework for national security of supply strategies. Second, it demonstrates how different national security of supply strategies influence security levels, future electricity costs and spatial distribution of capacity and lastly sheds light on the misalignment between collective benefits and national interests and demonstrates that benefits of market integration are not distributed equally among all participating countries.

This essay outlines four different security of supply strategies drawing from theories of International Relations. The strategies are depicted across two dimensions: trust in reciprocal security and willingness to depend on electricity imports. For the purpose of this analysis, the four strategies are implemented in a Pan-European electricity market model that represents the technological and cost parameters of a potential future electricity system in 2050.

The results show that ensuring security of supply on collective level has significant advantages: in terms of system cost, the collective security strategy is dominant while preserving high security levels on collective European system level. However, the advantages of cooperation are unequally distributed among the countries. In terms of electricity prices countries with very low generation cost are better off with a less cooperative security of supply strategy.

In a cost-optimal collective security strategy, most countries experience no supply interruptions, while a few countries face significant supply shortages. Also, the uneven distribution of capacity in a collective security strategy might be in conflict with national renewable expansion plans and national self-perception. In order to realize the benefits of collective security, these adverse effects to some member states have to be addressed.

The remainder of this essay is structured as follows. Section 2 gives an overview of existing literature on market integration and corresponding conflicts of interest. Section 3 briefly describes the historic development of the European electricity market, followed by the explanation of the generation adequacy concept and an introduction of the main theories on energy security. Section 4 details the model methodology applied in this essay and section 5 states how the national security of supply strategies are operationalized in the model. Section 6 contains the results and finally the findings are discussed in section 7.

3.2 Literature review: RES intermittency, market integration and conflicts of interest

A rich body of literature addresses the intermittency challenge of RES. Several papers study the intermittency that stems from different types of renewables, e.g. wind (Karagali et al., 2013), solar (Ela et al., 2013) and hydro generation (Kies, Schyska, & Bremen, 2016). A large number of studies focuses furthermore on potential solutions to smooth intermittent renewable generation, which include an optimal mix of generation technologies (Solomona, Kammenb, & Callaway, 2016), storage (Cebulla et al., 2017), sector coupling (Kirkerud, Bolkesjø, & Trømborg, 2017), transmission grid extension and market integration (Becker, Rodriguez, Andresen, Schramm, & Greiner, 2014; Schaber, Steinke, & Hamacher, 2012), as well as flexibility provided by classic back-up capacities (Schlachtberger, Becker, Schramm, & Greiner, 2016) and demand-side response (Söder et al., 2018). Some researchers also combine various flexibility options, e.g. Steinke, Wolfrum, and Hoffmann (2013) analyse the interplay of transmission grid extension and storage while deriving cost-optimal system designs and Skar, Jaehnert, Tomasgard, Midthun, and Fodstad (2013) assess Norway's potential to provide flexibility in a renewable European electricity system through its large hydro reservoirs.

Within the literature on market integration research predominantly focuses on the economic benefits. Research has shown that by harmonization of remuneration policies, as well as efficient utilization of capacities major welfare gains can be achieved. Especially efficient allocation between Spain and Germany is frequently mentioned as example (Böckers, Haucap, & Heimeshoff, 2013). Another aspect is the price convergence as a result of market integration that can result in short-term gains as high as EUR 3.9bn per year by increasing efficiency across borders within the European Union's of day-ahead and intra-day markets, as well as balancing services (Newbery et al., 2016). Extensive research focused on the future Pan-European electricity system design and implications for electricity prices. For example, Schlachtberger et al. (2017) simulate a Pan-European power system that achieves a 95 percent reduction in CO_2 emissions compared to 1990 levels. In the derived cost-optimal system transmission lines across countries are significantly extended to smooth renewable generation. Despite the highly renewable setup (cost-optimal system is dominated by wind and hydro power), average system costs are comparable to today's power system. The economic benefits of sector coupling are widely acknowledged in literature, however political feasibility and security aspects are not adequately addressed.

A second important strand of literature focuses on policy implications, especially on the cross-border effects of capacity mechanisms (Bhagwat, Richstein, Chappin, Iychettira, & Vries, 2017; Cepeda, 2018; Mastropietro et al., 2015; Meyer & Gore, 2014; Ochoa & Ackere, 2015). Exclusion of foreign operators in capacity mechanisms can result in significant welfare losses associated with over- and under-procuring of capacity. Furthermore, the exclusion distorts the cross-country trade of electricity. Opening up the national capacity mechanism to foreign capacity and interconnectors is required to ensure cohabitation of the single market with national capacity policies (Cepeda, 2018). However, the complementary of coupled power systems is a decisive factor whether integration yields economic benefits. Ochoa and Ackere (2015) illustrate this based on interconnectors between Great Britain and France as well as Columbia and Ecuador. Designing targeted policies on national level is already far from obvious, however implementing appropriate policies to take advantage of the potential from market coupling becomes an even more complex task. Some studies on the capacity mechanisms in the European context also link their results to national security of supply strategies. For example, Mastropietro et al. (2015) mention that national initiatives, such as launching capacity mechanisms, can be rather seen as an aim at national autarky in contrast to the European Commission's objective of strengthening cooperation in the single market.

Lastly, an emerging strand of literature focuses on conflicts of interests in electricity market integration. A prominent theme is the conflict between national capacity mechanism and the European single market. Member states aim at ensuring security of supply within their own borders with the implementation of national capacity mechanisms. Hawker et al. (2017) claim that this is a response to technical and economic constraints, as well as a lack of trust in cross-trade flow (i.e. security of supply cannot be ensured on collective level in times of stress). A potential solution could be a single EU-wide capacity mechanism. Leiren et al. (2019) similarly identifies a tension between the European Union that strives for cross-country coordination and member states that favor national backup solutions. The authors investigate the reason why member states introduce national capacity mechanism as part of their security of supply strategy (focusing on United Kingdom, France and Poland) and conclude that the lack of investors' willingness to build adequate capacity is the most important reason. For Poland potential future electricity shortages are also one of the key concerns for the new policy. Policy makers gave higher priority to avoiding supply shortage than ensuring the well-functioning of the single market.

To conclude, the existing literature addresses the economic benefits and technological aspects of market integration as well as implications of specific policy instruments, such as capacity mechanisms. Only few studies examine potential tension and conflicts of increased cooperation, among the member states as well as with the European Union. As a result, the existing literature falls short in systematically identifying potential roadblocks for countries to agree to a more cooperative electricity system, in particular with regards to security of supply. To guide this analysis, a conceptual framework of security of supply strategies that outlines relevant dimensions of cooperation and strategy archetypes is currently lacking. Lastly, studies relying on energy market models only implicitly include assumptions on countries' willingness to cooperate, hence research is lacking that demonstrate how different security of supply strategies influence the structure of the electricity market and its economic conditions.

3.3 Security of supply: historical context and theoretical perspectives

3.3.1. From state-controlled electricity markets to the European single market

Historically, the electricity markets within the European Union used to be significantly influenced by national governments. The large majority of electricity generation sectors and transmission grids were state-owned and monopolized. National governments ensured security of supply on national level by central planning of investments in generation capacity. Liberalization reforms replaced central planning with a market-based approach in the 1980s and 90s. Since then, generation operators are required to compete in the wholesale market and react to price signals. These spot price signals are supposed to convey sufficient information regarding generation adequacy and should subsequently trigger investments in new generation capacities if required. This market-led approach, however, also removed the ability of national government to directly influence the level of generation adequacy (Hawker et al., 2017).

The European Union promoted the liberalization of electricity markets and subsequent development of an internal European electricity market by enhancing competitiveness, promoting investment in infrastructure and reorganizing the regulatory supervision with the foundation of the Agency for the Cooperation of Energy Regulators (ACER). In mid-2019 the 'Clean energy for all Europeans' package became effective that reforms the design and improves the operations of the European electricity (and gas) market. The aim is to further strengthen the regulatory cooperation within the European Union without establishing centralized decision making. Instead, the national regulatory bodies stay in charge of regulatory supervision. ACER is proposed as a platform to coordinate and orchestrate the regulatory actions of the member states. However, ACER should receive new limited competencies for cases, in which national regulation falls short of ensuring the smooth operations of the single market across borders. In addition, ACER is assigned a role in the development of a coordinated EU-wide methodology for assessing generation adequacy. National capacity remuneration mechanisms must be based on the common assessment methodology and should allow for the participation of capacity providers that are located in other member states. Yet, it is unclear if enough trust in the cross-border flow as an element of the national security of supply strategy can be built, or as Hancher & Winters (2017) noted:

> *"Convincing Member States to rely on surplus capacity availability in neighboring Member States who may also in turn face shortages may prove difficult. Complex rules will be required to ensure that cross-border participation can be realized to its fullest extent". (p. 9)*

Furthermore, the new regulation does not touch on the question how costs and benefits of cooperation among members states should be shared. If one grid operator expands its transmission grid or builds up interconnector capacity, the benefits are possibly enjoyed by customers outside of the grid operator's zone, while the costs need to be eventually passed on to the customers of the grid operator (Hancher & Winters, 2017).

The case of unplanned power flows in the interconnected transmission systems of Central and Eastern Europe illustrates this issue vividly. The large-scale deployment of wind generation capacity in Northern Germany leads to power surpluses in times of high wind levels, which need to be routed demand centers in Southern Germany and Austria. Due to insufficient grid capacity along the North-South corridor in Germany, the power flows through adjacent countries (Poland and Czech Republic) and stresses the stability of the national grid systems in these countries. Simulations show that without the planned grid extensions until 2020, the Polish national transmission grid will be vulnerable to congestion and destabilization (Singh, Frei, Chokani, & Abhari, 2016). Clearly, the distribution of costs and benefits are not aligned among the member states: while German customers enjoy the benefit of 'green' electricity, Polish grid customer need to bear the costs of grid upgrades in order to preserve the stability of their system.

3.3.2. Market-based approach to derive generation adequacy and policy interventions

In an 'energy only' market, the generators receive payments for the sold volume of electricity, which cover the variable and fixed costs of the power plants. Without market distortions the revenues are sufficient to cover costs of economically efficient plants (i.e. plants are frequently enough part of the 'economic dispatch') and the market price signals incentivize new investments in power plants to reach the cost-optimal level of generation adequacy in the long run (Hogan, 2005).

A market equilibrium is reached when the marginal cost of generation equals the welfare loss associated with unserved load. The welfare loss can be expressed as the value of lost load (VoLL). Typically, the value of lost load is very high (between 1,500 and 22,940 EUR/MWh in Europe (CEPA, 2018)) and normally not reached in the wholesale market. When prices reach the VoLL customers opt to reduce demand, which is otherwise considered to be inelastic, and accept the welfare loss associated with the foregone use of electricity. The energy that could be only provided at prices above the VoLL are referred to as supply deficiencies. This corresponds to the concept outlined by the International Energy Agency that energy insecurity is not limited to supply interruptions, but can also be induced by prices that are not competitive (International Energy Agency, 2007).

Despite the liberalization of the electricity markets, the macro-economic optimum as described above might not be reached due to political interventions. Political considerations might result in a deviation from the economic optimum to achieve higher levels of security of supply. Hence, regulators might tend toward capacity overinvestment, which is considered socially preferable (Ranci, 2007).

Another reason for policy interventions are concerns over market distortions. One prominent example is the 'missing money' problem. It arises, when price spikes occur too rarely to recover the cost of the existing plant/the investment in a new plant. This is problematic, as peak plants are required for the large-scale integration of renewables to kick-in in times of shortfalls of wind and solar PV generation. In addition, investors are reluctant to invest in new conventional capacity due to uncertainty about future electricity, fuel and CO_2 prices, load factors and regulatory changes (Meyer & Gore, 2014). Several EU-member states are increasingly concerned about these distortions in the market, which might result in a threat to the generation adequacy. As a consequence, several countries established capacity mechanisms to address these market failures (Hawker et al., 2017; Meyer & Gore, 2014).

3.3.3. Energy security theories

Political views on energy security are usually embedded in a wider national security strategy and are shaped by the prevailing stance within a country towards foreign relations (Jan Kalicki & Goldwyn, 2013). History, culture and social movements influence the way a state perceives opportunities and threats to its national security. Consequently, uniform energy security strategies do not exist, rather the country's individual internal and external relationships influence the complex policy decision-making. Nevertheless, it is important to understand the main theoretical grounds, on which energy security strategies are based. Proskuryakova (2018) provides a comprehensive overview of common energy security theories. The two most prevailing theories in literature and politics, neo-realism and neo-liberalism, are briefly summarized below (Proskuryakova, 2018):

Neo-realism is the most frequently studied theory of energy security. Neo-realists discuss energy policy with relation to national interests and resulting (military) conflicts among states (Daddow, 2017). Neorealism in international politics focuses on the states as main actors, which pursue self-interest in an 'anarchic setting' without central authority to enforce global order. As Proskuryakova (2018) notes:

> *"Neo-realist researchers believe that national interests should dominate energy policy, and bilateral deals should dominate over multilateral contracts."* (p. 205)

Neo-liberalism, in contrast, highlights the advantages of cooperation and the importance of non-state actors in establishing order in energy trade flows. As the ability of single states to ensure security of supply is limited, international institutions, such as the World Trade Organization and the Energy Charter Treaty, are required to set standards and rules for international cooperation. Market forces determine investment levels in energy infrastructure and ultimately shape the dynamics of energy trade (Goldthau & Witte, 2010).

National energy policies with regard to security of supply are often routed in one of these two theories. Szulecki (2016) illustrates that even countries with similar resource endowments and within a rather homogenous political zone, such as the European Union, can follow diverging paradigms: while Poland and Germany resemble in characteristics and development of the energy sector, their political angles toward security of supply are in clear opposition. Germany's security of supply strategy is shaped by the view of neo-liberalism. Kraemer (2016, p. 7) describes this as follows:

"The German Federal Republic changed its outlook from national energy security (with the option of autarchy) toward collective energy security, or energy policy in the context of collective security framework provided by the West" (p. 7)

On the contrary, Poland follows a neo-realism view on security of supply. Since the end of the Cold War energy security in Poland has been mainly discussed in relation to the dependence on gas imports from Russia. In addition, the state influence on the energy sector continues to be substantial in Poland, as it is perceived of national importance. This illustrates that in the case of Poland there is a close link between the national interests and the energy sector (Szulecki, Gullberg, & Fischer, 2016).

As described above, the ideas of neo-realism and neo-liberalism significantly shape the political perspectives on energy security. Furthermore, examples of both schools of thought can be found in real-life governmental policies. Hence, these two energy security theories serve as superordinate structure of the conceptual framework for security of supply strategies which is developed in the next section.

3.3.4. Conceptual framework for security of supply strategies

Using the energy security theories of neo-realism and neo-liberalism as cornerstones, this section introduces a conceptual framework of security of supply strategies. The framework outlines four archetypes along two dimensions: the trust in reciprocal security and the willingness to depend on electricity imports. Figure 1 summarizes these four archetypes and provides an overview of energy policy instruments that correspond to the respective security of supply strategy. The first strategy, *national autarky*, is an extreme form of neo-realism, in which the national electricity system is protected from foreign influence, i.e. interconnections with adjacent countries are almost non-existent. A country that follows this strategy neither trusts in the ability of foreign generation to ensure security of supply, nor is willing to accept significant dependence on foreign electricity imports.

The second strategy, *collective security*, is as a strong form of neo-liberalism, in which the multilateral approach is emphasized. Security of supply is delegated from the country level to a supra-national level, in which the collective benefits of the entire system are given priority over individual national interests.

Willingness to depend on electricity imports ↓ / Trust in reciprocal security →	Low	High
High	**Moderate integration** The benefits of market integration are acknowledged, yet policy makers are concerned that foreign generation capacity might be not available to provide capacity in times of supply shortages. Limited control in foreign jurisdictions is perceived as a barrier to trust in reciprocal security *Related policy instruments: capacity mechanism for domestic generation, establishment of a 'strategic reserve'*	**Collective security** Security of supply is perceived as cross-national task, which can be most effectively tackled with a multilateral approach. Policy maker strive for full integration of electricity markets within a collective security of supply framework *Related policy instruments: collective capacity mechanism, facilitation of investments in grid infrastructure/ interconnectors, open feed-in tariffs to foreign generation*
Low	**National Autarky** Policy makers share a strong mistrust in availability of foreign generation capacity in times of shortage and fear import dependency. Influence of foreign policy makers and companies is perceived as a threat to national security *Related policy instruments: (partly-) nationalized electricity sector, central planning of generation adequacy, regulated electricity tariffs, high regulatory requirements for foreign companies to enter the national market*	**Import independence** Mutual interdependence ensures trust; security of supply is achieved collectively via cooperation. However, as energy infrastructure decisions are long-term and hard to reverse, critical infrastructure and capabilities should be kept domestically. In order to avoid vulnerability, the energy trade-balance should not be one-sided, hence significant dependence on foreign capacity is avoided *Related policy instruments: collective capacity mechanism, protection/creation of 'national champions', tax exemption for domestic generation, national feed-in tariffs*

Figure 3.1 Conceptual framework for security of supply strategies

Between these opposing perspectives, two further strategies are defined. The strategy of *moderate integration* resembles the currently prevailing position in Europe, that limited integration is economically favorable, however foreign capacity can only to small extent contribute to national security of supply. The fundamental belief of this strategy is that within the national jurisdiction security of supply can be ensured only with sufficient domestic firm capacity.

The last strategy, *import independence*, adopts a balanced approach to market integration. On the one hand, security of supply is perceived as a cross-national task and foreign capacities constitute an integral part of total required generation. On the other hand, a high degree of import dependence should be avoided. In this strategy policy makers are concerned about keeping relevant levels of energy infrastructure within the national jurisdiction and retaining capabilities and knowledge within domestic companies to ringfence an industry of paramount importance for national welfare. In addition, policy makers are concerned about keeping jobs in the energy sector and use energy policy to promote a social agenda, e.g. environmental protection.

The conceptual framework described in this section is used to structure the quantitative analysis and hence enables the systematic investigation of the impact of security of supply strategies on electricity cost, security levels and spatial distribution of capacity in a future European electricity system. The four security of supply strategies serve as scenarios in the electricity market model presented in the next section.

3.4 Methodology

This essay adopts a model-based approach, in which the effects of different national security of supply strategies on electricity cost, security levels and spatial distribution of capacity are examined. For this purpose a Pan-European investment and dispatch model is introduced, which derives the cost-optimal system design to withstand weather fluctuations over a 32-year period. Four scenarios are calculated that reflect each of the introduced national security of supply strategies.

Multi-year fluctuations of renewable generation are studied in this essay as the main threat to the security of supply of the power system; hence other risks such as terror attacks and technical failures are not assessed (see Johansson (2013) for a broad typology of energy and security). In order to achieve this, the model uses extensive time series of intermittent wind and solar PV generation profiles: renewable supply is modelled based on the synthetic weather data of 1985-2016 (Staffel & Pfenninger, 2018b).

The future power system is likely to be characterized by a high share of renewable generation and high interconnectedness of countries to tackle the intermittency challenge of renewables. Both characteristics are reflected in the model that is calibrated to represent a potential future interconnected European power system that is dominated by renewable generation. All technology-specific input parameters, as well as the demand pattern reflect a 2050 perspective.

The temporal resolution is set to daily values to solve a complex set of system constraints, while preserving computational tractability. Hence, hourly input values, e.g. for renewable capacity factors, are sampled down to days. It is assumed that sufficient flexibility options, such as Lithium-batteries, vehicle-to-grid and demand-side responses, are available within the system to smooth generation on an intra-day level. Several studies already address the intra-day variability and corresponding flexibility requirements (Cebulla et al., 2017; Child, Bogdanov, & Breyer, 2018;

Rodríguez-Benítez, Arbizu-Barrena, Santos-Alamillos, Tovar-Pescador, & Pozo-Vázquez, 2018). The model is developed in Matlab and solved with the commercial solver CPLEX.

Nomenclature

n	Node (country)	$g_{n,d,i}$	Electricity generated
d	Day of the time period	$s_{n,d,i}$	Electricity charged or discharged
i	Generation and storage technology	$pf_{n,d}$	Power flow
l	Interconnector between two nodes	$lf_{l,d}$	Transmission line flow
a	Annual	c_i	Annualized investment and fixed cost
$DEM_{n,d}$	Demand	c_l	Annualized investment cost of interconnector
$G_{n,i}$	Generation capacity	mc_i	Marginal cost
$S_{n,i}$	Storage conversion (charge/discharge) capacity	$\alpha_{n,d}$	Nodal marginal price
$SC_{n,i}$	Storage capacity	eff_i	Efficiency factor for generation and storage
$SL_{n,d,i}$	Storage level	e_i	Emission factor
NTC_l	Net transfer capacity	COB_n	Emission base as of 1990
IM	Incidence matrix of the network	COT_n	Emission reduction target

3.4.1 Objective function

The objective function of the model is the minimization of system costs, including annualized investment, fixed (operating and maintenance) and marginal costs for renewable generation, conventional generation, power storage and transmission grid extensions. The renewable and conventional generation capacity G_i, their dispatch $g_{n,d,i}$, the storage conversion capacity S_i and storage capacity SC_i, the storage operations $s_{n,d,i}$ as well as the net transfer capacity NTC_l and transmission line flows $lf_{l,d}$ are subject to optimization. An overview of cost and technological assumptions is provided in table 3.1.

$$min\begin{pmatrix} \sum_{n,i} G_{n,i}\, c_i + \sum_{n,i,d} g_{n,d,i}\, mc_i + \\ \sum_{n,i} S_{i,n}\, c_i + \sum_{n,i} SC_{i,n}\, c_i + \\ \sum_{l} NTC_l\, c_l \end{pmatrix} \tag{1}$$

3.4.2 Power balance

Synthetic demand profiles for all countries are constructed based on the load curve of the year 2016 (ENTSO-E, 2017) and on projected values for the total annual demand of 2050 (Osorioa, Nahmmacher, Schmid, & Knopf, 2018). Power flows within the system must be balanced at all times, so that demand at each node is fulfilled by available generation technologies (including curtailment), charge or discharge of storage and power flows among the nodes.

$$DEM_{n,d} - \sum_i g_{n,d,i} - \sum_i s_{n,d,i} = pf_{n,d} \leftrightarrow \alpha_{n,d} \quad (2)$$

In order to study security of supply, one sub-category of generation technologies is 'energy not supplied'. Thus, the optimal solution can contain unserved load, however this imposes a penalty payment that equals to the macro-economic opportunity cost for customers, i.e. the value of lost load. The estimations for the value of lost load (VOLL) per country are based on the final report prepared for ACER by CEPA (2018). The study details the VoLL across industries and for domestic consumption for all EU member states. The report does not cover Norway and Switzerland, as they are not part of the European Union. For these two countries the corresponding values have been added following a similar methodology as in the study by CEPA (2018). Excess electricity can be curtailed at each node, e.g. by pitch regulation of wind parks or spillage in hydro reservoirs. The dual $\alpha_{n,d}$ of this constraint is used to determine nodal marginal prices, i.e. market clearing price.

Table 3.1 Cost and technological assumptions

	Wind on-shore	**Wind off-shore**	**Solar PV**	**Bio-mass**	**Run-over-River**	**Open-cycle gas turbine**	**Pumped storage/ hydro reservoir[c]**	**Power-to-Gas[c]**	**Trans-miss-ion line**
Investment cost [EUR/kW][a]	1,075	2,093	425	1,951	3,000	400	1,100[d]	1,300	1,000
Technical lifetime [a]	25	25	25	20	30	30	60	23	100
Annual fixed cost [EUR/kW]	46	76	26	100	75	15	2%	0	-
Efficiency [%]	-	-	-	49	-	40	81/90	60	100
Fuel price [EUR/MWh_{th}]	-	-	-	23.0	-	38.2	-	-	-
Carbon content [t / MWh_{th}]	-	-	-	-	-	0.20[b]	-	-	-
Investment cost for storage capacity [EUR/kWh][a]	-	-	-	-	-	-	30[e]	0.5	-

a Overnight investment costs annualized with interest rate of 4%
b Carbon price of 57 EUR/MWh
c Initial storage level of 50% assumed for pumped storage and Power-to-Gas; country-specific level calculated for hydro reservoirs
d Only for replacement of turbines after end of lifetime
e Only replacement investments for pumped storage and no cost assumed for hydro reservoirs as natural basins

Source: Based on (Agora Energiewende, 2014; International Energy Agency, 2015; IRENA, 2018c; Osorioa et al., 2018; Pape et al., 2014; Schröder, Kunz, Meiss, Mendelevitch, & Hirschhausen, 2013; Umweltbundesamt, 2018; Zerrahn & Schill, 2017) and own assumptions. Detailed overview of assumptions in appendix D

3.4.3 Network structure

In the network model each country is represented by one node. The network consists of 28 countries, which include all European Union member states (excluding the island countries Cyprus and Malta), as well as Switzerland and Norway. The network nodes are connected via high voltage transmission interconnectors. The network typology, as well as the lines' existing net transfer capacities, have been derived from ACER (2017) and ENTSO-E (2018). The transmission line length is calculated in a similar way as in Schlachtberger et al. (2017) assuming point-to-point connections between the geographical centers of each countries.

$$gf_{n,d} = \sum_{lf} lf_{l,d}\ IM_{n,l} \tag{3a}$$

The network is modeled with the transshipment approach (Medjroubi et al., 2017; Nygard et al., 2011), where the power flow among nodes is constraint by a net transfer capacity (NTC) and in which the transmission lines are considered dispatchable.

$$0 \leq lf_{l,d} \leq NTC_l \tag{3b}$$

This approach abstracts from complex power flows within a highly interconnected European power grid network. Instead, the NTC defines the maximum boundary for power trade between the nodes. As the transmission expansion is modelled endogenously, the NTC can be increased (investment costs are based on NTC and length of lines). It is justified to consider transmission lines dispatchable, as argued by Schlachtberger et al. (2017). The authors point out that many interconnectors are already dispatchable point-to-point high-voltage direct current (HVDC) connections (e.g., between France and Great Britain), while high-voltage alternating current (HVAC) capacities are traded based on NTCs in market clearing. In addition, the capacity of transmission lines is constrained by minimum, which is determined by the existing transfer capacity (assuming investments at levels, which at least replace current interconnectors), as well as by maximum, which is set at 20 times the existing net transfer capacity to reflect geographical and socio-technological boundaries.

3.4.4 Generation

The dispatch of conventional generation and biomass is constrained by the installed capacity of the corresponding technology type.

$$0 \leq g_{n,d,i} \leq G_{n,i} \bullet 24 \tag{4a}$$

The generation of the renewable technologies is calculated based on capacity factors. The capacity factors for wind and solar PV are derived from the renewables.ninja database (Staffel & Pfenninger, 2018b) with hourly resolution for the years 1985-2016. In order to account for future changes in spatial distribution of wind parks within each country the dataset for the near-term future is used. It covers current wind parks, as well as those under construction or with planning approval as of Dec 2016. This is particularly relevant for the offshore wind parks, as significant build-up efforts will change the spatial distribution significantly (e.g., Germany plans to increase the offshore wind capacity from 5.4 GW in 2017 to almost 32 GW until 2040, mainly in the Northern Sea (Bundesamt für Seeschifffahrt und Hydrographie, 2017a)). For countries without major changes in the spatial distribution of wind parks the current capacity factors are used. While capacity factors for photovoltaics and onshore wind are provided for all countries in scope, offshore wind capacity factors are only available for countries with significant offshore wind capacity installed or planned.

For the run-over-river and hydro reservoir plants the inflow has been estimated based on ENTSO-E data from 2016 (ENTSO-E, 2018). Time series have been scaled to match total renewable hydro generation, as reported by IRENA (2019c).

All capacity factors have been aggregated to daily values, as described in the beginning of the methodology section.

The build-up of photovoltaics, onshore and offshore wind capacities is capped based on their country-specific geo-technological potential (Gerbaulet & Lorenz, 2017; Osorioa et al., 2018). In addition, the existing installed base of renewables has been set as a minimum, assuming at least replacement investments.

The installed renewable capacities as of 2017 for onshore wind, offshore wind, photovoltaics, biomass and run-over-river are derived from ENTSO-E (2018) and the renewable capacity statistics by IRENA (2019c). Hydro capacities are derived from Gerbaulet and Lorenz (2017). Biomass plants are assumed to be fully dispatchable. Due to environmental concerns and competition with food production, the generation potential for biomass is capped per year based on Osorioa et al. (2018).

$$\sum_{d=1}^{365}\sum_{n} g_{n,bio} \leq g_{n,bio}^{max} \tag{4b}$$

In addition to the renewable capacity build-up, the installation of conventional generation capacities is part of the optimization. However, it is assumed that due to the ongoing decarbonization efforts and stricter emissions constraints, conventional generation is mainly used as backup for peak demand periods and at times with low renewable generation. The prime characteristics for required conventional generation is therefore operational flexibility and economic viability despite few full load hours. Open-cycle gas turbines (OCGT) are well suited for such requirements. Significant downsides exists for other conventional technologies, such as lignite and coal (high emissions), nuclear (high investment cost, unclear regulatory prospects) and closed-cycle gas turbines (longer start-up times and higher investment cost compared to OCGTs). Therefore, only OCGTs are implemented in the model.

3.4.5 Storage

The model includes three storage types: pumped hydro storage (PHS), hydro reservoirs and power-to-gas (P2G). For the pumped hydro storage and hydro reservoirs, the current installed capacities are assumed to be constant over time, i.e. no new builds due to geographical constraints and environmental concerns, but replacements after end of the technical lifetime. Following the approach by Gerbaulet and Lorenz (2017), PHS are assumed with a storage-to-conversion capacity (E/P) ratio of 8 hours. For reservoirs, country-specific average values are used, which are derived from Gerbaulet and Lorenz (2017).

Power-to-Gas, i.e. storage based on the conversion of electricity to synthetic methane, is included as one promising alternative for long-term storage applications, as costs for storage capacities are relatively low, while costs for conversion capacities are high. While most storage technologies, especially batteries, require a high number of charging-discharging-cycles, the techno-economic characteristics of Power-to-Gas allow large storages without frequent charging cycles. The P2G conversion unit is assumed to have coupled hydrogen and methane production and re-conversion to electricity is only possible via OCGTs. No pre-defined E/P ratio is assumed for the P2G storage, thus the P2G conversion capacity, the storage capacity, as well as the re-conversion via OCGT capacities are independently optimized in the model. It should be noted that consequently OCGTs can be fired with natural gas, as well as with synthetic methane based on the P2G technology, and the financial viability of OCGTs relies on the combined potential. It is assumed that the cost for the P2G conversion unit will significantly decrease over time due to ongoing research efforts and potential from industrial manufacturing.

Cost assumptions for all storage technologies are summarized in appendix D. Costs of both conversion capacities [EUR/MW] and storage capacities [EUR/MWh] are modelled separately. Due to the temporal resolution of the model short-term storage technologies such as Li-Ion batteries are not included. The storage levels are set to a pre-determined initial level at the start of the optimization. The storage level at the end of the optimization must be at least at the initial storage level.

$$SL_{n,1,i} \leq SL_{n,D,i} \tag{5a}$$

The storage levels are calculated as the storage level in the previous time set, adjusted for charging and discharging, as well as for spillage and natural inflow (for hydro reservoirs).

$$SL_{n,d,i} = SL_{n,d-1,i} + s_{n,d,i}^{charge} eff_{i,charge} - s_{n,d,i}^{discharge} eff_{i,discharge}^{-1} - s_{n,d,i}^{spillage} + s_{n,d,i}^{inflow} \tag{5b}$$

The storage level cannot exceed the storage capacity, which is specified by a P/E ratio for PHS and hydro reservoirs, while the storage capacity is optimized for Power-to-Gas.

$$0 \leq SL_{n,d,i} \leq SC_{n,i} \tag{5c}$$

The charging and discharging is restricted to the available conversion capacity of the storage type.

$$0 \leq s_{n,d,i} \leq S_{n,i} \tag{5d}$$

3.4.6 Carbon emission

The dispatch of conventional generation is restricted by greenhouse gas emissions limits. It is assumed that emissions are reduced by 95 percent compared to base levels in 1990. This target needs to be achieved every year in each country. To calculate the emissions of conventional generation, technology-specific efficiency and emission factors are used.

$$\sum_{d=1}^{365} \sum_{i} g_{n,d,i} \frac{1}{eff_i} e_i \leq COB_n \, COT_n \tag{6}$$

3.5 Operationalization of security of supply strategies

As national security of supply strategies are quite complex, they are implemented through a set of various regulations. A government that strives for national autarky might, for example, carry out generation adequacy planning centrally and enforce generator operators to comply with these plans. In addition, parts of the electricity sector can be nationalized to secure critical infrastructure and knowledge from foreign influence. Furthermore, national laws can regulate electricity tariffs, establish complex approval procedures for foreign companies that want to enter the market and prohibit transmission system operators (TSOs) from supplying foreign jurisdictions in time of domestic shortages. Other national security of supply strategies consist of various policy instruments to reflect the government's overall approach towards national energy security (see figure 3.1).

Due to the variety of policy instruments and their different areas of application, the national security of supply strategies cannot be adequately implemented in the model on policy level, as this would compromise the tractability of results. Instead, national security of supply strategies are operationalized in a simplified way focusing on the primary goals of each of the strategies.

The *collective security strategy* can be considered as base case, in which the optimal level of security of supply is derived collectively for the entire system, based on equations 1-6. It is assumed that no national policy interventions restrict market forces in the system, hence no further constraints are implemented in the model.

As the *national autarky strategy* focuses on self-sufficiency and domestic generation and perceives foreign influence as a threat to national security, the transmission line capacity between the countries in this strategy is set to zero.

$$NTC_l = 0 \tag{7a}$$

The *moderate integration strategy* implies that sufficient domestic generation capacity has to be available to secure domestic demand in times of shortage. It is noteworthy, that it is not relevant, if the capacity is actually dispatched, but rather that the required capacity is available. This is assessed using a system adequacy evaluation based on capacity balances per country (50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, & TransnetBW GmbH, 2017a): peak demand is compared to installed generation and storage capacities, adjusted for standard availability factors (see table 2)[7]. The availability factors for wind and solar PV generation are calculated based on the 99th quartile in the 32-year weather time series used. Similar approaches are used for wind generation in national capacity balances (50Hertz Transmission GmbH, Amprion GmbH, et al., 2017a).

$$\max_d(DEM_{n,d}) \leq \sum_i G_{n,i}\, x\ availability\ factor_i + \sum_i SC_{n,i} \bullet availability\ factor_i \tag{7b}$$

Table 3.2 Standard availability factors

Technology	Standard availability factor
OCGT	100%
Biomass	65%
Run-over-river	25%
Pumped storage / hydro reservoir	80%

Note: country-specific availability factors for wind and solar PV generation are calculated based on the 32-year time series used

In the *import independency strategy,* imports should not reach a level that would allow foreign players to exercise geopolitical influence against the government. Therefore, this strategy is operationalized by implementing a constraint on net imports (aggregated power flows) on country level. It is assumed that net imports need to stay below 65% of domestic demand, i.e. at

[7] This simplified approach seems reasonable, as its main objective is to reflect the regulators' lack of 'political appetite for risk' and the strong focus on domestic generation. It is not intended to provide a detailed stochastic assessment of capacity availability based on stochastic convolution (as further assumptions, e.g. on plants sizes would be required). Details on stochastic capacity credit calculation with a high share of renewables can be found e.g. in Grave et al. (2012)

least 35% of domestic demand is generated locally, to protect and sustain critical infrastructure, as well as capabilities and knowledge in domestic companies.

$$\sum_{d=1}^{365} pf_{n,d} \leq \sum_{d=1}^{365} DEM_{n,d} \bullet 0.65 \quad (7c)$$

3.6 Results

First, the system costs are assessed as a function of the security of supply strategies, followed by discussing the effectiveness of the applied security of supply strategies. Lastly, an overview of the spatial distribution of the optimal capacity for each strategy is provided.

3.6.1 Cost as a function of the security of supply strategy

Figure 3.2 shows the average annual total system cost (generation, storage and transmission) of each security of supply strategy. *Collective security* is the strategy with the lowest system cost, as it can exploit the full potential of market integration, most importantly merit order effects, and geographical smoothing of intermittent renewable generation. The *moderate integration strategy* is more expensive than *collective security,* while the cost for the *national autarky strategy* are considerably higher. Restricting the imports to 65% in the *import independence strategy* has no major influence on total system cost.

If all member states within the system would adopt a *collective security strategy*, the cost advantages would amount to 7bn EUR per year compared to the *moderate integration strategy* (3.1% of total system cost). Compared to the *national autarky strategy* benefits as high as 42bn EUR p.a. could be realized (16.0% of total systems cost). This corresponds to the value of implementing a European security of supply strategy without national interference in adequacy planning and cross-border trade, which is referred to in many studies and usually perceived as an optimal European electricity system design. However, as described in the previous section, the financial advantages of a European collective security approach need to be assessed against the social and political implications. While benefits are achieved on collective level, some member states would be disproportionately negativly affected.

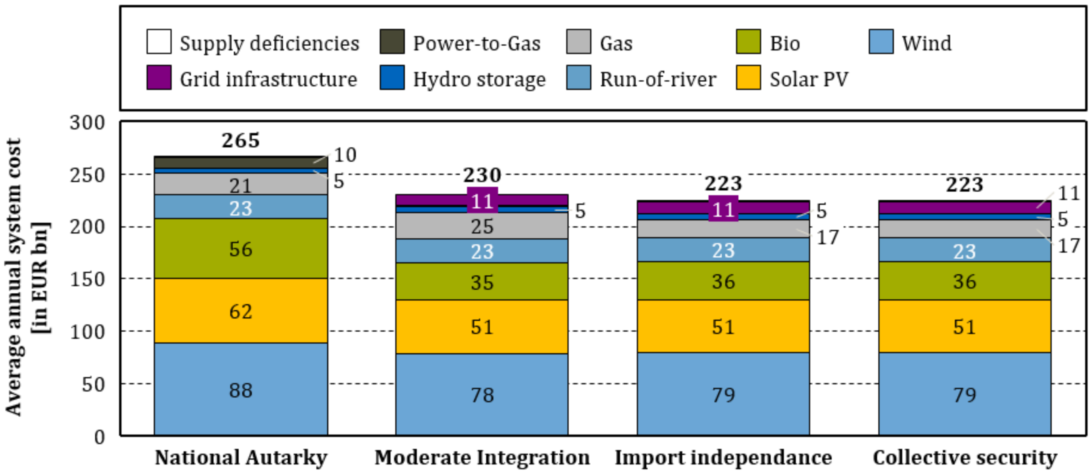


Figure 3.2 System cost comparison of security of supply strategies

The differences in nodal spot prices illustrate that countries benefit to different extent from market integration (figure 3.3). In line with overall system costs the nodal spot prices of the *national autarky strategy* are higher compared to all other strategies for the majority of countries. That means that customers benefit from lower electricity prices (assuming that wholesale electricity prices translate into lower retail prices) due to increasing market integration. However, this is not the case for all countries: autark systems would result in lower nodal spot prices in Norway and Switzerland, as generation cost are already very low. In these countries, market integration leads to an increase in demand due to increased exports to adjacent countries, resulting in higher spot prices (+83% and +16%, respectively compared to *national autarky*). While this is beneficial for local generators, rising wholesale prices could translate into a welfare loss for consumers in these two countries.

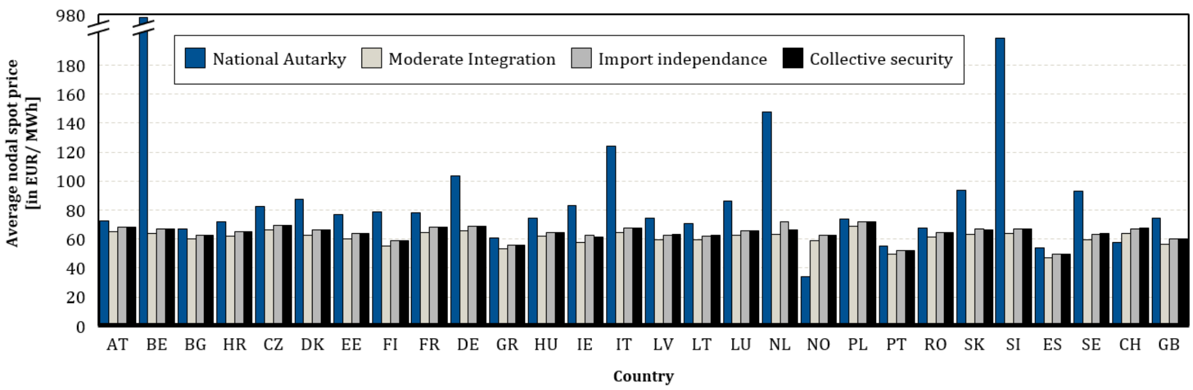


Figure 3.3 Country-specific average nodal spot prices for each security of supply strategy

Furthermore, the benefits of integration are unevenly distributed among the remaining countries. While Belgium, Netherlands, Slovenia and Italy experience a significant reduction of electricity nodal spot prices of more than 40%, nodal spot prices in Greece and Spain drop by only 8%.

Countries with favorable renewable generation conditions benefit less or not at all from market integration. On the contrary countries lacking favorable renewable generation conditions benefit over-proportionately. The case of Belgium exemplifies this: without market integration nodal spot prices reach up to almost 1,000 EUR/MWh, as the country's renewable resources are limited (due to geo-technological constraints). In order to ensure self-sufficiency in the *national autarky* strategy, a very inefficient use of technologies (including the large-scale deployment of Power-to-Gas) is required to limit supply deficiencies.

Changes in nodal spot prices not only affect consumers, but also influence the profitability of electricity generators: more efficient dispatch of generation capacity as a result of market integration leads to reduced rent extraction for generators. While rents (revenue over generation and storage costs) in the *national autarky strategy* are on average 56.7%, the rent drops to 8.4% and 8.3% in the *import independence* and *collective security strategy* respectively. The *moderate integration strategy* results in a negative generator rent of -0.7%, as generator operators are forced to keep capacity in the market, which is not operated profitably. This is also the reason, why nodal spot prices in the *moderate integration strategy* appear lower than in the *collective security strategy.* In order to ensure economic viability of generators, additional payments, e.g. in the form of capacity renumeration, might be required, which in turn could be transferred to customers.

Lastly, the capacity allocation and system cost are not very sensitive to the rate of import dependence. Stricter import independence results in replacement of wind capacity with solar PV and biomass capacities. Costs are moderately rising with stricter import restrictions. However, even restricting imports to 10% of domestic demand still results in a significantly lower costs than in the *national autarky strategy*.

3.6.2 Effectiveness of security of supply strategies

The effectiveness of the security of supply strategies is measured with two criteria:

Supply deficiencies are defined *as* the electricity that could only be supplied at prices above the macro-economic opportunity cost for electricity. Hence, this represents the demand that is forced out of the market due to unaffordable prices. Supply deficiencies are measured in TWh and also in the equivalent hours of demand not fulfilled. The latter are calculated as the supply deficiencies over total electricity demand multiplied by 8760 hours. Several countries set target security of supply levels (often 3-4 hours per year), which serve as a reference for this criteria (CEER, 2014).

Import dependency rate is defined as the net electricity imports compared to total demand in the time horizon under consideration. For comparison: The EU member states' net electricity import rate ranged from 94.3 % to 0% in 2017. While several large countries such as Germany and France were net exporter of electricity, other major economies such as Italy (11.8%), the United Kingdom (4.4%) and Spain (3.4%) relied to certain extent on electricity imports. Finland, Hungary, Luxembourg, Lithuania and Croatia imported more than 20% of their electricity inland demand in 2017. If considering also imports of solid fuels and natural gas, the entire European Union imports approx. 35% of its energy consumption; if petroleum products are included the energy import rate rises to 55% (Eurostat, 2019e).

3.6.2.1 European system level

Table 3.3 shows the effectiveness of the four security of supply strategies on the European system level. In terms of supply deficiencies, the *moderate integration strategy* performs best, as no supply deficiencies occur. That means the entire demand could be met at prices below the cut-off price, i.e. below the value of lost load. In the *national autarky strategy* 1.5 TWh of supply deficiencies occur, while in the *import independence strategy* and *collective security strategy* supply deficiencies of 5.2 TWh and 5.3 TWh occur. The hourly equivalent for all strategies remains significantly below the targeted level of security of supply of 3-4 hours/year.

Table 3.3 Effectiveness of security of supply strategies on European system level

Strategy	**Supply deficiencies in TWh (hourly equivalent/year)**	**Import dependency rate (in %)**
National autarky	1.5 (0.1)	0%
Moderate integration	0	22%
Import independence	5.2 (0.4)	21%
Collective security	5.3 (0.4)	21%

Note: exporting countries have been considered as zero import dependent

Regarding import dependency, *national autarky* results in no dependency, as countries are set to be self-sufficient. The other strategies result in import dependency between 21% and 22%. *Moderate integration* and *collective security* do not result in significantly higher dependency rates.

3.6.2.2 Supply deficiencies on national level

In line with the results on system level, the *moderate integration strategy* leads to no supply deficiencies in any country. The strategy is therefore very effective from a national perspective. The results for the *national autarky strategy* show low supply deficiencies across all countries (Bulgaria faces the highest supply deficiencies with 0.8 hours p.a.). On the contrary, in the *import independency* and *collective security strategies* the results among countries vary significantly: while most of the countries experience no supply deficiencies at all, four member states face pronounced electricity shortages (most severely Bulgaria with up to 12.2 hours and Croatia with 10.5 hours). Both countries' supply deficiencies amount to more than the 3-4-hour target for security of supply (see figure 3.4).

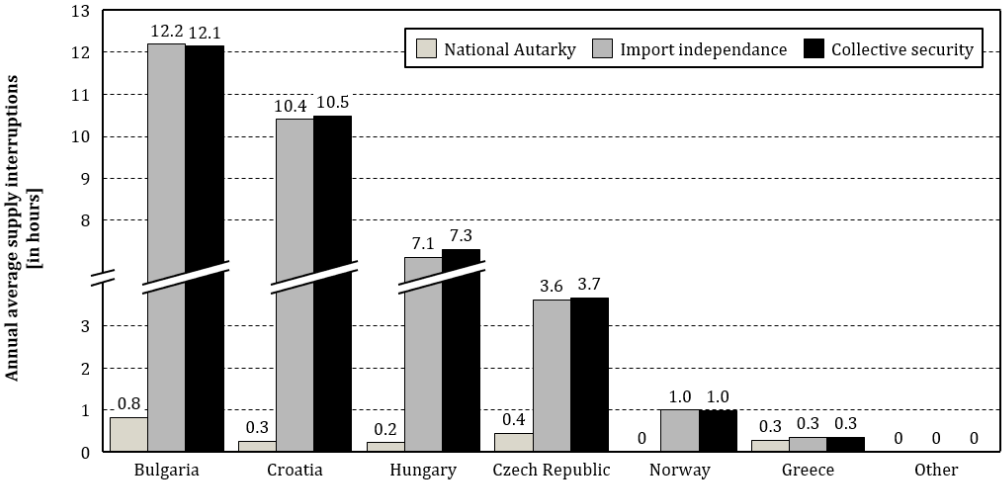


Figure 3.4 Supply deficiencies in selected countries

These supply deficiencies are an outcome of two underlying mechanisms of the energy market: the market-based approach for deriving capacity adequacy and the market clearing across countries. The market-based approach for deriving system adequacy implies that capacity is built up to the point, at which marginal generation cost equals the marginal welfare loss. When countries are assessed in isolation, these mechanisms typically result in very high levels of security of supply, as the marginal welfare losses are high compared to the marginal cost of avoiding electricity interruptions (as observed in the *national autarky* strategy). In a highly integrated system, however, the point of reference changes: while in isolation the country-specific VoLL determines the marginal welfare loss, in an integrated system the country with the lowest welfare cost in the entire system sets the cut-off price for capacity deployment in all countries (given sufficient interconnector capacity).

The change in reference point does not constitute a problem as long as all electricity can be supplied at prices below the cut-off price. However, in a shortage situation, when markets are interconnected and cleared based on market prices, countries with higher electricity productivity are able to pay higher prices than countries with lower productivity. Hence, electricity is exported to countries with a higher willingness-to-pay. As a result, supply deficiencies accumulate in countries with lowest macro-economic opportunity costs compared to adjacent countries. Due to this mechanism countries with high productivity ensure their security of supply by being able to import electricity from countries with lower electricity productivity (only constrained by the available grid capacity) and thus they disproportionately benefit from market integration. This mechanism is illustrated in figure 3.5.

Therefore, without further policy instruments the *import independence* and *collective security strategy* can be considered not effective for Bulgaria and Croatia from a political perspective, as these countries experience shortages which would not be the case without extensive market integration. Hence, without regulatory changes to the market design and policies Bulgaria and Croatia might not be willing to further integrate their markets into a reciprocal system of supply security.

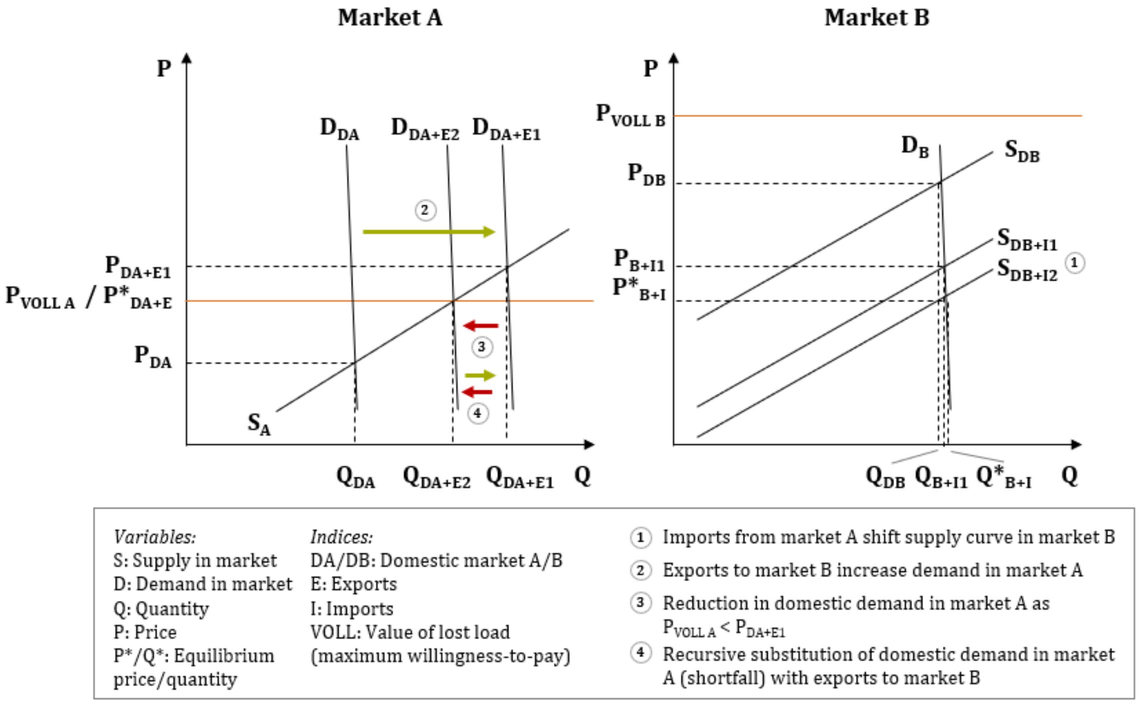
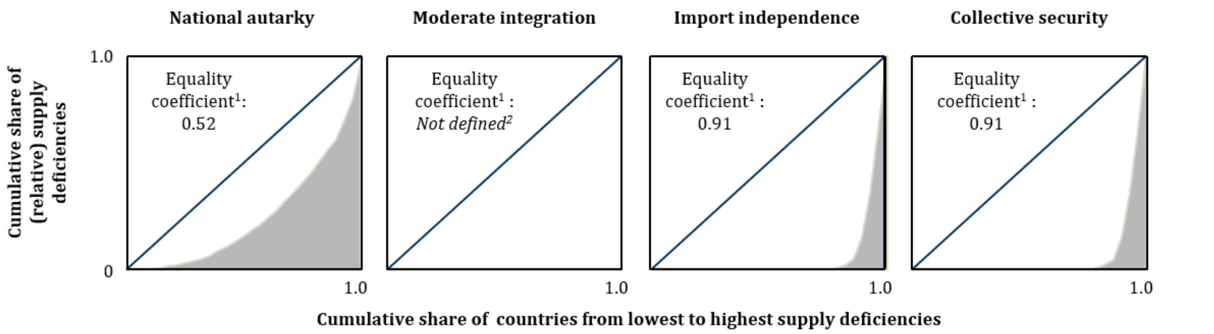


Figure 3.5 Coupling of two markets with significant differences in value of lost load

Furthermore, the results of Norway are remarkable. Despite significant renewable resources and storage facilities the country faces supply deficiencies of 1-hour equivalent. The reason for this is that Norway has one of the lowest value of lost load (4,291 EUR/MWh) among the European countries. The low VoLL is driven by comparably low electricity productivity in the industrial sector (gross value add over electricity consumption).The uneven distribution of supply deficiencies across countries can be expressed with the equality coefficient (EC) based on the Gini coefficient. Typically, the EC is used to represent inequality in a society in terms of income distribution. It takes values between 0 and 1. Values closer to 0 indicate a more equal distribution, while values towards 1 are interpreted as highly unequal distribution. Figure 3.6 shows that the equality differs significantly across countries with regards to the supply deficiencies encountered. An EC of 0.52 the *national autarky strategy* shows higher equality compared to the *import independence* and *collective security strategy*. In the two latter, an EC of 0.91 indicates highly unequal distribution. In these strategies few countries are confronted with the majority of supply deficiencies as described above. In the *moderate integration strategy* no supply deficiencies occur to any country. Hence, the EC is not defined.



1 Equality coefficient based on Gini coefficient. Coefficient can range from 0 to 1 where 0 expresses perfect equality and 1 utmost inequality
2 The equality coefficient is not defined for values equaling zero, however as no supply deficiencies occur to any country, it can be considered as being perfectly equally distributed among the countries

Figure 3.6 Measuring the equality of supply deficiency distribution

3.6.2.3 Import dependency on national level

A clear separation into importing and exporting countries exists with regard to the dependency level. In the *collective security strategy* more than 80% of demand in the Netherlands and Slovakia depend on imports from other countries. Eight countries, including large economies such as Germany and France, source more than 30% of their supply form abroad. Ten countries, including Spain and the United Kingdom, are electricity exporter.

As described in the previous sections, national governments tend to be cautious with regard to their energy security strategy as energy-related investments are long-term and hard to reverse. Convincing member states to rely on other countries to supply more than 80% of their domestic demand seems challenging. This is especially the case, when current political perspectives of these countries are taken into account. For example Slovakia, which is supposed to have the second highest import level of 82% (based on the *collective security strategy*) is an particularly illustrative example of how national perspectives clash with collective benefits. While Slovakia supports further integration of the European electricity market and acknowledges the importance of the EU to resolve energy security issues, it is concerned about its influence on the decision making on EU level. Slovak politicians perceive themselves to be in a defensive position vis-a-vis large and 'old' EU member states, such as Germany (Mišík, 2016). In order to prevent itself from high dependency on electricity and gas imports, Slovakia tries to diversify its supply base and continues to rely to large extent on nuclear energy. This example illustrates how national resentment and lack of trust can restrain the EU from unlocking the full potential of the collective security strategy.

Other countries face similar political considerations: the Czech Republic currently meets most of its electricity demand with domestic supply using mainly lignite and coal combustion. Compared to other European countries it relies to a significantly smaller degree on oil and gas imports (Eurostat, 2018). Due to its natural resources, which enable a high degree of import independence, current Czech policy makers stress the importance of domestic supplies and energy security. While the country overall supports the integration within the European electricity market, it perceives reliance on other countries for imports and dependence on other countries for its security of supply as risky (Lehotský, Černoch, Osička, & Ocelík, 2019; Mišík, 2016; Sivek, Kavina, Jirásek, & Malečková, 2012).

3.6.3. The spatial distribution of infrastructure

In all security of supply strategies the power system design is dominated by wind, followed by solar PV. In the *collective security strategy* the generation and storage capacity is spread out across Europe to take full advantage of geographical diversification effects. Large-scale capacities of onshore wind are installed in countries with high wind capacity factors (mainly United Kingdom, France, Spain and Finland). Due to availability of attractive locations and its favorable cost structure onshore wind prevails over offshore wind. Similarly, large-scale build-up of solar PV occurs in sunny Southern countries (mainly France, Spain, Italy, Greece). The system is complemented by existing hydro capacities, as well as strong build-up of biomass (in particular in Germany, France, Italy and Poland). In order to balance shortfalls of renewable generation, significant OCGT capacities are installed. The transmission grid lines are extended to 7.0 times the existing NTC capacity. No build-up of P2G facilities is required, as geographical smoothing in combination with the installed OCGT backup capacities already provide sufficient flexibility to the system.

In the *moderate integration strategy* renewable generation capacity is allocated similarly cross countries as in the *collective security strategy* with minor re-allocations of capacity from exporting nations towards importing countries, e.g. a reduction of wind capacity in Spain and Hungary and wind build-up in France. In order to fulfill the security requirements OCGT capacity is increased: for example Germany requires capacity of 58GW (1.8x compared to the *collective security strategy*), France 61GW (4.6x) and the United Kingdom 47GW (1.9x). These backup capacities are installed to ensure that even in times of shortages the states can avoid supply interruptions. While biomass could also be used as dispatchable back-up capacity, no further build-up occurs compared to *collective security* as the standard availability factor for biomass is relatively low compared to OCGTs. Spain is the only country that introduces significant Power-to-Gas conversion (3.2 GW) and storage capacities (6 TWh). The transmission line capacities are similar to the *collective security strategy* with transmission capacity reaching 7 times the NTC as of today.

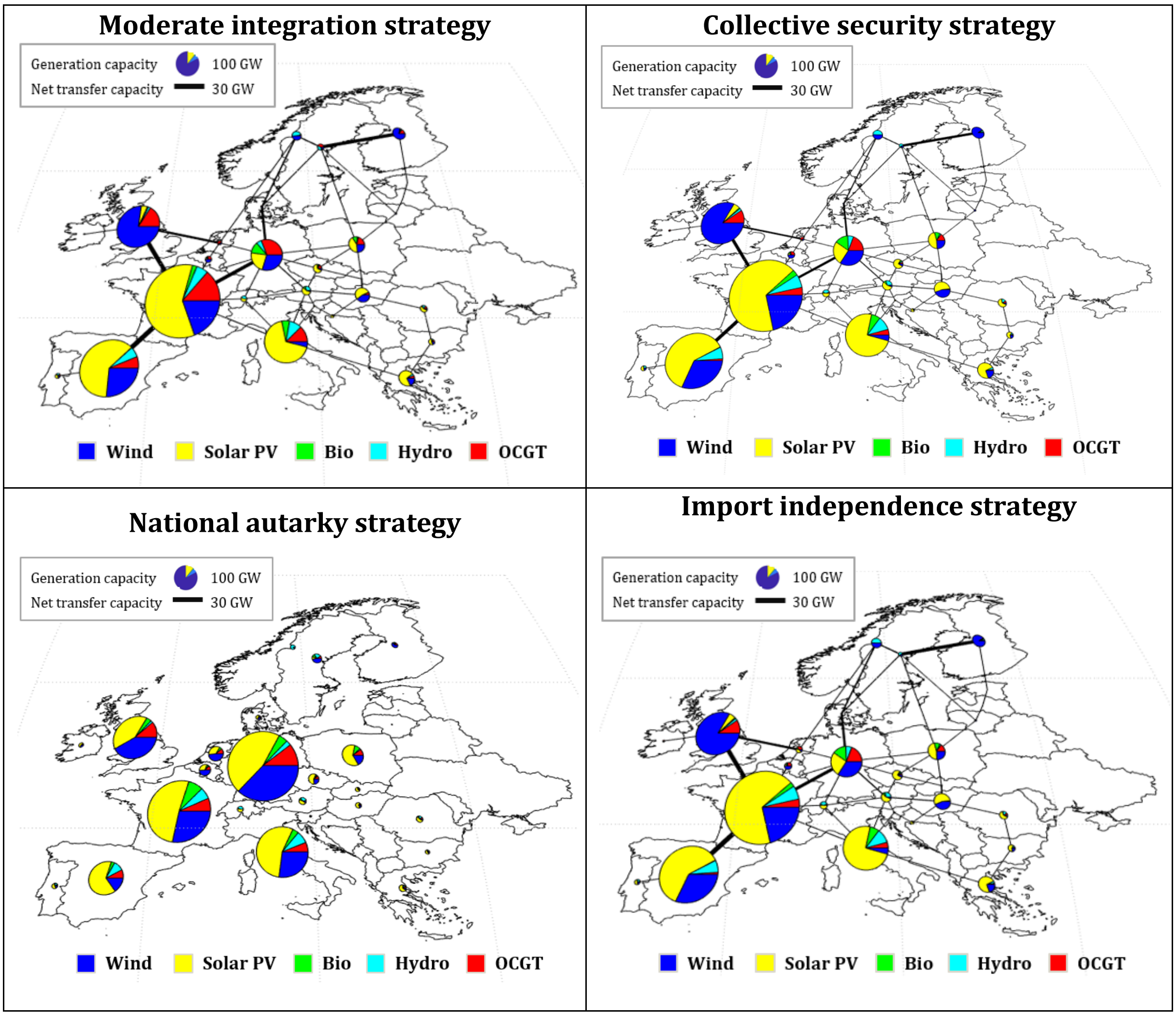


Figure 3.7 Capacity allocation in security of supply strategies

The *national autarky strategy* results in a significant increase of overall generation capacity, however the magnitude of the increase varies among countries. Countries, which mainly depend on imports from other countries in the *collective security strategy*, are now required to build up capacities, e.g., Germany, Belgium, Slovakia. Several countries reach their maximum geo-technological renewable potential for onshore wind and solar PV. Thus, these countries need to switch to less cost-effective generation, such as offshore wind, and turn to installation of storage facilities to avoid curtailments and supply deficiencies. The constrained generation conditions of these countries are also reflected in the nodal spot prices (e.g. see Belgium in figure 3.3). Exporting countries in the *collective security strategy* rebalance their portfolio by shifting capacity from wind to solar PV, e.g. United Kingdom, or overall reducing their generation capacities, such as Spain and Norway, as less capacity is required to sustain domestic demand. The *import independency strategy* results in only minor adjustments compared to the *collective security strategy*. The main difference is that countries with high import dependence in the *collective security strategy* substitute the imports with local solar PV generation (mainly Netherlands and Slovakia). The generation capacity allocation and transmission network for all strategies are illustrated in figure 3.7.

3.6.4 Policy implications

Developing an integrated European electricity system, which is characterized by true solidarity and trust, as envisioned by the European Commission (European Comission, 2015a) requires significant commitments from member states and is likely to face local resistance as cost and benefits are unequally shared among member states. Governments pursuing national interests likely prevent reaching a macro-economic optimal system. For instance, in order to reach the cost-optimal system setup in the *collective security strategy* significant efforts to deploy renewables are required, however required efforts vary among the member states and partly conflict with the existing extension plans. As the cost-optimal setup highly depends on market integration, only a few countries with most favorable conditions need to deliver most of the build-up of wind and solar PV (see figure 3.8).

Other countries need to focus solely on replacement investments without increasing the capacity beyond current levels. One example for this is Germany: due to unfavorable conditions for solar PV and onshore wind it is optimal not to invest further in renewables in Germany in the *collective security strategy*. However, the German government intends to significantly increase the renewable asset base in the upcoming years (BMWi, 2018). The pioneering role in RES deployment became an integral part of German energy policy in the previous two decades and continues to be a defining characteristic of today's policy. This political agenda was backed up by substantial subsidies for large-scale renewable deployment.

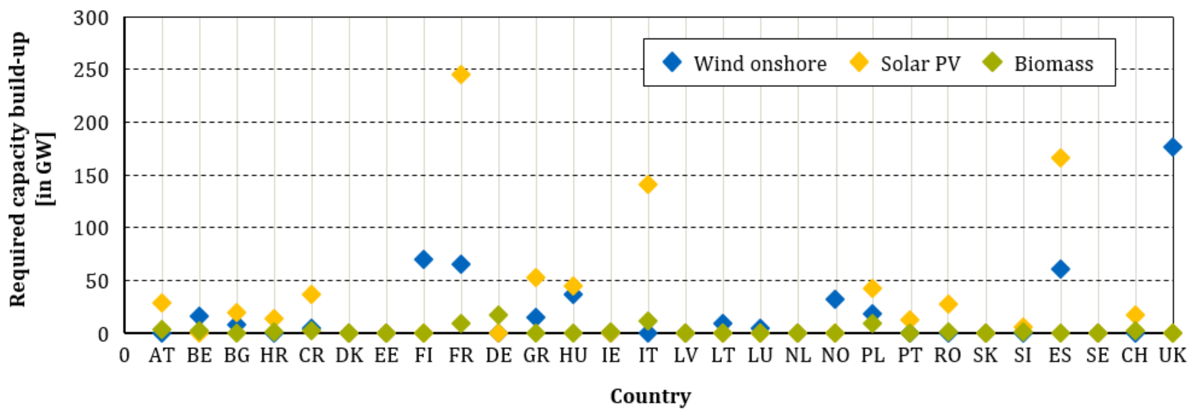


Figure 3.8 Required additional build-up of wind and solar PV capacity [in MW]

While these policies are driven by environmental concerns, it appears that industrial policy considerations also play a role: becoming a leading provider of cutting-edge technologies in the renewable sector further strengthens the industrial sector in Germany and helps to sustain international exports. These national considerations are likely to influence policy making also in the future and thereby dilute the spatial distribution of capacity from the *collective security strategy* to satisfy national interests.

Also, with regard to security of supply consideration, it seems unclear if countries are willing to fundamentally change their electricity system to comply with a system optimal solution, considering their current cautious perspective on import dependence (e.g. in Slovakia). Furthermore, complex changes to the national electricity system would be required that likely come along with impacts on the employment situation in the electricity sector.

It seems unrealistic that the current policy framework within the European Union will be strong enough to ensure system development towards a collective security strategy as national interests dominate market structure decisions, infrastructure investments and renewable funding. A potential solution could be the further completion of the European Energy Union which would allow central steering and harmonized regulation across all member states, including:

- Pooling of renewable subsidies on European level and incentivizing build-up of renewable in the most-cost efficient location
- Establishing a European grid regulator that ensures integrated grid planning and financing, especially with regard to interconnector capacity
- Distribution of cost across all member states, irrespective in which member states the costs occurred
- Definition and assertion of uniform security levels

For this to unfold, a wide-ranging political debate both on the EU- as well as on member state level is required which should result in clear, consistent and long-reaching political commitment of the member states.

3.7 Discussion

3.7.1 Comparison of model results to existing literature

Increased interconnectedness of countries within the European electricity market leads to a decrease of overall system cost, as generation capacity can be allocated more efficiently. Furthermore, market integration enables smoothing of renewable intermittency, which in turn reduces capacity requirements. These findings are consistent with several other studies (Becker et al., 2014; Brouwer, Broek, Zappa, Turkenburg, & Faaij, 2016; Schlachtberger et al., 2017).

The average system costs (for generation, transmission and storage) in this study range from 59.5 EUR/MWh to 70.8 EUR/MWh depending on the security of supply strategy. Comparable values can be found in literature with similar system setups. Schlachtberger et al. (2017) simulate a future electricity system for Europe with a 95% reduction in CO_2 emissions, focusing on optimal transmission grid extensions. Average system costs in their study range from 64.8 EUR/MWh for the optimal transmission case to 84.1 EUR/MWh without cross-border interconnectors. These cases resemble the *collective security strategy* and the *national autarky strategy* evaluated in this essay. Differences in average system costs are partly a result of the minimum renewable constraints applied in this essay, as well as the omission of short-term balancing requirements (e.g. battery storage results in costs of 9.9 EUR/MWh in the zero-transmission case in Schlachtberger et al.). Furthermore, the authors derive a system optimum with significantly increased grid capacity, i.e. 9.2 times the existing net transfer capacity (286 TWkm transmission grid capacity), while in this essay NTCs increase by 7.0 times (217 TWkm) in the *collective security strategy* are calculated. Similar to this study, the electricity system in the Schlachtberger et al. study is dominated by wind power. Importance of wind power can be also found in Becker et al. (2014), who highlight that interconnectedness impacts the optimal mix of wind and solar. With increasing grid transmission capacity more intermittent wind capacities can be integrated. This ultimately leads to skewed distribution of generation technologies on national level, as countries focus on the most favorable generation technologies. A case in point is the United Kingdom in the *collective security strategy*: the generation portfolio almost solely consists of wind capacity. This is only possible as the intermittency can be balanced with other countries via the well-developed transmission lines.

Bussar et al. (2014) develop a 100% renewable power system for the EUMENA region with a time horizon of 2050. The authors require countries to be self-sufficient (domestic generation meets 100% of demand), while power balancing across countries is allowed. This approach is comparable to the *import independence strategy* presented in this essay. However, in this essay a self-sufficiency rate of 65% is used as base case. Average system costs are estimated by Bussar et al. at 69 EUR/MWh which corresponds well to the 68.0 EUR/MWh found in this study for the import independence strategy with 100% domestic supply in the sensitivity analysis. Relieving the constraint for self-sufficiency from 100% to 65% in the base case results in significant lower average system costs of 59.5 EUR/MWh.

Ochoa and Ackere (2015) simulate the effect of increasing interconnector capacity between France and Great Britain on social welfare: in both countries social welfare increased, but benefits are not equally distributed. British consumers benefit to a large extent from the access to cheaper electricity at the expense of French consumers, who now need to pay the 'European price' for electricity. Hence, French producers are 'winners' of the market integration. This is in line with the results derived in this essay for Norway and the operators of large hydro reservoirs.

Ringler, Keles, and Fichtner (2017) highlight similar issues in their study. The authors found that coupling of European markets generally increases welfare, while not all consumers might benefit: in the simulations Belgium consumers gain from market integration due to electricity imports from neighboring countries. On the contrary, French consumers' welfare gains from increased adequacy are outweighed by the welfare losses due to increases in electricity prices. Similarly, this study has shown that collective welfare benefits can be contradicted by adverse outcomes to some member states. With regard to transmission extension the study by Ringler et al. (2017) state that there is a trade-off between reaching a market-wide welfare optimum and generation adequacy. Hence, regulators face a complex task in achieving partly conflicting political objectives. The authors also conclude that extensive collaboration of various stakeholders from the participating countries is required to deliver the benefits of market coupling. This study elaborates on this finding by pointing out that for extensive cooperation first a transparent set of regulation need to be established that specify how cost and benefits are shared, as well how shortage situations are resolved. Furthermore, it is essential that these regulations are backed up by long-lasting commitments.

3.7.2 Limitations of the model

While the model presented in this essay includes most components of a power system, certain aspects have been omitted to reduce complexity. First, the analysis is restricted to the electricity sector and therefore neglects potential effects of coupling with the transport and heat sectors. Sector coupling could help to smooth renewable generation (e.g. grid-to-vehicle solutions), while on the other hand the system imbalances might increase (e.g. due to seasonal heat demand).

Due to the daily resolution of the model, aspects, which are particularly relevant for intra-day smoothing, e.g. stationary batteries and demand-side response management, have been neglected. In addition, the model results might understate the capacity requirements due to temporal smoothing, as pointed out by Pfenninger (2017). However, the approach allows to assess both perspectives that are required for the analysis of security of supply in Europe: rare, extreme weather events to account for shortage situations, as well as 'average' weather conditions to model the economics of market integration. Different approaches, e.g. focusing on extreme events by heuristic sampling, might bias the results towards overcapacity (Pfenninger, 2017).

Nevertheless, further analysis with higher temporal resolution would be beneficial to validate the model results.

In addition, the model simplifies the grid layout to country-to-country lines, disregarding transmission and distribution grid infrastructure within the countries. However, previous studies have shown that cost for optimal transmission and distribution extension are relatively low compared to total system cost (Schlachtberger et al., 2017). A lack of internal grid infrastructure (e.g. due to lack of public acceptance) would have an impact on the capacity allocation, which would favor local generation (mainly solar PV) and thereby reduce the benefits of market integration. Further technical simplifications regarding transmission line efficiency as well as plant ramping times have been made. Furthermore, the deterministic optimization influences system performance for example with regard to the optimal operation of storages.

Finally, the national security of supply strategies are implemented without detailed modelling of individual policy instruments. Hence, specific mechanisms of policy instruments, different implementation on national level and potential policy side-effects are not incorporated in the study.

3.8 Conclusion

This essay analyzes the impact of different national security of supply strategies on electricity costs, security levels and spatial distribution of capacity in a future electricity system in Europe. Cooperation among countries is getting increasingly important as electiricty market integration is seen as one of the most promising approaches to smooth electricity generation over time. However, increased interconnectedness conflicts with prevailing national security of supply strategies. This essay investigates and quantifies the benefits of cooperation and identifies potential roadblocks for countries to agree to a more cooperative security of supply strategy. The power system implications of four security of supply strategies are assessed: *national autarky*, *moderate integration*, *import independence* and *collective security*.

A Pan-European investment and dispatch model is introduced, which derives the cost-optimal system design for each security of supply strategy. The model is calibrated to represent a future European power system that is heavily reliant on renewable generation. All technology-specific input parameters, as well as the demand pattern reflect a 2050 perspective.

The results show that the economic advantages of market integration on collective level are unequivocal: in terms of system cost the *collective security strategy* achieves the lowest system costs, as it can exploit the full potential of coupled markets. The *moderate integration strategy* is more expensive than *collective security,* while the costs of the *national autarky strategy* are significantly higher. The system cost advantage of the *collective security strategy*, and thus the value of a European security of supply strategy, is in the range of 7-42bn EUR per year (3-16% in terms of total annual system cost*)* compared to the *moderate integration strategy* and *national autarky strategy respectively.*

However, with regard to prices, winners and losers of market integration can be identified: countries with very low generation cost, e.g. Norway and Switzerland, are better off with the *national autarky strategy,* as exports to adjacent countries result in higher spot prices in the *collective security strategy* (+83% and +16%, respectively, compared to *national autarky*). Furthermore, the benefits of integration are unevenly distributed among the remaining countries. While Belgium, Netherlands, Slovenia and Italy experience a significant reduction in the electricity nodal spot price of more than 40%, nodal spot prices in Greece and Spain drop by only 8% (comparing *collective security* versus *national autarky*).

Furthermore, differences exist also with regard to the security level. While on European system level all outlined strategies achieve low supply interruptions, the level of supply security varies on national level depending on the applied security of supply strategy: the *moderate integration strategy*, which enforces the build-up of significant national backup capacities, is very effective for all countries in preventing supply deficiencies, whereas the level of electricity shortages varies among countries in the *collective security strategy*. Most countries experience no supply interruptions at all, however some countries (to the largest extent Bulgaria and Croatia) face significant supply deficiencies. This is the result of market-based adequacy derivation in combination with price clearing in integrated electricity markets. Countries with high economic electricity productivity and resulting higher willingness to pay ensure their security of supply by being able to import electricity from countries with lower productivity in times of domestic shortage (only constrained by the available grid capacity). Hence, countries with higher electricity productivity benefit more from market integration than low-productivity countries.

Besides shortage situations, a second concern —the dependence on imports— is analyzed in this study: in the *collective security strategy* some countries are highly dependent on electricity imports from neighboring states (e.g. Netherlands and Slovakia with more than 80% import dependency rate). These countries might be unwilling to accept such high dependency rates, as high import levels are often perceived as a threat to national energy security. Restricting the import dependency rate as in the *import independence strategy* results in an increase of solar PV capacity build-up in highly import dependent countries.

Another point to consider is that few countries with the most favorable conditions need to deliver most of the build-up of wind capacity (mainly United Kingdom, France, Finland and Spain) and solar PV (mainly France, Spain, Italy, Greece). It remains unclear how these countries should be compensated for building up renewables at scale, significantly beyond of what is required to supply their domestic demand. On the contrary, other countries need to focus solely on replacement investments without increasing the capacity beyond current levels, which partly conflicts with national renewable extension plan and self-perceptions as renewable pioneers, e.g. in Germany. Hence, early alignment on European level could facilitate the efficient allocation of capacities across Europe in the future. Table 3.4 summarizes the results across electricity cost, security level and spatial distribution of capacity.

Table 3.4 Implications on electricity costs, security levels and capacity distribution

	Electricity costs		**Security levels**		**Spatial distribution of capacity**	
Security of supply strategy	Average annual system cost (EUR bn)	Range of nodal spot prices (EUR/MWh)	Total system-wide supply deficiencies in TWh (hourly equivalent/year)	Equality coefficient of supply deficiencies (0=perfect equality)	Total renewable build-up vs. 2018[b]	Share of TOP3 countries in total RES build-up
National autarky	265.2	34-978	1.5 (0.1)	0.52	5.8x	40%
Moderate integration	229.8	47-69	0 (0)	Not defined[a]	4.74x	52%
Import independence	222.8	50-72	5.2 (0.4)	0.91	4.73x	50%
Collective security	222.7	50-72	5.3 (0.4)	0.91	4.72x	51%

[a] The equality coefficient is not defined without supply deficiencies in any country
[b] Only considering wind onshore, wind offshore, solar PV and biomass

To conclude: while the economic benefits of market integration and a truly European security of supply strategy are apparent, the resulting consequences of such a collective security might be sometimes in conflict with national interests of member states. This essay attempts to shed light on national perspectives on the often-proclaimed target of collective security within the EU and outline potential obstacles that may come along on the way towards a truly European security of supply strategy. In order to reach this goal, this essay suggests that a wide-ranging political debate both on the EU- as well as on member state level is required, which ultimately results in transparent and fair set of regulations, as well as clear, consistent and long-reaching political commitment of the member states.

4 | How the energy transition shifts power within Europe: developing a model to measure the energy-related geopolitical influence

by Fridolin Pflugmann

The transition to low-carbon energy sources affects not only companies and consumers, but also national states and their inter-country relationships. Due to the vital importance of energy for economic prosperity and national security, developments in the energy sector always have a geopolitical dimension. Countries with greater energy-related geopolitical influence have more weight in the foreign policy arena and are more likely to shape the outcome of inter-country policy negotiations. To understand the complex process of joint energy policy making in transnational institutions, such as the European Union, it is relevant to explain to what extent countries can exercise their political influence and how this may change in the course of the energy transition.

This essay develops a new theoretical model to describe how countries accumulate energy-related geopolitical influence. A new methodology is suggested to measure this influence with a set of 12 indicators. The results show that in the early 2000s the energy-related geopolitical influence in Europe used to be concentrated in an exclusive club of 5 Northern countries, however their hegemony has deteriorated. The energy transition may impact the energy-related geopolitical power balance within Europe in the future: (1) Several countries are very likely to experience resource scarcity also in a renewable future (2) Geographical positioning remains to be a key factor for energy-related geopolitical influence (3) Countries in Southern and Eastern Europe, as well as island states are likely to be among the winners of the shift to renewables (4) Proclaiming pioneers of the energy transition as inevitable geopolitical winners is premature (5) Emerging interdependencies could allow to unify European energy policy, as well as to develop a more consistent European foreign policy towards energy exporter, especially towards Russia.

Keywords: *Energy transition, Renewables, Geopolitics, Influence, Europe*

4.1 Introduction

Fighting global warming is one of the greatest challenges of our times. Countries across the globe have set up plans to reduce their carbon emissions in the upcoming decades. the European Union (EU) leads the way to combat climate change with particularly ambitious carbon emission reduction targets and decarbonization efforts (European Comission, 2018). The transition to a low carbon economy dramatically alters the dynamics of the energy markets in Europe: increased interconnector capacity form European-wide electricity markets; legacy fossil incumbents compete against low-carbon technologies, potentially leading to stranded assets; increasing number of small generation units (e.g. rooftop photovoltaics) leads to a greater market fragmentation; energy value chains are broken up and re-configurated; and renewables with zero marginal cost question market clearing based on variable cost (Goldthau, Keim, & Westphal, 2018).

Hence, the energy transition leads to significant changes in technologies employed, spatial allocation of capacity and governance systems. In Europe the first signs of these changes are already visible, as European countries started to reorganize their energy system in the early 2000s. The transition process has accelerated since then and is likely to speed up further to meet the decarbonization targets in the upcoming decades (IRENA, 2019c). The profound changes of the energy system also impose new challenges for governments and regulators: welfare and influence will be re-distributed among the countries and will potentially result in winners and losers of the energy transition (Scholten et al., 2014). Due to the vital importance of energy for economic prosperity and national security, developments in the energy sector always have a strategic and geopolitical dimension.

Countries which accumulate more energy-related geopolitical influence can also exercise more influence in the foreign policy arena. Consequently, national states are inclined to protect their interests and aim at increasing their influence vis-à-vis other states. How powerful a particular state can be in shaping European politics depends amongst other things on its energy-related geopolitical influence. Therefore, it is important to understand to what extent countries can exercise political influence to shape European energy policy, and how countries' energy-related geopolitical influence is affected by the energy transition. This essay aims at shedding light on both — the ability to exercise influence *and* how this is affected by the energy transition process. The corresponding research questions are: (1) What is the current ability of countries to exercise energy-related geopolitical influence within Europe? (2) How will the transition to low-carbon technologies affect the energy-related geopolitical influence of countries within Europe?

This research proposes a novel index as a more rigorous and structured approach to assess the implications of the energy transition on geopolitics, which allows to bridge conceptual, anecdotal studies of geopolitics and more established literature on indexes that systematically map the relative strength of countries. Indexes and indicators are well equipped to analyze complex, multi-dimensional realities that usually cannot be captured by traditional methodologies in social science (Saisana & Tarantola, 2009). In this study the energy-related geopolitical influence is measured over time with a set of 12 indicators, reflecting geopolitical strength of conventional, as well as renewable energy sources.

This essay contributes to the discussion on the geopolitical implications of the energy transition by developing a novel theoretical model that explains the formation of energy-related geopolitical influence. Furthermore, the essay shows how influence shifted in the European Economic Area since the early 2000s based on historical data and outlines how the transition to low-carbon technologies could influence the power balance going forward. A deeper understanding of the geopolitics enables policy makers to navigate in a new world of energy conflicts and cooperation and assist policy maker to early on address potential conflicts of interests. Furthermore, geopolitical considerations used to and stay top of the mind for investors when confronted with decision on energy investments, infrastructure and technology financing. This research project equips investors with a deeper understanding of geopolitical factors to consider when making investments in energy technologies and infrastructure in a rapidly changing environment.

The results show that the hegemony of Northern European countries has eroded over the last two decades and Southern and Eastern European countries have caught up. The transition to low-carbon technologies is likely to further fuel this trend: Southern and Eastern European countries are potentially among the winners of the geopolitical re-balancing in Europe. However, despite the universal access to renewable energy sources, power imbalances are likely to prevail also in the future. Furthermore, the countries with the greatest decarbonization efforts are not necessarily the sole winners of the transition. The results of this paper suggests that some countries with limited decarbonization ambitions, but with a pivotal geographical position, such as France, can still preserve their leading position. Lastly, increasing interdependence of the countries in Europe and reduced dependence on fossil imports from outside the EU could lead to a convergence of interests, which ultimately could help to further integrate the European Union, especially with regard to foreign policy towards energy exporter, such as Russia.

This essay is structured as follows: the first section provides an overview of the status of the energy transition in Europe, followed by a structured literature review. In the subsequent section the research design is laid out with a focus on the theoretical model. Hereafter, the results are presented, and policy implications outlined. The essay ends with a discussion of the results and concluding remarks.

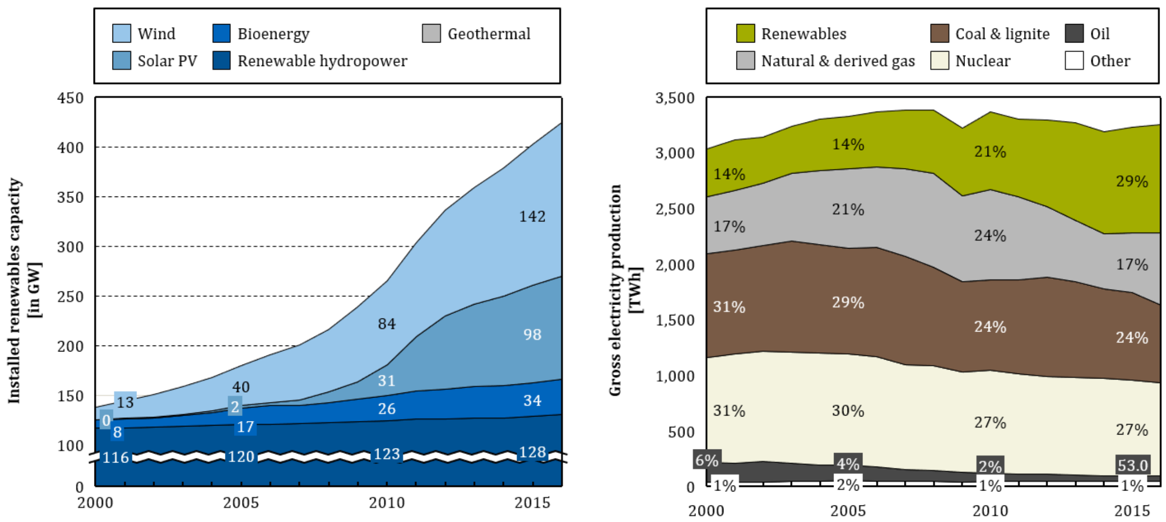
4.2 On the doorstep to a wide-ranging energy transformation

Since the industrial revolution, the energy system constantly has undergone changes driven by shifts in the dominant energy carrier. While steam engines based on coal-firing were the working horse of the early industrial revolution, oil started to emerge in the beginning of the 20th century and to play a pivotal role in economic growth, as well as for military capacity; and it has remained the prime energy carrier for decades. In the second half of the 20th century the evolution of new energy carriers, such as natural gas (for a long time considered only a wasteful byproduct of oil extraction) and uranium, diversified the energy mix (Högselius, 2019). Every time a new energy carrier emerged, significant efforts occurred to re-calibrate the energy system with new combustion and transportation infrastructure, e.g. deployment of new pipeline systems for natural gas. Alongside these developments the geopolitical map was transformed. For Europe these changes had significant geopolitical implications: while European countries could rely on domestic coal supply during the Industrial Revolution, the emergence of oil as primary energy carrier turned European countries into energy importers. The geopolitical vulnerability caused by energy import dependence has been observed over the course of history across several incidents, for example, the OPEC oil embargo in 1973 and the temporary interruption of gas supply by Russia in 2006 (Högselius, 2019; Rutland, 2008). The emergence of renewable energy could reduce energy import dependence and may alter the geopolitical map in favor of the import-dependent European countries (IRENA, 2019b).

It is important to note, that renewable energy per se is not new as hydro power has been used for centuries and large-scale applications have been in use in the industrialized age for decades (Ahenkorah et al., 2011). Not the evolution of renewable energy itself characterizes the contemporary 'energy revolution', but rather the speed and the profound changes it causes across various domains of life. While previous evolutions of the energy system were mainly driven by economic and geopolitical considerations, environmental concerns dominate in the shift to renewable energy today.

It is widely acknowledged that average global temperature increase must be limited to 1.5-2° Celsius, otherwise irreversible effects, such as rising sea levels, extreme weather phenomena, and extinction of species will occur (IRENA, 2019b). The replacement of fossil fuels by renewable energy is an important cornerstone to reach this target. While the power sector is the departing point of the transition, significant efforts across all emission sectors (power, industry, transportation, agriculture & forestry) are required to fight global warming.

Within the European power sector, clear signs of this transition are visible: the installation of renewable energy sources (RES) started in the 2000s and accelerated significantly in recent years (see figure 4.1). Renewable capacity has doubled since 2008, mainly driven by large-scale deployment of wind and solar capacity. Wind capacity has replaced hydro as the largest renewable energy source in terms of capacity (IRENA, 2019c). Nevertheless, we are rather at the doorstep of a wide-ranging energy system transformation: despite the significant growth rates, the electricity generation mix has only slightly shifted in the past decade (see figure 4.1). The share of renewable energy in the electricity production has increased from 13-14% between 1990 and 2005 to 29% in 2015. Other sectors are even further behind in the transition: renewable energy accounted for only 7.4% of total energy in the transport sector in 2017 (Eurostat, 2019d). Low-carbon technologies have not yet reached market maturity outside of the power sector, e.g. electric vehicles account for just 1.5% of new registrations in the European Union (European Enviornment Agency, 2018).



Source: IRENA Capacity Statistics 2019 (IRENA, 2019c), Eurostat (Eurostat, 2019e)

Figure 4.1 The energy transition in the European Union since 2000

As a consequence, the implications of the profound changes are only starting to emerge and will become more pronounced in the upcoming decades. Several fundamental trends will drive the rapid deployment of renewables and unfold their full potential in the upcoming years: technological innovations and subsequently declining cost of renewable technology, tightening regulation and political targets, as well as activism of public, corporate sector and investors (IRENA, 2019b).

Nevertheless, significant differences with regard to the pace of energy transition exist within the countries of the European Union. Despite a joint climate agenda and agreed emission reduction targets, the member states show varying levels of political support for the decarbonization agenda in their countries. Ultimately that results in different levels of transition speed towards a low-carbon economy. For example, Germany already implemented a feed-in tariff for renewable energy in the beginning of the 2000s and sees huge public support, which is reflected in the rising number of votes for the 'Green party' (Grant & Tilley, 2018). As a result of this policy one third of the total EU capacity build-up since 2001 is attributable to Germany (IRENA, 2019c). On the contrary, Poland has implemented a long-term commitment to lignite and considers building new coal plants (Rentier, Lelieveldt, & Kramer, 2019).

Despite the fact that we are currently only at the beginning of a wide-ranging energy system transformation, we see first signs of geopolitical conflicts that arise from the energy transition: one example is the large-scale deployment of wind generation in Northern Germany, which is not backed with sufficient extension of transmission grid capacity within Germany to ensure the energy flow from Northern to Southern parts of the country. As a result power surpluses from German wind generation flow through adjacent countries, mainly Poland and the Czech Republic, and impair the stability of the national grid systems in these countries. Studies simulating the grid system conclude that without significant grid extensions until 2020, the Polish national transmission grid will be vulnerable to congestion and destabilization (Singh et al., 2016). Different interests causes tensions among the countries.

Different transition speeds, historically-developed diverging perceptions of energy security and increasing interconnectedness within the European continent raise questions about how the energy transition will influence the relations among countries and, ultimately, the geopolitical balance in this part of the world.

4.3 Literature review

A large body of literature addresses the implications of the energy transition from a technological and economic point of view. In particular, scenarios and development paths towards a low-carbon economy have been studied intensely (Child, Kemfert, Bogdanov, & Breyer, 2019; Connolly, Lund, & Mathiesen, 2016; Distelkamp & Meyer, 2019; Zappa et al., 2019). Several studies also address the economic benefits of a potential future European electricity system (Bigerna, Bollino, & Micheli, 2016; Newbery et al., 2016; Schmid & Knopf, 2015). Literature furthermore investigates the cooperation across countries that is required to achieve the ambitious reduction plans. For Europe this has been mainly discussed from two angles: the benefits of integrating electricity markets and infrastructure within Europe (Becker et al., 2014; Brown et al., 2018), as well as the potential contribution of renewable resources from North Africa (Benasla, Hess, Allaoui, Brahami, & Denaï, 2019; Bussar et al., 2014; Platzer et al., 2016). Nevertheless, the allocation of renewable generation capacities, as well as infrastructure is mainly discussed under economic and technological considerations. Only a growing sub-strand within the literature starts to address the social, as well as political concerns and conflicts that might arise from intensifying cooperation in the energy space (Hawker et al., 2017; Ochoa & Ackere, 2015). However, a systematic analysis from a geopolitical perspective is lacking.

Literature on geopolitics of energy, which is mainly routed in the field of International Relations, focuses predominately on oil and natural gas. Research in this area stresses the vital importance of energy for prosperity. Consequently, governments aim at securing access to energy resources at affordable prices (Yergin, 1988). As fossil energy sources are distributed unevenly across countries, a key area of research is the topology of fossil-fuel reserves and its implication on inter-state relations. Especially, the import dependence of countries and potential threats from the disruption of supply are widely discussed (Kaijser & Högselius, 2019; Toft, 2011). Jong et al. (2014), for example, discuss how the shale gas revolution in the United States reduces the country's dependence on imports and conclude that the changed import-export relationship could shift the focus of U.S. foreign diplomacy from the Middle East towards East Asia. Another extensively studied example is the European Union's effort to secure natural gas supply from Russia during the 2005/2006 Ukraine crisis. The dispute over gas prices between Russia and Ukraine resulted in a temporary discontinuation of supplies. The European Union was indirectly affected as large amounts of gas is transmitted via Ukraine to Europe (Rutland, 2008). As a result, ongoing research analyzed Europe's gas dependence on Russia and the related 'pipeline diplomacy' (Blinick, 2008; Proedrou, 2018). In response to these threats, European politics intensified efforts to reduce dependence levels by diversifying the supply base (European Comission, 2014). A significant amount of literature also focuses on the impact of the energy transition on Russia and fossil fuel-rich countries in the Middle East (Bradshaw et al., 2019; Tagliapietra, 2019).

Literature about the geopolitics of renewables started to emerge in the last years. However, a significant part of the work is still 'grey' literature, i.e. working papers, reports, dissertations. As one of the first authors Criekemans (2011) discusses whether the geopolitics of renewables differs from the ones of conventional energy. He points out that similarities among the two exist, as control over the energy infrastructure (pipelines in the case of conventionals, power lines in the case of renewables) strengthens influence in both 'energy worlds'. However, a more decentralized distribution of resources might lead on the other hand to a multipolar world, in which power is more equally spread across the globe (Criekemans, 2011). Paltsev (2016) adds that more equally distributed renewable resources make supply-side geopolitics less influential. Instead new centers of power are expected to emerge as power shifts to developers of carbon-free solutions.

Several authors conclude that the reduction in import dependence is likely to decrease the potential for conflicts over energy (Scholten & Bosman, 2016). However, Habib, Hamelin, and Wenzel (2016) point out that competition over critical materials for low-carbon technologies might rise, e.g. indium and gallium, which are required for the production of photovoltaic modules. Furthermore, power systems that rely on intermittent renewables potentially require more control systems, which in turn increases the risk for cyberattacks (Månsson, 2015). However, both propositions —conflicts over critical materials and growing risk of cyber-attacks— are challenged by Overland (2016). According to him, critical materials are not scarce, but rather their mining is burdensome and current supply is limited. As for cyber security, it is not clear how renewables are changing geopolitics, also as real life examples are currently limited (Overland, 2019).

The geopolitics of renewables are predominately discussed in the context of European decarbonization efforts, as the deployment of renewables occurs at greater scale in the European Union than in other regions of the world. Scholten et al. (2014) conceive a thought experiment on the geopolitical implications of the EU Energy Policy. The authors conclude that the current policies may produce winners and losers among the EU member states, e.g. due to concentration of production and employment in few countries. For a successful integration of the European power markets, high levels of trust, shared control over grid assets and a clear regulatory framework are required (Scholten et al., 2014). Szarka (2016) also discusses the change to a 100% renewable system in Europe. He notes that European Union is not speaking with one voice with regard to energy matters. The member states' ambition towards the energy transition varies from country to country and in some occasions is not in line with the direction set up by the European Union.

To conclude, the existing literature on the energy transition mainly investigates technological and economic implications, while literature on geopolitics focuses on fossil-based energy. Only few studies started to examine the impact of the energy transition on country relationships and power structures. As a result, the existing literature does not follow a systematical approach and lacks a theoretical model to describe how nations accumulate energy-related geopolitical influence that incorporates both, the conventional and the renewable energy sphere. Furthermore, the existing literature mainly relies on narratives backed up only by limited empirical research. Lastly, existing studies rather illustrate abstract issues instead of concretely examining how specific countries are affected by the transition.

4.4 Research design

The analysis of renewable energy sources in the context of geopolitics is a relatively novel area, and therefore research frameworks and methodologies for this field have only started to emerge. Established approaches from fossil-based energy studies can hardly be transferred to the world of renewables, as fundamental characteristics of these two energy systems differ, e.g. renewables are considered energy flows, while fossil fuels are energy stocks. Nevertheless, in certain areas parallels can be drawn, e.g. Paltsev (2016) argues that the importance of electricity transmission for low carbon energy systems can be compared with pipeline and oil tankers in fossil-based systems.

As a result, the majority of studies provide narratives, anecdotal work, and rather conceptual perspectives on how renewables can change the geopolitics of energy. One widely recognized study by Scholten and Bosman (2016) introduces structured thought experiments as a methodological approach to distinguish major implications of renewable deployment. While their approach can provide first insights about how renewables shape geopolitics, Scholten and Bosman (2016) admit that this approach lacks cohesion and internal consistency.

This research proposes a novel index as a more rigorous and structured approach to assess the implications of the energy transition on geopolitics, which allows to bridge conceptual studies of geopolitics and more established literature on indexes that systematically map the strengths and weaknesses of countries. Assessing geopolitical strength is at the core of geopolitical research as it studies a country' ability to influence world politics and to pursue its interests vis-à-vis other nations with potentially conflicting agendas. As the interests differ across many dimensions and towards several actors, it is not possible to develop a universal metric for assessing geopolitical strength. This would require the evaluation of the specific contexts for any international event under investigation. Therefore, most scholars apply a resource-based or capability-based approach, which is also used in this essay. The rationale behind this approach is fairly simple: countries with greater access to resources and capabilities tend to prevail in international dispute (Beckley, 2018). This approach is used for measuring the overall power of nations (Beckley, 2018) as well as geopolitical influence within conventional energy space (Gu & Wang, 2015).

Indexes, especially composite indicators that integrate various sub-indicators in one comprehensive metric, are increasingly recognized as useful tool to guide policy analysis. As a result, the number of studies using indicators has been growing over the past years[8]. They are

[8] See Bandura (2006) for an overview of 160 composite indicators measuring country performance. Overland, Barilian, Uulu, Vakulchuk, and Westphal (2019) furthermore provide an overview of 34 indicators used in the energy transition and geopolitics space

used to analyze and illustrate complicated and sometimes elusive topics in wide-ranging fields, such as economy, environment, society or technological development (OECD, 2008).

Indexes and indicators are well equipped to analyze complex, multi-dimensional realities that usually cannot be captured by traditional methodologies in social science. Furthermore, indicators allow to assess the progress of countries over time in relation to a complex set of objectives and variables and thus enable researchers and practitioners to compare complex dimensions effectively. While indicators help to reduce the visible size of information, the underlying information base is not dropped (Saisana & Tarantola, 2009). Researcher following this school of thought assert that there is value in calculating composite indicators to define a bottom line for analysis and that such analysis can capture reality with sufficient accuracy and is meaningful (Sharpe, 2004).

The results of the index are used as starting point for the development of theses on future developments. This approach was chosen as there exist still uncertainties about the possible future of the energy transition in Europe. With the formulation of theses, supported by analysis of the existing knowledge and given uncertainties, the necessary discussion processes to determine more precisely the possible future implications of the energy transition on geopolitics can be fueled.

4.4.1. A novel theoretical model for assessing energy-related geopolitical influence

Geopolitical strength in the energy space used to be closely linked to fossil-fuel reserves. Thus, measuring the reserves of combustible fuel, mainly oil and gas, already resulted in a clear representation of the power distribution among countries. In a low-carbon energy world however, additional factors, such as access to technology, power lines, rare earth materials and storage, influence the geopolitical strength, as pointed out by Paltsev (2016). This essay builds on his conceptualization of relevant additional factors and further extends it in a systematic way. For this purpose, a novel two-stage theoretical model is developed, which conceptualizes the formation of energy-related geopolitical influence: in the first stage geopolitical foundations are discussed, and in the second stage the transformative capacity is introduced as a prerequisite to be able to exercise power. The theoretical model is summarized in figure 4.2.

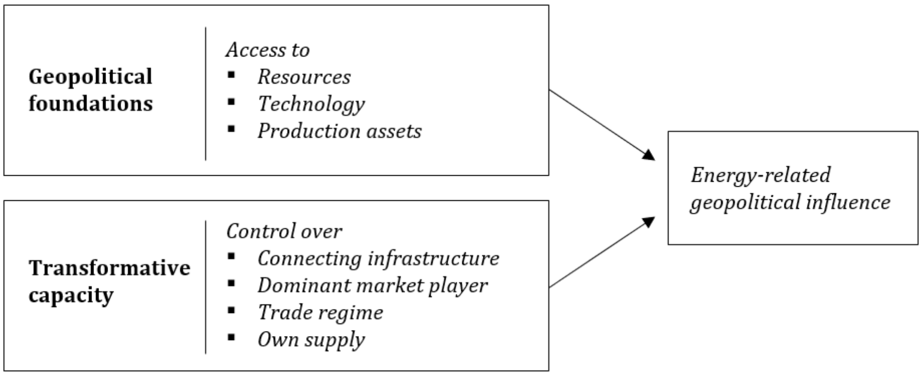


Figure 4.2 Theoretical model of energy-related geopolitical influence

4.4.1.1 Geopolitical foundations

The geopolitical influence of a country is based on tangible strengths, which put the country in a relative advantage to other countries. In classic energy geopolitics that is most often interpreted as having access to large reserves of fossil fuels (Rutland, 2008; Yergin, 2008). However, access to other, renewable energy resources, such as wind, solar power or biomass need to be considered as well (Criekemans, 2011). This *access to resources* can be only exploited, if the country has *access to technologies,* which are required to extract the resources. Patents, which grant access to such technologies, are hence considered as an increasingly important geopolitical weapon (Bonnet, Carcanague, Hache, Seck, & Simoën, 2019; Paltsev, 2016). Finally, if resources can be extracted, *production assets* are required to convert the energy source into the desired energy carrier, such as electricity, heat and/or fuels. This could take various forms, e.g. gas-firing plants, oil refinery stations or storage facilities. The access to resources, technology and production assets are defined as the foundations of energy-related geopolitical influence.

4.4.1.2. Transformative capacity

The geopolitical foundations must be combined with the means to shape the interactions with other countries; otherwise countries lack the ability to turn geopolitical foundations into geopolitical influence. A case in point is Turkmenistan: the country has one of the largest proven gas reserves in the world —40% greater than North America's reserves and half of the Russian reserves (BP, 2019). Despite the access to large resources the country does *not* have the ability to shape the global energy regime. The explanation for this apparent paradox is Turkmenistan's lack of what is termed transformative capacity, i.e. ability to transform foundations into geopolitical influence. A country needs to have control over pivotal aspects of the inter-country energy relationship in order to exercise influence. A frequently mentioned example is *control over connecting infrastructure*, such as pipelines or power interconnectors (Paltsev, 2016). Both, exporting countries, as well as transit countries, benefit from control over such infrastructure assets.

Second, a country needs to be able to turn policies into actions. For this *control over dominant market player* is required, as usually the extraction, production and trade of energy resources are handled by companies. Especially multinational oil and gas corporations have been used as tools to pursue geopolitical interests in the past (G. Collins, 2017). It is significantly easier to exercise power, if resources and capabilities are shared between a small number of companies. The concentration of vast resources in the two state-controlled Russian companies Gazprom and Rosneft is a prominent example. If the resources and energy capabilities are spread across many actors, the effort required to instruct, align and control them in a consistent manner increases significantly and thus the ability of governments to effectively exercise geopolitical influence decreases.

Third, relationships among countries are to a large extent shaped by their trade relationships. Hence, control over the trade regime, i.e. trade institutions, commercial governance and terms of trading, improves the ability to enforce national interests in the energy field as well.

Lastly, the geopolitical strength of countries is influenced by their own vulnerability or *control over their own supply.* Countries, which depend on other countries for energy supply, are less effective in responding to geopolitical threats, hence their geopolitical strength shrinks (IRENA, 2019b).

4.4.2. Constructing an index to measure energy-related geopolitical influence

Each of the outlined factors that influence the geopolitical strength of countries is measured with a respective indicator. The *access to resources* is measured along two dimensions: domestic fossil fuel reserves and domestic renewable generation potential. The domestic fossil fuel reserves are calculated as the combined energy potential of proven oil, gas and coal reserves, as reported by the BP Statistical Review of World Energy (BP, 2019) in Tons of Oil Equivalents (TOE). Only significant reserves have been included as identified by BP. Shale oil reserves have been added based on estimations by Dyni (2006). Domestic renewable potential is defined as the combined annual generation potential from onshore and offshore wind, solar PV, biomass and hydro power in comparison to the gross inland energy consumption. Hence, the indicator can be interpreted, as to which extent the country can supply itself from renewable sources. Wind potentials have been drawn from NREL (2014), solar PV from Pietzcker, Stetter, Manger, and Luderer (2014), biomass from Osorioa et al. (2018) and European Enviornment Agency (2006), hydro from IRENA (2019c) and the gross inland energy consumption from Eurostat Eurostat (2018).

The *access to technology* is measured with the number of patent applications at the European patent office in the field of 'Electrical machinery, apparatus, energy' (European Patent Office, 2019).

The *access to production assets* is determined by three indicators: the total installed fossil and renewable availability-adjusted electricity generation base, the capacity of assets available for electricity balancing functions, and the capacity of oil refineries. The data for the first two indicators is drawn from Eurostat (2019b) and IRENA (2019c), and the latter indicator comes from BP (2019).

The *control over connecting infrastructure* is measured with the power interconnector capacity drawn from ACER (2017) and the capacity of gas interconnectors and LNG terminals based on ENTSOG (2018).

The *control over dominant market player* is determined using two indicators: the cumulative electricity market share of the main generating companies based on data from Eurostat (2019a), and the number of major O&G companies listed in the S&P TOP 250 Global energy companies (S&P Global, 2019).

The *control over the trade regime* is measured with the gross energy exports derived from Eurostat (2019e).

Table 4.1 Indicators for measuring energy-related geopolitical influence

	Influencing factor	Indicator	Definition	Weight
Geopolitical foundations	Access to resources	Domestic fossil fuel reserves	Combined domestic oil, shale oil, natural gas and coal reserves in Terajoule	8.3%
		Domestic renewables potential	Combined domestic renewable generation potential from wind onshore, offshore, solar PV, CSP and biomass in comparison to gross inland consumption	8.3%
	Access to technology	Patents in energy technology	Number of patent applications at the EPO in the field of 'Electrical machinery, apparatus, energy'	16.7%
	Access to production assets	Generation assets	Installed fossil and renewable availability-adjusted electricity generation capacity in GW	5.6%
		Balancing assets	Installed conversion capacity of hydro storage assets.	5.6%
		Oil refineries	Installed capacity of oil refining plants in thousand barrels per day	5.6%
Transformative capacity	Control over connecting infrastructure	Power interconnectors	Total power interconnector transfer capacity in MW	6.3%
		Gas interconnectors and LNG terminals	Total gas pipeline interconnector capacity combined with LNG terminal capacity in GWh per day	6.3%
	Control over dominant market player	Largest electricity producer	Cumulative electricity market share of the main generating companies as a percentage of the total generation	6.3%
		Major O&G companies	Companies listed in the 'S&P TOP 250 Global Energy Companies' with operations classified as oil and gas exploitation, transmission and trade or listed as multi-utilities	6.3%
	Control over trade regime	Energy exports	Gross energy exports of oil, natural gas, solid fuels and electricity in Terajoule	12.5%
	Control over own supply	Import independence	Share of net imports over gross inland consumption	12.5%

The *control over own supply* is measured with the import independence, defined as the net imports over gross inland consumption. The data is derived from Eurostat (2018). Table 4.1 summarizes the aforementioned indicators.

All indicators are normalized prior to comprehensive assessment assuming a normal distribution. Hence, a positive or negative score in the assessment shows the relative strength of the energy-related geopolitical influence compared to the other countries in the dataset.

$$z = \frac{x_i - \mu}{\sigma}$$

Where:
z: Resulting index score
x_i: Country-specific indicator value
μ: Mean of indicator values
σ: Standard deviation

The country's total index score for energy-related geopolitical influence is calculated as average-weighted index score of all indicators. The index weight is split equally between geopolitical foundations and transformative capacity as both stages are deemed equally important. Similarly, the influencing factors within the two stages have been assigned equal weight. All 30 countries of the European Economic Area (EEA), except Liechtenstein, are included in the assessment. The values of years 2001 and 2018 are compared in the time series analysis for all indicators. If the data was not available for these reference years, the earliest or latest respective data point was used.

4.5 Results

4.5.1. The energy-related geopolitical influence today versus the early 2000s

In the early 2000s energy-related geopolitical influence in Europe was centered in a few Northern European countries: Germany, France, Netherlands, Norway and the United Kingdom. Italy, which comes next in the ranking, accumulated less than half of the influence of the United Kingdom. Within this club of leading countries, Germany could be perceived as *Primus inter Pares.* The country's influence clearly stood out and was driven by its technological access, high interconnectivity and access to production assets. France followed Germany as it accumulated significant influence through large number of production assets, high interconnectivity and strong electricity, as well as oil and gas players.

While these Northern European countries continue to be in powerful positions today, their hegemony deteriorated over the last two decades. France, the Netherlands and the United Kingdom significantly lost energy-related geopolitical influence, while Germany remains in the leading position with only a minor change of its index (see table 4.2).

Table 4.2 Country ranking based on energy-related geopolitical influence

Country ranking			Energy-related geopolitical influence		
Today	Early 2000s	Country	Today	Early 2000s	Index point change
1	1	Germany	208	207	1
2	2	France	94	108	-13
3	4	Norway	81	76	5
4	3	Netherlands	67	83	-16
5	8	Poland	40	19	22
6	5	U. Kingdom	40	68	-28
7	6	Italy	37	33	4
8	7	Spain	36	29	7
9	9	Iceland	7	3	3
10	16	Austria	-1	-21	19
11	11	Sweden	-4	-4	0
12	10	Czechia	-5	-3	-3
13	13	Romania	-12	-10	-2
14	19	Estonia	-17	-29	12
15	14	Belgium	-20	-11	1
16	24	Hungary	-21	-36	15
17	20	Bulgaria	-21	-29	9
18	12	Denmark	-21	-5	-16
19	22	Finland	-24	-30	6
20	27	Portugal	-28	-49	21
21	17	Slovakia	-29	-24	-4
22	18	Greece	-30	-27	-4
23	26	Ireland	-31	-40	8
24	21	Croatia	-31	-29	-2
25	25	Slovenia	-33	-36	3
26	23	Latvia	-42	-32	-10
27	15	Lithuania	-48	-19	-29
28	28	Cyprus	-56	-52	-3
29	29	Malta	-62	-58	-4
30	30	Luxembourg	-74	-65	-9

'Winning' countries
'Losing' countries

Most remarkable is the decline of the United Kingdom. The UK's fossil fuel reserves shrank by 77% between 2001 and 2018. Not only the exploitation of oil and gas reserves let to the decrease, but also the large-scale use of coal for power generation resulted in the depletion of coal reserves. The fact that UK lost its relevance as fossil fuel player also affected its influence over the trade regime: the gross energy exports dropped by 42% since 2001. The Netherlands now replaces the UK as the major oil and gas trade hub in Europe, as it accounts for almost 22% of total gross energy exports. Also, the UK reduced its foothold in terms of production assets, in particular, oil refinery capacity dropped by 31%.

For historic and geographical reasons, the UK lacks significant power interconnections with the European continent. In spite of recent efforts to build power interconnectors, the current net transfer capacity of around 3GW makes the UK the 8th least interconnected country on the list. Finally, as a result of the reduced ability to produce oil and gas and the phase-out of domestic coal as main energy carrier, the import independence significantly dropped by 35 percentage points since the beginning of the century. While the UK is currently deploying renewables at large-scale, the build-up cannot compensate for the decline of fossil fuel reserves.

The largest oil and gas exporter in Europe —Norway— also experienced a 26% reduction of fossil resources since 2001. Nevertheless, the gross energy exports of Norway dropped only slightly compared to the early 2000s. Unlike the UK, Norway still remains a net energy exporter and thus is comparably independent of foreign energy imports. Moreover, Norway was able to increase its access to production assets, including power generation, storage capacity as well as oil refinery capacity.

The hegemony of these five countries has been broken by Poland that was able to rise from rank #8 to #5, overtaking the United Kingdom. Poland has access to extensive fossil fuel resources of 15.7 billion TOE which mainly consist of anthracite and bituminous coal. While the fossil reserves in Norway, the Netherlands and the United Kingdom have been shrinking considerably, the Polish coal reserves would still last more than 200 years with the current reserves-to-production-ratio. Furthermore, the country is potentially endowed with large fields of shale gas in the Baltic Sea basin. Due to these significant reserves, fracking could ensure Polish energy independence for several more decades. Poland also developed its oil and gas sector in the past: several Polish companies are now among the worldwide leading oil and gas exploitation and trading companies. These factors make Poland by far the most powerful EU-country in Eastern Europe. Poland increased its geopolitical standing not by investments into renewables, but by focusing on conventional energy.

Italy and Spain are situated below the aforementioned countries on the list of energy-related geopolitical influence. While both of these countries used to have significantly less influence than the five Northern European countries, the gap has narrowed significantly over the last two decades. Nowadays the UK, Poland, Spain and Italy are in close proximity to one another with regard to energy-related geopolitical influence.

Italy and Spain are characterized by insignificant fossil fuel reserves, but considerable renewables potential. Historically, their influence has been mainly driven by access to production assets and —despite their lack of resources— by control over several major O&G players, such as Eni and Repsol. Only recently the development of renewable resources and flexible generation plants have started to improve their positioning in the ranking. For example, Spain significantly increased the installed power generation capacity between 2001 and 2016 by 70%, mainly by deploying wind power and gas-fired plants. Furthermore, the country almost tripled its energy exports during that time. Not only electricity exports have been rising, but also the country has started to extensively use its LNG infrastructure (with terminal capacity of almost 2 GWh/day) to develop itself into an important hub for gas trade. The more active exploitation of domestic renewable potential also has increased Spain's import independence by 5 percentage points from 23.4% to 28.1%.

The index further shows that Austria climbed up 6 ranks, benefitting from its pivotal positioning in Europe by increasing interconnectedness in gas (+34%) and electricity lines (+78%). In addition, it significantly increased its storage facilities (+43%) and almost tripled its energy exports.

Interesting is the relative positioning of the three Baltic states: while Estonia is now positioned in the middle of the list, as it has gained some influence since the early 2000s, Lithuania and Latvia are located in the last quartile. Main drivers for this are changes in the import independence of these countries. Estonia increased its import independence from 67.8% to 93.2%. This was possible due to the expansion of large-scale exploitation of shale oil that allowed Estonia to be more self-sufficient and also to increase its gross energy exports. Lithuania, on the other hand, lost 18 percentage points in the import independence indicator, caused by the phase-out of nuclear power in 2010.

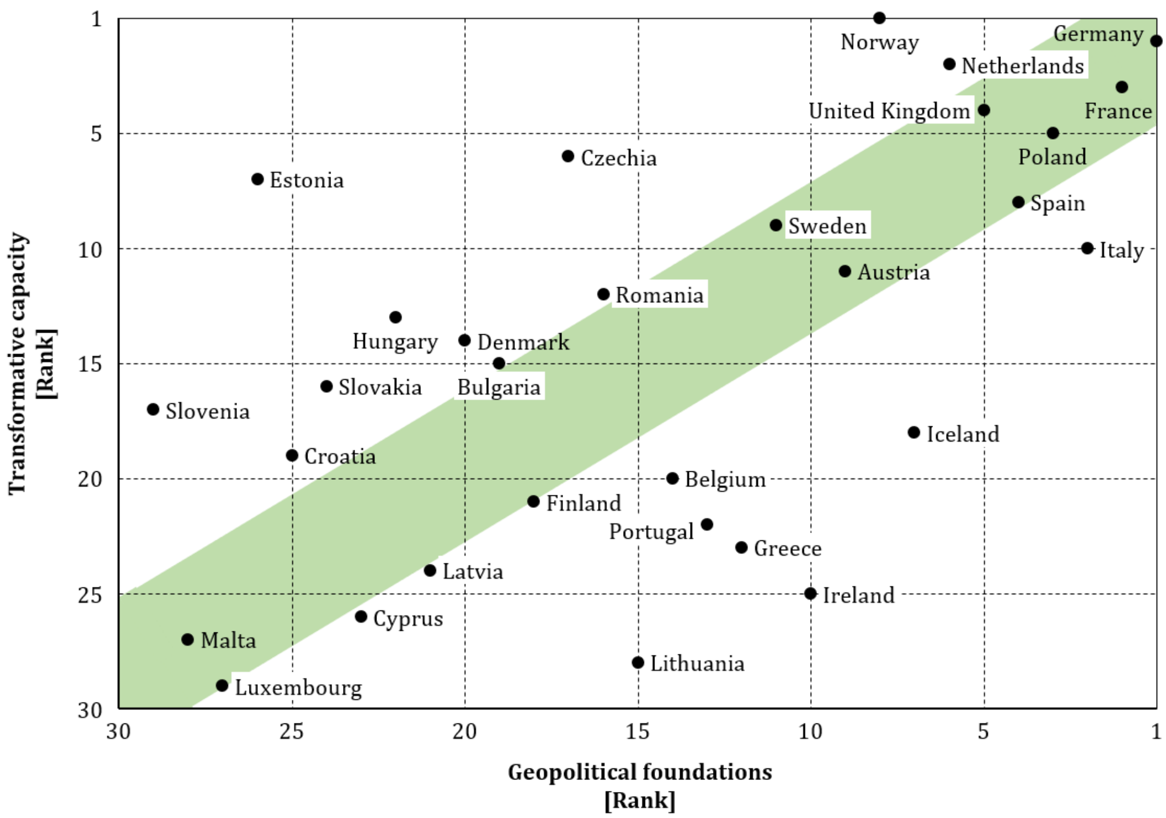


Figure 4.3 Geopolitical foundations versus transformative capacity

Small island states, such as Cyprus and Malta, as well as Luxembourg, are in the last quartile of the list due to their lack of conventional resources, as well as low interconnectivity.

While evaluating energy-related geopolitical influence, interesting insights can be drawn by differentiating between countries, whose power is based on the factors that are part of the first stage —the geopolitical foundations— or the second stage —the transformative capacity. Figure

4.3 plots the country ranking in the respective stages. Countries along the diagonal green line build their influence upon the indicators of both stages, e.g. Germany and France, whereas other countries, such as Iceland, Portugal, Greece, Ireland and Lithuania, possess powerful geopolitical foundations, but are comparably weak in turning these foundations into geopolitical influence, partly due to their peripheral geographical position. On the other hand, countries, such as Czech Republic, are well positioned to transform access to resources into geopolitical influence, however they lack access to resources and therefore are unable to take full advantage of their transformative capacity. Appendix E and F provides a detailed overview of the respective index scores.

4.5.2. Changes in relation to the shift to low-carbon technologies

While the last two decades already resulted in a significant re-balancing of power within the European Economic Area as shown in the previous section, it can be expected that the accelerating energy transition will result in further shifts within Europe's energy hierarchy. This section introduces five theses, on how the energy transition may impact the energy-related geopolitical influence going forward.

Thesis 1: Several countries in Europe are very likely to experience resource scarcity also in a renewable future

Fossil fuel resources are unequally distributed among the countries in Europe. For example, Norway, the United Kingdom and the Netherlands alone account for over 90% of the EEA's oil and gas resources due to their abundant gas reserves in the Northern Sea. Similarly, Germany and Poland possess over 77% of the total coal reserves. In contrast, the renewable energy potential is significantly more equally spread across the countries. Virtually all countries have some access to renewable resources (especially solar and wind power) and could thus substitute foreign supply with local resources. However, the potential to do so differs among the countries.

Countries can be grouped into those that tend towards *resource abundance* and the ones that tend towards *resource scarcity* (see figure 4.4). Two dimensions are used for the classification: first, the domestic renewables potential is assessed in relation to the gross inland consumption (depicted on the x-axis). Countries with greater energy consumption also require larger renewable resources to be able to reach self-sufficiency (at least a factor of 1.0). For instance, Belgium has a larger RES potential than Hungary (431 TWh/a vs. 329 TWh/a). Nevertheless, Hungary's RES potential is 3.2 times the gross inland consumption, while Belgium's RES potential only covers 0.65 of its gross inland consumption. Second, only countries, in which the absolute domestic renewable potential is comparably large can export energy at scale and become dominant market player (depicted in the y-axis). Countries with large absolute renewable potential, which exceeds domestic demand several times, can be referred to as countries with renewable energy *resource abundance*, such as Spain and Norway. On the contrary, countries, such as Belgium, the Netherlands, Austria and Luxembourg, lack the potential to be energy self-sufficient. Also, the domestic renewables potential of Germany only slightly exceeds the gross inland consumption. Therefore, this group of countries experiences renewable *resource scarcity*. Especially, highly industrialized countries with small land areas, e.g. Belgium, are likely to experience resource scarcity, as industrialization is driving up energy consumption, while the geographical area of the country limits the renewable potential.

Even if countries have the renewable potential to be self-sufficient, economic reasons might induce them to continue importing energy. While the access to renewable resources might be universal, the ability to produce at competitive prices varies among the countries. For instance, capacity factors for solar PV in Spain were twice as high as in Denmark in 2016, and thus the cost of solar PV electricity generation in Spain drastically undercut those in Denmark. Ultimately countries are quite often faced with a make-or-buy decision, in which economics needs to be evaluated against security arguments.

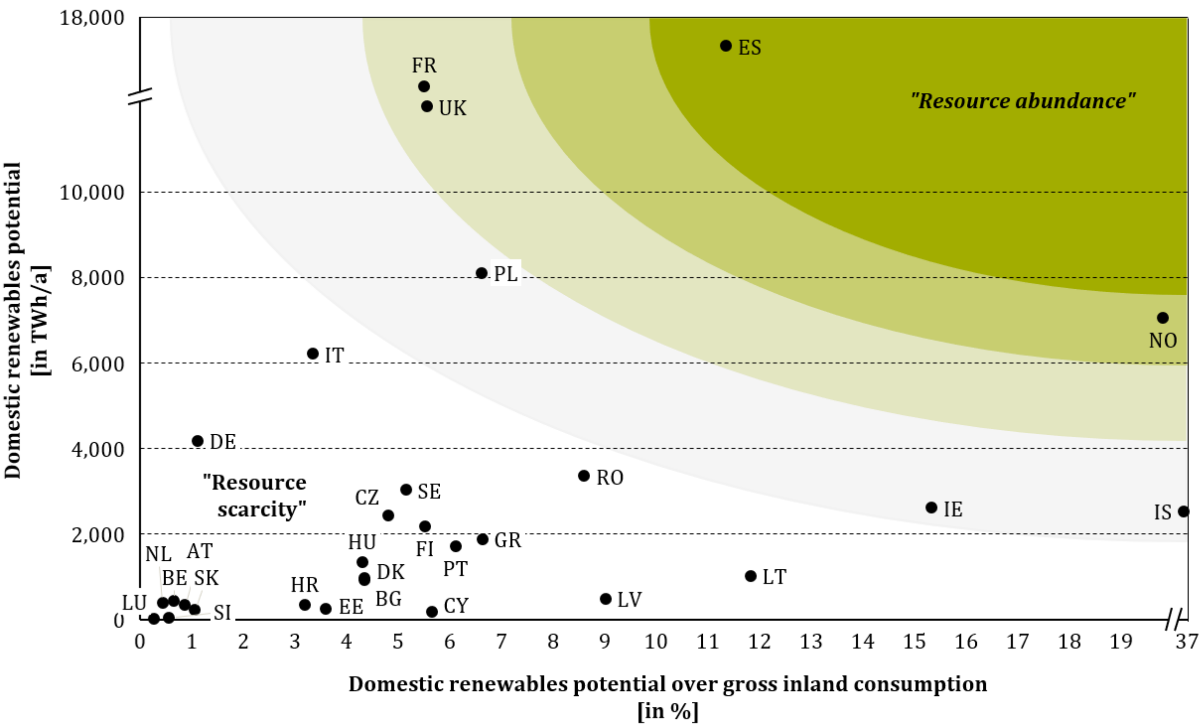


Figure 4.4 Domestic renewable resource abundance versus resource scarcity

As a result, the geopolitical realities of countries with resource scarcity and/or without the ability to generate electricity cost competitive might look similar to today's situation in which resource-poor countries rely on energy imports. Countries differ significantly in their ability to become self-sufficient and this is reflected in their energy-related geopolitical influence. Despite universal access to renewables, the level of effort required to achieve their energy goals varies greatly among the countries.

Thesis 2: Despite more equal distribution of renewable resources, geographical positioning remains to be a key factor for energy-related geopolitical influence

One could argue that with universal availability of renewables the importance of geography in energy-related geopolitics is shrinking. Indeed, geographical characteristics of a country seem to be less important in the future, however, energy systems become increasingly interconnected instead of reverting back to autarkic systems. In such interconnected systems, which are governed by complex inter-country trade relationships, the second stage of formation of energy-related geopolitical influence —transformative capacity— is of increasing importance. Especially, the control over infrastructure, the trade regime, as well as powerful market players are relevant aspects in the global energy-related geopolitical discussion.

Particularly, countries, which have an important geo-strategic position or those situated at crossroads of relevant trade routes are in an advantageous position. Conversely, countries located at the periphery of the EEA have rather limited ability to influence the European energy order and compete with the aforementioned countries due to their unfavorable geographical position.

Currently, gas transit countries, such as the Ukraine and Czech Republic, benefit from their geographical position. However, in an all-renewables world this role might be handed over to other countries that are located between nations with most favorable renewable production factors (e.g. Spain, Italy and the United Kingdom) and the centers of energy demand (mainly in Northern Europe). One example of these countries is France: France's importance is likely to increase as a 'gatekeeper' of one of the future key electricity transmission routes from Spain to Central Europe. Currently France is not at the intersection of the major oil and gas trade routes. Hence, the new renewable energy order is likely to improve its geopolitical power. In classic energy geopolitics —that focuses on energy resources instead of adopting a more holistic perspective— the role of France would not be accurately captured and thus its energy-related geopolitical influence would be understated.

In a similar way the importance of geographical position for balancing functions within a European supergrid can be discussed. Several studies emphasize the rising importance of power balancing and storage in a renewable energy system (Scholten & Bosman, 2016). Central European countries with significant hydro power capacity, such as Austria, France, Germany and Switzerland, are among those who gain the most from the increased balancing requirements of highly renewable energy systems of the future, due to their high interconnectivity and close geographical proximity to demand centers. Existing research often describes Norway as a 'green battery' for Europe (Skar et al., 2013), however from a geopolitical perspective it seems rather implausible that the Nordic country will dominate balancing markets in Europe. First, required power transmission lines to Norway are very costly and significant efficiency losses would occur due to the large distance covered. Second, possible resistance from local political leaders and activists in Norway due to economic and environmental concerns reduce feasibility of a 'green battery for Europe' concept (Gullberg, 2013).

To summarize, the transition to low carbon energy does not make geography an irrelevant factor in energy-related geopolitics in Europe. In fact, the geographical position can play an important role, if the country is located at the intersection of new energy trade flows, or if it can take advantage of its natural storage facilities by being strongly interconnected to demand centers.

Thesis 3: Several highly import dependent countries in Southern and Eastern Europe, as well as island states are likely to be among the winners of the shift to renewables

The geopolitical decline of fossil-fuel producers, such as the United Kingdom, has been visible since the beginning of the 21st century. Not only the sharp decline in fossil fuel reserves, but also the lack of control over connecting infrastructure has contributed to the deterioration as described in the previous sections.

The picture is less straightforward with regards to the winners of the transition to a low carbon energy system. Indeed, several countries were able to climb up the ranks in the last two decades, however the reasons for the positive developments are diverse: while Austria gained importance due to increased interconnectedness and storage build-up, Estonia reached import independence by exploiting shale oil reserves. Undoubtedly Estonia has increased its influence, however not by transitioning to low-carbon technologies —rather the opposite.

In order to arrive at a more clear-cut picture, the indicators are split in the ones that are predominantly linked to fossil-fuel energy ('all-conventional indicators') on the one hand and those that are more closely related to an renewable energy system ('all-renewable indicators') on the other hand (see Appendix G for classification). While this is a solely theoretical depiction of energy-related influence, it highlights potential shifts in geopolitical influence in the transition from conventional energy systems to renewable energy systems. Based on this analysis, three groups of countries can be considered winners of the energy transition, as their geopolitical position in the all-renewable world is significantly better than in the all-conventional energy world.

When only the indicators related to renewables are considered, Spain appears among the top three countries (see table 4.3). It would therefore replace Norway, which is a leading country when considering indicators that take into account both renewable and conventional factors of today's energy system. Thus, Spain is positioned particularly well to gain from the transition to renewable power. The country possesses the largest domestic renewable potential in Europe, from which only 10% is needed for the domestic consumption, whereas the remaining would be available for export at relatively competitive prices due to high capacity factors.

Table 4.3 Leading countries in an all-renewable and all-conventional energy system

	Energy-related geopolitical influence ranking					
	All-renewable indicators		**All-conventional indicators**		**All indicators (today's ranking)**	
#	**Country**	**Index score**	**Country**	**Index score**	**Country**	**Index score**
1	Germany	153	Germany	292	Germany	208
2	France	143	Poland	175	France	94
3	Spain	84	Italy	122	Norway	81

In contrast to its rich renewables potential, Spain has very limited access to domestic fossil reserves. As a result, Spain is currently among the countries with the highest energy import dependence. Thus, the shift to renewable energy is likely to allow the country to liberate itself from high dependence and potentially reverse the trade relationships by creating dependencies on its abundant renewable resources. However, Spain would need not only to further scale up its renewable deployment, but also to invest significantly in grid infrastructure, as the connection of the Iberian Peninsula to the heart of the European continent is currently weak.

Furthermore, the analysis indicates that island states, such as Ireland, Iceland and Cyprus, could be considered winners of the transition to renewables. They have access to rich domestic renewable resources (when compared to their gross inland energy consumption) and can therefore significantly reduce their import dependence. However, these countries lack control over connecting infrastructure and the energy trade regime to transform these geopolitical foundations into greater geopolitical influence.

Some Eastern European countries can improve their geopolitical influence. New energy trade flows could put countries that do not have much say in the pipeline diplomacy in Eastern Europe as of today in a more powerful position. For instance, Croatia, Slovenia and the Czech Republic could become bigger players due to their well-established electricity grid connections.

Even though the position of Poland has improved over the last two decades, an all-renewables scenario would potentially lead to a reduction of its energy-related geopolitical influence. Its heavy reliance on fossil fuels makes it the second strongest country in an all-conventional setting (see table 4.3), but the country is the biggest loser when comparing an all-renewable and all-conventional setting.

Thesis 4: Proclaiming pioneers of the energy transition as inevitable geopolitical winners is premature

The speed of transition to renewable generation, as well as the commitment of national governments to pursue a decarbonization agenda, significantly differ amongst countries within the EEA. Countries can be divided in four groups: *pioneers* that have actively pursued decarbonization policies early on and have already managed to replace a great proportion of fossil generation with green energy; *followers* that show moderate efforts and *laggards* that predominately stick to fossil generation and show little progress in deploying renewable generation technologies. A fourth group of countries can be termed as *incumbents* that already rely on renewable sources, mainly hydro, as main energy carrier and have not undergone transformative changes in their power system.

Figure 4.5 shows the development of the share of renewable generation as part of total gross electricity generation for selected examples based on data from Eurostat (2019e). It shows that pioneers increased the share of renewable generation by more than 20%; followers by more than 10%; while laggards reached just a moderate increase below 10%. Incumbents already achieved more than 50% renewables share in 2001 (see Appendix H for full overview of country classification).

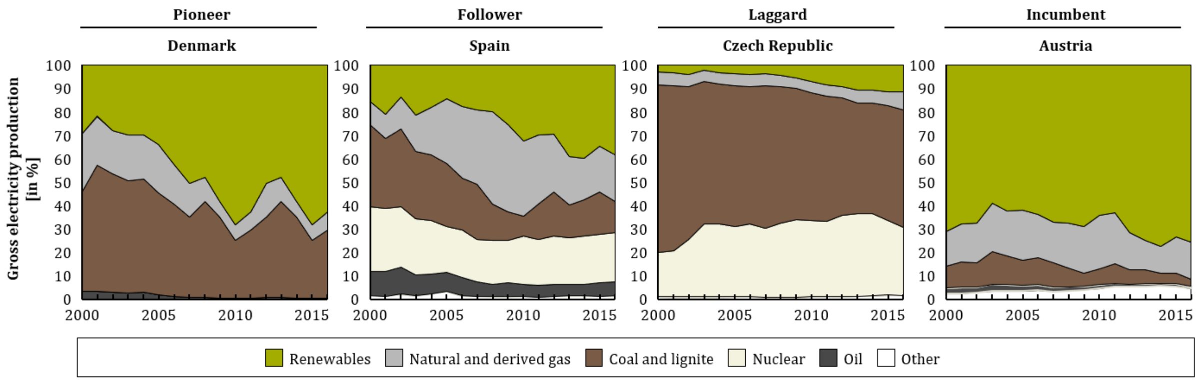


Figure 4.5 Pioneers, followers, laggards and incumbents of renewable deployment

Literature often suggests that countries that are leading the energy transition, e.g. by deploying renewable generation at large scale or investing in technological advancements, are likely to increase their geopolitical standing, and thus could be considered winners of the geopolitical rebalancing (IRENA, 2019b; Øverland & KjÆrnet, 2009). However, the observations of the last decade are more ambiguous. While some pioneering countries, such as Germany, Portugal and Ireland, are defending their ranks or climbing up, other pioneers, especially the UK, Denmark and

Lithuania, have significantly lost their influence over the last two decades. The decline in their conventional energy sources was not fully compensated by the growth of renewables.

The UK's oil and gas resources depleted strongly since the early 2000s. Similarly, the coal reserves got exhausted. Exports were dropping in line with the depleting resources. Even if the UK would prefer to continue with fossil fuels, the country lacks the domestic resources to do so. Similarly, Lithuania needed to build up renewables to compensate for the drop in generation caused by the phase-out of nuclear energy in 2010. Even with large-scale build-up of renewables both of the countries lack other critical infrastructure, e.g. power transmission lines, to compensate for the decline in generation capacity and ultimately to restore their geopolitical energy-related influence.

On the contrary, some countries from the group of laggards are likely to be quite influential regardless of their faint-hearted commitment to renewables; most notably France. There are few countries, which have been less invested into renewables than France, partly driven by their carbon-neutral nuclear plants. Despite its very reluctant approach, France is able to secure its high geopolitical ranking due to its pivotal geographical position as a 'gatekeeper' between renewable rich countries, such as Spain, and the energy demand centers, e.g. in Germany.

Besides France, Germany is going to be in a powerful position to shape how Europe addresses the transition to low-carbon technologies. Despite its rather mixed track record in the energy transition, it can actively shape the energy governance on European level, due to the technological know-how that the country has accumulated over the years (in 2016 Germany applied for three times as many energy-related patents as France, which goes second), and it can influence the discussions on connecting infrastructure due to its geographical position at the crossroads of Europe.

As a result, 'system building' of the new carbon-free energy system will not solely be steered by countries that lead in the transition to renewables, but also by countries that possess strategic assets and influence over energy governance structures despite their partly moderate commitment to a decarbonization agenda.

Thesis 5: Emerging interdependence could allow to unify European energy policy, as well as to develop a more consistent European foreign policy towards energy exporter

Recent studies argued that in the course of the energy transition the dependence on fossil fuel exporting countries could be replaced with new dependencies on countries with large and cheap renewable production capacity (Paltsev, 2016). While it seems plausible that new trade relationships emerge, these dependencies are likely to be not as one-sided as they used to be in the world of fossil fuel domination.

For one-sided renewable dependencies to develop (i.e. countries assume either the role of exporter or importer), capacity would need to be build-up at the most efficient locations in Europe resulting in one-directional energy flows. However, the prerequisites for such centralized capacity build-up are not (yet) in place: first, no unified regulatory framework for capacity allocation and monetary support exists on the EU-level. Instead of jointly building-up renewable capacities at the most cost-efficient locations in Europe governments act nationally and incentivize investments within their borders. While the European Commission pushes for market integration and price convergence in the electricity market, the appetite for transnational central steering seems relatively limited. Second, the build-up of the required grid infrastructure is lagging behind grid extension plans. For instance, the critical transit corridor from Spain to France had a net transfer capacity of around 2 GW in 2016 (ACER, 2017), whereas model simulations state that transfer capacity of this transit line should reach ten times the current capacity in 2050 to be able to establish Spain as a major electricity supplier for Europe (Schlachtberger et al., 2017).

Nevertheless, in such a low-carbon energy world cross-country interconnections are still required. Connecting electricity grids across large geographical areas could not only help to smooth variations in weather conditions, but also balance demand peaks due to differences in electricity use (Frauenhofer IWES, 2015). Such interconnections are especially beneficial if energy sources employed differ among the countries and the respective generation profiles are complementary to one another. For instance, one country may have substantial wind generation, while the other country has favorable conditions for solar power. Market integration is economically beneficial for both countries, as it reduces the need for domestic flexibility measures. Therefore, this reciprocity of energy trade translates into mutual interdependence. Increased interconnectedness of the countries, as opposed to just one-sided import dependencies, could reduce the potential for energy-related conflicts within Europe and could unify European energy policy.

Finally, an ongoing challenge for the European Union is to agree on a joint foreign policy and thereby be able to ‘speak with one voice’ in the international political arena. Different energy policy priorities and interests of some member states have made it difficult on some occasions in the past, e.g. to agree on a joint policy towards Russia. Harsem and Claes (2013) point out that countries with a ‘special relation’ to Russia, such as Germany, occasionally undermine EU policies while dealing with this country, whereas more hostile countries, such as Poland, might try to block cooperative EU policies towards Russia. Taking energy geopolitics out of the equation might make it easier for the European Union to align on matters of foreign policy.

To sum it up: on the one hand greater interdependence of European countries could serve as a mean to align interests within the EU and pursue a more unified European energy policy. On the other hand, reduced external dependence on major oil and gas suppliers could allow the European Union to formulate more consistent foreign policy towards energy exporters, such as Russia.

4.6 Policy implications

With further integration of European electricity markets and the subsequent development of a European 'supergrid', the need for an effective and fair institutional energy governance is becoming more urgent. Besides the question on how powerful the regulator should be, it is important to understand, which countries are the most powerful players within the regulatory body (O'Sullivan, Overland, & Sandalow, 2017).

The results of this study show that even though energy-related geopolitical influence of some countries have considerably changed, Germany and France remain in leading positions. Hence, the political agenda of these two countries inevitably set the direction for the entire continent. For European energy policy this currently creates a dilemma: both countries fall short of delivering their emission reduction targets for 2020 (Crellin, 2019; EEA, 2018) and follow diverging strategies for decarbonization. The next decade will be decisive for setting the course for widespread adoption of green technologies and phasing out of fossil fuels —this is a prerequisite for achieving European ambitious emission reduction target of at least 80% by 2050. Based on the current trajectory it is highly questionable whether this goal will be reached: currently 10 out of 28 countries are not on track to fulfill their emission reduction targets (EEA, 2018).

Despite the fact that the two leading nations remain important, the overall energy-related power balance is transformed as the hegemony of the Northern European countries is deteriorating. With the increasing importance of Southern and Eastern European countries it might get even more difficult to align interests on European level. The agenda of Southern European nations might vary significantly from the interests of the Northern European countries. For instance, while Northern and Eastern European countries consider gas imports from Russia of vital importance, this is not the case for Spain and Italy. Furthermore, Southern nations show limited understanding for countries, such as Poland, that are rather protective of their domestic coal plants and advocate for longer phase-out timelines. Thus, understanding how the different interests of Southern European countries will alter European energy policy is an important area for further research. Recent proposals of the Spanish government to introduce EU carbon tax on energy imports exemplifies the country's ambition to increase its influence on European energy policy (Carreño, 2019).

Besides the growing influence of some countries, it is also worthwhile to have a closer look at countries that are potential 'geopolitical losers' of the transition to low-carbon technologies.

Energy policies need to proactively address the pain points of these countries and develop measures to mitigate the potentially negative effects. Otherwise these countries might resist the transition, block initiatives and thereby hamper the implementation of the European energy and climate agenda.

The uncertainty about the setup of the future energy market and the resulting geopolitical implications pose a question on how the institutional governance should be designed to effectively manage these challenges. The current policy framework, in which the European member states are free to implement regulations that reflect national interests, as long as overall European policies are fulfilled, might prove not to be strong enough to solve the potential geopolitical conflicts. While the coordination of regulatory bodies was strengthened in the fourth energy package, significant inconsistencies in energy policy still exist among the member states. As a result, capacity allocation across Europe is not cost-efficient, the grid development is not keeping up with renewable deployment and uncoordinated phase out of secured capacity raises concerns over security of supply.

Establishing a strong independent European system operator that would take over responsibility from national operators could be a potential solution. It could harmonize regulations on renewable support schemes, further streamline grid extension projects and ensure an efficient transition to a low-carbon energy system. However, promoting the idea of tighter European integration might prove to be difficult in light of growing nationalistic sentiment, even though it might be the most effective and cost-efficient way to reach the carbon emission targets.

Lastly, the potential positive impact of the energy transition on European foreign policy is another important policy implication. With growing independence of the European continent from Russian natural gas and oil, it could become easier for the member states to agree on a common foreign policy.

4.7 Discussion

Europe is at the doorstep of a wide-ranging energy system transformation: the legacy fossil-fuel based energy system is replaced with new low-carbon technologies. Despite the wide-ranging implications of renewables on national economies and inter-country relationships, the geopolitics of the energy transition are not yet fully understood. Rigorous analytical frameworks and studies with empirical data are currently lacking. By developing a new theoretical model and complementary data analysis this study contributes to the ongoing academic discussion on the geopolitical implications of the energy transition. Furthermore, this research project equips policy makers and investors with a deeper understanding of geopolitical factors to consider when making investments in energy technologies and infrastructure in a rapidly changing business environment.

The findings in this study help to refine narratives about the geopolitical implications that have been presented by research in the past. While most studies forecast disruptive changes in the energy supply chain and consequent dramatic changes in the energy world order going forward (IRENA, 2019b), this study takes a more cautious stand on the shift of geopolitical influence —at least within the European Economic Area. The hegemony of the leading Northern European countries is likely to deteriorate and other countries' influence is likely to increase, however the geopolitical arithmetic is far from being turned upside down. Countries like Germany and France used to *and* remain in a powerful position. Hence, the energy transition can be rather described as a gradual recalibration of the power balance than a radical transformation.

Nevertheless, from a global perspective the shift could be more transformative, especially for countries, such as Russia, Qatar and Saudi Arabia, whose economic welfare depends to a large extent on energy exports. With shrinking dependence on energy imports, these exporters may lose geopolitical influence. In comparison, European exporters are not as negatively affected as their economics are more diversified and energy exports are only one of several drivers for national prosperity, but not the single one.

Also the findings regarding winners of the energy transition fit to exiting research: countries with large renewable potential, as well as island states, have been previously mentioned as potential winners (IRENA, 2019b; Overland et al., 2019). However, in contrast to previous narratives in literature, this study argues that proclaiming pioneers of the energy transition as inevitable geopolitical winners is premature.

Previous studies also indicate that the energy transition will reduce the potential for regional conflicts (Sweijs et al., 2014). As this study points out, conflicts of interests within the EU could be mitigated due to greater energy interdependence. In literature this is often referred to as 'Saint-Simonian imperative': energy can be used in inter-state relationships to mobilize countries for a joint purpose and to strengthen the cooperation among them (Högselius, 2019). In this context this study outlines how the energy transition could help to strengthen the European Union internally and potentially allow to develop a more stringent EU foreign policy. Criekemans (2019) also highlights that joint renewable projects, such as the North Sea Offshore grid initiative, could soften geopolitical challenges within Europe.

It is important to recognize the limitations of the research approach and the underlying assumptions that were made. First, the scope of the study is limited to the European Economic Area, and thus insights cannot be generalized for other regions without adjusting for their specific political and cultural context. Second, the research is deterministic with regard to the use of technology, even though the indicators are designed to be technology-neutral. Hence, innovations in technology could change the process and exact specifications of the energy transition and the subsequent power shifts. Third, as pointed out by Scholten and Bosman (2016), several factors can affect inter-country relationships, such as the distribution of wealth, the structure of financial markets, the socio-cultural context and political power of the counties investigated. The latter includes but is not limited to energy-related geopolitical influence.

4.8 Conclusion

This essay explores the energy-related geopolitical influence within the European Economic Area and sheds light on how the energy transition might shift the power balance among the countries. Countries' ability to exercise power vis-a-vis other nations is particularly relevant to understand policy making in transnational institutions, such as the European Union. Furthermore, this research project enables policy makers, investors and other stakeholders to navigate in a new world of energy conflicts and cooperation. Especially, policy makers need to keep energy security concerns in mind when building new energy market structures and set up energy governance structures in order to reach a low-carbon energy system in a cost-effective way.

This essay develops a new theoretical model to describe how countries accumulate energy-related geopolitical influence. Furthermore, a new methodology is suggested to measure this influence with a set of 12 indicators across several dimensions, such as access to conventional energy resources, renewable potential, technology, as well as control over connecting infrastructure and the inter-country trade regime.

The results show that energy-related geopolitical influence used to be concentrated in five Northern European countries (Germany, France, Netherlands, Norway and the United Kingdom) in the early 2000s, however their hegemony has deteriorated in the following two decades. The energy-related influence of Poland, as well as Spain has increased over the last 20 years. The energy transition may further impact the energy-related geopolitical power balance going forward. Southern and Eastern European countries are potentially among the winners of the geopolitical re-balancing in Europe. Nevertheless, the results suggest that countries in pivotal geographical positions, such as France, can still preserve leading positions in the European energy hierarchy.

Furthermore, the energy transition will most likely not lead to the democratization of energy as suggested by some scholars, rather power imbalances are likely to prevail also in the future despite universal access to renewable energy sources. However, the transition to low-carbon technologies could result in stronger interdependence of countries within Europe, which may lead to a convergence of interests and ultimately to further integration of the European Union.

The implications for European energy policy are two-folded: first, it is apparent that the two leading European energy nations —Germany and France— should join forces and reach an agreement regarding the decarbonization pathway and lead the rest of the continent to actively engage in the energy transition. While both countries seem to accept their leadership position in this matter, both of them struggle to advance their own national energy policy and as a result fall short in reaching their own-set climate targets, jeopardizing the European climate agenda. Second, European policy needs to reflect the interests of potential losers of the transition process, such as Poland, in order to ensure that these countries do not turn against the joint climate initiatives to protect national interest.

The results of this essay furthermore illustrate that the academic discussion on geopolitics of renewables needs to develop from high-level narratives (e.g., 'fossil-fuels vs. renewables') to a more differentiated and nuanced analysis. The impact of the energy transition on countries' influence and geopolitical power should be assessed along a variety of factors.

Further research could detail and test the theses outlined in this essay. Especially event-related research that would study the outcome of concrete energy policy decisions on European level could help to further verify the outlined propositions. Moreover, studies focusing on the transition process itself, as well as research from a more technology-specific perspective could further enhance the academic discussion.

5 | Geopolitical and Market Implications of Renewable Hydrogen: New Dependencies in a Low-Carbon Energy World[9]

by Fridolin Pflugmann and Dr. Nicola de Blasio

Renewable hydrogen is enjoying increasing political and business momentum. But taking full advantage of its potential will require scaling technologies, reducing costs, deploying enabling infrastructure, and defining policies and market structures. Since renewable hydrogen could be an important piece in the carbon-free energy puzzle, it is relevant to explore its geopolitical and market implications as it enables policy makers and investors to navigate a new world of energy conflicts and cooperation. Key variables to consider are technology, infrastructure, global markets, and geopolitics. Focusing on renewable hydrogen, we propose a methodology to frame these variables, address the challenges they cause, and the potential opportunities. We assess the role a country could play in the future renewable hydrogen market based on its renewable energy and freshwater endowment as well as infrastructure potential.

Our analysis shows that countries are very likely to assume roles in the future market designating countries as exporting or importing nations. Thus, future geopolitical realities of resource-poor countries in Europe and Southeast Asia might be very similar to today's situation, as energy import dependencies may continue. The world may also witness an emergence of new energy export champions—such as Australia and Morocco—due to their superior cost positions and access to large import markets. If adopted at scale, we believe the dynamics of the future markets would be similar to today's natural gas markets —with the potential for similar geopolitical conflicts.

Keywords: *Renewable hydrogen, Energy conflicts, Geopolitics of energy, Energy infrastructure*

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5.1 Introduction

Carbon-rich fuels —coal, petroleum, and natural gas— offer many advantages over other energy sources. They have a superior energy density relative to almost all other fuel sources, they have a wide range of use, and they are relatively easy to transport and to store. Often, they are also relatively inexpensive: particularly when existing infrastructure allows supply to meet demand (De Blasio & Nephew, 2017). At the same time, carbon-rich fuels present significant downsides, particularly related to their impact on environment and climate. These issues, taken in combination with the persistent desire of countries around the world for more stable, more secure energy supplies, have sparked widespread interest in alternative energy sources.

While hydrogen has been a staple in energy and chemical industries for decades, it has recently attracted increasing attention from policy makers and practitioners worldwide as a versatile and sustainable energy carrier that could play a significant role in the transition to a low-carbon economy. Hydrogen had experienced a short-lived wave of enthusiasm in the early 2000s that ended in disillusionment, but the current trend might prove to be more robust, with a conceivable path toward impacting the long-term future of energy (Staffell et al., 2019).

As governments become more serious about addressing climate change, it seems the time has finally come for hydrogen to become a major energy alternative to carbon-rich fuels. Thanks to the first universal and legally binding agreement reached at the 2015 United Nations Climate Change Conference in Paris, the traction to implementing environmental policies has increased. However, if the global community intends to stand by its commitment to limit global warming to less than 2°C, carbon emissions must be reduced far beyond what is currently agreed in the Intended Nationally Determined Contributions (United Nations Environment Programme, 2018). Thus, governments must show actions that reach beyond replacing coal with renewable electricity, and all emitting sectors will need to contribute to emission reduction efforts. Renewable hydrogen could play a pivotal role in tackling "hard-to-abate" sectors and in mitigating the shortcomings of renewable energy sources (RES). Due to its versatility, hydrogen is sometimes described as the "missing link" in global decarbonization (Hulst, 2018). Renewable hydrogen can be used both in mobility and in stationary applications; as a mobility energy carrier, it can power fuel-cell electric vehicles (FCEV) and/or be a feedstock for synthetic fuels. In stationary applications it can be used as a means for storing renewable energy at utility scale but also off grid. Hence providing backup power to buffer RES intermittency and/or serve as a carbon-free heating source.

A prominent example highlighting the non-transient nature of this new hydrogen age is Japan's 2017 pledge to become a "hydrogen society" (Ministerial Council on Renewable Energy, 2017).

This endeavor is supported by considerable government investment in technology and infrastructure development for both stationary and mobility application. Japan's largest company, Toyota, plays a pivotal role in this plan and in contrast to many other car manufacturers, it began to view hydrogen as a renewable fuel source not requiring customers to change their driving and fuel habits as early as 1992 (Nied, 2015; NPR, 2019).

In 2019, South Korea released a similar plan for renewable hydrogen integration (Dae-sun & Ha-yan, 2019). In countries such as Australia, New Zealand and Morocco, national hydrogen strategies are currently under development (World Energy Council, 2019). In the same year, both the IEA (2019a) and IRENA (2019a) published papers on the future of hydrogen, further invigorating the global conversation.

Most hydrogen is currently produced from fossil fuels, through natural gas cracking or coal gasification (IEA, 2019a). Even if more expensive, various processes exist to produce hydrogen in a carbon-neutral way that contributes to emission reduction targets. In this paper we will focus on electrolysis (the splitting of water into hydrogen and oxygen) using renewable electricity. Hydrogen produced by electrolysis using renewable electricity is from now on referred to as *renewable hydrogen*.

For renewable hydrogen to reach its full potential as a clean energy solution, the international community must tackle several transitional challenges. Technological and economic questions need to be addressed in order to enable large-scale commercialization: industrial-scale production for renewable hydrogen still needs to prove its technological viability while achieving competitive cost levels. Currently renewable hydrogen production is around 2-3 times more expensive than hydrogen production from fossil fuels[10]. However, there are several strategies that could help increase its competitiveness, namely technology improvements, cost reductions along the entire value chain and/or, carbon pricing. Other key obstacles include lack of enabling transportation and distribution infrastructure, established markets and uniform regulations and/or policies. While hydrogen can be blended into existing natural gas grids, country-specific standards and regulation set a cap between 2-10% of the transmitted volume (IEA, 2019a). Upgrades of pipelines and compressor stations would be required to enable the inclusion of higher shares of hydrogen. Similarly, significant investments in hydrogen-fueling infrastructure would be necessary for scaling up adoption in the transportation systems, which would also face competition with EVs. Besides these technological and economic challenges, the use of renewable hydrogen poses significant geopolitical implications.

[10] Current hydrogen production costs are around 1-2.5 USD/kgH_2 depending on local natural gas or coal prices. Renewable hydrogen production costs are in the range of 2.5 to 6.8 USD/kgH_2. See IEA (2019) and BNEF (2019) for detailed cost assumptions

The transition to low-carbon energy will likely shake up the geopolitical status quo that has governed global energy systems for nearly a century, hence policy makers need to consider the role their country could/should play in a new energy world. Renewables are widely perceived as an opportunity to break the hegemonies of fossil fuels-rich states and to "democratize" the energy landscape (Casertano, 2012). Virtually all countries have some access to renewable resources (e.g., solar and wind power) and could thus ideally substitute foreign supply with local resources. In the case of renewable hydrogen, whether resources will be as concentrated as today's oil and gas supply or decentralized like renewables is strongly related to future market structures, technology and enabling infrastructure availability. Our analysis shows that the role countries are likely to assume in future renewable hydrogen systems will be based on their resource endowment and infrastructure potential. As a result, the fossil energy dependence of resource-poor countries in Europe and South-East Asia might be replaced with dependence on renewable hydrogen imports.

Furthermore, the potential impact of interruptions in hydrogen supply depends on how global the market will develop. If liquification and shipping across several thousands of kilometers became cost competitive, interruptions of supply in one part of the world could have impact on global prices. However, it seems plausible that hydrogen, similar to natural gas, will initially flourish in regional markets.

Our study explores the overarching question of whether a low carbon energy world would enable a more uniform access to energy, or if old dependencies perpetuate while new ones emerge. As hydrogen could play an important role in the carbon-free energy puzzle, it is key to understand how the geopolitics of hydrogen would look like, if adopted at scale. Hence, these considerations raise the following question: what are the potential geopolitical and market implications of renewable hydrogen? In other words: how might renewable hydrogen influence energy-related inter-nation relationships? We believe a deeper understanding of these nascent dynamics is needed so that policy makers and investors can better navigate the challenges and opportunities of a low carbon economy without falling into the traps and inefficiencies of the past. Furthermore, our work aims to provide stakeholders the means to take informed decisions on policy instruments, technology innovation funding, and long-term investments in energy infrastructure.

The remainder of this essay is structured as follows: section 2 introduces the envisioned scenario. Section 3 provides an overview of renewable hydrogen production, applications and market potential. Section 4 reviews renewable hydrogen production and transportation costs. In section 5 the map of renewable hydrogen is drawn. Section 6 analyzes the geopolitical implications of future renewable hydrogen markets. Section 7 addresses policy and business options. Section 8 provides an overarching conclusion and options for further analysis.

5.2 The scenario: A world powered by renewable energy

This paper explores the general principles of how hydrogen may reshape the structure of global energy markets and the geopolitical game between countries; to do so we propose an analytical framework, using renewable hydrogen as our case study. This framework can then be easily applied to other technologies, contexts, and/or transition pathways. In other words, our goal is to develop a useful tool to address "what if?" analyses on the opportunities and/or challenges facing the adoption of hydrogen at scale.

Renewable hydrogen could play a key part in decarbonizing our energy systems because it offers a pathway towards meeting climate and pollution goals while avoiding reliance on imported fuels and opening new avenues for developing clean technology manufactured goods. Technology innovation and policy are key transitional variables in accelerating the adoption of renewable hydrogen on a global scale.

Like the development and deployment of other low carbon technologies, a renewable hydrogen transition will be gradual. Initial R&D efforts are generally followed by first movers trying to leverage opportunities for site specific applications, followed by production and infrastructure deployment at scale. Various transition pathways and speeds can be envisioned and are likely to depend on the industrial sector being considered and might occur in parallel and/or sequence as a function of technology innovation. For instance, stationary applications in the power sector might adopt renewable hydrogen earlier than mobile applications in the transportation sector, but technological learning curves in the former could catalyze an accelerated deployment in the later. Regardless of the scenario and/or the transition pathway considered, a combination of a sharp decline in production costs —spurred by technology innovation— together with strong policy support (e.g., carbon pricing) for the deep decarbonization of the energy systems will be required to drive adoption at scale.

To showcase the proposed analytical framework, we envision a low carbon energy world powered by renewable energy sources. We assume that renewable hydrogen will be widely adopted as a result of technology innovation and active national decarbonization policies and hence a relevant component of a low-carbon energy world. According to IRENA, more than 50 countries have already committed to some form of 100% renewable energy targets (IRENA coalition for action, 2019). For instance, the European Commission published its long-term vision to achieve climate neutrality by 2050 (European Comission, 2019).

For the sake of our analysis we establish three key premises:

- First, we envision future energy systems, in which renewable hydrogen will capture a considerable part of energy demand (around 10%). Hence, we assume that either not all applications can be directly electrified or that the use of renewable hydrogen for decarbonization is more cost-efficient, or both.
- Second, we assume that among all renewable energy sources, solar and wind power will become dominant sources due to their large-scale potential and favorable cost structures. Hence, these two energy sources will be primarily used for renewable hydrogen production in our scenario; even if also nuclear could play a role.
- Third, we assume that public acceptance for alternative, carbon-free hydrogen production processes is at present limited. While as mentioned, nuclear power could play a role, economic, public, and safety concerns are limiting its development and deployment. Furthermore, in a global low-carbon economy carbon capture and storage (CCS) will also need to play a role but this goes beyond the scope of our analysis.

5.3 The Hydrogen Molecule: Production, Applications and Market Potential

While hydrogen has been a staple in the energy and chemical industries for decades, it has recently attracted increasing attention from policy makers and practitioners worldwide as a versatile and sustainable energy carrier that could play a significant role in the transition to a low-carbon economy.

In this capacity, hydrogen is being pursued for both stationary and mobility applications as:

- A means to store renewable energy
- A fuel in stationary fuel cell systems for buildings, backup power, and/or distributed generation
- A sustainable mobility energy carrier, namely for fuel-cell electric vehicles (FCEVs)

Hydrogen is the most abundant element in the solar system, and stars such as our sun consist mostly of hydrogen. On earth, hydrogen naturally occurs only in compound form with other elements in gases, liquids, or solids, and hence it must be produced through one of several processes: thermo-chemical conversion, biochemical conversion, or electrolysis i.e. water splitting (Shell, 2017).

Today, fossil fuels are the primary source for hydrogen production and Steam Methane Reforming (SMR) using natural gas is the dominant production process. Electrolysis, which is considerably more costly, currently accounts for less than 3% of global hydrogen production (IEA, 2019a). We assume that, in the future, hydrogen production from electrolysis will rise significantly if surplus electricity from renewables and/or nuclear will become increasingly available and production costs decrease.

4.3.1 Renewable hydrogen production by electrolysis

In this process, electricity is used to split water into hydrogen and oxygen. The required electricity can be provided by any energy source, but to be fully carbon-free, renewable energy such as solar or wind power is essential. In most countries, the current electricity mix is not purely renewable; therefore, electrolysis using grid electricity fails to fully eliminate carbon from the process (U.S. Department of Energy). The direct coupling of renewable generation assets and electrolysis facilities could circumvent this issue, but at the same time would limit electrolysis utilization times. In comparison to hydrogen production from natural gas (mainly SMR), water electrolysis plants operate at smaller scales i.e. <5 MW_{el} (IEA, 2019b) . Besides electricity, freshwater is a key resource: to produce 1kg of hydrogen, nine times the amount of freshwater is necessary, i.e. nine liters.

Operating electrolysis with sea water is complicated by its high salinity, as salt leads to electrode corrosion. However, researchers from Stanford and other universities recently developed a coating that could make seawater electrolysis viable (Kuang et al., 2019). This emerging technology is particularly relevant for Middle Eastern countries, which possess rich renewable resources but are freshwater constrained.

Synthetic hydrocarbons

Hydrogen can be combined with carbon dioxide to form synthetic hydrocarbons (e.g., synthetic methane), or synthetic liquid fuels (e.g., synthetic gasoline or jet fuel). The needed carbon dioxide can be supplied from carbon-emitting power plants or industrial facilities; alternatively, it can be captured directly from the atmosphere.

The main benefit of synthetic hydrocarbons is their integrational capacity in the existing energy infrastructure. For instance, synthetic methane can be stored and transported through existing natural gas systems. However, both alternatives have disadvantages. CO_2 capture from power plants and industrial facilities is not carbon neutral, as carbon emissions are regardless ultimately released into the atmosphere. Direct capture from the atmosphere is highly energy-intensive — and thus costly— due to carbon dioxide’s low atmospheric concentration (Batteiger, Falter, Martos, Dufour, & Iribarren, 2018). Furthermore, low overall efficiency increases production costs.

5.3.2 Areas of Application

It is clear that hydrogen could play an integral role in decarbonization as a versatile fuel and effective energy carrier. Yet the pathways to enacting these major global transitions have yet to be developed, leaving it unclear to experts whether direct electrification or low-carbon fuels such as hydrogen will dominate the markets of tomorrow. While the energy transition has started in the power sector and its transition pathways are clearly visible, all other carbon-emitting sectors—mobility, buildings (heat and cooling), industry and agriculture—must find further ways to substantially reduce emissions.

The energy transition has started in the **power sector** and its transition paths are clearly visible. On a global level, the largest potential for renewable generation exists in solar and wind power (Criekemans, 2011). However, several countries also hold significant potential for hydro generation (e.g., Brazil and Norway). Since 2000, the installed renewable capacity has tripled worldwide (IRENA, 2018b), and in 2015, global capacity additions of renewables overtook conventional power generation technologies for the first time (IEA, 2016).

A key challenge in the transition to renewables is their intermittent nature. A high-renewable electricity system needs to be flexible enough to withstand situations in which a significantly higher amount of electricity is generated than required and, more importantly, situations in which renewables are unable to meet required demand. While several flexibility options exist, storage applications are the most straightforward. Hydrogen can be stored in large quantities for extended periods of time at a lower cost than electricity[11], and hence well-suited to balance fluctuations in renewable generation.

Countries relying on natural gas could use existing infrastructure for large-scale hydrogen storage and/or partly replacing natural gas. Initially, hydrogen could be directly injected into gas grids between 2-10% of the transmitted volume depending on country-specific standards and regulation (IEA, 2019a). Higher concentrations would require infrastructure upgrades. Alternatively, synthetic methane could be used as a drop-in alternative.

In the **mobility sector,** hydrogen has various application pathways. In the light-duty vehicles/passenger car market, two technologies currently compete: battery electric vehicles (BEVs) and fuel-cell electric (FCEVs) vehicles. BEVs rely on electric batteries for power, while FCEVs utilize hydrogen. To date, most car manufacturers have invested in BEVs, including Tesla,

[11] See Jülch (2016) for cost comparison of various storage technologies and REN21 (2017) for an overview of storage system capacities

Volkswagen, and Renault. However, especially in Japan and South Korea, several car makers are developing FCEVs. BEVs are commonly projected to capture most of the carbon-free light vehicles market, primarily because ownership costs are lower in the foreseeable future. Charging infrastructure for hydrogen-powered vehicles is also lacking, while BEVs can be charged at various power grid access points (Arthur D. Little, 2017).

For heavy-duty vehicles, hydrogen is likely to play a larger role due to longstanding issues with battery systems in this sector. Large battery stacks are required to power heavy vehicles over long distances; in addition, recharging large stacks requires several hours[12], while refueling with hydrogen could be performed within minutes (ICCT, 2017). As utilization is a key performance driver, a short recharge time is a key purchasing criterion. Unless the entire stack of batteries could be easily and cost-effectively replaced instead of recharging (which on the other hand would raise liability and/or insurance issues), hydrogen may remain ahead of its competition[13].

Nevertheless, both technologies are currently being developed for the truck segment, such as the electric Tesla's Semi and the Kenworth/Toyota fuel-cell electric truck (Wyatt, 2019). For similar reasons, decarbonization of air and marine transport will likely need to rely on hydrogen or biofuels (Hydrogen Council, 2017).

Within the **building (heating and cooling) sector**, hydrogen could be used in fuel cells to generate heat (and electricity). Japan and South Korea have programs for residential combined heat and power (CHP) fuel-cell; in the United States, larger fuel cells are present in the commercial heat market (Dodds et al., 2015). Furthermore, synthetic methane, based on renewable hydrogen, could replace natural gas in existing gas heating with the possibility of leveraging existing transmission and combustion infrastructure and thus avoid expensive replacements. Natural gas is a common heat source in regions with large seasonal temperature differences, such as northern Europe, Russia, and parts of the U.S. For moderate-climate areas direct electrification alternatives, such as electric radiators or heat pumps, are more suitable (Hydrogen Council, 2017).

In the **industry sector** (including mining, manufacturing and construction), hydrogen could play a dual role as a feedstock in chemical processes or high-temperature heat generation. The most straightforward use of hydrogen as a chemical feedstock is in ammonia production. Hydrogen could also be utilized in new steel manufacturing techniques i.e., direct-reduced iron (Vogl, Åhman, & Nilsson, 2018).

[12] Recharging times of light-vehicles are also up to 10 hours on standard household 220-240 Volt outlets, however long recharging times in the light-duty vehicle segment are considered less critical due to customer driving patterns

[13] Another way for direct electrification of heavy-duty vehicles could be the construction of trolley wires along major highways (similar to the operations of electric buses in cities), however this requires significant infrastructure investments

For industrial heating, hydrogen-fueled furnaces could provide medium-to-high-temperature heat (>400°C), which is otherwise hard to decarbonize. Hydrogen could thus complement direct electrification such as heat pumps and electric heaters, which are more suitable for low-temperature heat up to 400°C. Hydrogen combustion is likely to fit better to the existing industrial process design and hence could be a more efficient route for decarbonization than electrification (Hydrogen Council, 2017).

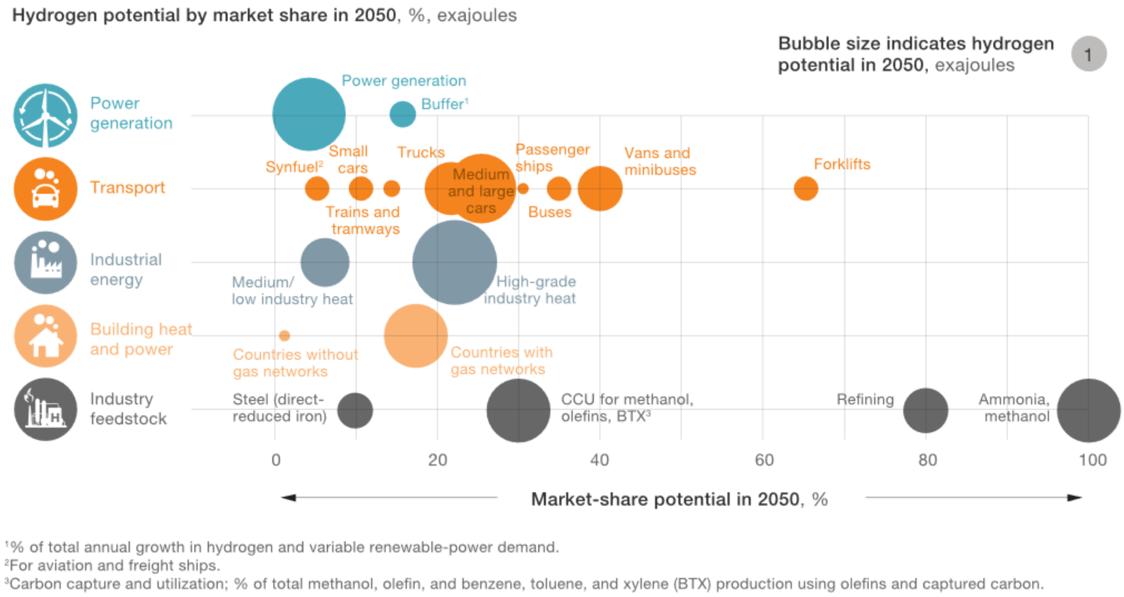


Figure 5.1 Hydrogen potential by market share in 2050. Source: McKinsey (2018)

5.3.3 Market potential

The role hydrogen will play in each sector is still uncertain. McKinsey (2018) provides an overview of the market share hydrogen could capture by 2050 across sectors (figure 5.1). It is highly probable that hydrogen will spike particularly as an industrial feedstock; as a high-temperature combustion fuel; and as an energy carrier in heavy transport applications.

Estimates on annual demand for hydrogen by 2050 vary widely among reports. The Hydrogen Council (2017) estimates global demand at approximately 78 EJ, which would equate to around 14% of the world's total energy demand. Studies by BNEF (2019) and DNV GL (2018) are more conservative, with estimates hovering between 5 and 39 EJ annually. Shell (2018) predicts that the hydrogen market will not grow considerably before 2050. In 2100 the hydrogen market is expected to reach 69 EJ equating to about half of the current global demand for natural gas. Table 5.1 provides a comparison of the various estimates.

Table 5.1 Estimated annual demand for hydrogen in 2050

	Study	Estimated annual demand (in EJ)	Remarks
Hydrogen demand in 2050	Hydrogen Council (2017)	78	Driven mainly by transportation (22 EJ) and industrial energy (16 EJ)
	BNEF (2019)	5-39	Estimates reflect conservative and optimistic scenarios
	DNV GL (2018)	15-39	Industrial feedstock accounts for more than 40% of demand in all scenarios
	Shell (2018)	9	Market only grows considerably after 2050 reaching 69 ET in 2100 (mainly driven by road transport, as well as heavy and light industry)
For comparison: Current annual demand for			
Hydrogen	IEA (2019a)	9-11	Global annual demand 2018[14]
Oil	BP (2019)	195	Global primary consumption 2018
Natural gas	BP (2019)	139	Global primary consumption 2018

Source: Hydrogen Council (2017), BNEF (2019), DNV GL (2018), Shell (2018), IEA (2019a), BP (2019)

5.4 Production cost of renewable hydrogen

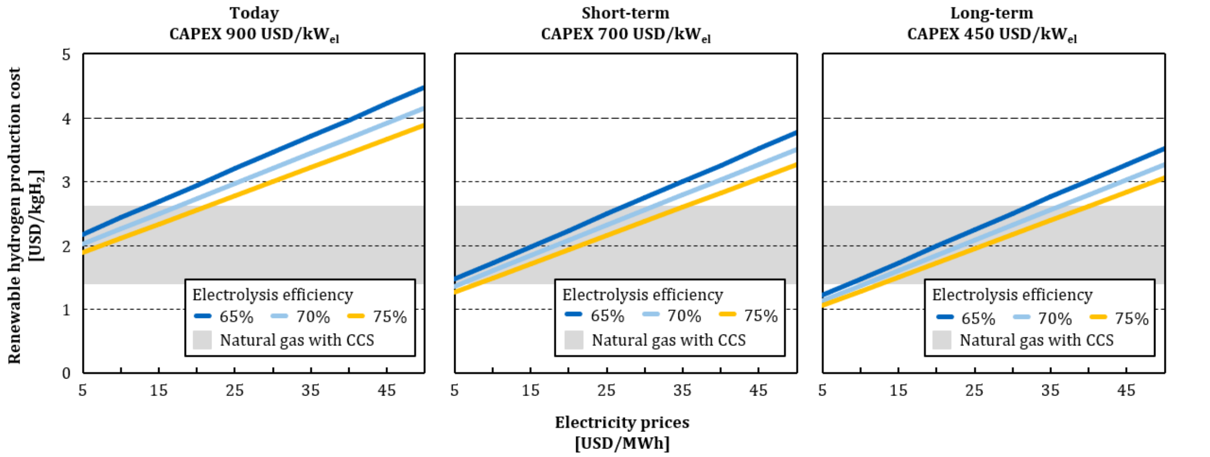
Renewable hydrogen is not yet cost-competitive with fossil-fuel based production. Depending on local prices of natural gas and coal, current production costs range from 1 to 2.5 USD/kgH_2. In comparison, renewable hydrogen costs range from 2.5 to 6.8 USD/kgH_2[15]. However, significant renewable hydrogen production cost reductions and implementation of carbon pricing policies[16] could drive its competitiveness.

The production cost of renewable hydrogen is driven by three primary factors: electricity prices, capital expenditure for electrolysis units, and operating costs. If hydrogen is not immediately used at its production location, costs for storage, transportation and distribution would also need to be taken into consideration.

Technology innovation and economies of mass production have resulted in a sharp decline in the costs for solar and wind generated electricity over the past decade. For example, solar module costs fell by about 90 percent between 2009 and end of 2018 (IRENA, 2019d), while cumulative installations soared from 22.8 gigawatt to 480.6 GW (IRENA, 2019c). Similar dynamics are expected to drive down also electrolysis costs, due to the decline in CAPEX, improved lifetime and greater efficiency. Figure 5.2 illustrates how lower electricity costs, a decline in CAPEX costs and

[14] Hydrogen used in pure form; a further 5-6 EJ is used in industry without prior separation from other gases
[15] See IEA (2019a) and BNEF (2019) for detailed cost assumptions
[16] A carbon price of 100 USD/ton approximately translates into a price increase of ~1 USD/kgH_2 for hydrogen produced with steam methane reforming using natural gas and ~2 USD/kgH_2 for hydrogen produced with coal gasification —in both cases without carbon capture (Own calculation)

advancement in electrolysis efficiency can help to make water electrolysis cost competitive to steam methane reforming with carbon capture and storage (CCS).



Note: Assuming a lifetime of 100,000 operating hours, 2,500 annual operating hours and OPEX equivalent to 2% of CAPEX. Assumptions based on IEA (2019a)

Figure 5.2 Cost sensitivity to CAPEX, electricity prices and electrolysis efficiency

Even if renewable hydrogen production costs are expected to sharply decline, these costs will still significantly differ among countries. The main cost component of electrolysis is the electricity cost, which is a function of RES load factors, or in other words operating hours. As full load operating hours vary greatly geographically based on solar radiation and wind speeds, so does the resulting cost of electricity. Figures 5.3 and 5.4 depict the differences in solar irradiance and wind speed around the world (Vaisala, 2019). For example, while most solar plants in Germany operate between 800 and 1,050 full load hours, Morocco's solar plants can generate between 1,400 and 1,750 full load hours with consequences for electricity costs (Pietzcker et al., 2014). Due to these geographical differences, it may be more cost-efficient for some countries to import renewable hydrogen rather than to produce it domestically, inducing transportation cost considerations, while also raising geopolitical issues[17].

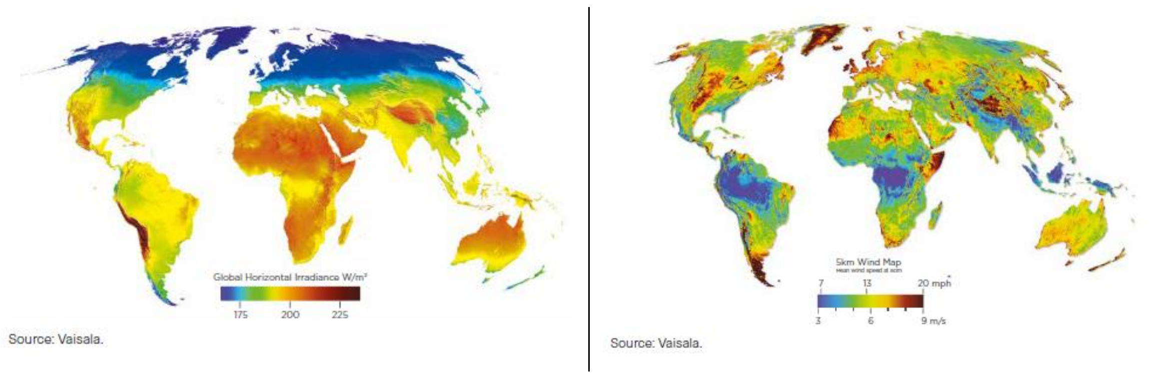


Figure 5.3 and 5.4: World solar potential (left) and world wind potential (right). Source: Vaisala (2019)

[17] Besides the renewable potential, some countries might also lack space to produce sufficient amounts of renewable hydrogen and are thus inclined to import renewable hydrogen

Hydrogen can be transported by either pipelines or ships. Pipelines allow to transport hydrogen in its gaseous form, but capital costs are high since they are a linear function of the pipeline length, hence making shipping the more cost-competitive option for distances beyond 1,500 kilometers (IEA, 2019a).

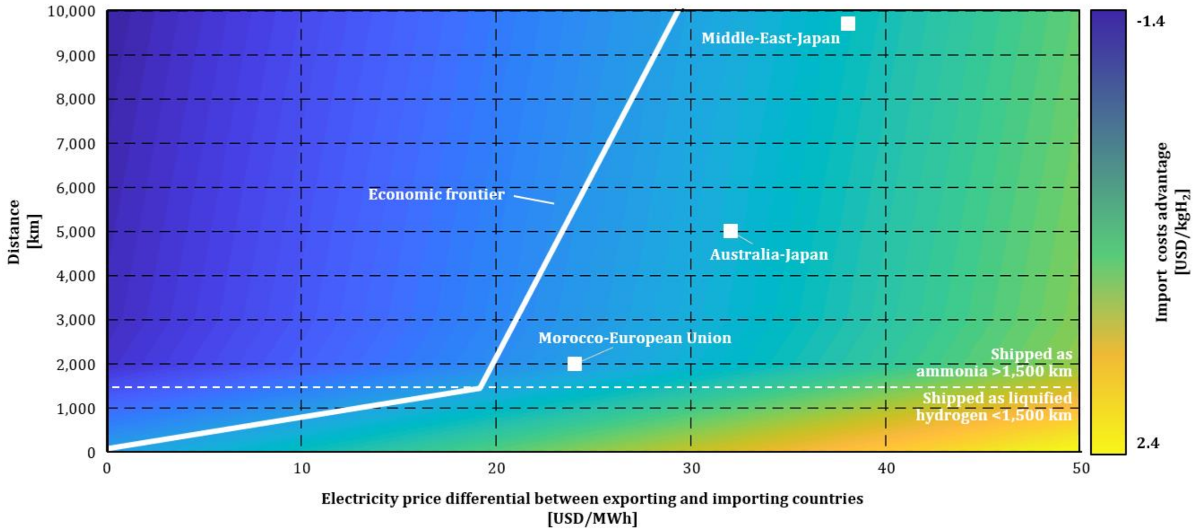
When using ships hydrogen must be either liquified or converted into hydrogen-based fuels and/or feedstocks. With existing technology, liquefication costs hover at around $1 USD/kg (IEA, 2019a). Shipping liquified hydrogen is additionally expensive due to the high capital cost of the ships themselves and associated hydrogen boil-off during transport[18].

Due to its higher hydrogen content, ease of transportation, existing infrastructure and established international trade routes ammonia could present a valid and economic alternative to liquified hydrogen (IEA, 2019a). Ammonia production costs would need to be taken into consideration together with any reconversion costs to hydrogen, if ammonia could not directly be used as fuel in ammonia fuel cells and/or in ammonia-fired power plants. These complexities underline the stark need of a detailed comparison of shipping and production costs on a case-by-case basis.

Renewable hydrogen costs as a function of transportation distance and electricity prices are shown in figure 5.5. These two variables are also key whether imports are cost competitive to domestic generation. While pipelines are most economical for regional transportation, shipping as liquified hydrogen or as ammonia is most cost effective for greater distances. Moreover, greater differences in electricity prices may justify transportation over longer distances as shown by the economic frontier in figure 5.5.

The analysis shows that for Japan and the European Union (EU), importing renewable hydrogen could be a cost-competitive replacement for domestic production, assuming production cost reductions and deployment of enabling infrastructure (see Figure 5.5). In practice, the cost advantage of importing hydrogen might shrink due to price markups by the exporter. Production costs in exporting countries could fall even further due to lower wages and cheaper building materials. Furthermore, manufacturers could potentially lessen transportation costs by upgrading existing gas infrastructure rather than designing new hydrogen-specific infrastructure.[19]

[18] Capex amounts to around 400 million USD per ship with a capacity of 11,000 tons of H_2. See IEA (2019a)
[19] However, due to the lower energy content of hydrogen significant less energy can be transported in the existing infrastructure



Note: Assuming the following long-term cost and efficiency projections: CAPEX of 450 USD/KW_{el}, electrolysis efficiency of 70% with a lifetime of 100,000 hours and annual operating hours of 2,500 hours, OPEX of 2% of CAPEX investment. Ammonia production costs of 1 USD/kgH_2 assumed. Furthermore, it is assumed that imported ammonia can be directly used e.g., in ammonia fuel cells, thus assuming that reconversion to hydrogen is not required. See IEA (2019a)

Figure 5.5 Hydrogen/ammonia import costs advantage

5.5 The structure of future renewable hydrogen markets

The role a country could play in renewable hydrogen markets will depend on its ability to produce and distribute renewable hydrogen cost competitively and at scale. As discussed, the production of renewable hydrogen through electrolysis requires both renewable energy and freshwater resources. Therefore, to analyze a country's renewable hydrogen potential we consider three parameters: (1) renewable energy resources (RES) endowment; (2) renewable freshwater resource endowment; and (3) infrastructure potential, defined as a nation's capacity to build and operate renewable hydrogen production, transportation and distribution infrastructure.

1) Renewable energy resources (RES) endowment

RES endowment is defined as the combined generation potential of wind and solar power (Figure 7)[20] . A country's RES endowment is also an indication for the attainable renewable electricity generation cost, as higher resource endowment often translates into higher capacity factors, which in turn influences generation costs. We consider a country's RES poorly available if its potential for renewable generation is less than 1.5 times its domestic primary energy consumption across all sectors (EIA, 2019b). Space constraints may also emerge for countries with high population density (above 150 inhabitants per square kilometer). In these denser

[20] The combined renewable generation potential is calculated based on the wind power potential of a country derived from NREL (2014) and solar power potential derived from Pietzcker et al. (2014)

nations, finding land for RES infrastructure forces competition with other industries such as agriculture and transportation.

We consider a country's RES abundant if renewable generation potential exceeds domestic primary energy consumption by at least 7.5 Petawatt hours, or about 5% of current global primary energy consumption. This excess renewable energy could be exported once internal energy demand is fulfilled.

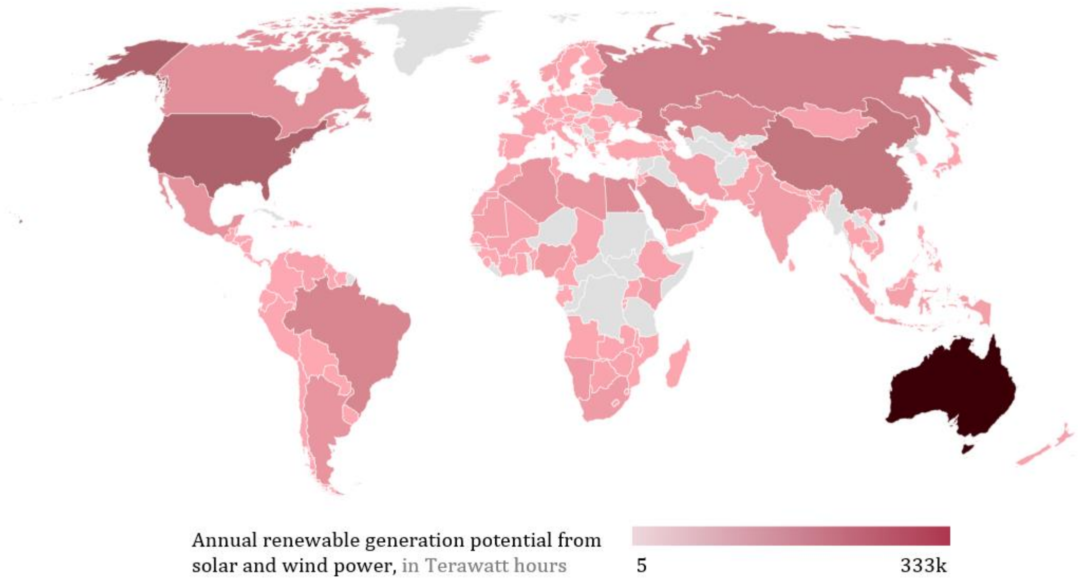


Figure 5.6 Annual renewable generation potential from solar and wind power (in TWh)

2) Renewable freshwater resources endowment

A country's freshwater resources are considered scarce if its total annual internal renewable water resources are under 800 m³ per inhabitant[21]. Countries in this category use their water resources predominantly for drinking, household consumption, industrial use, and/or irrigation. Our data for renewable freshwater resources is derived from the AQUASTAT database (FAO, 2016).[22]

3) Infrastructure potential

As of today, no country has considerable renewable hydrogen production facilities or widespread transportation infrastructure. Therefore, we must rely on the status of a country's existing infrastructure to estimate its ability to build and operate hydrogen production, transportation and distribution. Thus, our proxy measurement is the overall infrastructure score

[21] For comparison: The United States withdraws 1,369 m³ per inhabitant, India 602 m³ per inhabitant and Germany 309 m³ per inhabitant. Countries with limited freshwater resources tend to withdraw proportionately more in order to irrigate their fields

[22] AQUASTAT is a global water information system developed by the Food and Agriculture Organization of the United Nations

in the World Economic Forum's 2019 Global Competitiveness Index, depicted in figure 5.7 (World Economic Forum, 2019a). Countries with scores below 4 (on a 1-7 scale) are considered infrastructure constrained.

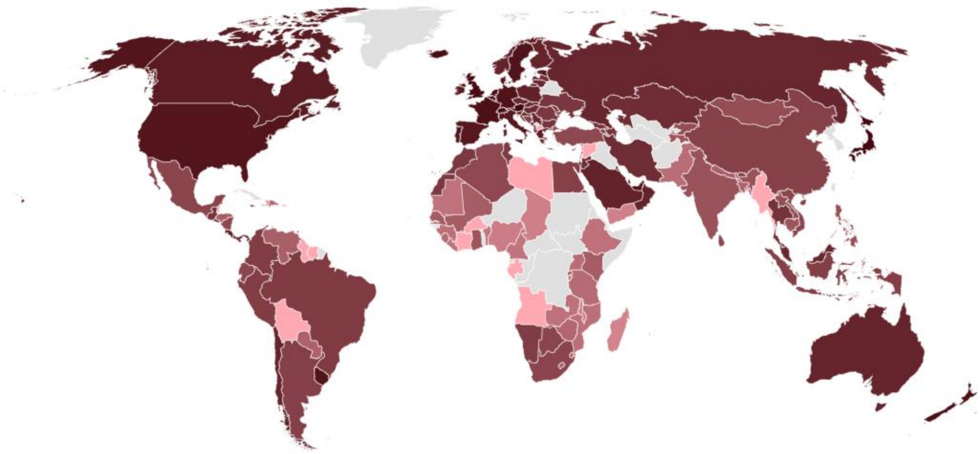


Figure 5.7 Quality of overall infrastructure (scale 0-7, where 7 is the highest score)

The below table 5.2 aggregates countries into five groups based on the discussed three analysis parameters: renewable energy resource endowment, renewable freshwater resource endowment.

Table 5.2 Classification based on resource endowment and infrastructure potential

#	Group	Resource endowment: Renewable energy resources	Resource endowment: Renewable freshwater resources	Infrastructure potential	Example countries
1	Export champions with vast renewable energy and water resources, as well as high infrastructure potential	++	+	+	Australia, United States, Morocco, Norway
2	Renewable-rich, but water-constrained nations with high infrastructure potential	++	--	+	Saudi Arabia, potentially China
3	Renewable-constrained nations with high infrastructure potential	-	+	+	Parts of the EU, Japan, Korea
4	Resource-rich nations with high infrastructure potential	+	+	+	Turkey, Spain, Thailand
5	Resource-rich countries with low infrastructure potential	+	+/-	-	Most parts of South America

Legend: abundant/very high (++), available/high (+), poorly available/constrained (-), scarce/highly constrained (--)

Group 1: Export champions with vast renewable energy and water resources, as well as high infrastructure potential

Nations labeled "export champions" are well-positioned to emerge as suppliers in future renewable hydrogen markets: they are rich in water and renewable energy resources and possess clear capacity to deploy the requisite infrastructure. Some countries in this group, such as Australia, have already recognized the global potential of renewable hydrogen and taken steps to invest in domestic production. Group 1 also contains countries that are strong in conventional energy exports, increasing the likelihood of substantial success in exporting renewable hydrogen.

Cross-country renewable hydrogen trade would create opportunities to strengthen diplomatic ties, specifically between North Africa and the EU. For example, Morocco is especially well-situated to act as a key supplier of renewable hydrogen to European nations. In a 2019 study for Morocco's Energy Ministry, Frauenhofer ISI highlighted this potential:

> *"Morocco's strategic geographical proximity to Europe, along with its exceptional potential in wind and solar energy, particularly in the south of the country, as well as its current and future port and gas infrastructure, makes it a potential supplier of green molecules with very high added value." (Eichhammer et al., 2019, p. 1)*

In the long term, Morocco aims to reach 100% domestic renewable energy production. Its renewable generation capacity has almost doubled in the last five years, progressing towards the national goal of generating 52% of its electricity consumption with renewable sources by 2030.

Group 1 Case Study: Australia

- The Australian Energy Council is working on a national strategy for its hydrogen industry and seeks to position Australia as a major global player by 2030 (World Energy Council, 2019).
- A study conducted for the Australian Renewable Energy Agency (ARENA) estimates that by 2040, Australia's hydrogen exports could swell to over three million tons per year, a figure worth up to $9.1 billion USD per annum. In addition, the study states that over 7 million jobs could be associated with the hydrogen sector in Australia by the same year. Japan, South Korea and Singapore have been identified as the main trading partners (Acil Allen Consulting, 2018).
- To overcome development barriers, ARENA provides financial support/funding for R&D in renewable hydrogen production, storage and use. At the end of 2018, the Agency

announced plans to provide about 15 million USD in funding for 16 research projects (Australian Renewable Energy Agency, 2019).

- According to the IEA Hydrogen Project database, three electrolysis pilot plants started operations in 2019; three additional plants are expected to launch in 2020 and 2021 (IEA, 2019b).

Group 2: Renewable-rich but water-constrained nations with high infrastructure potential

Group 2 countries have abundant renewable energy resources but limited freshwater resources, challenging their likelihood of becoming hydrogen export champions. These countries could use seawater as an alternative; however, this would require desalination before the electrolysis process, increasing costs. Scientific breakthroughs allowing direct seawater electrolysis could significantly improve the positions of Group 2 countries as potential renewable hydrogen suppliers (Kuang et al., 2019).

For instance, if Saudi Arabia, one country belonging to this Group, wished to compete in renewable hydrogen markets, it would need to build new desalination capacity and deploy considerably more RES. Producing enough hydrogen to equal around 15% of Saudi Arabia's annual oil production (or around 10% of a future global hydrogen market of 40 EJ), the country would need to produce around 26 million tons of renewable hydrogen yearly, a feat requiring around 230 million m^3 of freshwater. To produce the necessary freshwater, Saudi Arabia would have to add at least five new large-scale desalination plants to its existing fleet of 31, currently contributing a total of about 1.8 billion m^3 of freshwater per year.

Because water is scarce in Saudi Arabia, renewable hydrogen production would directly compete with other water-intense industries, such as agriculture. Furthermore, even without major investment in renewable hydrogen production, the Saudi demand for freshwater is projected to rise steeply[23] .

To become a large-scale exporter of renewable hydrogen, Saudi Arabia would also need to dramatically increase its solar power capacity from currently below 1 gigawatt (IRENA, 2019c) to approximately 213 GW[24]. The country's current plan is to install an additional 40 gigawatts of photovoltaic power and 2.7 gigawatts concentrated solar power by 2030 (Helio SCSP, 2019).

[23] Demand is expected to double until 2035 according to De Nicola et al. (2015). However, changes in the pricing structure (e.g., reduction of subsidies) and increased efficiency could slow down demand growth

[24] Assuming no conversion losses. With conversion losses for CSP (34% capacity factor) and electrolysis unit (74%) solar power capacity of 457 GW would be required

Looking at China, while as a whole the county is not water constraint, freshwater availability varies greatly among regions[25]. Furthermore, increasing industrialization poses growing threats to the nation's access to adequate freshwater resources. For this reason, China could be forced to import renewable hydrogen, rather than leading as a global export champion. Our analysis shows that, it will likely be more affordable for some Chinese regions to forgo extensive infrastructure development and import hydrogen from neighboring countries instead. These issues make us categorize China as partly water-constrained.

Group 3: Renewable-constrained nations with high infrastructure potential

Countries in Group 3 will need to import renewable hydrogen due to their limited renewables potential and/or land availability. Most countries in this group —including Japan and parts of the EU— are already dependent on energy imports today. Hence, energy dependencies might perpetuate also in the future.

A global transition to low-carbon technologies may not change the geopolitical position of these countries, given that reliance on foreign fossil fuels would simply be replaced with reliance on foreign renewable energy supplies. Thus, for these nations, the energy sector may not yield the geopolitical gains suggested by some scholars.

Because several Group 3 nations are leading in global decarbonization efforts, new domestic regulations might give them a head-start on growing their renewable hydrogen systems and sectors. In turn, this market opportunity may spur significant renewable hydrogen investments in Group 1 countries (see the Japan-Australia trade arrangements in the Group 3 Case Study).

Group 4: Resource-rich nations with high infrastructure potential

Countries in Group 4 have the renewable and freshwater resources potential to satisfy their renewable hydrogen demand through domestic production. While these countries are potentially self-sufficient, they may still complement domestic production with imports due to cost considerations. Hence, nations in Group 4 are typically faced with a make-or-buy decision.

EU member states in Group 4, such as Spain and France, have the potential to develop their renewable hydrogen industries beyond domestic production needs and thus to export surpluses to neighboring countries. While these nations lack the renewable resources potential to become major global export champions, they could still thrive as regional exporters. Taking this scenario

[25] According to the Food and Agriculture Organization of the United Nations (FAO) the renewable water resources per capita vary from less than 500 m^3/year in the Huai and Hai-Luan river basins in Northern China, to over 25,000 m^3/year in river basins in South-West China. (FAO (2011) Country profile China. Water resources. http://www.fao.org/nr/water/aquastat/countries_regions/CHN/index.stm)

into consideration, as a whole the EU could have the potential to meet most of its hydrogen demand internally.

Group 3 Case Study: Japan

- In 2017, aiming to mitigate climate change and increase energy security, Japan announced its goal to develop into a “hydrogen-based society” (Ministerial Council on Renewable Energy, 2017).
- According to the government’s plans, renewable hydrogen will make a significant contribution to reducing Japan’s carbon emissions from power generation, transportation, heating, and industrial applications. Furthermore, the introduction of hydrogen is seen as a means of diversifying supply sources, which fundamentally increases energy security for the country.
- Japan intends to build a global supply chain that can produce and deliver large amounts of hydrogen produced inexpensively in foreign countries. Japan aims to lead hydrogen projects in producing countries, and it is developing long term supply agreements like existing LNG contracts.
- Japan is currently carrying out three pilot projects on hydrogen: one in the Fukushima Prefecture and two international ones in Brunei (based on natural gas) and one in Australia (based on coal with CCS).
- The Fukushima Prefecture plant, designed to produce up to 900 tons of hydrogen per year, will be one of the world’s largest renewable hydrogen production plants and it will be powered by solar generated electricity (Japan Times, 2018).
- By 2030, the Japanese Basic Hydrogen Strategy aims to increase the country’s commercial hydrogen supply chain capacity to 300,000 tons per year and lower production costs to $3 USD/kg. By the same year, the number of fuel-cell electric vehicles in Japan is planned to reach 800,000 from today’s approximate 2,500 (Ministerial Council on Renewable Energy, 2017).
- The 2020 Summer Olympics will take place in Tokyo from July 24-August 9, granting Japan massive international exposure. The Japanese government plans to showcase the advantages of its hydrogen technologies throughout the games.

Group 5: Resource-rich countries with low infrastructure potential

Countries in Group 5 have vast access to renewable resources but are likely unable to build the required infrastructure for the production, transmission, and distribution of renewable energy. The larger the geographical extension of a country, the more complex and costly it is to deploy a cohesive national infrastructure. Therefore, a likely path forward for these countries is hydrogen production at smaller off-grid sites. While these off-grid solutions cannot benefit from large-scale economies, they might still be the most effective solution given the infrastructure constraints.

India exemplifies this: due to its infrastructure challenges throughout the vast subcontinent the country spans, India will likely employ a mix of off-grid and large-scale grid solutions to produce renewable hydrogen. To support the extremely dense populations in certain regions, India might also need to import large quantities of hydrogen. Therefore, our analysis considers India as partly resource-constrained with low infrastructure potential.

Another example in this Group, Russia, is considered partly infrastructure-constrained due to its Global Competitiveness Index score falling below the discussed threshold. However, one could argue that Russia's extensive energy infrastructure demonstrates its potential to build also the required hydrogen infrastructure. However, Russia's existing infrastructure was largely made possible by its exceptional low natural gas and oil production costs (Gustafson, 2020). It is unlikely that Russia could achieve such favorable conditions in renewable hydrogen markets: while the country's vast extension could support large-scale production of renewable energy, comparably low solar radiation and wind speeds limit Russia's chances of becoming cost-competitive. Figure 5.8 depicts the country classification in Groups 1 to 5.

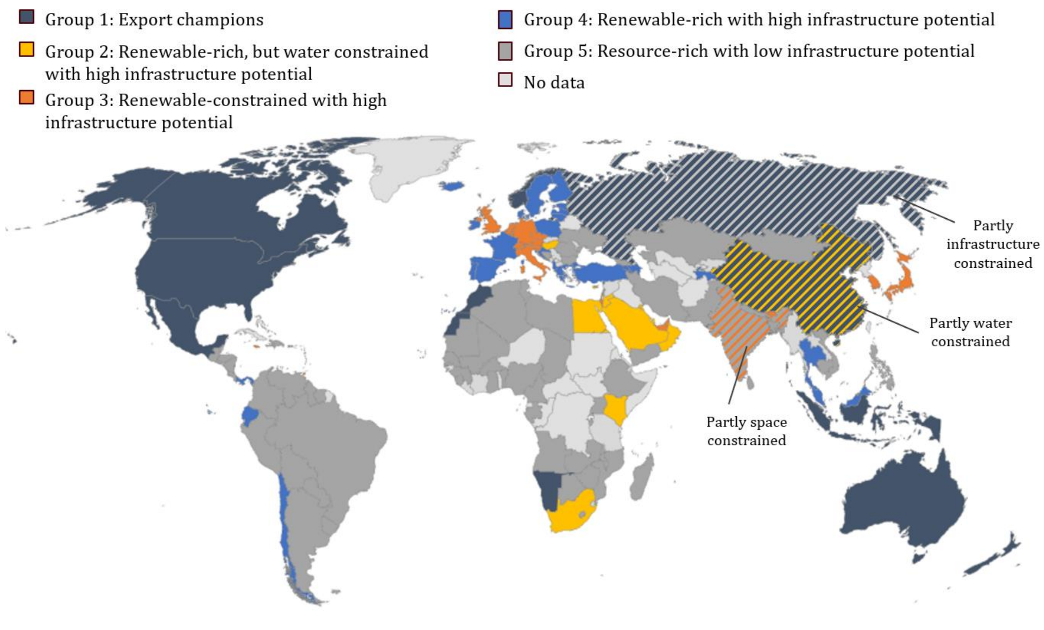


Figure 5.8 The global renewable hydrogen map.

5.6 Geopolitical implications of renewable hydrogen markets

In a low carbon future, geopolitical dynamics will depend not only on energy systems and markets dynamics, but also on which energy sources will dominate the energy mix. A separate analysis is therefore necessary for the geopolitical implications of renewable hydrogen, given its unique physical characteristics, value chain structure and applications.

Resource-specific geopolitical tensions are well-documented in conventional energy markets, frequently centering around oil (e.g. the OPEC oil embargo in 1973) and/or natural gas (e.g. the Russia-Ukraine gas dispute in 2006).

On the other hand, few examples have centered around coal as coal markets are either domestic or regional due its high transportation costs. Furthermore, high-energy-consuming countries like the United States usually produce enough coal to meet needs domestically, which limits the growth of international markets (BP, 2019). Coal is also mainly used for heat and/or electricity generation, and thus it can be easily substituted with other energy sources like natural gas. On top of these considerations, market choices of coal exporting countries are rarely driven by geopolitical concerns. One rare example was China's decision to establish de-facto ban on Australian coal imports in 2019, possibly to bolster domestic trade[26].

In the same way conventional energy sources need to be evaluated individually, renewable hydrogen must be assessed separately from renewable electricity. The geopolitical implications of rising renewable electricity adoption will not translate accurately to the geopolitics of renewable hydrogen. From some angles, it is our opinion that the geopolitics of renewable hydrogen would compare more closely to the international dynamics of conventional energy carriers, like natural gas, than to renewable electricity.

Geopolitical realities of renewable hydrogen

As discussed, today's geopolitical tensions often link to energy: resource abundance creates geopolitical influence, while lack of resources reveals vulnerability. Consequently, unequal access to resources often serves as a catalyst for international conflict. Natural oil reserves are highly concentrated in specific parts of the world: five countries account for over 60% of total oil reserves (BP, 2019). Renewable resources, however, are found around the globe, presenting an opportunity to disrupt the hegemony of these resource-rich states and "democratize" the energy landscape (Casertano, 2012).

[26] In February 2019 China set quotas for coal imports from Australia after several political disputes including disregarding Huawei as supplier for 5G broadband technology and denying visa to an important Chinese business traveler. See Reuters (2019)

Virtually every country has some access to renewable resources (e.g., solar and/or wind power), and could thus increase its energy security by reducing energy imports in favor of domestic production. In fact, current investment strategies in renewables indicate that countries tend to prioritize domestic energy security and hence local renewable deployment even if international cooperation and efficient allocation of renewable resources could lower overall energy costs[27]. Even for countries within close-knit political alliances like the EU, renewable investments usually serve national agendas rather than optimizing collective outcomes.

For the renewable hydrogen industry, future levels of regional concentration will be determined by global market structures, technological advancements, and infrastructure development. As illustrated in section 5 of this essay, countries will assume specific roles based on their renewable and freshwater resource endowment and infrastructure potential.

Several countries identified as candidates to become renewable hydrogen "export champions," such as the U.S. and Australia, are pivotal players in today's energy system. On the other hand, some of today's conventional energy exporters, like the oil-heavy yet water-constrained Saudi Arabia, might be prevented from replicating their influence due to limited resource endowment. In contrast from today's fragile authoritarian states dominating the oil trade, the countries we have identified as potential hydrogen export champions are largely secure market economies. Thus, the reshuffling of power could significantly boost stability throughout global energy markets.

It is almost certain that the Middle East would play a less prominent role in renewable hydrogen markets than it occupies in today's oil markets. As a result, international political interest in the region could deteriorate, shifting to regions like North Africa with rich renewable resources. One could argue that less global meddling in the Middle East would lessen conflict in the area. But considering that fossil fuels exports are a vital source of government revenue for Middle Eastern oil states, shrinking economic relevance could easily destabilize the region further.

For Group 3 countries that would need to import renewable hydrogen, geopolitical opportunities might see little change. Parts of the EU, Japan, and South Korea are RES-constrained, perpetuating dependency on foreign energy. On the contrary, some Group 4 European nations currently dependent on imports could meet renewable hydrogen demands internally and eventually develop into regional energy exporters. Such countries might grow increasingly influential in regional energy geopolitics. For example, due to their resource endowment and importance as

[27] Connecting electricity grids across national borders could help to smooth variations in renewable generation, as well as balance demand peaks due to differences in electricity use

transit hubs for imports from North Africa, Spain and other European Group 4 member states could assume a greater role within EU's energy hierarchy.

New alliances

One of the main reasons why renewable electricity is expected to reduce geopolitical tensions is the reciprocity of trade. With increasing interconnection of transmission lines and the subsequent build-up of regional electric *supergrids,* countries are becoming increasingly interdependent thus reducing the risk of geopolitical tensions (Scholten & Bosman, 2016). Electricity interconnection is especially beneficial if generation profiles are complementary. For example, one country may have a suitable topology for wind generation, while another may have a vast landmass and high solar penetration (Ochoa & Ackere, 2015). Coupling such markets would be economically appealing for both sides, but such extensive cooperation would result in codependence. This trade reciprocity may ultimately reduce the risk of geopolitical power plays by any one participant.

These equitable dynamics could prove different for renewable hydrogen: if hydrogen is produced where resources are most abundant and costs the cheapest, the supply flow could become one-sided, designating countries as either importers or exporters. Under this circumstance, the geopolitics of energy may continue to revolve around access to resources, security of supply, supplier rents and transportation disputes.

However, new alliances and trade relationships could emerge between export champions in Group 1 and import states in Group 3. For instance, Australia might deepen its trade relationships with countries in Southeast Asia, particularly Japan and South Korea. European hydrogen demand might come to rely on exports from North Africa or North America. While increased cooperation with North Africa would fit into the European Neighborhood Policy to foster stabilization, security and prosperity in the region (European Union External Action, 2016), it would also increase EU relations with more fragile trade partners. Alternately, increasing energy trade with North America would strengthen the transatlantic partnership, but those diplomatic benefits would be accompanied by higher supply costs.

Especially in the case of Europe, these new trade relationships would result in a profound geopolitical shift. For decades, Russia has been by far EU's main supplier of natural gas and oil, accounting for 40.5% and 27.3% of extra-EU imports in 2018 (Eurostat, 2019c). These trade dynamics exert considerable influence on EU's relations with Russia, and despite EU's efforts to reduce its energy dependency, Russian imports have increased in recent years. While Russia could leverage its vast geography for large-scale renewable energy production, comparably low solar radiation and wind speeds limit its ability to be cost-competitive. Therefore a transition to a low carbon economy is likely to reduce EU's energy dependency on Russia, while, at the same time new dependencies on renewable hydrogen exporters might emerge.

New game – old rules?

Despite their dominant market power, energy exporters usually prefer not to simply cut off supplies, as they depend on the associated revenues to fund their extensive government programs. Nevertheless, many countries have used and use energy as a geopolitical weapon to serve their agendas, and this could perpetuate also with renewable hydrogen.

Pascual (2015) provides a comprehensive overview of possible market interventions to influence energy markets and serve national interests. Several of these interventions—such as constraining production capacity, flooding markets, and/or starving markets—could be similarly exercised if hydrogen production becomes highly concentrated.

Similarly, geopolitical defensive strategies aimed at protecting a nation's energy security could work for renewable hydrogen: such as fuel-switching, forced load shedding for industrial customers, and building strategic reserves. As with natural gas, a strategic reserve of hydrogen could keep a country from running dry even during longer supply interruptions[28]. Finally, supply diversification would be needed to reduce the risk of politically driven supply disruptions and increase a country's energy security.

Furthermore, renewable hydrogen infrastructure would be prone to the same geopolitical threats as those faced by oil and gas. For example, in the case of oil markets, the Strait of Hormuz is of paramount importance, with over 20% of global oil trades passing through it (EIA, 2019a). The Strait of Hormuz could remain highly relevant also in a low carbon economy, if renewable hydrogen produced in the Middle East were to be exported.

Transporting renewable hydrogen from North Africa to Europe using pipelines faces the same geopolitical uncertainties as the current system transporting natural gas. However, new supply routes (e.g., between Australia and/or Southeast Asia) could also pose geopolitical risks. In this case the main shipping routes would likely run through the East China Sea, which regularly draws international attention due to territorial disputes between China and Japan, yet with less media scrutiny than the multi-stakeholder dispute in the South China Sea (Chandran, 2019).

Impact of conflicts

The recent drone attack on Saudi Arabia's oil infrastructure illustrates the global impact of oil supply interruptions. After the attack, oil prices soared worldwide, amounting to the sharpest

[28] For instance, Spain obliges natural gas and liquified petroleum gas operators to maintain minimum stocks equivalent to 20 days of consumption in underground storages

increase in 30 years (Wearden, 2019). On the other hand, natural gas disruptions due to the intrinsic regional nature of natural gas markets tend to be more geographically contained. Russia's gas cut-off to Ukraine in 2006 which mainly affected European supply, with little effect on prices and supply beyond the continent, exemplifies this.

The potential impact of hydrogen supply disruptions depends on how global hydrogen markets will become. If renewable hydrogen were to be adopted at scale, we believe that future market dynamics will resemble today's regional natural gas markets—with corresponding potential for similar geopolitical conflicts. At the same time, regional markets negatively affect a country's energy security by reducing options to diversify supply and find alternatives in the case of disruptions. This is particularly true if hydrogen were to be shipped mainly via pipeline and alternative infrastructure was not available.

Finally, we must also consider the extent to which critical infrastructure and key economic sectors are reliant on hydrogen. As stated in the technological analysis in section 3, many industrial applications are likely to be directly electrified; a breakdown in the transmission grid could thus have a more devastating impact than interruptions to hydrogen supplies. However, if hydrogen were also to be used in power generation, supply disruptions would immediately impact the grid and affect all customers. In the case of hydrogen supply, disruptions would have a more delayed impact as shorter interruptions could be buffered with supplies from reserves and/or fuel switching.

5.7 Policy and commercial options

We believe only a deeper understanding of these nascent dynamics will allow policy makers and investors to better navigate the challenges and opportunities of a low carbon economy without falling into the traps and inefficiencies of the past. Based on the considerations outlined in the previous sections, it becomes clear that policymakers, investors and other stakeholders need to assess the economic, environmental, and geopolitical implications of renewable hydrogen, develop strategies to address them and define implementation plans. In the following section, we outline some of the key policy and commercial options for each group of countries:

Export champions with vast renewable energy and water resources, as well as high infrastructure potential (Group 1):

"Export champion" nations may define policies to trigger renewable hydrogen infrastructure investments, thus paving the way for a dominating position in future markets. A key obstacle would be sustaining RES deployment rates high enough to achieve the needed scale. For instance, supplying 5% or 2 EJ of future global hydrogen markets in 2050, would require countries to deploy more than 100 gigawatts of dedicated renewable capacity, even under favorable generating conditions.

Furthermore, targeted federal policies could help to lower market risk and address commercialization barriers. Since the renewable hydrogen industry is still nascent, countries may start by focusing funding on innovation and/or pilot projects. Such policies could contribute to achieve the required economies scale, and eventually to reach the tipping point at which renewable hydrogen technologies become cost competitive. We believe policy efforts to reduce market risks as well as direct government support are key to secure the necessary private investments needed for commercialization at scale.

Because of their potential dominant positioning in renewable energy markets, Group 1 countries are more likely than their peers to become international advocates for a hydrogen-fueled future. In addition, clear international regulations and standards on renewable hydrogen production, transportation and "green certification" would open the gates for trade at scale. This could be achieved by establishing international agencies responsible for developing these standards and working with national regulatory bodies to facilitate implementation (IRENA, 2019a). Internally, countries may also revisit their own regulatory frameworks to ensure that oversight is streamlined for new hydrogen regulations.

Renewable-rich but water-constrained nations with high infrastructure potential (Group 2):

Renewable-rich countries scarce in water resources must address two questions: how many water resources to allocate for renewable hydrogen production, and whether it makes economic sense to try to compete with Group 1 countries. Strategic investments in desalination capacity would be key to address water scarcity issues.

If other forms of water consumption need to be prioritized over renewable hydrogen production, these countries will need to assess how to best meet their domestic renewable hydrogen needs. Like countries in Group 3, Group 2 countries may initiate trade partnerships and devise strategies to secure diversified hydrogen supplies.

Renewable-constrained nations with high infrastructure potential (Group 3):

Import countries in Group 3 may set policies to stimulate local renewable hydrogen markets focusing on their climate policy goals (e.g., by defining blend-in quotas for gas grids). Transparent regulations and long-term investments in hydrogen infrastructure would send strong signals to investors in countries in Group 1, thus spurring their investments in renewable hydrogen production capacity. Long-term contracts and direct investment by Group 3 countries would further help to reduce market risk for producers.

Furthermore, countries within this group may cooperate with exporting champions to establish international standards for renewable hydrogen production, transportation and use.

In order to mitigate dependencies, and increase national energy security, governments in importing countries need to define clear long-term hydrogen development and deployment strategies including options to diversify supply. Specific policies should then be implemented to catalyze investment in partner countries to build a diversified supply base. These analyses should also entail a strategic decision if hydrogen is to be transported via pipelines or by shipping. While pipelines present economic advantages for imports from countries in proximity, pipelines are highly inflexible and the option to shift to different suppliers very limited.

Resource-rich nations with high infrastructure potential (Group 4):

Countries in Group 4 face similar policy options as those in Group 1. The primary goal may be to establish a domestic renewable hydrogen industry able to supply internal demand. Beyond minimizing energy imports, policies that support RES deployment; establish enabling market conditions for renewable hydrogen; provide funding for research and commercialization; and remove regulatory hurdles are the key goals for Group 4.

Insufficient investment in the domestic renewable hydrogen industry could lead to a scenario in which Group 4 countries cannot produce renewable hydrogen at competitive prices due to lack of technology, infrastructure and/or talent; and therefore depend on imports to meet demand.

On the other hand, if the national hydrogen industry thrives, Group 4 countries could decide to invest in becoming a regional supplier. Regional trade could be an important pillar for the future EU energy security strategy: import-dependent EU countries could cooperate directly with potential suppliers within the EU rather than relying on export champions beyond the EU.

Resource-rich countries with low infrastructure potential (Group 5):

Countries in group 5 lack the capability to build and maintain large-scale hydrogen infrastructures: a serious roadblock for development. Policymakers therefore need to address this fundamental challenge. Two general options should be considered: 1) investing in cohesive nation-wide energy and water infrastructure and/or 2) developing distributed off-grid solutions.

Taking into consideration local energy needs, natural resource endowments, access to capital, and existing infrastructure a combination of both options will likely prove the most efficient and cost-effective solution for Group 5 countries.

Policies could focus on catalyzing foreign investments in infrastructure projects. Nations should reduce investment risk through well-designed laws and regulations, efficient federal administrations, effective law enforcement, and strong institutions. Furthermore, governments should focus on bringing foreign investors, project developers, and local communities together to develop off-grid hydrogen production capacity.

5.8 Conclusion

In order to accelerate a global transition to a low-carbon economy, all energy systems and sectors (power, mobility, buildings, and industry) must undergo deep decarbonization. This process will likely require the deployment of clean energy carriers at scale beyond electricity. Renewable hydrogen, with its variety of potential applications, is emerging as a flexible option and its presence rapidly expanding in policies and projects around the world. But taking full advantage of this political and business momentum will require scaling technologies; reducing costs significantly; deploying enabling infrastructure; and defining appropriate policies and market structures. Since renewable hydrogen could serve as an important piece in the global carbon-free energy puzzle (capturing up to 14% of the future global energy markets), it is essential to explore its geopolitical and market implications. We believe a deeper understanding of these nascent dynamics will allow policy makers and investors to better navigate the challenges and opportunities of the transition to a low carbon economy without falling into the traps and inefficiencies of the past.

A successful wide-scale integration of renewable hydrogen will depend on two main factors: competitiveness of production costs and deployment of enabling infrastructure at scale. Currently, renewable hydrogen production is around 2-3 times more expensive than hydrogen production from fossil fuels. However, there are several strategies that could help increase its competitiveness, namely technology improvements, cost reductions along the entire value chain, and/or carbon pricing. If renewable hydrogen were to be adopted at scale, we believe that future market dynamics will resemble today’s regional natural gas markets—with corresponding potential for similar geopolitical conflicts.

This paper explores the general principles of how hydrogen may reshape the structure of global energy markets and the geopolitical game between countries. To do so we propose an analytical framework, using renewable hydrogen as our case study. In order to evaluate the role nations are likely to assume in future renewable hydrogen systems, we developed a methodology to analyze a country’s renewable hydrogen potential based on three parameters: (1) renewable energy resources (RES) endowment; (2) renewable water resource endowment; and (3) infrastructure potential, defined as a nation's capacity to build and operate renewable hydrogen production, transportation and distribution infrastructure.

Our analysis shows that future geopolitical realities of resource-poor countries in Europe and Southeast Asia might be very similar to today's situation, as energy import dependencies may continue. The world may also witness an emergence of new energy export champions—such as Australia and Morocco—due to their superior cost positions and access to large import markets. These countries should start by implementing policies to trigger innovation and infrastructure investments thus paving the way for dominant positioning in future hydrogen markets. At the same time sustaining high renewable deployment rates will be key to achieve the needed scale. Targeted federal policies could help to lower market risk and address commercialization barriers. On the other hand, importing countries should facilitate cooperation with exporting countries to establish international standards for renewable hydrogen production, transportation and use. In order to increase their energy security governments in importing countries would also need to define long-term hydrogen strategies including options to diversify supply. Furthermore, our analysis shows that it is almost certain that the Middle East would play a less prominent role in renewable hydrogen markets than it occupies in today's oil markets. As a result, international political interest in the region could deteriorate, shifting to regions like North Africa with rich renewable resources.

Beyond the direct scope of our analysis, we have identified several adjacent research topics in need of further academic analysis. Potential areas include, but are not limited to:

- Applying our analytical framework to other production technologies and/or renewable energy sources. In particular, the analysis of hybrid global energy systems, which utilize a mix of renewable and conventional energy sources, could yield interesting insights (e.g., with respect to blending renewable hydrogen into the natural gas infrastructure).
- Examining the transition to low-carbon energy systems and assess implications for various nations. This analysis could also identify important decision points and possible barriers to large-scale adoption of renewable hydrogen. Further research could address questions such as: How would the geopolitical landscape change during this transition? What factors would be key to which phases of the transition process (e.g., if renewable hydrogen is at 30% of its market potential compared to 85%)?
- Carrying out a geographically focused review of the implications of renewable hydrogen adoption at scale; for example, by focusing on selected countries and/or regions. Such an analysis could focus on heterogeneous or geopolitically complex regions, for instance Europe, North Africa or Southeast Asia.

6 | Conclusion

6.1. Summary of research findings

In this dissertation, I examine new challenges of the transition to a low-carbon economy at the intersection of energy and security. The first essay broadens the understanding of how multi-year fluctuations of RES generation can affect the security of supply in highly renewable energy systems. The findings suggest that multi-year RES variability has a significant influence on security of supply and that insufficient representation of this variability in energy modeling greatly underestimates the associated supply risk, as the flexibility required to buffer low RES generation is not accounted for. This has a direct implication for energy research: if possible, multi-year time series should be used to capture the full impact of multi-year weather variability; or else, at least a deliberate choice should be made regarding the year of observation. Using a randomly-chosen year or simply the most recent data may adversely affect the robustness of results. Moreover, the findings of the essay demonstrate that ensuring security of supply will be of growing importance for energy policy in light of soaring RES deployment. Furthermore, the results raise the question if the current set of instruments can sufficiently address the security of supply risks associated with multi-year RES variability or if further policy instruments (such as capacity remuneration) are required.

In the second essay I investigate the benefits of cooperation on European level with regard to security of supply and identify potential roadblocks for countries to agree to a more cooperative security of supply strategy. I demonstrate that different national security of supply strategies influence future electricity costs, security levels and spatial distribution of capacity. The results show that ensuring security of supply on collective European level has significant advantages: in terms of system cost, the collective security strategy dominates while preserving high average security levels. However, the advantages of cooperation are unequally distributed among the countries. In terms of electricity prices countries with very low generation costs are better off with a less cooperative security of supply strategy. Furthermore, while most countries experience no supply interruptions in a collective security strategy, a few countries face significant supply shortages. Also, the uneven distribution of capacity in a collective security strategy might contradict national renewable expansion plans and national self-perception. In order to realize the benefits of collective security, these challenges need to be addressed.

Developing a truly European electricity system, which is characterized by true solidarity and trust, as envisioned by the European Commission, requires significant commitments from member states and is likely to face local resistance, as cost and benefits are unequally shared among the member states. The policy implication is clear: a wide-ranging political debate both on the EU- as well as on member state level is required, which should ultimately result in a transparent and fair set of regulations, as well as clear, consistent and long-reaching political commitment by the member states.

The third essay explores the energy-related geopolitical influence within the European Economic Area and sheds light on how the energy transition might shift the power balance among the countries going forward. The essay contributes to the ongoing academic discussion on the geopolitical implications of the energy transition. The results show that energy-related geopolitical influence was centered in five Northern European countries (Germany, France, the Netherlands, Norway and the United Kingdom) in the early 2000s, however their hegemony has deteriorated over the following two decades. The ongoing energy transition could further alter the energy-related geopolitical balance on the continent: import dependent countries in Southern and Eastern Europe, as well as island states, are likely to be among the winners of the shift to renewables. However, the geopolitical realities in Europe will not resemble a multi-polar world, as clear differences are likely to persist in the ability to become energy self-sufficient. Furthermore, pivotal geographical positioning will remain one of the key factors for energy-related geopolitical influence.

A deeper understanding of how the energy transition affects energy-related geopolitical influence enables policy makers, investors and other stakeholder to navigate in a new world of energy conflicts and cooperation. Furthermore, it can assist policy makers to address potential conflicts of interest and take informed decisions on policy instruments. Especially, European energy policy needs to reflect the interests of potential losers of the transition process, such as Poland, in order to ensure that these countries do not turn against the joint climate targets to protect national interests. The results of this essay furthermore illustrate that the academic discussion on geopolitics of renewables need to develop from high-level narratives ('fossil-fuels vs. renewables') to a more differentiated and nuanced analysis.

In the fourth essay my co-author Dr. Nicola de Blasio and I explore general principles of how hydrogen may reshape the structure of global energy markets and the geopolitical game between countries. The research project proposes a novel analytical framework that assesses the role a country could play in the future renewable hydrogen market based on its renewable energy resource and freshwater endowment, as well as infrastructure potential, defined as a nation's capacity to build and operate renewable hydrogen production, transportation and distribution infrastructure.

The analysis shows that countries are very likely to assume specific roles in the future global hydrogen market, which characterize them as exporting or importing nations. Countries with constrained resources or limited land availability, such as Japan and some countries in Central Europe, are very likely to rely on energy imports also in the future. Thus, for these nations, the transition to low-carbon technologies may not yield the geopolitical gains suggested by some scholars. Even for countries with high domestic production potential, imports could still be an attractive alternative to local supply, as favorable production conditions in exporting countries may outweigh transportation costs.

Furthermore, the emergence of new energy export champions—such as Australia and Morocco—seems plausible due to their superior cost positions and access to large import markets. These countries may start to implement policies to trigger innovation and infrastructure investments thus paving the way for their dominant positioning in future hydrogen markets. However, sustaining high renewable deployment rates will be key to achieve the needed scale. Targeted federal policies could help to lower market risk and address commercialization barriers. On the other hand, importing countries should facilitate cooperation with exporting countries to establish international standards for renewable hydrogen production, transportation and use. In order to increase energy security, governments in importing countries would also need to define long-term hydrogen strategies including options to diversify renewable hydrogen supply. A deeper understanding of these nascent dynamics will allow policy makers and investors to better navigate the challenges and opportunities of a low-carbon economy and understand their options for actions with regard to market structure design, technology funding and energy infrastructure investments.

6.2. Avenues for further research

These research findings are bound to the methodologies applied and thus have their limitations. For instance, the energy system models employed in the first two essays are restricted to the electricity sector. Further research could therefore explore how coupling electricity, transport and heat sectors would affect the results. Sector coupling could help to smooth renewable generation (e.g. grid-to-vehicle solutions), while on the other hand the system imbalances might increase, for example due to the seasonal demand profile in the residential heat sector. Another interesting aspect worthwhile studying is the weather impact on demand, as temperatures affect electricity and heat demand.

The analysis on security of supply strategies could be extended by modelling individual policy instruments in detail. Modelling specific mechanisms of policy instruments, variations in implementation on national level and potential side-effects of policies could help to better understand the influence of security of supply strategies on the future electricity system design. Moreover, further research could test the theoretical frameworks outlined in essays I-III. Especially event-related research that studies the outcome of concrete energy policy decisions on European level could help to further verify and refine the model-based results.

The analytical framework proposed in essay IV could be extended to hybrid global energy systems, which utilize a mix of renewable and conventional energy sources. Furthermore, examining different stages within the transition period to low-carbon energy systems and assessing implications for various stakeholders could yield interesting insights. This analysis could also identify important decision points and possible barriers to large-scale adoption of renewable hydrogen.

We only start to understand how the transition to a low-carbon economy influences our global community in terms of energy security, wealth distribution and political power. The energy transition has not only the potential to protect human kind from the adverse impact of climate change, but also to create a world, in which energy resources are more fairly distributed and, as a consequence, a world in which less conflicts over energy occur. Or how the former US congressman Dennis Kucinich described the sustainable energy future: *"It is time for a sustainable energy policy which puts consumers, the environment, human health, and peace first"* (Sep 27, 2005). However, the road ahead is uncertain, and many challenges need to be addressed along the way. Hence, the discussion on the decarbonization pathways will most likely intensify in the upcoming years. This dissertation contributes to the ongoing academic and political debate by broadening our understanding of how the transition to a low-carbon economy impacts the energy-security nexus.

6 | Appendix

Appendix A. Overview of Value of lost load studies

Authors	Country/ Region	Year	Combined estimate for VoLL (EUR/KWh)	Sector-specific estimates for VoLL (EUR/KWh)[29]
Bliem (2005)	Austria	2004	8.1	Agriculture: 3.7 Construction industry: 48.1 Production: 2.4 Service: 10.5 Households: 18.1
Fischer, Kubis, Greve, and Rehtanz (2012)	Germany	2011	12.88	-
Growitsch, Malischek, Nick, and Wetzel (2013)	Germany	2007	-	Agriculture: 2.49 Manufacturing: 2.19 Construction: 102.93 Services: 11.04 Households: 11.92
Röpke (2013)	Germany	2008-2010	12.51	Agriculture:2.22 Industry: 2.81 Public Administration: 6.50 Trade and Services: 15.37 Transport: 7.61 Households: 15.05
Praktiknjo (2016)	Germany	2007	-	Primary sector: 5.46 Secondary sector: 3.33 Tertiary sector: 17.32
CEPA (2018)	Germany (and other European countries)	2015	12.41	Domestic: 12.41 Industry: 0.41-6.09 Service: 8.55

[29] Some studies include even more detailed breakdown in sectors and sub-sectors

Appendix B. Overview of techno-economic assumptions

	Value	Unit	Source
GENERAL			
Carbon price	130	EUR / t	Pape et al. (2014)
Value of lost load (VoLL)	12,400	EUR / MWh	CEPA (2018)
Initial storage level	20%		Own assumption
Value of stored energy	62	EUR / MWh	Own assumption
Interest rate p.a.	4%		Own assumption
CONVENTIONALS			
Hard coal			
Efficiency	46	Percentage	Gerbaulet and Lorenz (2017), International Energy Agency (2015)
Carbon content	0.34	t / MWh	Umweltbundesamt (2018)
Fuel price	23.04	EUR/MWh_{th}	Nitsch et al. (2012), (Schill & Zerrahn, 2018)
Overnight investment cost	1,300	EUR/kW	Schröder et al. (2013)
Technical lifetime	40	Years	International Energy Agency (2015)
Annualized investment costs	66	EUR/kW	
Annual fixed cost	30	EUR/kW	Schröder et al. (2013)
Gas			
Efficiency	60	Percentage	Gerbaulet and Lorenz (2017), International Energy Agency (2015)
Carbon content	0.2	t / MWh	Umweltbundesamt (2018)
Fuel price	38.16	EUR/MWh_{th}	Nitsch et al. (2012), (Schill & Zerrahn, 2018)
Overnight investment cost	880	EUR/kW	Schröder et al. (2013)
Technical lifetime	30	Years	International Energy Agency (2015)
Annualized investment costs	51	EUR/kW	
Annual fixed cost	20	EUR/kW	Schröder et al. (2013)
Waste			
Efficiency	100	Percentage	Gerbaulet and Lorenz (2017)
Carbon content	0.29	t / MWh	Umweltbundesamt (2018)
Fuel price	14.4	EUR/MWh_{th}	Gerbaulet and Lorenz (2017)
Overnight investment cost	1,951	EUR/kW	Gerbaulet and Lorenz (2017)
Technical lifetime	30	Years	Gerbaulet and Lorenz (2017)
Annualized investment costs	113	EUR/kW	
Annual fixed cost	100	EUR/kW	Gerbaulet and Lorenz (2017)

	Value	Unit	Source
RENEWABLES			
Wind onshore			
Overnight investment cost	1,075	EUR/kW	Schröder et al. (2013)
Technical lifetime	25	Years	IRENA (2018c)
Annualized investment costs	69	EUR/kW	
Annual fixed cost	46	EUR/kW	IRENA (2018c), Schröder et al. (2013)
Maximum capacity	200	GW	Frauenhofer IWES (2011)
Wind offshore			
Overnight investment cost	2,093	EUR/kW	Schröder et al. (2013)
Technical lifetime	25	Years	IRENA (2018c)
Annualized investment costs	134	EUR/kW	
Annual fixed cost	76	EUR/kW	IRENA (2018c), Schröder et al. (2013)
Maximum capacity	31.9	GW	Bundesamt für Seeschifffahrt und Hydrographie (2017a), Bundesamt für Seeschifffahrt und Hydrographie (2017b)
Solar PV			
Overnight investment cost	425	EUR/kW	Schröder et al. (2013)
Technical lifetime	25	Years	IRENA (2018c)
Annualized investment costs	27	EUR/kW	
Annual fixed cost	26	EUR/kW	Schröder et al. (2013)
Maximum capacity	400	GW	Frauenhofer IWES (2012)
Biomass			
Efficiency	38	Percentage	Gerbaulet and Lorenz (2017)
Carbon content	0		
Fuel price	14.4	EUR/MWh_{th}	Gerbaulet and Lorenz (2017)
Overnight investment cost	1,951	EUR/kW	Schröder et al. (2013)
Technical lifetime	20	Years	IRENA (2018c)
Annualized investment costs	144	EUR/kW	
Annual fixed cost	100	EUR/kW	Schröder et al. (2013)
Maximum energy	60	TWh	Nitsch et al. (2012)
Run-over-River			
Overnight investment cost	3,000	EUR/kW	Schröder et al. (2013)
Technical lifetime	30	Years	IRENA (2018c)
Annualized investment costs	173	EUR/kW	
Annual fixed cost	75	EUR/kW	IRENA (2018c)
Geothermal			
Overnight investment cost	2,740	EUR/kW	Schröder et al. (2013)
Technical lifetime	25	Years	IRENA (2018c)
Annualized investment costs	175	EUR/kW	
Annual fixed cost	100	EUR/kW	IRENA (2018c)

	Value	Unit	Source
STORAGE - Base Scenario			
Lithium-Ion			
Efficiency	92	Percentage	Pape et al. (2014)
Overnight investment cost - conversion capacity	90	EUR/kW	Agora Energiewende (2014)
Overnight investment cost - storage capacity	400	EUR/kWh	Agora Energiewende (2014)
Technical lifetime	15	Years	Agora Energiewende (2014)
Annualized investment cost - conversion capacity	8	EUR/kW	
Annualized investment cost - storage capacity	36	EUR/kWh	
Annual fixed cost	2%	Percent of Invest	Agora Energiewende (2014)
Pumped storage			
Efficiency	80	Percentage	Pape et al. (2014)
Overnight investment cost - conversion capacity	1,100	EUR/kW	Agora Energiewende (2014)
Overnight investment cost - storage capacity	30	EUR/kWh	Agora Energiewende (2014)
Technical lifetime	60	Years	Agora Energiewende (2014)
Annualized investment cost - conversion capacity	49	EUR/kW	
Annualized investment cost - storage capacity	1.3	EUR/kWh	
Annual fixed cost	2%	Percent of Invest	Agora Energiewende (2014)
Power-to-Gas (without re-conversion to electricity)			
Efficiency	60	Percentage	Pape et al. (2014)
Overnight investment cost - conversion capacity	1,300	EUR/kW	Agora Energiewende (2014)
Overnight investment cost - storage capacity	0.5	EUR/kWh	Agora Energiewende (2014)
Technical lifetime	23	Years	Agora Energiewende (2014)
Annualized investment cost - conversion capacity	88	EUR/kW	
Annualized investment cost - storage capacity	0.03	EUR/kWh	
Annual fixed cost	2%	Percent of Invest	Agora Energiewende (2014)

	Value	Unit	Source
STORAGE - Aggressive Scenario			
Lithium-Ion			
Efficiency	92	Percentage	Pape et al. (2014)
Overnight investment cost - conversion capacity	70	EUR/kW	Pape et al. (2014)
Overnight investment cost - storage capacity	200	EUR/kWh	Pape et al. (2014)
Technical lifetime	15	Years	Agora Energiewende (2014)
Annualized investment cost - conversion capacity	6	EUR/kW	
Annualized investment cost - storage capacity	18	EUR/kWh	
Annual fixed cost	2%	Percent of Invest	Agora Energiewende (2014)
Pumped storage			
Efficiency	80	Percentage	Pape et al. (2014)
Overnight investment cost - conversion capacity	1,100	EUR/kW	Pape et al. (2014)
Overnight investment cost - storage capacity	30	EUR/kWh	Pape et al. (2014)
Technical lifetime	60	Years	Agora Energiewende (2014)
Annualized investment cost - conversion capacity	49	EUR/kW	
Annualized investment cost - storage capacity	1.3	EUR/kWh	
Annual fixed cost	2%	Percent of Invest	Agora Energiewende (2014)
Power-to-Gas (without re-conversion to electricity)			
Efficiency	60	Percentage	Pape et al. (2014)
Overnight investment cost - conversion capacity	800	EUR/kW	Pape et al. (2014)
Overnight investment cost - storage capacity	0.1	EUR/kWh	Pape et al. (2014)
Technical lifetime	23	Years	Agora Energiewende (2014)
Annualized investment cost - conversion capacity	54	EUR/kW	
Annualized investment cost - storage capacity	0.01	EUR/kWh	
Annual fixed cost	2%	Percent of Invest	Agora Energiewende (2014)

Appendix C. Results of sensitivity analysis of valuation of stored energy (first optimization stage)

Value of stored energy (in EUR/ MWh)	Installed capacity based on first optimization stage						
	Wind on-shore (in GW)	Wind off-shore (in GW)	Solar PV (in GW)	Short-term storage conversion capacity (in GW)	Short-term storage capacity (in GWh)	Long-term storage conversion capacity (in GW)	Long-term storage capacity (in TWh)
0.01	105.5	31.5	134.0	37.4	225.0	18.3	23.4
1	105.5	31.5	134.0	37.4	225.0	18.3	23.4
10	105.5	31.5	134.0	37.4	225.0	18.3	23.4
20	105.5	31.5	134.0	37.4	225.0	18.3	23.4
30	105.5	31.5	134.0	37.4	225.0	18.3	23.4
40	105.5	31.5	134.5	37.4	224.8	18.7	22.8
50	106.1	31.9	134.9	37.4	223.7	19.3	20.8
60	106.1	31.9	135.2	37.4	223.7	19.2	20.9
70	106.0	31.9	135.1	37.4	223.8	19.2	21.0
80	105.9	31.9	135.3	37.4	224.0	19.2	21.0
90	105.6	31.9	135.7	37.8	224.9	19.2	21.0
100	105.5	31.9	135.9	37.9	225.0	19.2	21.1

Appendix D. Detailed assumptions on technological parameters and cost

	Value	Unit	Source
GENERAL			
Interest rate	4%		Own assumption
TRANSMISSION (NTC)			
Efficiency	100	in percent/ 1,000km	Own assumption
Overnight investment cost	1000	EUR/MWkm	Osorioa et al. (2018)
Technical lifetime	100	Years	Osorioa et al. (2018)
Annualized investment costs	41	EUR/MWkm	
STORAGE			
Pumped storage and hydro reservoir			
Full-cycle efficiency (pumped storage/hydro)	81/90	in percent	Schröder et al. (2013), Pape et al. (2014), Own assumption
Overnight investment cost - conversion capacity	1100	EUR/kW	Agora Energiewende (2014)
Overnight investment cost - storage capacity*	30/0	EUR/kWh	Schröder et al. (2013), Pape et al. (2014)
Technical lifetime	60	Years	Agora Energiewende (2014)
Annualized investment cost - conversion capacity	49	EUR/kW	
Annualized investment cost - storage capacity	1	EUR/kWh	
Annual fixed cost	2%	Percent of Invest	Agora Energiewende (2014)
Note: Only replacement of turbines assumed after end of technical lifetime			
Power-to-Gas			
Conversion efficiency	60	in percent	Pape et al. (2014)
Overnight investment cost - conversion capacity	1300	EUR/kW	Agora Energiewende (2014)
Overnight investment cost - storage capacity	0.5	EUR/kWh	Agora Energiewende (2014)
Technical lifetime	23	Years	Agora Energiewende (2014)
Annualized investment cost - conversion capacity	88	EUR/kW	
Annualized investment cost - storage capacity	0.03	EUR/kWh	
Annual fixed cost	2%	Percent of Invest	Agora Energiewende (2014)
Initial storage level	50%		Own assumption
CONVENTIONALS			
OCGT			
Efficiency	40	in percent	International Energy Agency (2015)
Carbon price	57	EUR / t	Pape et al. (2014)
Carbon content	0.2	t / MWh_{th}	Umweltbundesamt (2018)
Fuel price	38.16	EUR/MWh_{th}	Zerrahn and Schill (2017)
Overnight investment cost	400	EUR/kW	Schröder et al. (2013)
Technical lifetime	30	Years	Schröder et al. (2013)
Annualized investment costs	23	EUR/kW	
Annual fixed cost	15	EUR/kW	Schröder et al. (2013)

	Value	Unit	Source
RENEWABLES			
Wind onshore			
Overnight investment cost	1075	EUR/kW	Schröder et al. (2013)
Technical lifetime	25	Years	IRENA (2018c)
Annualized investment costs	69	EUR/kW	
Annual fixed cost	46	EUR/kW	IRENA (2018c), Schröder et al. (2013)
Wind offshore			
Overnight investment cost	2093	EUR/kW	Schröder et al. (2013)
Technical lifetime	25	Years	IRENA (2018c)
Annualized investment costs	134	EUR/kW	
Annual fixed cost	76	EUR/kW	IRENA (2018c), Schröder et al. (2013)
Solar PV			
Overnight investment cost	425	EUR/kW	Schröder et al. (2013)
Technical lifetime	25	Years	IRENA (2018c)
Annualized investment costs	27	EUR/kW	
Annual fixed cost	26	EUR/kW	Schröder et al. (2013)
Biomass			
Efficiency	49	in percent	Schröder et al. (2013)
Carbon content	0		
Fuel price	23.03	EUR/MWh_{th}	Zerrahn and Schill (2017)
Overnight investment cost	1951	EUR/kW	Schröder et al. (2013)
Technical lifetime	20	Years	IRENA (2018c)
Annualized investment costs	144	EUR/kW	
Annual fixed cost	100	EUR/kW	Schröder et al. (2013)
Run-over-River			
Overnight investment cost	3000	EUR/kW	Schröder et al. (2013)
Technical lifetime	30	Years	IRENA (2018c)
Annualized investment costs	173	EUR/kW	
Annual fixed cost	75	EUR/kW	IRENA (2018c)

Appendix E. Index scores of the energy-related geopolitical influence in the early 2000s

	First stage: Geopolitical foundations						**Second stage: Transformative capacity**						
	Access to resources		**Access to technology**	**Access to production assets**			**Control over connecting infrastructure**		**Control over dominant market player**		**Control over trade regime**	**Control over own supply**	**Total score (weighted average)**
	Domestic fossil fuel reserves	*Domestic renewable potential*	*Patents in energy technology*	*Generation assets*	*Storage*	*Oil refinery*	*Power interconnector capacity*	*Gas interconnectors and LNG terminal capacity*	*Largest electricity producer*	*Major O&G companies*	*Gross energy exports*	*Import independence*	
Weight	8.3%	8.3%	16.7%	5.6%	5.6%	5.6%	6.3%	6.3%	6.3%	6.3%	12.5%	12.5%	
Belgium	-33	-81	-19	-21	-6	48	30	154	51	-50	13	-99	-11
Bulgaria	-18	-30	-37	-32	-20	-60	-51	-25	-37	-50	-44	22	-29
Czechia	11	-23	-35	-23	-14	-46	44	65	-27	-50	-39	95	-3
Denmark	-28	-30	-22	-34	-66	-49	35	-80	-44	-50	-21	182	-5
Germany	481	-75	489	310	178	305	382	303	-51	58	62	-31	207
Estonia	-32	-40	-37	-64	-66	-80	-62	-82	85	-50	-53	69	-29
Ireland	-33	123	-29	-57	-53	-67	-88	-68	51	-50	-52	-130	-40
Greece	-17	2	-36	-44	-34	-10	-63	-73	99	-50	-15	-58	-27
Spain	-28	68	-17	69	181	145	-26	26	58	177	12	-79	29
France	-32	-14	123	279	281	252	222	51	65	365	10	5	108
Croatia	-33	-46	-37	-70	-53	-80	-38	-83	147	-50	-50	20	-29
Italy	-23	-44	10	144	256	341	84	71	-143	108	12	-108	33
Cyprus	-33	-12	-37	-69	-66	-80	-88	-86	154	-50	-56	-153	-52
Latvia	-33	35	-37	-69	-66	-80	-9	-72	65	-50	-54	-25	-32
Lithuania	-33	74	-37	-55	-31	-39	-35	-72	38	-50	-37	21	-19
Luxembourg	-33	-86	-35	-72	-16	-80	-88	-82	10	-50	-56	-158	-65
Hungary	-27	-30	-36	-42	-66	-43	-22	-36	-78	-31	-45	-5	-36
Malta	-33	-60	-37	-73	-66	-80	-88	-86	154	-50	-56	-166	-58
Netherlands	-11	-84	133	0	-66	136	67	100	-126	256	310	63	83
Austria	-33	-78	-4	-38	116	-46	24	64	-147	9	-32	-45	-21
Poland	212	2	-35	31	13	-15	13	11	-215	-1	-10	147	19
Portugal	-33	-5	-37	-44	-38	-28	-58	-64	-58	-50	-40	-115	-49
Romania	-18	29	-37	-27	-66	-2	-54	-32	51	-50	-43	91	-10
Slovenia	-33	-83	-37	-64	-66	-80	-39	-79	120	-50	-50	6	-36
Slovakia	-33	-76	-36	-49	-24	-59	-34	186	31	-50	-45	-35	-24
Finland	-33	-14	-23	-18	-66	-36	-33	-75	-78	19	-35	-9	-30
Sweden	-33	-19	-16	22	-64	-3	133	-81	10	-50	-14	50	-4
U. Kingdom	2	-13	30	202	62	220	-88	148	17	-50	98	182	68
Iceland	-33	424	-37	-69	-66	-80	-88	-86	-	-50	-56	81	3
Norway	28	185	-34	-24	-4	-28	16	81	-201	48	386	182	76

Appendix F. Index scores of the energy-related geopolitical influence today

	First stage: Geopolitical foundations						Second stage: Transformative capacity						
	Access to resources		**Access to technology**	**Access to production assets**			**Control over connecting infrastructure**		**Control over dominant market player**		**Control over trade regime**	**Control over own supply**	**Total score (weighted average)**
	Domestic fossil fuel reserves	*Domestic renewable potential*	*Patents in energy technology*	*Generation assets*	*Storage*	*Oil refinery*	*Power interconnector capacity*	*Gas interconnectors and LNG terminal capacity*	*Largest electricity producer*	*Major O&G companies*	*Gross energy exports*	*Import independence*	
Weight	8.3%	8.3%	16.7%	5.6%	5.6%	5.6%	6.3%	6.3%	6.3%	6.3%	12.5%	12.5%	
Belgium	-36	-81	-15	-23	-15	51	-41	117	22	-67	13	-92	-20
Bulgaria	-11	-30	-39	-53	-27	-47	-44	-36	60	-67	-44	58	-21
Czechia	-9	-23	-38	-16	-21	-51	85	36	10	-67	-39	75	-5
Denmark	-33	-30	-20	-43	-70	-50	-1	-75	-168	-67	-21	147	-21
Germany	313	-75	478	326	214	267	349	368	50	208	62	-44	208
Estonia	-33	-40	-41	-67	-70	-80	-81	-54	86	-67	-53	175	-17
Ireland	-36	123	-28	-50	-58	-67	-95	-67	79	-67	-52	-65	-31
Greece	-8	2	-41	-34	-41	9	-83	-71	47	-10	-15	-83	-30
Spain	-16	68	-19	144	185	185	73	23	-24	151	12	-76	36
France	-35	-14	148	243	231	131	217	51	108	208	10	19	94
Croatia	-36	-46	-40	-65	-58	-80	-2	-77	105	-67	-50	17	-31
Italy	-22	-44	11	161	239	242	82	52	-159	277	12	-98	37
Cyprus	-36	-12	-40	-69	-70	-80	-100	-81	177	-67	-56	-170	-56
Latvia	-36	35	-41	-69	-70	-80	-62	-66	-97	-67	-54	19	-42
Lithuania	-36	74	-41	-67	-38	-39	-58	-59	-130	-67	-37	-98	-48
Luxembourg	-36	-86	-34	-74	-15	-80	-93	-78	-87	-67	-56	-170	-74
Hungary	-5	-30	-40	-47	-70	-52	42	-44	71	24	-45	-13	-21
Malta	-36	-60	-41	-73	-70	-80	-100	-81	177	-67	-56	-188	-62
Netherlands	-21	-84	135	21	-70	139	-23	155	-71	47	310	24	67
Austria	-36	-78	15	-39	168	-47	166	70	-77	2	-32	-40	-1
Poland	419	2	-37	29	5	18	5	4	-183	162	-10	84	40
Portugal	-36	-5	-38	-39	36	-24	3	-63	24	13	-40	-82	-28
Romania	-28	29	-40	-24	-55	-37	-32	-17	-12	-67	-43	115	-12
Slovenia	-36	-83	-38	-66	-63	-80	-8	-74	136	-67	-50	14	-33
Slovakia	-36	-76	-40	-57	-31	-59	-0	111	29	-67	-45	-27	-29
Finland	-36	-14	-21	-30	-70	-36	-51	-73	-15	13	-35	26	-24
Sweden	-35	-19	-11	11	-66	-3	39	-78	31	-33	-14	78	-4
U. Kingdom	-20	-13	36	158	46	128	-63	131	-39	-67	98	65	40
Iceland	-36	424	-41	-67	-70	-80	-100	-81	-	-67	-56	128	7
Norway	41	185	-38	-19	-5	-22	-25	57	-150	82	386	201	81

Appendix G. Detailed methodological overview

Influencing factor	#	Indicator	Definition	Weight	First year	Last year	Source	Data availability	Category	Methodological notes
First stage: Geopolitical foundations										
Access to resources	1	Domestic fossil fuel reserves	Combined domestic oil, shale oil, natural gas and coal reserves in Terajoule	8.3%	2001	2018	BP (2019), Dyni (2006)	Only significant reserves as identified by BP included for coal, natural gas and oil; Oil and gas available for time series 1990-2018; Coal only for 2001 and 2018	**Conv**	
	2	Domestic renewable potential	Combined domestic renewables potential from wind onshore, offshore, solar PV, CSP and biomass in comparison with gross inland consumption 2017	8.3%	n/a[a]	n/a[a]	NREL (2014), Pietzcker et al. (2014), IRENA (2019c), Osorioa et al. (2018), European Enviornment Agency (2006)	No time series available[a]	RES	Only 'near' sites for wind, solar PV and CSP locations considered, biomass potential beyond 2030 used
Access to technology	3	Patents in energy technology	Number of patent applications with the EPO in the field of 'Electrical machinery, apparatus, energy'	16.7%	2009	2016	European Patent Office (2019)	Time series for 2009-2018 available	Not included	
Access to production assets	4	Generation assets	Installed fossil and renewable availability-adjusted electricity generation capacity in GW	5.6%	2001	2016	Eurostat (2019b), IRENA (2019c)		RES	Availability for renewables based on actual generation in 2016 (based on IRENA); for combustible fuels, nuclear and other fuels availability of 100% assumed
	5	Balancing assets	Installed conversion capacity of hydro storage assets	5.6%	2001	2016	(IRENA, 2019c)		RES	Only including hydro assets as other storage technologies are insignificant
	6	Oil refineries	Installed capacity of oil refining plants in thousand barrels per day	5.6%	2001	2016	BP (2019)	Only countries with significant capacity	Conv	Time series analysis include only refinery capacity online in 2018

[a] Domestic renewable potential does not change over time

Influencing factor	#	Indicator	Definition	Weight	First year	Last year	Source	Data availability	Category	Methodological notes
Second stage: Transformative capacity										
Control over connecting infrastructure	7	Power interconnector capacity	Total power interconnector transfer capacity in MW	6.3%	2006	2016	ACER (2017), ENTSO-E (2018)	2006 and 2016	RES	Only connectors within countries in scope considered (except. Switzerland), for indexation transfer capacity is used in 2016 and due to data availability, the net transfer capacity is used in 2006
	8	Gas interconnectors and LNG terminal capacity	Total gas pipeline interconnector capacity combined with LNG terminal capacity in GWh per day	6.3%	2010	2017	ENTSOG (2018)	2010 and 2017	Conv	
Control over dominant market player	9	Largest electricity producer	Cumulative electricity market share of main generating companies as a percentage of the total generation	6.3%	2009	2017	Eurostat (2019a)	Iceland is missing	RES	Companies are considered as "main" if they produce at least 5% of the national net electricity generation
	10	Major O&G companies	Companies listed in the 'S&P TOP 250 Global Energy Companies' with operations classified as gas exploitation, transmission and trade or listed as multi-utilities	6.3%	2002	2018	S&P Global (2019)		Conv	
Control over trade regime	11	Gross energy exports	Gross energy exports of oil, natural gas, solid fuels and electricity in Terajoule	12.5%	2001	2016	Eurostat (2019e)		Not included	
Control over own supply	12	Import independence	Share of net imports over gross inland consumption	12.5%	2001	2016	Eurostat (2018)		Not included	Import dependence is converted to import independence; values >100% have been capped at 100% (only relevant for Norway)

Appendix H. Classification of countries in leaders, followers, laggards and incumbents

	Pioneers	**Followers**	**Laggards**	**Incumbents**
Criteria: Share of renewable generation over total gross electricity generation	Increase by more than 20 percentage points since 2001	Increase between 10 to 20 percentage points since 2001	Increase by less than 10 percentage points since 2001	Share of more than 50% already in 2001 since 2001
Countries	Denmark	Belgium	Czechia	Austria
	Germany	Bulgaria	France	Sweden
	Ireland	Estonia	Cyprus	Latvia
	Greece	Spain	Hungary	Croatia
	Lithuania	Italy	Netherlands	Iceland
	Portugal	Luxembourg	Slovenia	Norway
	UK	Malta	Slovakia	
		Poland	Czechia	
		Romania		
		Finland		

Source: Based on data by Eurostat (Eurostat, 2019e)

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