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German Energy Transition and Energy Security

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Youngho Chang, Singapore University of Social Sciences, SG
Ridwan D. Rusli, Technische Hochschule Köln, D
& Université du Luxembourg (Extramural Research Fellow)
Jackson Teh, Nanyang Technological University, SG

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For editorial correspondence, please contact: dem@uni.lu
University of Luxembourg
Faculty of Law, Economics and Finance
6, Rue Richard Coudenhove-Kalergi
L-1359 Luxembourg

German Energy Transition and Energy Security

Youngho Chang[1], Ridwan D. Rusli[2] and Jackson Teh[3]

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Abstract

The natural gas supply disruptions and European energy crisis following the Ukraine-Russia war and the West's economic sanctions made energy security a top priority issue for the German government. We use the 4A framework of energy security to analyze Germany's energy transition ("Energiewende") over the last 20 years. While the acceptance of climate change policies is very high among its society and voters, affordability to energy consumers and availability of energy resources have steadily decreased in recent years. High feed-in tariffs and fuel taxes force German households to pay the highest electricity tariffs and among the highest fuel prices worldwide. More of the country's fiscal capacity is required to support energy-intensive industries and fund energy subsidies. Exit from nuclear and coal electricity production necessitates increasing natural gas imports, requiring new LNG terminals, extensive collaboration with European neighbors and partially undermining the environmental benefits of the coal exit. Moreover, growth in renewables capacity has slowed down, hampered in part by local public resistance and increasing bureaucratic hurdles. The technological leadership of the country's multinationals and SMEs has been challenged by increasingly sophisticated and efficient competitors, for example from China. To ensure Germany's energy security the country must accelerate domestic renewables capacity and infrastructure, expand European gas and power interconnector investments and diversify its natural gas supply options.

Keywords: Energy transition; Energy security; 4-A framework; Energiewende; Power interconnector investments; Diversification
JEL Classifications: Q41; Q42; Q48

[1] Singapore University of Social Sciences, yhchang@suss.edu.sg
[2] Technische Hochschule Köln and University of Luxembourg, ridwan.rusli@th-koeln.de
[3] Nanyang Technological University, jacksonteh@ntu.edu.sg

1. Introduction

After two oil shocks, studies on energy security examined supply disruptions and international cooperation (Bohi and Toman, 1986; Murphy et al, 1986) or how alternative fuels such as natural gas could mitigate the negative consequences of oil crisis (Schlesinger et al, 1982). Following the collapse of world oil prices in 1986, the U.S. Department of Energy published a comprehensive report on Energy Security responding to then concerns mainly about increasing import dependence (Singer, 1988). Whether and how physical availability in domestic and foreign source would affect the security of supply has been the focus of studies of energy security (Hartley and Medlock, 2009; Holz et al, 2009; LaCasse and Plourde, 1995; Lichtblau, 1994; Chester, 2010; Sovacool and Brown, 2010; Sovacool et al, 2011; Vivoda, 2010). Electricity and hydrogen were expected to be the main final energy while nuclear energy and renewable energy resources are expected to be the main primary energy (Matsui, 1998). Political openness, whether political regimes are democratic or not, appeared to affect the decision of oil supply within the borders of an oil-producing country (Metcalf and Wolfram, 2015).

Energy security can be defined as the adequate and reliable supply of energy resources at a reasonable price (c.f., Yergin, 1988; Bielecki, 2002; Energy Commission Annual Report, 2013; Yao and Chang, 2014; Tongsopit et al, 2016). Following this definition, the 4A framework of energy security has been developed and applied to various countries or region such as China, Pakistan, Bangladesh and the Association of Southeast Asian Nations (Yao and Chang 2014; Tongsopit et al., 2016; Malik et al, 2020; Amin et al, 2022). It measures four dimensions on how energy resources reach the end user, namely, 1) scientific (i.e., "availability of energy resources"), 2) engineering or technological (i.e., "applicability of energy resources"), 3) environmental (i.e., "acceptability of energy resources"), and 4) economic (i.e., "affordability of energy resources").

These energy security dimensions may not always be congruent with the goals and process of energy transition, however. The energy transition, a pathway toward transformation of the global energy sector from fossil-based to zero-carbon, may at times be in direct conflict with energy security objectives. First, the transition away from fossil fuels to renewable energy can reduce consumer and societal affordability, due to higher costs associated with new technological requirements and initial lack of scale economies. Second, to ensure continued availability and energy supply while transitioning to a renewable energy-based economy often necessitates increased dependence on non-renewable or “less safe” energy resources in the interim, like natural gas and nuclear fuels, at least until adequate capacity of renewable energy is installed and is sufficiently affordable.

Germany has been a pioneer in investing in renewable energy and in planning its economy’s transition out of coal and nuclear energy. The vision of Germany’s energy transition (“Energiewende”) is to move Germany’s economy and society to alternative, clean, affordable and safe means of energy production and consumption (Öko-Institut, 2021). They include building up renewable energy capacity and improving energy efficiency, and phasing out of coal and nuclear energy. Successive German governments progressed the efforts, while balancing the interests of voters and consumers, industry and public finances, through a series of Renewable Energy Acts (“EEG”), the energy carbon taxes of 1999 and other energy and climate change policies between 2005 and 2010 (BMWi 2021, Duffield, 2009; Ruszel, 2017). Germany and the EU also introduced the Emissions Trading System (“EU-ETS”) between 2005 and 2007 and published the “European strategy for sustainable, competitive and secure energy” paper in 2006 (Wicke and Schulte von Drach, 2013). Additionally, in the aftermath of the Great Eastern Japan earthquake and Fukushima reactor melt-down in 2011 and in line with the nuclear law (“Atomgesetz”) of 2002, the German parliament set 2022 as the shut-down date of the countries’ last nuclear power plants. More recently, in July 2020 the parliament ratified the formal exit process from coal power starting in 2030.

Peculiarly, energy security was never consistently high on the German government’s agenda. While crises like the 1970s oil shocks and the 2006 Russian-gas pipeline and supply problems in Ukraine and Georgia did raise temporary government attention, energy security concerns were frequently eclipsed by climate change and industrial-political objectives (Duffield, 2009). Although energy efficiency and fuel import diversification measures were introduced and negotiations on contract governance with Russia were attempted, German exporters lobbied the Ministry of Economy (“BMWi”), which also oversees energy policy through one of its directorates, to continue an accommodating foreign policy stance towards Russia (Duffield, 2009).

Following Yao and Chang (2014) as well as Tongsopit et al (2016), this study applies the 4A framework of energy security to examine that status of and changes in energy security in Germany from 2000 to 2019. There are four objectives. First, we examine the overall progression and status of energy security in Germany over the two decades. Second, we evaluate whether and how Germany's investments in renewable energy have enhanced energy security in Germany. Third, we discuss how Germany's nuclear energy policies have affected energy security. Fourth, we examine how coal and its policies have shaped energy security. In particular, we examine the anticipated consequences of the coal and nuclear phase-outs on the true energy security status of the country in the years to come. This will help shed some light on whether Germany's transition to cleaner energy sources has been successful, achieving less pollution while maintaining energy security for the country.

We find that, while applicable technologies are largely available in Germany through its multinationals and SMEs ("Mittelstand") and the acceptance of climate change policies is very high among its society and voters, the availability of energy resources and the affordability to energy consumers steadily decreased in recent years. With regard to the availability of energy resources, the anticipated growth in electric mobility will increase electricity demand beyond the originally anticipated demand growth from industry and consumers. While renewable electricity production capacity has successfully increased and renewable power already made more than 40% of gross electricity production in 2019, the planned nuclear and coal phase-outs are set to increase the country's reliance on natural gas, at least for the foreseeable future (Coester et al., 2018). Considering disruptions in piped natural gas supply in the wake of the war it has become very important for the country, in cooperation with its northern neighbors and the EU, to continue its efforts to diversify energy supply options, including through LNG and renewable power imports (Götz, 2007; Duffield, 2009; Gullberg et al., 2014; Lenzen, 2018).

When it comes to affordability, the huge infrastructure investment requirements and the introduction of fuel taxes and feed-in tariffs for renewable electricity imposed by the government to help project developers, suppliers, service and technology providers (the "renewables industry") has resulted in German consumers paying among the highest fuel and the highest electricity tariffs in the world (Wicke and Schulte von Drach, 2013; Eurostat Energy EU, 2021). This puts a undue burden on low-income households.

Nevertheless, we argue that the high fuel and electricity prices paid by German consumers contribute to both financing the country's energy transition and to eventually improving the country's energy security status. As the proportion of renewable energy continues increasing and starts dominating the country's total primary energy consumption, reliance on natural gas from its European neighbors and Russia will eventually diminish and energy feedstock availability increase again. At the same time, as energy efficiency measures in generation, transmission and dispatch bear fruits and the cost of renewable energy and electricity decreases to the levels of fossil fuel energy, feed-in and consumer tariffs can be reduced and energy affordability will increase again. The key conditions to lowering future energy tariffs are the build-out of energy and electricity transmission and storage infrastructure and future German governments' commitment to reigning in the power of the industry lobby.

Our study contributes to the existing literature on energy security and energy policy in Germany and the EU. In particular, we examine the four dimensions of energy security, availability, applicability, acceptability and affordability in a holistic way. One could divide the relevant literature into several interdependent themes. The first theme examines Germany's energy transition process and the Energiewende and its consequences to industry and electricity wholesale prices (Wicke and Schulte von Drach, 2013; Renn and Marshall, 2016; Gierkink et al., 2020). When it comes to the energy security status of Germany, several studies are noteworthy (Duffield, 2009; Feldhoff, 2014; Westphal, 2014; Ruszel, 2017; Gillessen et al., 2019). A number of specific works examine how natural gas imports from Russia adversely affect German (and EU) energy security (Götz, 2007; Umbach, 2007; Lenzen, 2018). Others posit that Germany's rapid phase-out of coal and nuclear exemplifies Germany's focus on environmental justice and climate change policy (Rehner and McCauley, 2016), and that the energy security issue has become more pressing (Duffield, 2009). Equally pertinent are studies on the social challenges of expanding electricity production and transmission infrastructure (Komendantova and Battaglini, 2016; Wicke and Schulte von Drach, 2013). Another set of literature deals with energy policy cooperation and conflicts between Germany and its EU partners (Duffield and Westphal, 2011; Gullberg et al., 2014; Austvik, 2016; Ruszel, 2016; Heinrich et al., 2016; Szczerbowski, 2018).

We structure this study as follows. Following this introduction, Section 2 discusses the current energy landscape in Germany. Section 3 describes our methodology and data collection, while section 4 elaborates on our results and section 5 on policy implications. The final section 6 concludes the study with open questions for future research, which is followed by the reference list.

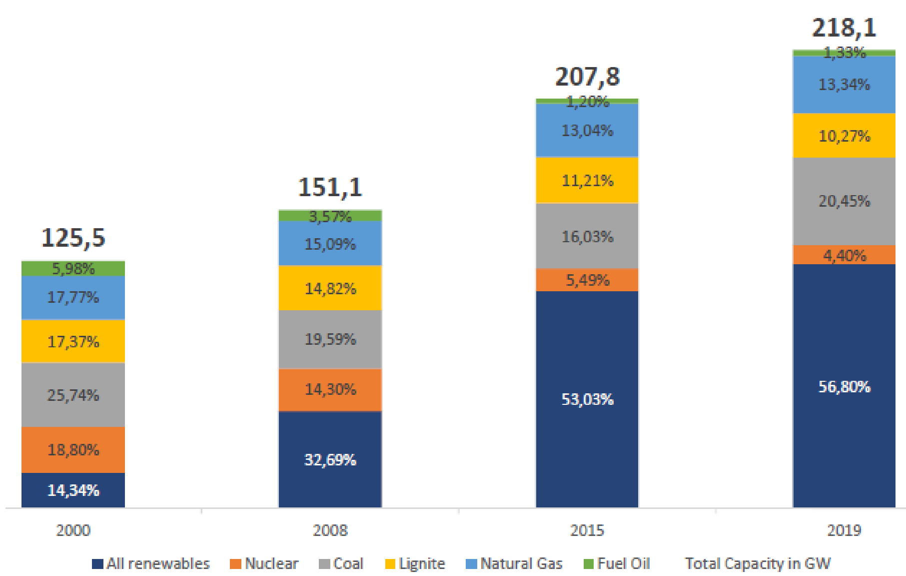
2. Energy Landscape in Germany

2.1 The renewable energy laws ("EEG")

The "Energiewende" is Germany's transition to a low-carbon, nuclear-free economy. It has enjoyed broad public backing and cross-party support, even as the coronavirus pandemic dominated public concerns. In the last 20 years a series of renewable energy acts ("EEG") were enacted to regulate the expansion of renewable energy capacity and consumption in coordination and collaboration with various EU laws and guidelines. The goal is to reach an 80% share of electricity generation and consumption from renewable sources. A summary of the pertinent German laws and EU guidelines are depicted in the Appendix.

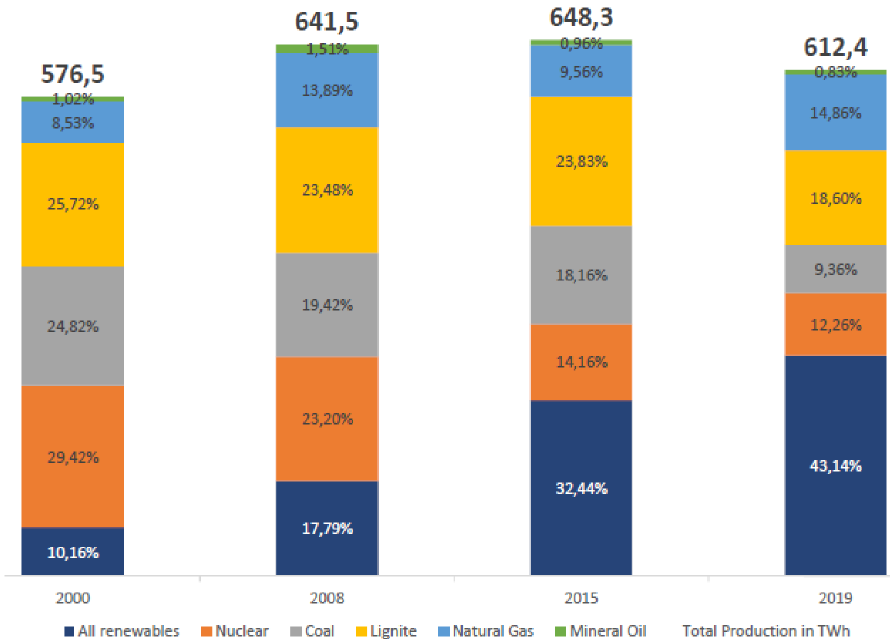
Following this legislative evolution, financed with consumer feed-in tariffs and incentives for the renewables industry, electricity generation capacity and production from renewable sources have reached 57% and 32% in 2019, respectively (Figures 1 and 2):

Figure 1: German electricity generation capacity by fuel type (Gigawatt)



(Source: BMWiE)

Figure 2: German electricity production by fuel type 2000-2019 (Terawatt-Hour)



(Source: BMWiE)

2.2 European Emissions Trading System

Together with the EU, the German government also introduced the Emissions Trading System ("ETS") between 2005 and 2007 and published the "European strategy for sustainable, competitive and secure energy" paper in 2006 (Wicke and Schulte von Drach, 2013). The ETS operates in all EU countries plus Iceland, Liechtenstein and Norway (EC, 2021). It limits emissions from around 10,000 installations in the electricity sector and manufacturing industry, as well as airlines operating between these countries. It covers about 40% of the EU's greenhouse gas emissions.

The ETS is managed by the EC's Directorate-General for Climate Action, which is responsible for redefining the targets and strengthening the market stability reserve linked to the review of the ETS, as well as for revising the ETS directives concerning aviation, member states' emission reduction targets, CO_2 emissions performance standards for new passenger cars and vans (EC, 2021). Based on the ETS Directive, it works as the 'cap and trade' system. Set-up in 2005, it is the world's first international emissions trading system. It covers greenhouse gases like CO_2 from electricity and heat generation and from energy-intensive industries, nitrous oxide produced in the chemical industry and perfluorocarbons from aluminum production. Certain smaller facilities and aviation sub-sectors are exempt from the cap and trade system under certain conditions. Following revisions, the ETS now operates in its fourth trading phase (2021-2030).

The ETS has achieved mixed results since its inception. On the one hand, it has reduced emissions from participating facilities and installations by about 35% between 2005 and 2019 (EC, 2021). On the other hand, many sectoral and facility exemptions and the ETS sold by these covered facilities to polluting sectors has resulted in increased coal fired-electricity generation in some years, resulting in little overall reduction in CO_2 emissions (Wicke and Schulte von Drach, 2013). Furthermore, it is contended that the EU-ETS, through its initially free allocation of certificates to relevant industries, has resulted in windfall profits in the order of ca. 50 billion Euros to companies across Europe. As the initial certificate-holding companies on-sell these ETS to operators of coal- and gas-fired power plants, the overall net reduction in carbon emissions is marginal at best (Wicke and Schulte von Drach, 2013). While the Market Stability Reserve introduced in 2019 resulted in higher carbon prices in recent years, critiques contend that the costs of carbon emissions are still too low to significantly curb climate change. Thus OECD (2018) argues that worldwide carbon pricing levels including taxes and emissions trading, while increasing over time, are still too low.

2.3 Exit from nuclear and coal electricity generation

In addition to the efforts to decarbonize the economy and transition towards climate neutrality, in the aftermath of the Great Eastern Japan earthquake and Fukushima reactor melt-down in 2011 and in line with the nuclear law ("Atomgesetz") of 2002, on 6 June 2011, the German parliament voted to shut-down eight major nuclear power plants and set 2022 as the shut-down date of the countries' last nuclear-based power plants.

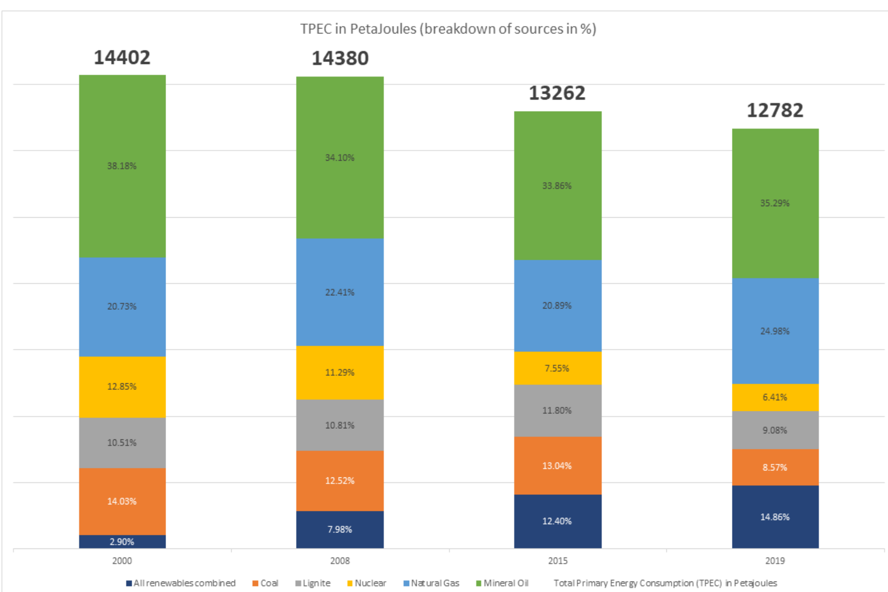
With regard to exiting coal, in June 2018 the German government formed the so-called WSB-Commission to plan for the step-wise reduction and exit from coal-powered electricity generation. In July 2020 the German parliament voted its Coal Exit Law ("Kohleausstiegsgesetz"), which formally regulates the exit milestones, compensation payments, exemptions and fiscal incentives for affected industries, formally reaffirms the 65% renewable energy share target of electricity generation and makes adjustments to the electricity network infrastructure and heat-electricity co-generation laws. A detailed study conducted by a major energy think tank, the "EWI" in Cologne, forecasts that, based on the enacted coal-exit scenario 16 GW of lignite- and 17 GW of anthracite-burning capacity will still be operational by 2030, with 6 GW of anthracite-based co-generation capacity remaining as late as 2050 (Gierkink et al., 2020).

2.4 The Energiewende and its Challenges

As the country aims to cut climate-harmful greenhouse gases to near-zero by mid-century as part of the EU's climate neutrality drive, the Energiewende has to go well beyond expanding renewable energy while phasing out coal and nuclear power. All economic sectors are required to adapt, and cooperation across Europe and globally is increasingly seen as key to success (Gierkink et al., 2020).

Despite the growth in renewable electricity generation capacity, Germany's total primary energy consumption (TPEC) continues to be dominated by increasing consumption of oil for transportation fuels and natural gas to compensate for the exit from nuclear and coal. This can be seen in the country's TPES break-down and evolution in Figure 3:

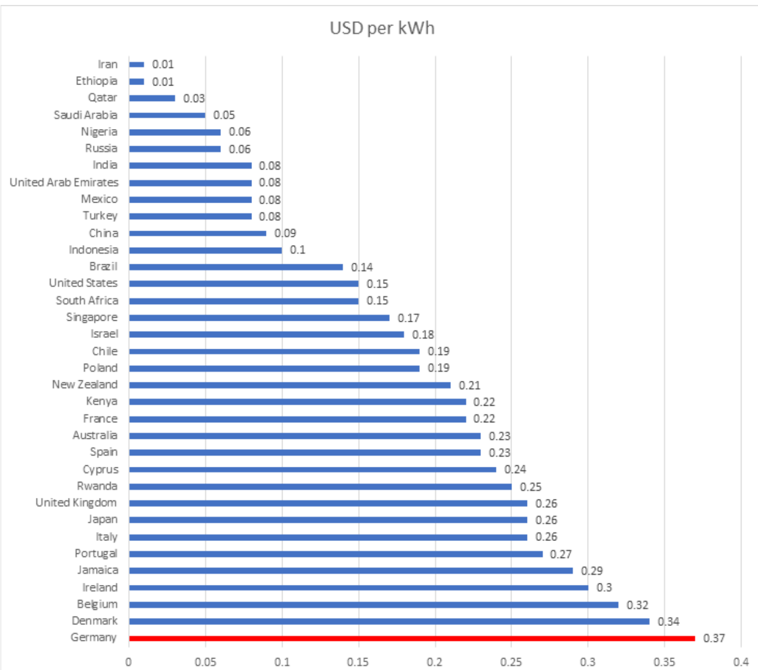
Figure 3: Germany TPEC evolution 2000-2019

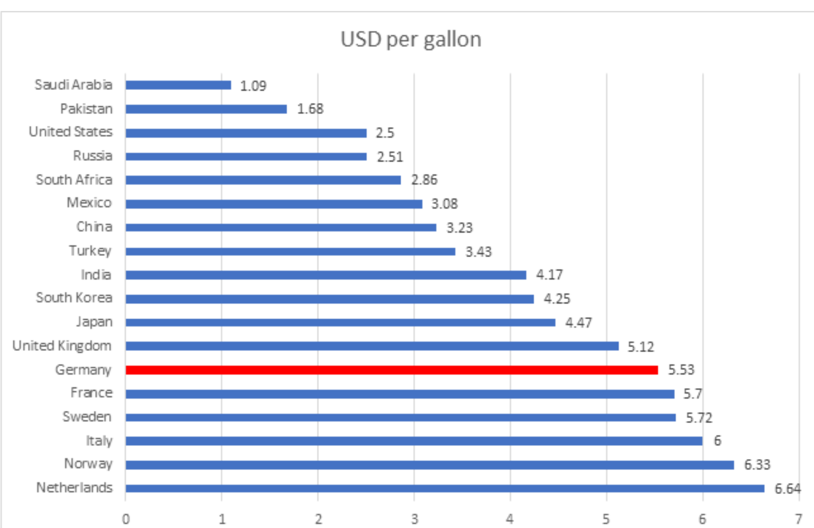


(Source: BMWiE)

As an early starter internationally and across Europe, Germany's energy transition is watched closely for valuable lessons on weaning a major economy off fossil fuels. Many environmentalists cite Germany as a proof that an industrialized nation can abandon fossil fuels without sacrificing growth. Nevertheless, critics argue the German experience confirms that such transformation comes at a high cost to consumers, taxpayers and industry – and doesn't automatically reduce carbon emissions (Wicke and Schulte von Drach, 2013). Germany's households already pay the highest electricity tariffs and among the highest gasoline prices in the world (Figures 4a and 4b):

Figures 4a and 4b: Electricity tariffs and gasoline retail prices





The high electricity tariffs are driven by the increasing feed-in tariffs for renewable electricity and the cost of expanding the interconnection, transmission and market infrastructure. As of 2021 the electricity retail tariff of roughly 32 Euro cents includes the feed-in tariff (20.4%), value-added and electricity taxes (22.4%). Thus, less than half of the end-tariff covers the generation and infrastructure costs (Strom Report 2021). On the transportation fuel side, a retail price of 1.55 Euro for standard unleaded gasoline includes 19% value-added and more than 40% fuel taxes.

Germany is extending the scope of its energy transition, introducing emissions reduction targets for each sector with a major climate law, as well as national CO_2 prices for transport and heating fuels. It aims to power industry, mobility and buildings almost entirely with renewables – a move with massive implications for its large and powerful carmakers, freight industry, energy-intensive businesses, households and consumers. Green hydrogen looks set to become the technology of choice to decarbonize sectors where emissions reductions are particularly difficult, for example in heavy industry and aviation, but requires technological and infrastructure innovations to make it economical. Concurrently, a lot must still be done to increase efficiency and reduce the energy appetite of the world's fourth largest economy.

3. Methodology and Data Transformation

3.1 Descriptions and Justifications of Indicators

Resources are minerals including oil, coal, gas and uranium that are considered to exist in the Earth's crest and expected to be extracted sometime in the future. Resources become reserves with the known certainty of existence and the economic feasibility of recovery (Everett et al, 2012). Reserves will be extracted with appropriate amount of effort such as extraction technologies and costs (Conrad and Clark, 1987; Neher, 1990; Chang and Yong, 2007; Conrad, 2010; Everett et al, 2012). The extraction of available reserves may be delayed or will not be realized if other external factors such as the politics of the climate, transport and power supply are considered, which governs the acceptability of the reserves by a society (Mitchell, 2002) or the degree of political openness in an oil-exporting country (Metcalf and Wolfram).

The study selects the indicators of energy security based on how energy resources reach the end-users as stated in the preceding paragraph, which takes four stages. At the first stage, an economy must have physical endowments of energy resources in its national boundary or abroad. At the second stage, an economy must have energy technologies to harness the physical endowments of energy resources. At the third stage, an economy must accept the energy resources harnessed from the physical endowments. At the fourth and final stage, the energy resource should be affordable. If an energy resource does not pass any stage, the energy resource will not reach the end-users. Cor or nuclear energy is one example. Many countries in the world shun coal or nuclear energy and hence these energy resources fail to pass the third stage of acceptability and are not utilized. Another example is solar and wind energy. Solar and wind energy are unlimited and accepted by society. However, along with the vagaries of the solar and wind energy, the costs of harnessing the solar and wind energy are still high compared to other energy resources and hence they are not affordable.

Following Yao and Chang (2014), this study constructs a 4A framework. Each A has seven indicators. Table 1 presents the list of indicators for the availability of energy resources.

Table 1: Availability

Index	Descriptions	Units	Aim	Source
AV1	Share of oil imports in TPES	%	Lower	BMWuK, destatis.de
AV2	Reserve/Production of coal	Years	Higher	BP
AV3	Share of gas imports in TPES	%	Lower	BMWuK
AV4	Gross total electricity generation capacity all fuels (end of year)	GW	Higher	BMWuK, EBdW
AV5	Total oil imports	Kton	Higher	BMWuK, Reuters, BWuAK
AV6	Total natural gas imports	PJ	Higher	
AV7	Share of electricity imports in Total electricity production	%	Lower	BMWuK, EBdW

Source: Authors' compilation

Availability refers to "geological existence of fossil energy resources" (Chang and Yong, 2007; Yao and Chang, 2014; Tongsopit et al, 2016) and the possibility that they be replaced by alternative energy resources including imports. AV1 represents an oil import dependency ratio, which increases the availability and energy security status when oil imports decline. AV2 shows the intrinsic capacity of energy supply from coal, a major fossil fuel in Germany, whose increase improves the availability of energy and the status of energy security. AV3 represents a natural gas import dependency ratio. Natural gas is the main energy source in Germany and higher import dependence is detrimental to energy security. AV4 represents the supply capacity of electricity from all sources. The gross generation capacity of electricity represents the maximum possible capacity available, which thus improves the availability index component of energy security. It does not necessarily mean, however, that the capacity is fully utilized. The actual amount of electricity generated is dependent on various factors like economic, environmental, and technological conditions. AV5 shows the total oil imports volume. This indicator helps identify how imported oil has contributed to energy security in Germany. It is desirable that these volumes are higher, but they stand in contrast and are counterbalanced by the above relative import dependency ratio, which should ideally be lower. AV6 represents the total volume of gas imports, which should also be higher. AV7 considers how electricity import dependency has affected energy security in Germany. To secure energy supplies this proportion should be maintained at sufficiently low or manageable levels.

Table 2 presents the list of indicators measuring the applicability of energy resources.

Table 2: Applicability

Index	Descriptions	Units	Aim	Source
AP1	Energy intensity (2015)	Mtoe/US$	Lower	BMWuK
AP2	Gross electricity production/Capacity (capacity utilization)	%	Higher	BP
AP3	Nuclear electricity production/ Capacity (utilization)	%	Higher	BMWuK, EBdW
AP4	Renewable electricity production/ Capacity (utilization)	%	Higher	
AP5	Total energy R&D investments (2015)	US$ mn	Higher	BMWuK, cleanenergy wire.org
AP6	Share of renewables R&D in Total energy R&D Investments	%	Higher	
AP7	Coal electricity production/ Capacity (utilization)	%	Higher	BMWuK, EBdW

Source: Authors' compilation

Applicability refers to the existence of appropriate and efficient energy technologies that can harness usable energy from the available energy resources. Various measures of energy efficiency or the rates of utilization are employed to present the status of applicable energy technologies in Germany. AP1 shows the overall efficiency of the energy sector. Efforts must be made to reduce energy intensity to improve energy security. AP2 represents the efficiency of the overall electricity generation sector. AP3 measures the efficiency of nuclear power generation plants, which represents the economically sound and technologically viable energy technology. This positive contribution to energy security is to be offset by a negative contribution to the acceptability of energy resources as a society tends not to accept nuclear energy in its energy mix. AP4 presents the efficiency of the renewable energy sector. All four capacity utilization measures AP2-AP4 and AP7 for coal (see below) must be increased or maximized, taking into account average and peak load requirements. AP5 considers the amount of R&D invested in the energy industry, based on the assumption that energy R&D can improve efficiency of the energy sector. AP6 considers R&D expenditures specifically in the renewables sector. AP7 describes the capacity utilization of coal-fired electricity, which must also be increased to improve energy security.

Table 3 presents the list of indicators for the acceptability of energy resources by a society.

Table 3: Acceptability

Index	Descriptions	Units	Aim	Source
AC1	CO_2 per capita emissions	Tons	Lower	Our World in Data CO2
AC2	SO_x per capita emissions	kg	Lower	OECD
AC3	NO_x per capita emissions	kg	Lower	
AC4	GHGs per capita emissions	Tons	Lower	
AC5	Share of nuclear electricity production in Total electricity production	%	Lower	BMWuK, EBdW
AC6	Share of renewable electricity production in Total electricity production	%	Higher	
AC7	Share in global emissions of CO_2	%	Lower	Our World in Data CO2

Source: Authors' compilation

Acceptability refers to how a society accepts a specific energy source. As direct measures for acceptability are not available, indirect measures are employed. AC1 to AC4 present how much carbon dioxide, sulfur oxides, nitrous oxides and greenhouse gases are emitted per capita, respectively. High levels of emissions per capita represent a society's tendency to accept the use of fossil fuels, but lower emissions imply an increased acceptability of the resource and the country's energy security status increases. AC5 considers how a society views using nuclear energy. A high share of nuclear generation indicates a higher acceptance of nuclear energy, but for energy security per se, a lower share of nuclear energy is desirable. AC6 considers how a society views the use of renewable energy. A high share indicates that renewable energy is more acceptable and contributes positively to energy security. AC7 represents an overall status of contribution to carbon dioxide emissions at a global level. A high share represents that fossil fuels are comparatively more acceptable. Nevertheless, a higher level of acceptability and energy security status is ensured when a country produces a lower share of global carbon dioxide emissions.

Table 4 presents the list of indicators for the affordability of energy resources.

Table 4: Affordability

Index	Descriptions	Units	Aim	Source
AF1	Primary energy consumption per capita	GJ	Higher	BMWuK
AF2	Electricity consumption per capita	kWh	Higher	BMWuK, enerdata.net
AF3	Electricity price (2015)	cts/kWh	Lower	BMWuK, cleanenergy wire.org
AF4	Crude oil import prices (2015)	US$/bbl	Lower	OECD
AF5	Price of natural gas (2015)	cts/kWh	Lower	BMWuK
AF6	Price of coal (2015)	€/tce	Lower	
AF7	Household energy expenditure/ Total private consumption expenditure	%	Lower	BMWuK, EBdW, BDEW

Source: Authors' compilation

Finally, affordability refers to how energy resources are affordable to the end-user. AF1 and AF2 show the amount of primary energy and electricity consumed by each person, respectively. A high amount of primary energy and electricity consumption per capita indicates that primary energy and electricity are more affordable. AC3, AC4, AC5 and AC6 present the levels of electricity price, crude oil import price, natural gas price and coal price, respectively. Low prices of electricity, oil import, natural gas and coal indicate that each energy source can be afforded by more consumers. Lastly, AC7 shows a share of household's average expenditure on energy. A lower share represents that energy is more affordable for all households.

The 4A framework is applied to Germany to examine the status of the country's energy security. The time span is from 2000 to 2019. Values of individual indicators are normalized using the following min-max normalization methods. Suppose data of an indicator appear in range A. For the indicators that aim to maximize exposure i.e., when higher is better, the normalized energy security indicators,

$$X^{'} = 1 + (\frac{X - Min_A}{Max_A - Min_A}) \times (10 - 1)$$

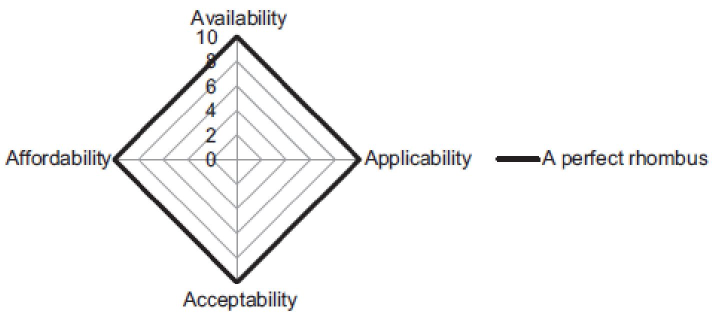
Increase with increasing underlying indicators, while for the opposite case of indicators that aim to minimize exposure i.e., when lower is better, the normalized energy security indicators,

$$X^{'} = 1 + (\frac{X - Max_A}{Min_A - Max_A}) \times (10 - 1),$$

increase with decreasing underlying indicators. Thus *X'* is the normalized value of the data range A, *X* is the value of the data range A, Min_A is the minimum value of the data range A and Max_A is the maximum value of the data range A. The normalized value *X'* takes 1 as the lowest and 10 as the highest value. A higher ordinal value represents a higher level of energy security.

The four A's construct a rhombus as figure 5 below presents. The inside area of the rhombus is deemed to indicate the overall status of energy security, where 10-points represent the maximum level of energy security for the A dimension.

Figure 5: A Rhombus



Source: Authors' compilation

3.2 Normalized Values of Indicators for Germany

Data is collected from various sources, namely, BP, Clean Energy Wire, the World Bank, BDEW, BMWiE, Fraunhofer Institute, IEA, OECD, Destatis.de, EuroStat, and Global Carbon Project. Table 5-8 presents the normalized values of the availability, applicability, acceptability and affordability indicators, respectively.

Table 5: Normalized values of availability indicators

Year	AV1	AV2	AV3	AV4	AV5	AV6	AV7	Average
2000	2,12	9,97	8,59	1,00	9,10	1,00	3,42	5,03
2001	1,00	9,76	7,60	1,22	10,00	1,34	4,18	5,02
2002	4,63	9,49	7,17	1,15	5,62	1,70	3,33	4,72
2003	5,64	9,64	8,38	1,30	5,45	2,08	2,98	5,07
2004	6,84	1,00	7,69	1,75	4,26	2,72	3,47	3,96
2005	6,67	1,03	8,47	1,95	4,79	2,81	1,00	3,82
2006	5,78	1,06	7,27	2,22	6,06	3,12	3,88	4,20
2007	10,00	1,03	10,00	2,62	1,00	2,51	4,63	4,54
2008	6,87	1,09	8,04	3,13	4,63	3,00	5,87	4,66
2009	7,41	1,15	7,87	3,70	3,46	3,22	4,90	4,53
2010	6,62	6,69	8,65	4,79	5,15	3,79	5,34	5,86
2011	8,01	6,48	9,43	4,63	3,61	3,29	2,51	5,42
2012	7,92	6,22	9,15	5,51	3,17	3,68	4,29	5,70
2013	5,56	6,39	7,98	6,24	6,40	3,83	6,52	6,13
2014	5,52	6,54	9,86	6,88	6,03	3,39	5,95	6,31
2015	5,52	6,60	9,49	7,60	6,27	5,52	7,31	6,90
2016	4,51	6,19	6,71	8,17	7,06	5,12	9,82	6,80
2017	3,56	6,19	5,95	8,48	8,83	4,82	10,00	6,83
2018	3,44	6,42	4,52	8,97	8,01	6,05	8,74	6,59
2019	1,16	8,03	1,00	9,40	9,08	10,00	5,67	6,34
2020	3,89	10,00	2,72	10,00	4,42	8,88	2,40	6,04
2021	2,02	10,00	1,96	9,90	6,76	8,17	1,32	5,73

Source: Authors' compilation

Table 6: Normalized value of applicability indicators

Year	AP1	AP2	AP3	AP4	AP5	AP6	AP7	Average
2000	1,52	9,52	4,07	10,00	1,33	6,15	8,63	5,89
2001	1,00	9,45	4,32	6,53	1,64	7,66	8,69	5,61
2002	1,77	9,59	3,39	6,55	1,00	9,17	8,75	5,75
2003	1,77	10,00	5,02	3,50	2,82	2,53	9,73	5,05
2004	1,77	9,51	6,09	5,53	2,55	1,00	8,41	4,98
2005	2,03	9,33	5,54	4,47	2,86	3,65	9,01	5,27
2006	2,29	9,39	6,44	5,10	2,88	3,68	9,72	5,64
2007	4,35	8,83	2,07	8,24	2,95	4,01	9,86	5,76
2008	4,61	8,12	3,08	7,30	3,82	4,01	7,97	5,56
2009	4,61	6,25	1,00	4,24	5,36	7,46	6,55	5,07
2010	4,35	5,96	1,88	2,42	5,57	8,07	7,03	5,04
2011	6,41	5,66	10,00	1,23	6,77	10,00	8,45	6,93
2012	6,41	5,16	7,63	1,71	6,34	9,17	9,19	6,52
2013	6,16	4,70	7,02	1,26	7,35	9,98	10,00	6,64
2014	7,45	3,93	6,98	1,00	7,46	5,42	8,90	5,88
2015	7,45	3,78	8,49	2,68	7,86	5,95	7,70	6,27
2016	7,96	3,42	6,26	1,59	7,89	5,44	7,64	5,74
2017	8,22	3,27	3,67	3,09	9,22	6,98	6,98	5,92
2018	8,99	2,74	6,77	2,64	8,68	5,17	5,83	5,83
2019	9,51	1,90	6,44	3,38	9,21	6,82	3,13	5,77
2020	10,00	1,00	6,59	3,30	9,42	5,81	1,00	5,30
2021	9,77	1,24	8,51	1,66	10,00	5,84	3,68	5,81

Source: Authors' compilation

Table 7: Normalized value of acceptability indicators

Year	AC1	AC2	AC3	AC4	AC5	AC6	AC7	Average
2000	1,59	1,00	1,00	2,79	1,00	1,00	1,66	1,44
2001	1,00	1,53	1,62	1,00	1,11	1,02	1,00	1,18
2002	1,56	2,93	2,23	1,74	1,66	1,32	1,66	1,87
2003	1,91	3,46	2,62	1,82	2,14	1,26	1,99	2,17
2004	1,68	4,33	3,08	2,58	2,17	1,69	1,83	2,48
2005	2,86	4,86	3,62	3,50	2,60	1,86	3,31	3,23
2006	2,36	4,86	3,47	3,00	2,61	2,12	2,65	3,01
2007	3,24	5,21	3,93	4,06	4,70	2,75	3,97	3,98
2008	2,80	5,27	4,40	3,80	4,07	2,94	3,48	3,82
2009	4,95	6,48	5,24	5,97	4,35	3,29	6,29	5,22
2010	3,45	6,15	5,09	4,78	4,56	3,42	4,30	4,54
2011	4,19	6,61	5,24	6,79	6,84	4,32	5,30	5,61
2012	3,95	6,90	5,40	6,31	7,73	4,94	4,97	5,74
2013	3,33	7,32	5,48	5,70	8,00	5,18	4,14	5,59
2014	4,90	7,59	5,94	7,35	7,87	5,63	5,96	6,46
2015	5,01	7,84	6,25	7,28	8,52	6,46	5,96	6,76
2016	4,78	8,37	6,63	7,44	9,09	6,47	5,46	6,89
2017	4,16	8,72	7,17	4,40	9,75	7,45	4,85	6,64
2018	5,63	8,89	8,02	5,92	9,68	7,87	7,03	7,58
2019	7,55	9,24	8,49	7,28	9,43	9,10	8,27	8,48
2020	10,00	9,84	9,72	10,00	10,00	10,00	10,00	9,94
2021	8,76	10,00	10,00	8,74	9,71	9,21	9,83	9,46

Source: Authors' compilation

Table 8: Normalized value of affordability indicators

Year	AF1	AF2	AF3	AF4	AF5	AF6	AF7	Average
2000	8,80	3,88	10,00	9,47	10,00	9,48	9,35	8,71
2001	9,56	4,48	9,83	9,98	7,05	8,03	7,97	8,13
2002	8,81	5,14	8,54	10,00	8,33	9,30	9,29	8,49
2003	9,26	5,65	7,84	9,57	7,76	10,00	8,91	8,43
2004	9,22	6,12	7,38	8,65	7,76	8,02	8,05	7,89
2005	9,15	6,26	6,88	6,88	6,10	6,78	6,40	6,92
2006	10,00	6,62	6,31	5,65	2,94	7,24	4,47	6,17
2007	8,28	6,69	5,66	4,84	2,70	6,55	6,87	5,94
2008	8,91	6,50	5,03	2,12	1,00	1,00	2,64	3,89
2009	6,57	4,74	4,16	6,19	1,78	5,46	6,00	4,99
2010	8,57	6,86	3,91	4,36	3,86	4,72	3,28	5,08
2011	6,79	6,94	2,95	1,00	3,16	2,20	3,02	3,72
2012	6,30	6,89	2,75	1,01	2,34	4,06	1,72	3,58
2013	7,27	6,64	1,00	1,50	2,46	5,92	1,00	3,68
2014	5,32	5,78	1,17	2,71	2,82	6,84	4,88	4,22
2015	5,39	10,00	1,82	7,60	3,38	7,53	7,45	6,17
2016	5,85	9,96	1,98	8,64	4,19	7,72	9,24	6,80
2017	5,73	9,92	1,86	7,59	5,02	5,03	8,59	6,25
2018	4,43	9,13	2,03	6,08	5,60	4,77	8,15	5,74
2019	3,36	7,19	1,80	6,80	5,27	6,76	8,15	5,62
2020	1,00	6,14	1,43	8,92	5,66	8,67	10,00	5,97
2021	1,78	1,00	1,83	6,52	5,38	7,44	3,70	3,95

Source: Authors’ compilation

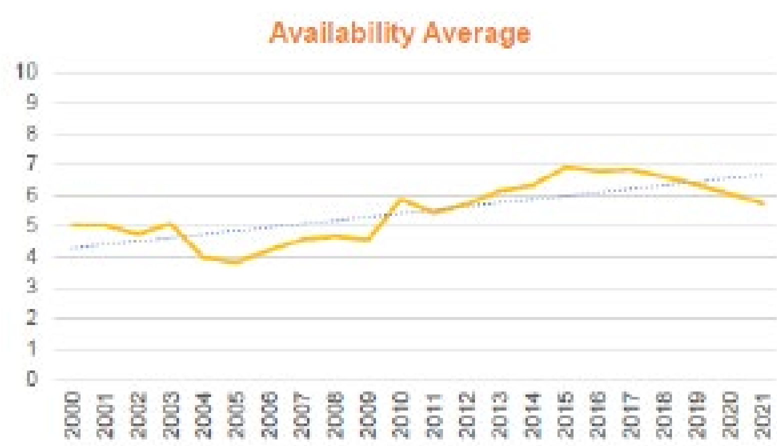
4. Results and Discussions

This section discusses our results and observations on the four research questions. First, it discusses the overall status of energy security in Germany. Of particular interest is the progression of the aggregate, normalized energy security indicators over the 19-year observation period. Second, it presents whether and how Germany's investments in renewable energy have affected energy security in Germany. Third, it shows how Germany's nuclear energy policies have influenced energy security in Germany. Fourth, it presents how coal and its policies have shaped energy security in Germany.

4.1 Overall Status of Energy Security in Germany

Figure 6 presents the country's trajectory of availability. It takes the average of seven indicators every year.

Figure 6: Germany's energy availability

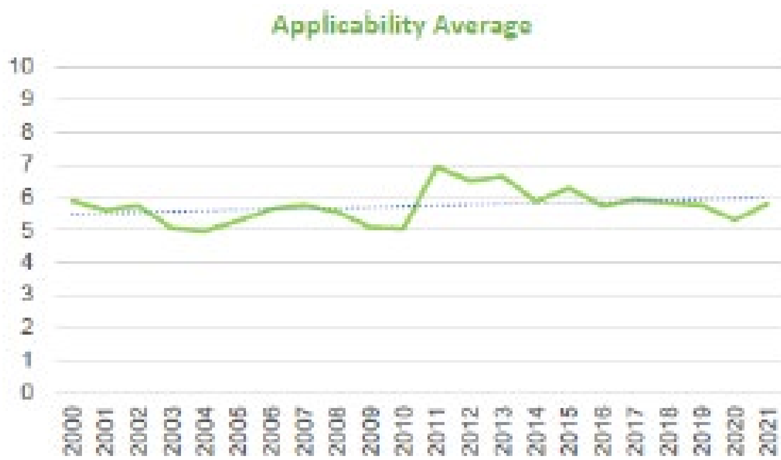


Source: Authors' calculation

The availability dimension increased, reaching its highest point in 2017, but decreased since then. Nevertheless, comparing the shape of the availability trend with Germany's GDP chart seems to indicate the role of the normal business cycles including the downturns in 2012, 2015, 2019 and the 2008-2009 global financial crisis. Broken down into its components, the decline in aggregate availability since 2017 is largely driven by several availability indicators, namely increasing oil imports over TPES (AV1), drastically increasing natural gas imports over TPES (AV3), and the increasing share of electricity imports over total electricity (AV7) in recent years. Particularly the gas import dependency has led to the energy crisis in the wake of the Russia-Ukraine war and the associated economic sanctions. Gross electricity production capacity (AV4) has increased steadily, fed in part by the strong growth in (now fragile) gas imports (AV6), but the share of electricity imports also increased in recent years. By contrast, coal reserve over production ratio (AV2) declined around 2004 and 2005, partially recovered in 2011 and remained relatively steady due in the last 10 years. The latter is presumably due to slowing production and the absence of new exploration investments once the long-term coal phase out was decided upon.

Figure 7 presents the trajectory of applicability. It takes the average of seven indicators every year.

Figure 7: Germany's energy applicability



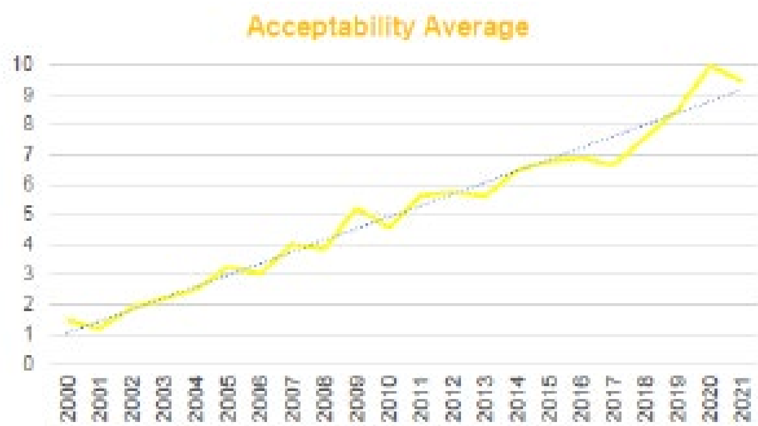
Source: Authors' calculation

Despite its intermittent volatility, the applicability dimension appears not to change much over the study period. The lowest point is in 2004 while the highest point is in 2011.Apart from during the downcycle year 2012 and the 2009 global financial crisis the normalized energy intensity indicator (AP1) steadily increased. This implies increasing economy-wide efficiency and decreasing energy intensity of industry. Throughout the 20-year observation period the electricity generation capacity utilization decreased steadily from 52.4% to 32.1%, which is reflected in the decreasing normalized indicator AP2. Nuclear production capacity utilization stagnated overall, dipping markedly during the global financial crisis and following the Japanese disaster in 2011 and the 2015 recessions (AP3). During the same period, renewable production capacity utilization decreased, though stabilizing in recent years (AP4), which may be a natural result of intermittent, seasonal and weather-dependent solar and wind power production.

Moreover, R&D expenditures in the energy industry (AP5) increased continuously, while the share of R&D investments into renewables (AP6) increased between 2003 and 2011, decreased and stabilized since 2014. The declining AP7 indicates that coal-sourced electricity capacity utilization decreased, as the coal exit gradually takes place, and coal and lignite generation capacity becomes increasingly idle.

Figure 8 presents the trajectory of acceptability. It takes the average of seven indicators every year.

Figure 8: Germany’s energy acceptability

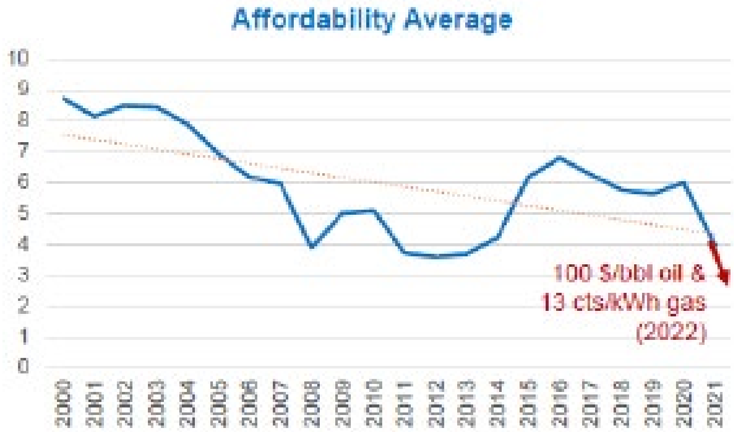


Source: Authors’ calculation

The acceptability dimension shows a steadily increasing trend. All the seven indicators show improvements over the study period. The per capita generation of CO_2 (AC1), SO_x (AC2), NO_x (AC3) and greenhouse gases (AC4) steadily decreased. The shares of nuclear power production (AC5) decreased, that of renewables production (AC6) increased and that of global CO_2 (AC7) decreased. All these are desirable trends and developments which resonate well with the public and consumers.

Figure 9 presents the trajectory of affordability. It takes the average of seven indicators every year.

Figure 9: Germany's energy affordability



Source: Authors' calculation

Affordability decreased until 2013 when it reached the lowest point. It rose relatively steeply until 2016, following which it decreased again. First, average per capita primary energy and electricity consumption (AF1 and AF2) decreased from their peaks in 2006 respectively 2015. Considering the concurrent decreasing energy intensity over the same time period (AP1), these declines indicate efficiency improvements and energy saving on the sides of consumers and industry. They should therefore not be interpreted as decreasing affordability to pay.

Second, real 2015 electricity prices (AF3) increased significantly, thus decreasing the affordability at least until 2013, remaining relatively low (i.e., less affordable) thereafter. This is partially a consequence of the high feed-in electricity tariffs required to incentivize the rapid build-up in the more expensive renewable energy generation infrastructure. Beyond 2013 the cost of renewable electricity has plateaued as scale economy kicked-in and the cost of renewable energy technology and production decreased.

Third, oil, natural gas and coal prices increased until the global financial crisis, partly driven by China's and India's economic growth. The affordability indicator AF5, reflecting natural gas prices, decreased over the years as prices increased. It remained rather stable for a few years, but has declined i.e., turned for the worse since the war started. Lastly but importantly, the share of energy of household expenditures (AF7) increased and the normalized affordability indicator decreased rapidly until 2013, recovered between 2013 and 2020 but declined again in last 2 years and especially due to the war.

It should be noted that the current war-driven energy crisis has significantly increased the prices of oil and gas, with severe detrimental effects on German energy affordability. The red arrow in figure 9 projects the affordability indicator when oil and gas prices stay high at $100 per barrel, respectively natural gas at 13 cents per kWh of gas.

As discussed in section 3 above and shown in figure 5, this study constructs a rhombus with the four dimensions by putting each A or dimension at the corner. Table 9 presents the average energy security indicators, the development of the rhombus area and the imbalance index for selected years, namely, 2000, the starting year, 2008 and 2015 and 2021, the last year:

Table 9: Total area of rhombus, selected years (unit: square units)

Year	Affordability Average	Acceptability Average	Applicability Average	Availability Average	Rhombus Area	Imbalance Index
2000	8,71	1,44	5,89	5,03	47,19	0,76
2008	3,89	3,82	5,56	4,66	40,06	0,80
2015	6,17	6,76	6,27	6,90	84,99	0,58
2021	3,95	9,46	5,81	5,73	74,19	0,63

Energy security in 2021 appears to be fifty percent better than it was in 2000, but still significantly below the ideal value of the perfect rhombus of 200. The corresponding imbalance index can also be calculated by subtracting the area of rhombus from the area of perfect rhombus, 200. The lower imbalance value, the less imbalanced status in terms of energy security. The trend of imbalance index also suggests that the status of imbalance has improved over the study period, albeit it is still far below the desirable level. Finally, in relation to the last two decades and theoretical minimum imbalance index of 0.00, which corresponds to the maximum rhombus area of 200, a significant improvement in Germany's energy security status is still possible and necessary. We shall return to this in section 5 below.

Figure 10 presents a rhombus of selected years, namely 2000, 2008, 2015 and 2021, which are combined into one rhombus chart.

Figure 10: Energy security status, 2000, 2008, 2015 and 2021

Source: Authors' calculation

Compared to the starting year of analysis, 2000, acceptability appears to have improved over the study period, applicability stagnated while both affordability and availability have decreased. The acceptability dimension shows a steady improvement trend. The applicability dimension reached its peak at 2011, decreasing since then, albeit not markedly. The affordability dimension was the highest in 2000 and the lowest in 2008. In recent years it was not as high as it was in 2000, thus the trend has been decreasing. Availability improved until 2015 and decreased since then.

The trend of the four dimensions of energy security dimensions can be rationalized as follows: Following public pressure, Germany has introduced significant climate change policies, starting with carbon taxation and feed-in electricity tariffs in the late 1990s and early 2000s coupled with exemptions for industry and generous ETS allocations as well as planned coal and nuclear phase-outs (c.f., first Energiewende, Wicke and Schulte von Drach, 2013). The nuclear phase-out was accelerated following the Fukushima reactor disaster and the coal phase-out period shortened (c.f., second Energiewende, Wicke and Schulte von Drach, 2013). This resulted in windfall profits for the energy and renewables industry and significant progress in the development of new renewable energy technologies and lower costs due to scale economies. It also motivated the energy and renewables industries to lobby the government to maintain the high feed-in tariffs, expensive subsidies and waivers. This has forced consumers to pay some of the world's highest worldwide energy prices (Wicke and Schulte von Drach, 2013).

Our model and indices reflect these developments clearly. The high acceptability index is a manifestation of Germans' climate consciousness and the abovementioned series of policies. This is a desirable development. At the same time, however, German energy policy and security face three major challenges:

First, the analysis indicates an overall declining and recently more rapidly decreasing of the affordability index. We do capture this especially through the energy cost as a share of disposable household income index. This poses a long-term threat to energy security and socioeconomic welfare in Germany, extremely exacerbated by the current war. The problem is that especially the weaker and lower income population of Germany is burdened relatively more heavily by the high fuel and electricity tariffs.

Second, applicability remained relatively steady, but nevertheless declined gradually in recent years. On the one hand, this could be a result of the German renewables industry losing competitiveness and investing less in R&D. Indeed, companies around the world, notably in China, have built significant competences in renewable energy technologies and are expected to profit from worldwide growth in renewables capacity. On the other hand, the decreasing applicability is driven by lower capacity utilization in conventional electricity generation, which is as expected.

Third, availability seems to decrease in recent years as nuclear electricity generation is reduced and the renewables capacity build-up slows down, though partially mitigated by higher natural gas imports in recent years. The increased use of natural gas may be necessary, but not conducive to achieving climate neutrality and zero carbon emissions targets. Moreover, Germany imports 43% of its natural gas from Russia, which makes up 19.4% of Russian pipeline gas (Ruszel, 2017; Statista, 2021). Together with France, Italy and the UK, Germany imports 38.3% of Russian gas exports (Statista, 2021). Indeed, the declining availability index in recent years is at least in part due to the increasing dependence on imported gas from Eastern Europe: this increases Germany’s vulnerability to supply disruptions, especially in the wake of the current Russia-Ukraine war.

4.2 Renewable Energy and Energy Security in Germany

Three of the four dimensions of our energy security framework have at least one indicator of renewable energy, with the exception of the affordability dimension. For applicability, two indicators are considered – a ratio of renewable-sourced electricity production over capacity (AP4) and R&D investments into renewables (AP6). For acceptability, a share of renewables production over total production (AC6) is considered. For affordability, a specific indicator has not been considered, although it is common knowledge that electricity prices have increased significantly due to the high feed-in tariffs introduced to incentivize R&D and infrastructure investments by the renewables industry.

However, the contribution of renewable energy to energy security in Germany through applicability is not clearly apparent. First, the ratio of renewable-sourced electricity production over capacity (AP4) has been fluctuating but decreased over the study period. Nevertheless, renewable energy appears to have slightly increased energy security in Germany since 2015, despite the renewables capacity utilization staying rather low. Second, R&D investments into renewables (AP6) have helped enhance energy security until 2011. Afterwards, its contribution to energy security in Germany appeared to decrease and dropped significantly from 2018 onwards. The contribution of renewable energy to the energy security in Germany via acceptability appears to be increasing over the study period, which is anticipated. Germany's renewables industry hopes to continue benefitting from future products, technologies and services exports. The share of renewables production over total production (AC6) has been increasing over the study period. In sum, renewable energy's contribution to energy security in Germany appeared not to be increasing monotonously. Rather, it had been fluctuating although it had picked up more recently.

4.3 Nuclear Energy, Policies and Energy Security in Germany

Nuclear energy has been explicitly considered in the study. For applicability, a ratio of nuclear-sourced electricity production over capacity (AP3) is considered. For acceptability, a share of nuclear production over total production (AC5) is considered. Nuclear energy is not explicitly considered with respect to affordability, but feeds indirectly through its influence on the electricity consumer prices and household spending.

The contribution of nuclear energy to energy security in Germany via applicability has been fluctuating. It made a minimal contribution from 2006 to 2009 but reached peak in 2010 and appeared to contribute significantly even following the mothballing of nuclear power plants in

Germany between 2011 and 2017. The share of nuclear production over total production (AC5) shows a decreasing trend over the study period. This implies that the acceptance of nuclear energy by the German people has decreased, which indirectly contributed to energy security in Germany.

4.4 Coal, Coal Policies and Energy Security in Germany

Coal has been one of the main sources in the fuel mix of Germany. For availability, the R/P ratio of coal (AV2) is considered. For applicability, coal-sourced electricity (AP7) is considered. Coal is not explicitly considered for the acceptability dimension, but emission indicators like CO_2 per capita (AC1), SO_x per capita (AC2), NO_x per capita (AC3), GHGs per capita (AC4) and the share of global CO_2 (AC7) represent indirect contributions from coal. In terms of affordability, the price of coal (AF6) is considered.

Coal's availability has been one of the key contributors to energy security from 2000 to 2003, made little contribution from 2003 to 2009, again contributing more to energy security in Germany from 2010 onwards. Coal contributed little to energy security in Germany via the applicability dimension and its contribution rapidly declined from 2013 onwards as coal production decreased. As indirect measures of acceptability, the five indicators, CO_2 per capita (AC1), SO_x per capita (AC2), NO_x per capita (AC3), GHGs per capita (AC4) and the share of global CO_2 (AC7) contributed to energy security by increasing public acceptability due to declining emissions. Lastly, from 2000 to 2011 coal's contribution to affordability appeared to fluctuate, faring worst during the peak coal price year of 2008, at the onset of the global financial crisis.

Coal appeared to contribute to energy security in Germany during the first half of our study period, except during peak coal price periods. During the later period, coal's contribution reflected a balance between decreasing applicability and increasing acceptability (for reduced coal-based power generation).

5. Policy Implications

While the energy and renewables industries have successfully made significant investments in renewable energy technologies and capacity in Germany, a large share of renewable energy projects is indirectly financed and owned by consumers, including households. The Energiewende has put significant strain on particularly lower income consumers and households, given the necessarily higher feed-in tariffs and fuel prices. Decreasing the feed-in tariffs may lead to lower investment incentives and a slower build-up of renewable energy infrastructure in the future. This in turn may slow the progress towards future GHG emissions reduction targets, especially as the build-up in renewable energy capacity must be accelerated. The latter is unavoidable since the simultaneous phase out of nuclear and coal energy coupled with growing energy demand has led to unchanged levels (the same level as the 1990's) of energy generation from gas, coal and lignite, leading to a slower decrease in CHG emissions levels in recent years. The interim increase in demand for natural gas will in turn further increase Germany's dependence on natural gas imports from Russia, which is highly risky, as the current Russian-Ukraine conflict clearly demonstrates.

To fulfill its medium- and long-term emissions targets and simultaneously improve its energy security status, the German government needs to reduce its dependence on Russian natural gas, strengthen its negotiation stance against Russia and ease the burden on energy and electricity consumers. Energy security in Germany (and in the EU) can be further enhanced if energy and electricity infrastructure within the EU is better integrated and alternative fuel sources are secured. For example, Germany's large natural gas storage capacity and transmission network is part of the government's strategy to diversify gas supplies and ensure its critical role as natural gas consumer and transmission hub for the EU. This mitigates the increasing import dependency (AV6) by diversifying the supply base.

Additionally, the domestic renewables capacity build-up must be debureaucratized and accelerated, while concurrently reducing the burden on energy consumers and forcing the renewables industry to accept lower subsidies and elimination of favorable waivers. At the same time, electricity interconnections with wind- and hydropower facilities in Denmark and Norway will improve stability and efficiency of the renewable energy supply and reduce dependency on natural gas imports (Gullberg et al., 2014; Ruszel, 2016). Multiple technological challenges such as grid capacity, stability, and flexibility are challenges that Germany's Energiewende must tackle to reach the 80% renewable energy target by 2050.

Reducing dependence on imported oil also requires major growth in electric mobility across the German transport system. So far the country has achieved a rather weak integration of the transport sector electrification and German city-level administrations' smart city initiatives with the hitherto energy transition policies. The three German automobile giants have been rather slow in adopting electric mobility, lagging behind its Chinese counterparts and companies like Tesla (Schüsseler, 2018). Concurrently, the German auto majors are developing synthetic e-fuels which, despite their inherent energy inefficiency, could help them maintain the greater part of their internal combustion engine infrastructure. The build-up in renewable electricity capacity will support a more rapid transition towards battery- and hydrogen-operated transport and industry in the future. In turn this will reduce the need for oil and gas imports and enhance the country's energy security status.

Germany's neighbors pursue different energy supply policies that have in past resulted in complaints such as unfair competition for electricity prices (Gullberg et al., 2014; Ruszel, 2016; Heinrich et al., 2016; Szczerbowski, 2018). The world is watching the German "experiment", to assess how the policies and energy security consequences can be adopted across Europe or on a global scale. This would require more transparent information on all financial and social costs and benefits of the Energiewende.

6. Conclusions

Energiewende has made significant progress towards the goals set. The recent changes to support schemes and the slowdown of growth of renewable energy in Germany in recent years, however, could be seen as indicators that new business models and different, non-economic support schemes are required now that renewables, and especially PV, are almost competitive in terms of cost with traditional, centralized generation. The electricity consumers are also the payers of the Energiewende in the form of feed-in tariffs, which are used to compensate the renewables industry. Due to the high feed-in tariffs, the average household electricity costs have increased over the last decades.

Germany's energy policy is anchored in the public opinion and enjoys a high degree of commitment of citizens. It now needs to find a way to continue rapidly building-up its renewable energy capacity while reducing the burden on especially low- and middle-income consumers, further expand the intra-EU natural gas and electricity transmission, storage and market infrastructure, while continuing to reduce energy intensity of industry and household energy consumption and, especially in wake of the Russian Ukrainian invasion and potential supply disruptions, diversifying the continent's natural gas import sources.

Our study poses important questions for future research on the micro- and macroeconomic impacts, the costs and financing alternatives and sources of Germany's Energiewende, this time, however, while simultaneously improving the country's energy security situation once again. The latter has been neglected in the past decades, as the current war clearly demonstrates.

7. References

Amin, Sakib Bin, Youngho Chang, Farhan Khan and Farhad Taghizadeh-Hesary, Energy security and sustainable energy policy in Bangladesh: From the lens of 4As framework. Energy Policy, Volume 161, Article 112719 (2022).

Austvik, Ole Gunnar. The Energy Union and security of gas supply. 2016. Energy Policy 96, 372-382

Bielecki, J.. 2002. Energy security: is the wolf at the door? Quarterly Review of Economics and Finance, 4292, 235 – 250.

Bohi, Douglas R. and Michael A. Toman. 1986. Oil supply disruptions and the role of the International Energy Agency. Energy Journal. Vol. 7, No. 2. 37 – 50.

Chang, Youngho and Jiayun Yong. 2007. Differing perspectives of major oil firms on future energy developments: An illustrative framework. Energy Policy 35(11), 5466 – 5480.

Chester, Lynne. 2010. Conceptualizing energy security and making explicit polysemic nature. Energy Policy, 38(2), 887 – 895.

Coester, Andreas, Marjan W. Hofkes and Elissaios Papyrakis. 2018. Economics of Renewable Energy Expansion and Security of Supply: A Dynamic Simulation of the German Electricity Market. Applied Energy 231, 1268-1284.

Conrad, Jon M. 2010. Resource Economics, 2nd Edition. Cambridge University Press, Cambridge, U.S.A.

Conrad, Jon M. and Collin W. Clark. 1987. Natural Resource Economics: Notes and Problems. Cambridge University Press. Cambridge, U.S.A.

Duffield, John. S. 2009. Germany and Energy Security in the 2000s: Rise and Falls of a Policy Issues? Political Science Faculty Publications 26.

Duffield, John S. and Kirsten Westphal. 2011. Germany and EU Energy Policy: Conflicted Champion of Integration? Political Science Faculty Publications 30.

Everett, Bob, Godfrey Boyle, Stephen Peake and Janet Ramage. 2012. Energy Systems and Sustainability: Power for A Sustainable Future. Oxford University Press. Milton Keynes, U.K.

Feldhoff, Thomas. 2014. Post-Fukushima energy paths: Japan and Germany compared. Bulletin of the Atomic Scientists 70(6), 87-96.

Gierkink, Max, Dominic Lencz and Fabian Arnold. 2020. Auswirkungen einer Beendigung der Kohleverstromung bis 2038 auf den Strommarkt, CO2-Emissionen und Ausgewählte Industrien. Energiewirtschaftliches Institut (EWI) and Ministry of the Economy, Innovation, Digitalization and Energy of the State of North Rhine Westphalia.

Gillessen, Bastian, Heidi U. Heinrichs, Jürgen-Friedrich Hake and Hans-Josef Allelein. 2019. Natural gas as a bridge to sustainability: Infrastructure expansion regarding energy security and system transition. Applied Energy, 251.

Götz, Roland. 2007. Russlands Erdgas und Europas Energiesicherheit (Russia's natural gas and European energy security). SWP-Studie S 21, Berlin: Stiftung Wissenschaft und Politik, Deutsches Institut für Internationale Politik.

Gullberg, Anne Therese, Dörte Ohlhorst and Mirande Schreurs. 2014. Towards a low carbon energy future – Renewable energy cooperation between Germany and Norway. Renewable Energy 68, 216-222.

Hartley, Peter R. and Kenneth B. Medlock III. 2009. Potential futures for Russion natural gas exports. Energy Journal. Vol. 30, Special Issue, 73 – 95.

Heinrich, Andreas, Julia Kusznir, Aleksandra Lis, Heiko Pleines, Karen Smith Stegen and Kacper Szulecki. 2016. Towards a common EU energy policy? Debates on energy security in Poland and Germany. ESPRI Policy Paper Series 02.

Holz, Franziska, Christian von Hirschhausen and Claudia Kemfert. 2009. Perspectives of the European natural gas markets until 2025. Energy Journal. Vol. 30, Special Issue, 137 – 150.

International Energy Agency (IEA). 2007. Energy security and climate policy: Assessing indicators, Paris, France.

Komendantova, Nadejda and Antonella Battaglini. 2016. Social Challenges of Electricity Transmission. IEEE power and energy magazine July/August 2016, 79-87.

LaCasse, Chantale and Andre Plourde. 1995. On the renewal of concern for the security of oil supply. Energy Journal. Vol. 16, No. 2. 1 – 23.

Lenzen, Raimer. 2018. Die Energiesicherheit der Bundesrespublik Deutschland (German energy security). Arbeitspapiere zur Internationalen Politik und Außenpolitik, (Working Paper AIPA 1/2018 series on international- and foreign policy.)

Lichtblau, John H. 1994. Oil imports and antional security: Is there still a connection? Energy Journal. Vol. 14, Special Issue. 329 – 346.

Malik, Sadia, Maha Qasim, Hasan Saeed, Youngho Chang and Farhad Taghizadeh-Hesary. Energy security in Pakistan: Perspectives and Policy Implications from a Quantitative Analysis. Energy Policy, Volume 144, Article 111552 (2020).

Matsui, Kenichi. 1998. Global demand growth of power generation, input choices and supply security. Energy Journal. Vol. 19, No. 2, 93 – 113.

Metcalf, Gilbert E. and Catherine Wolfram. 2015. Cursed Resources? Political conditions and oil market outcomes. Energy Journal. Vol. 36, No. 3, 331 – 357.

Mitchell, John V. 2002. A new political economy of oil. Quarterly Journal of Economics and Finance, 42(2): 251 – 272.

Murphy, Frederic H., Michael A. Toman and Howard J. Weiss. 1986. Energy Journal. Vol. 7, No. 3. 67 – 82.

MWIDuE-NRW (Ministry of Economics, Innovation, Digitalization and Energy of the State of North Rhine Westphalia). 2020. Hydrogen (“Wasserstoff”) Roadmap.

Neher, Philip A. 1990. Natural Resource Economics: Conservation and Exploitation. Cambridge University Press, Cambridge, MA, U.S.A.

OECD. 2018. Effective Carbon Rates 2018. OECD Series on Carbon Pricing and Energy Taxation.

Rehner, Robert and Darren McCauley. 2016. Security, Justice and the Energy Crossroads: Assessing the Implications of the Nuclear Phase-out in Germany. Energy Policy 88, 289-298.

Renn, Oetwin and Jonathan Paul Marshall. 2016. Coal, nuclear and renewable energy policies in Germany: From the 1950s to the “Energiewende”. Energy Policy 99, 224-232.

Ruszel, Mariusz. 2016. The political importance of energy cooperation between Germany and Denmark on the European Union energy market. E3S Web of Conferences 10.

Ruszel, Mariusz. 2017. Strategic Goals of Energy Security Policy of the Federal Republic of Germany. Politeja 5(50), 113-129.

Singer, S. Fred. 1988. A critical analysis of the DOE report. Energy Journal. Vol. 9, No. 2. 17 – 29.

Schlesinger, Benjamin, Nelson E. Hay and Jacquelyn S. Michell. 1982. The potential role of natural gas in a major oil crisis. Energy Journal. Vol. 3, No. 2. 101 – 118.

Sovacool, Benjamin K. and Marilyn A. Brown. 2010. Competing dimensions of energy security: An international perspective. Annual Review of Environment and Resources, 35, 77 – 108.

Sovacool, Benjamin K., Ishani Mukherjee, Ira M. Drupady and Anthony L. D’Agostino. 2011. Evaluating energy security performance from 1990 to 2010 for eighteen countries. Energy, 36(10), 5846 – 5853.

Szczerbowski, Radoslaw. 2018. The energy policy of Germany and its impact on the Polish and European energy security. Polityka Energetzyczna (Energy Policy Journal) 21(3), 19-30.

Tongsopit, Sopitsuda, Noah Kittner, Youngho Chang, Apinya Aksornkij and Weerin Wangjiraniran. 2016. Energy security in ASEAN: A quantitative approach for sustainable energy policy. Energy Policy, 90, 60 – 72.

Umbach, Frank. 2007. Deutsche Außenpolitik und Energiesicherheit (German foreign policy and energy security). In: Jäger, T., A. Höse and K. Oppermann (eds.), Deutsche Außenpolitik: Sicherheit, Wohlfahrt, Institutionen und Normen (German foreign policy: security, welfare, institutions and norms, Wiesbaden: VS Verlag für Sozialwissenschaften, 354-373.

Statista. 2021. German natural gas import statistics.

Vivoda, Vlavo. 2010. Evaluating energy security in the Asia-Pacific region: A novel methodological approach. Energy Policy, 38(9): 5258 – 5263.

Westphal, Kirsten. 2014. Institutional change in European natural gas markets and implications for energy security: Lessons from the German case. Energy Policy 74, 35-43.

Wicke, Lutz and Markus C. Schulte von Drach. 2013. Die Energiewende-Wende. Dr. Georg Winter, Wachholts-Verlag.

Yao, Lixia, and Youngho Chang. 2014. Energy Security in China: A Quantitative Analysis and Policy Implications, Energy Policy, 67: 595 – 604.

Yergin, Daniel. 1988. Energy security in the 1990s, Foreign Affairs, 67(1), 110-132.

Appendix

Selected German and EU energy transition legislation

Laws & Guidelines	Key components
EEG 2000	Doubling of renewables proportion of electricity generation and consumption. Introduction of five regulatory-step rules on interconnections, consumption, incentive compensation and infrastructure expansion and equalization arrangements. Minimum tariffs for electricity from renewable sources.
EEG 2004 and RL 2001/77/EG	Maintaining but adapting the five regulatory-steps of EEG 2000 to the EU renewable energy Directive (2001/77/EG) in the common electricity market.
EEG 2009, PV-Novelle 2010 and 2009/28/EG	Fundamental revision of the existing EEG 2004 and partial follow-up on the EU-Directive 2009/28/EG as part of the European climate and energy package. Subsequently renewed through the PV-Novelle 2010 to account for decreasing investment costs and further expansion of PV capacity, with consequential decrease in incentive compensations. Definition of legal basis for proof of origin and reporting for transmission and distribution operators.
EEG 2012 and PV-Novelle 2012	Revision of EEG 2009. Target definition for the share of renewable electricity consumption to 35% (by 2020), 50% (2030), 65% (2040) and 80% (2050). Emphasis on market, network and system integration, to optimize and improve interaction between renewables and conventional energy, storage and consumer. Revision of bioenergy compensation, exemption from feed-in tariffs for storage operators and, through the PV-Novelle, incentive compensation for PV facilities.
EEG 2014, European Council's Climate and Energy Framework 2014 and EU-Roadmap for Decarboni-zation	New start of the Energiewende, having achieved 25% proportion of renewable electricity but the system now suffering from steadily increasing feed-in tariffs and challenges to network stability and supply security. Focus on the competitiveness of energy- and electricity-intensive industries to protect employment and welfare. Key stipulations incl. continued expansion and market-integration of renewables capacity, pilot PV-tenders and market analyses, European coordination and timetable for the EEG-Reform 2014. The European Council's Framework targets and commits to a 40% reduction in greenhouse gas emissions from the 1990 level and a 27% minimum renewables share of total energy consumption, while aiming for a 27% energy savings target. This was complemented by the EU-Roadmap for European Decarbonization by 2050.
EEG 2017	Compensation payments to be set by competitive tenders versus regulatory stipulation. Coordination of renewables capacity- with network and infrastructure expansion, market- and system integration. Introduction of the new offshore wind power law ("WindSeeG"). Last but not least, definition and introduction of direct incentives and compensation for private solar PV-capacity build-up.
European Green Deal 2020	The EU commits to be the first climate-neutral continents by targeting zero net emissions of greenhouse gases by 2050, decoupling economic growth from resource usage and consumption. One third of the 1.8 trillion Euro investments from the NewGenerationEU Recovery Plan and the EU's 7-year budget will finance the European Green Deal.
Proposed European Climate Law	Includes a series of legislative proposals to deliver the 55% reduction in greenhouse gas emissions by 2030 ("2030 Climate Target Plan") and, in

	particular, a legally binding target of net zero greenhouse gas emissions by 2050.

Sources: Ministry of the Economy and Energy (BMWiE), Germany; the European Commission