



Optimizing Power-to-Gas Technology for Efficient Renewable Energy Storage and Integration in Germany: a Review

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ARTICLE INFO

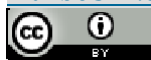
Keywords: Power-to-Gas Technology, Renewable Energy, Electrolysis Efficiency, Energy Storage, Sector Coupling

Received : 27, February

Revised : 20, March

Accepted: 25, April

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ABSTRACT

This study explores the integration of renewable energy sources into the German power grid, with a specific focus on the application of Power-to-Gas (PtG) technology as a solution for energy storage and optimization. Amidst the growing penetration of renewables, characterized by their intermittent nature, the challenge of maintaining a stable and reliable energy supply becomes paramount. This research delves into the use of Polymer Electrolyte Membrane (PEM) electrolysis for hydrogen storage and biological methanation within the PtG process chain, aiming to enhance the efficiency of methane production and the operational performance of trickle-bed reactors. By developing an economically viable approach for PtG technology and suggesting future business models, this work contributes to the identification of the most suitable electrolysis technology for sector coupling and grid integration. The findings indicate that PtG not only offers a promising pathway for the sustainable integration of renewable energies but also underlines the need for novel, application-oriented storage solutions and the optimization of system components for better market penetration and efficiency. This research underscores the pivotal role of PtG technology in bridging the gap between renewable energy production and the existing energy infrastructure, paving the way for a more sustainable and resilient energy system in Germany.

INTRODUCTION

Electrical energy production from RES such as solar and wind energy has the potential to play an important role in the future European electricity system (Sensfuss & Pfluger, 2014). This is because RES is sustainable and its use helps as well in the mitigation of climate change. Therefore, a high share of these RES unavoidably results in a strong demand for new electricity storage solutions (Dominik et al., 2020). It is a known fact that the largest electrical energy storage system in Germany is a pumped-storage hydropower plant that has a combined capacity of 6.8 GW with 0.05 TWh in its working volume at maximum filling level capacity, which this capacity can only be utilized between 6 – 8 hours' time-space in each case (Ess et al., 2012). A storage demand calculation based on a European scale for wind, and solar RES has been analyzed, and a forecast from the obtained results is given. The analysis suggested that total electricity storage between 80 and 100 TWh would be required in Germany for wind-only or solar-only electricity-based scenarios (Sensfuss & Pfluger, 2014). What this means in contrast, is that the chemical energy storage system of the natural gas grids in Germany can provide large capacities of around 260 TWh (Anne & Georg, 2008). Therefore, one can say or suggest that the procedure of transforming electricity into a long-term storable gas through electrolysis and in combination with subsequent conversion of the gained electrical power to molecular hydrogen methane would be an enviable solution in the long term (Sensfuss & Pfluger, 2014). In this manner, renewable energy sources can be stored in the country's current natural gas infrastructure and have access to the vast transportation capabilities of the network as well as gas storage facilities, which provide the greatest energy storage capacities in Germany. Storage gas is a renewable and adaptable energy source that can be converted back into electricity, used for heating and cooling, or utilized as a substitute fuel in transportation through combined heat and power plants (CHP)

(Anne & Georg, 2008; Sensfuss & Pfluger, 2014; Manuel et al., 2017; Amos et al., 2024a). Moreover, power-to-gas (P2G) technology might be the key technology for the energy sector and could be a major game changer to the future of the entire global energy system (Bernhard et al., 2017; Timo et al., 2018; Elegbede et al., 2023). The significance of power-to-gas in the future energy system is promising and rewarding because the quantity of electrical energy generated from RES can be transformed into storable natural gas (SNG) through electrolytic hydrogen production and subsequent conversion together with CO₂ to CH₄ and water gas (Stephen & Pierluigi, 2015). However, to utilize the excess quantity of electrical energy produced by the fluctuating Wind and Solar, electrolysis technology can transform this so-called waste energy to CH₄ (Dietmer et al., 2017; Amos et al., 2024b). Biological methanation within biogas plants could be an alternative to the classical chemical Sabatier process because biological methanation can be directly converted to methane by feeding hydrogen into the reactor due to the presence of hydrogenotrophic bacteria for example CO₂ + CH₄ (Mareike et al., 2014), taking temperature into account.

This review research study focuses mainly on the integration and market feasibility possibilities of biogas for biological methanation for power-to-gas

processes, energy storage, and optimization of methane production via electrolysis for long-term storage and for generation of electric power and other possible end-use applications. This research intends to make an investigation and offer solutions) to the questions, problems below, and recommendations for further research: Determine which electrolysis technology (PEM, Alkaline, etc.) is best suitable for the Power-to-Gas process chain. Demonstrate how the chosen technology for sector coupling is possible for grid integration. What is the best set-up of the system components (reactor, storage, electrolysis, CHP) in terms of size, storage, capacity, and investment? Developing an equation to optimize the system components of the chosen technology regarding, a given load curve (Mareike et al., 2014). How the chosen technology would help in improving the efficiency of the methanation processes and flexibility? In addition, brings about an improvement of the process chain for efficiency and flexibility of the methanation process in terms of application. The main objective of this study is to review the market structure and renewable integration into German power grids. A detailed design of the trickle-bed reactor, to improve the production capacity of the biogas significantly to meet demand is important for its optimization, but will not be the scope of this work

LITERATURE REVIEW

Renewables Integration into German Power Grids

A significant technological improvement and cost reduction observed so far in the renewable energy sector, especially in terms of power generation from wind and solar energy sources are now more competitive in comparison to many conventional power generation plants Ancona et al., 2016; Amos et al., 2024c). The direct consequence is that the energy market is now witnessing a high rate of penetration of renewables in the last few years as shown in Figure 1 concerning Germany. However, an increase in the penetration rate of renewables into the power grid poses new challenges to the entire power system. Therefore, as part of the major concern for energy security, for example, the installed capacity in Germany from renewables is much higher than the peak load in Germany, which, contributes annually approximately 32% to German average energy (Harald & Xiaoshu, 2017; Blanco & Faaij, 2018) production. Although the regional distribution of renewable generation and loads are not the same, for instance, in the northeastern part of Germany, the ratio of renewable energy is over 100%, which is because of low load with a high share of renewable penetration (Harald & Xiaoshu, 2017).

However, EEG (German Energy Law) is the main motivating instrumental tool for the significant addition of renewable energy sources to the German power grid, which ensures that investors in renewable energy generation will get a set feed-in tariff. Designated revenues per kWh are fixed for the next 20-year period by the year of commissioning. The EEG mandate stipulates that energy generation from renewables is been fed into the grid irrespective of where it is sited so far it can produce. In a situation in which overproduction from renewables temporarily exceeds the tolerable loading of lines or transformers respectively poses threats to the stability of the system in general, then, are the grid operators allowed to announce curtailments through

emergency measures (Note: the not produced energy has to be funded). The German geographical landscape is been divided into 3 zones with very different structures of load and renewable generation in Fig. 1. About 28% of the German population lives in the southern area, which is majorly dominated by a huge amount of very small photovoltaic installations, mounted on the roofs of the houses (Harald & Xiaoshu, 2017). Consequently, the majority of renewable input occurs during the day, which can be primarily absorbed by the growing daytime load of the powerful industries in the southern region of Germany.

The northwest of Germany, which is home to 52% of the country's population and has significant industrial districts far from the Main and Ruhr rivers and the Rhein. About 55% of German wind power is installed in the northwest, which causes a high level of fluctuating infeed and makes it challenging to balance home and industrial demand. In the northern portion of Germany, where just 20% of the population is industrialized, there are significant ground-based solar installations and wind farms accounting for around 45% of the country's total installed power (Harald & Xiaoshu, 2017; Blanco & Faaij, 2018). Therefore, the grid operators are conditioned to decide often due to the occurrence of massive volumes of renewable overproduction, curtailments assessed by re-dispatching conventional power plants or emergency shut-offs of renewables are required to keep the system stable temporarily. However, increasing shares of non-programmable renewables in generated power are creating additional challenges for the already existing electric distribution network. This is due to the unpredictable weather-prone nature of energy production from wind and solar sources, in Figure 3, and Figure 4. The integration of intermittent renewables into the grid or distribution networks brings to mind such questions in terms of power quality, voltage stability, reliability, and required flexibility margins during application for the electrical system. Consequently, a grid-scale energy storage system is thought to be a close to ideal solution, among other reasons, to deal with the high penetration rates of non-programmable renewable electric power into the current power grid infrastructure or electric network, as it can provide the necessary flexibility to the entire power system (Ancona et al., 2016; Blanco & Faaij, 2018).

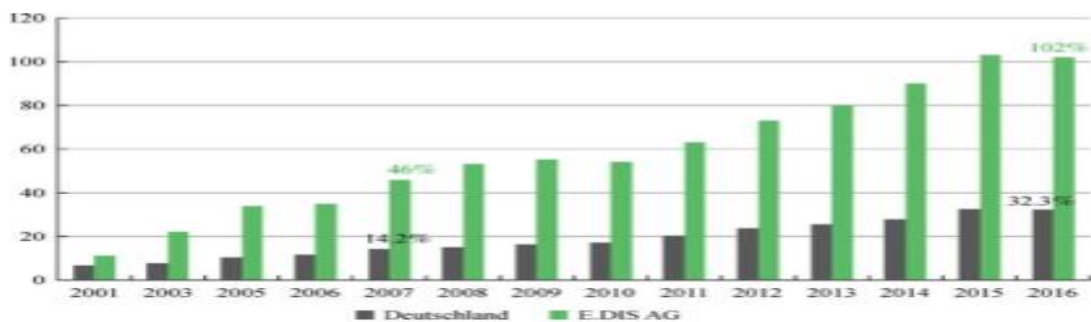


Figure 1: Share of renewable energies contributing to the yearly energy demand in the 110 kV grid until the end of 2016, compared with the whole of Germany (Deutschland)

Source: Blanco & Faaij

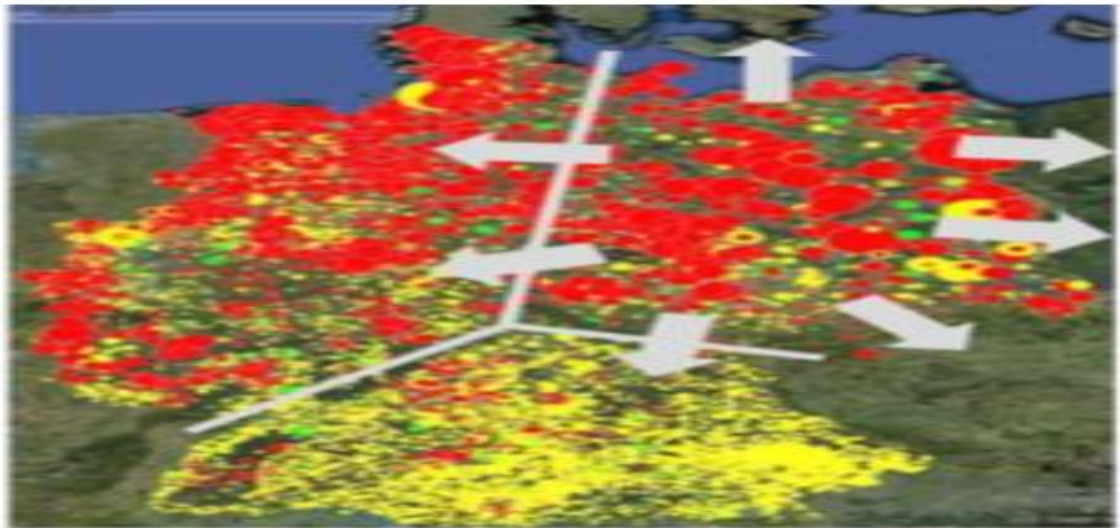


Figure 1: Distribution of 1500000 RE-units in Germany at the end of 2015 (red = wind; yellow = PV; green = biomass)
Source: Harald & Xiaoshu (2017)

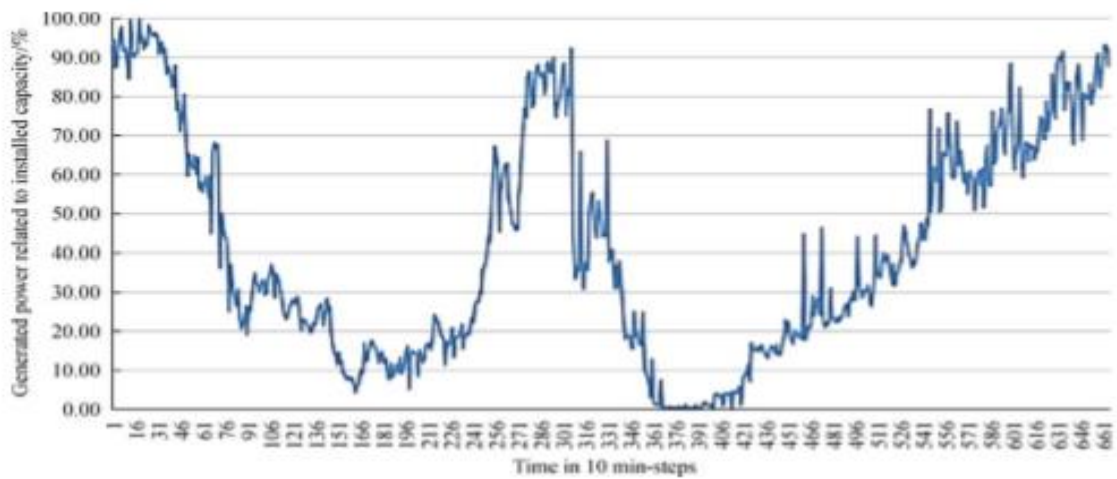


Figure 3: Fluctuating generation of a 300 MW wind farm within a period of about 5 days
Source: Blanco & Faaij (2018)

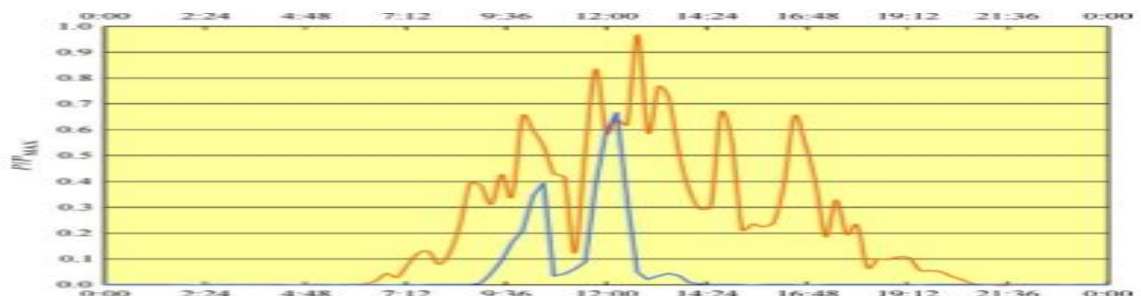


Figure 24: Fluctuating generation of a six MW PV - Installation in 24 hours for a summer day in red and a winter day in blue
Source: Harald & Xiaoshu (2017)

Four transmission control zones are also used to classify the German 400kV transmission system. The following power firms are in charge of it: LEAG,

which is the primary operator of the traditional power plants, and 50-Hertz transmission in the northeast. Along with RWE as the primary power source, Amprion is in charge of running the grid in the west and a portion of the south. As shown in Fig. 5, with the four German transmission system management zones, Transportnetz BW and EnBW in the southwest and trans power along with Tennet from the northwest to the southeast annex. Figure 6 displays the various regional distribution grid zones for Germany's northeast. A huge amount of energy production from renewable generation is connected to the north-eastern grid if compared with other regions in Germany because load demand in this area is relatively low. This made the ratio of renewable energy share about the annual energy demand above 100% in some of the distribution grids, whereas the same ratio for the whole of Germany in total is about 32%. The German government's target is to reach about 45% by the end of 2025 from energy generation renewables (Harald & Xianoshu, 2017; Adegoroye et al., 2024). In contrast, the renewable energy ratio of 100% in the northeastern regional distribution grid does not guarantee that these grids have the full capacity to supply their customers with renewable energies. Wind speed and solar radiation energy sources are erratic because there are times when they generate significantly more energy than is required to meet consumer demand, and there are also extended periods of time when they generate almost no energy at all. Both pose significant risks to the stability of the electricity grid and generate a lot of unclear circumstances.

According to Figure 6, there is a huge infeed of wind power supply to the northeastern grid towards the end of 2011 to early 2012, and a record of very high fluctuation day by day that does not correspond with the fluctuating demand of the consumers. Apart from infeed through renewable sources, the steam fired power stations called Independent Power Producers (IPP) are allowed equally to feed in power into the grid in compliance with the contracts they endorse with their customers (Harald & Xiaoshu, 2017; Blanco & Faaij, 2018).



Figure 35: Four German transmission grid control zones



Figure 6: Regional distribution grids within the 50-Hertz transmission control zone Source: Blanco & Faaij (2018)

Source: Harald & Xiaoshu (2017)

In addition, if the transport capacity of the interconnecting transmission lines that goes to the south and west of Germany is attained, the Transmission System Operators (TSO) are supposed to take emergency measures to curtail line tripping to make sure that the system is stabilized. The first approach of such curtailing measures is the re-dispatch of the conventional power stations. Whenever there is too much electrical power sold by IPP's to their customers in the south and simultaneously these lines are nearly overloaded, to this effect the TSO can mandate certain power stations in the northeast to lower their output. Likewise, manner certain stations in the south are supposed to increase their output so that the capacity of the line is not overburdened. The orange parts in Figure 7 represent the re-dispatch in power generation, which is supposedly compensated by the TSO, as regulating power, and the bill will be charged to the consumers' electricity utility costs (Blanco & Faaij, 2018). However, whenever such a re-dispatch is not adequate to prevent line overloading, the TSO should cut renewable infeed by emergency switch-off in which end users (customers) bear the cost incurred from loss of energy during the process. Figure 8 explains with clarity the number of days per year in the north-eastern grid (Blanco & Faaij, 2018) where re-dispatch procedures alone (pink bar) are insufficient to maintain system stability, and the number of days per year that re-dispatch combined with an emergency switch-off of renewable energy sources – will take place – are indicated. Since 2015, there have been at least one occasion every day where the TSO must interact quickly by taking such measures.

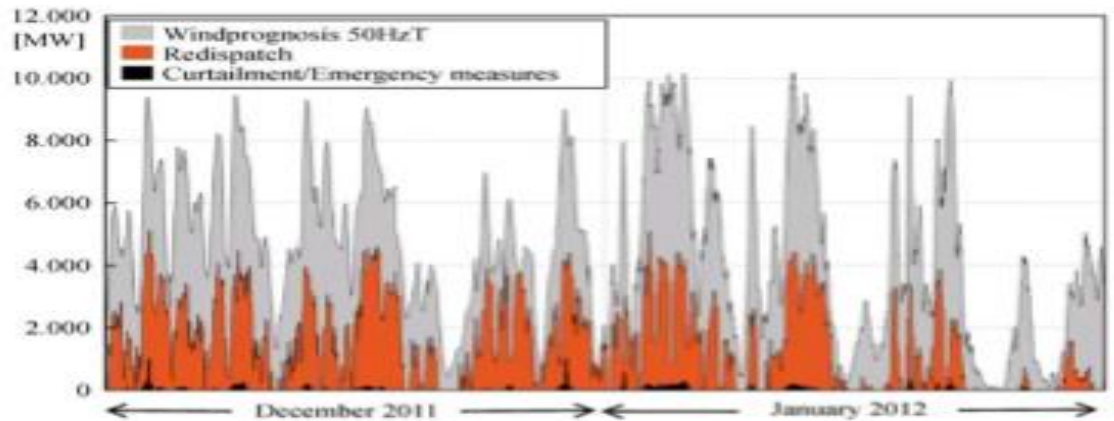


Figure 8: Days per year, where system stability is secure through curtailment of the conventional generation by re-dispatch denoted with pink or both re-dispatch and emergency shutdown of renewables denoted with red

Source: Harald & Xiaoshu (2017)

Amongst several other reviewed methodologies on how to solve and overcome such circumstances will be, to either upgrade the transport capacity of the German grid so that temporary overproduction of renewables from regions with low load to the regions that demand higher load or to encourage the installation of storage capacity in this region with renewables overproduction. However, this research study suggests that, power-to-gas technology (the storage of excess amounts of renewable electricity in the gas network will be a viable solution) to achieve such a goal on economically reasonable terms. Power-to-gas (PtG) technology is a sector coupling technology that can offer cheaper electricity because more energy production from renewables offers cheaper electricity for heating, vehicles, etc. in the end and simultaneously serves decarbonisation purposes. Note: (the idea for the size of needed storage capacity is vital).

To avoid the constant increase in the limitation of renewable generation, several technical methodologies and economical options with the view of costs benefit analysis through new energy market design, more flexibility in generation power-to-gas, power-to-heat, power-to-vehicle, or even smart meter application on the internal consumer side, thanks to new load-side flexibility from steam-fired units. Nonetheless, a number of storage solutions were looked into, including vehicle-to-grid, stationary batteries, compressed air storage, tube storage and regeneration, and pump storage units. Power-to-gas technology is more suitable and guarantees sustainable solutions to storage challenges in Germany. The German electric power infrastructure requires a peak load of 80 GW and an annual energy demand of 647 TWh for grid integration of renewable sources. About 118% of Germany's peak load and 26% of its energy demand are accounted for by the country's large variable renewable generation from photovoltaics and wind energy. The situation becomes more critical from a grid point of view if one is to look at it from a different regional perspective. For the 400 kV transmission control zone in the northeastern part of the country, about 23 GW of thermal power and 27 GW of renewable power generation are

connected to the grid. Comparing such with a peak load of 16 GW is a high over-installation. Renewable generation contributes 49% to the northeast German energy demand, in some regional grids; this quota reached 120% already (Harald & Xiaoshu (2017; Blanco & Faaij, 2018).

Review of the German Historical Power System

Currently, market integration, acceptability, cost-benefit effectiveness in the long and amount of renewable electricity generation through the concept of power to gas is still modest. Sector coupling is the guiding principle for the entire energy system whose electricity, gas, heat, and transport infrastructures already exist connect technically, and can physically interact. Energy generation from renewables can be completely and efficiently utilized through sector interconnectivity and integrated as well into separate sectors. This section provides some explanation of the recent and historical structure of the German electrical markets, with a focus on market liberalization policies that prioritize the integration of renewable energy sources. In the context of these energy markets, it also discusses the aggressive tactics used by the German government to increase the capacity for producing renewable energy. In the early decades of Germany's electrification process, the power grid was independently developed under governmental laws. Reliability and affordability are the primary policy aims. Different local and regional businesses built and ran power generating units and electric power systems in a decentralized manner. About two hundred and twenty kV transmission grids to connect both the local and regional power grid were built after the First World War. This led to a discussion and the need to have a national integrated electric power grid as well as contributed to increasing competition between companies from different regions, this created the emergence of market consolidation. The introduction and the issuing of the Energy Industry Act (EnWG) in 1935 put an end to the German government interference. The purpose of this law was to create an effective and efficient development of a nationally integrated and reliability in power grid.

The designed idea is to be achieved by assigning monopolistic rights to major companies at the forefront as a form of motivation for investments in generation units and towards grid infrastructure. The monopolistic approach was more appropriate to guarantee power grid reliability and grid operation should be cost effective through the lens of economies of scale. As a result of regional monopoly rights, EnWG forms a power system with a high rate of vertical integration and a low rate of competition. The ownership and operation of power generation and transmission assets belong to the integrated utilities, while power distribution and retail are managed by integrated municipal utilities. The local government manages municipal utilities and the integrated utilities which are responsible for generation and transmission, which later bring together all stages of the power supply chain into an entity company. EnWG mandated the companies to make sure that they provide electricity to all end users to ensure the protection of consumers against the market power of the newly assigned monopolies. The Act also makes provisions for construction regulation and expansion of power plants to avoid system instability. '

However, sustainability is a recent policy as an important shift in the electricity market's regulation regime, which had its origin in the 1970's during which environmental protection popularity was enforced as a new policy goal (Brunekreeft et al., 2015). In the wake of high levels of local and regional air pollution from the combustion of fossil fuels for power generation, the government introduced the Federal Pollution Control Act (BIM SchG) in 1974. This Act and its provisions mandated power plants to install filter technology to reduce the emission rate of sulfur dioxide (SO₂) or nitrogen oxides (NO_x). The German government further strengthened the statutory role of environmental protection in the early 1990s: The Act on the Feed-in of Electricity from renewable sources into the Public Grid in 1991 and the Renewable Energy Act (EEG) of 2000 was introduced as an incentive to make more investment into energy generation from renewable sources. In addition, another example of a policy shift that favours environmental protection is the Electricity Tax Act (StromStG) which was introduced in 1999 and aims at inducing consumers to consume less electricity by increasing the price of electricity.

However, citizens are more usually against any new energy infrastructures close to residential areas especially when they contribute to any form of environmental disturbances. The general public acceptance is a fourth energy policy goal and the increasing importance of sustainability has the support German people. A sizeable number of citizens are actually against investments in new wind farms, biomass power plants, or transmission lines (Siemens, 2014). In the last few years, quite several energy projects for new transmission lines and site demonstrations for carbon capture and storage have not been successful because of public disapproval (Brunekreeft et al., 2015). Consequentially, general public acceptance in recent times now gained consideration in the discussion as a fourth general energy policy goal in Germany, without which the government and the companies will not be able to maximize their investment plans (Brunekreeft et al., 2015). It is therefore imperative to know that there are three elements, which are very vital to ensure the needed support from the people towards investments in renewable energy infrastructure. It must clearly express the costs, benefits, and risks taken on new investments and technologies. At the same, the hidden motivations of the different stakeholders involved in a project should be available in the public domain and as well be carried along in the entire planning process of new projects. Private Citizens and other public stakeholders should be free to express their minds, take positions, and commit their financial funds to a project as an investment.

METHODOLOGY

This study employs a multi-disciplinary approach to explore the integration of renewable energy sources (RES) into the German power grid, emphasizing Power-to-Gas (PtG) technology. The methodology is segmented into several key areas: system design, data collection, analytical techniques, and validation processes. This section outlines the methods used to conduct the research and the rationale behind them. The electrolysis Process utilizes Polymer

Electrolyte Membrane (PEM) technology to convert electricity into hydrogen. Parameters such as efficiency, operating pressure, and temperature are optimized based on existing literature and experimental data. The methanation process studies biological and chemical pathways for converting hydrogen into methane using CO₂. The biological route includes the use of hydrogenotrophic methanogens, while the chemical pathway employs the Sabatier reaction. Therefore, solar and wind energy outputs are simulated using historical weather data to assess the variability in power supply and its impact on the PtG system. Data were collected on renewable energy which gathers and analyzes data from solar and wind farms across Germany to model the input variability to the PtG system. Also, information on grid operations including load demands, peak times, and existing storage capacities to understand the current infrastructure's capabilities and limitations was sourced. Lastly, reviews of current and projected costs associated with implementing PtG technologies, including capital investments and operational costs.

RESEARCH RESULT AND DISCUSSION

Power Generation and Consumption in Germany

The gross electricity generation of Germany in 2013 was estimated to be approximately 634 TWh (Harald & Xiaoshu, 2017). Coal remains the major primary energy production source, which accounts for over 45 % of total electricity generation (Brunekreeft et al., 2015; Harald & Xiaoshu, 2017; Blanco & Faaij, 2018). Nuclear power and gas occupy the second and third most important positions in the energy generation pattern in Germany, which accounts respectively for about 15 % and 11 % of the overall electricity production. About 24 % of the total electricity generation comes from renewable sources, with which wind energy sources account for about 8.4 %, biomass 6.7 %, solar 4.7 %, hydro 3.2 %, and waste produced from households 0.8 % (Brunekreeft et al., 2015). However, in the last two decades (20 years), the general electricity production curve witnessed a slight increase according to Fig. 9. To this effect, the composition of the electricity mix has changed drastically because of these two particular governmental policies: the promotion of renewable sources initiated in the 1990's as mentioned above and the decision phase out nuclear alongside decommissioning as highlighted in 2002. Therefore, there has been a steady downward shift in the quantity of electricity generated from nuclear power from 29.2 % in 1993 to 15.4 % in 2013, and coal from 55.7 % in 1993 to 45.2 % in 2013. In contrast, simultaneously the share of energy sources from renewables in the electricity mix has increased from 4.0 % in 1993 to 23.9 % in 2013 (Arbeitsgruppe, 2014; Brunekreeft et al., 2015). The rise in the share of renewable generation is synonymous with the importance of different renewable generation sources. In 1993, hydropower was the most important renewable generation source but in 2013, it contributed no more than a minor part. Whereas, wind, biomass, and solar power, were almost not viewed in 1993, but in 2013 till date remain the most important renewable generation sources.

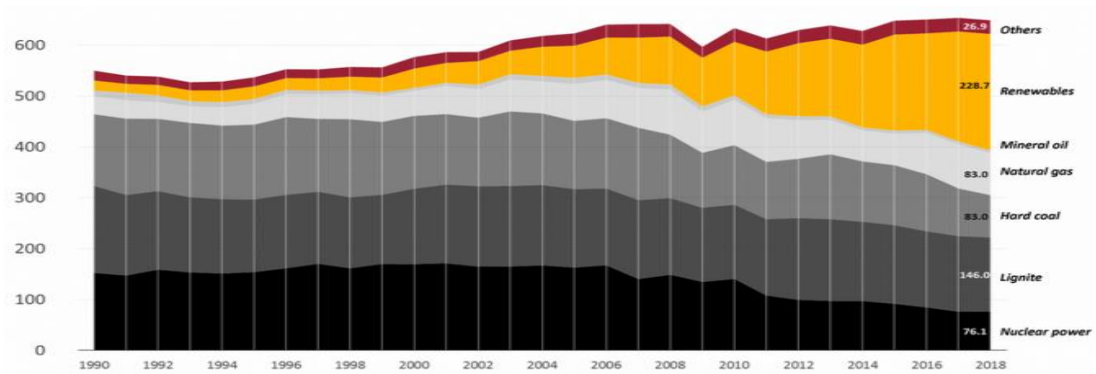


Figure 49: Electricity generation in Germany from 1990 to 2018 in TWh
Source: Clean Energy Wire (2018)

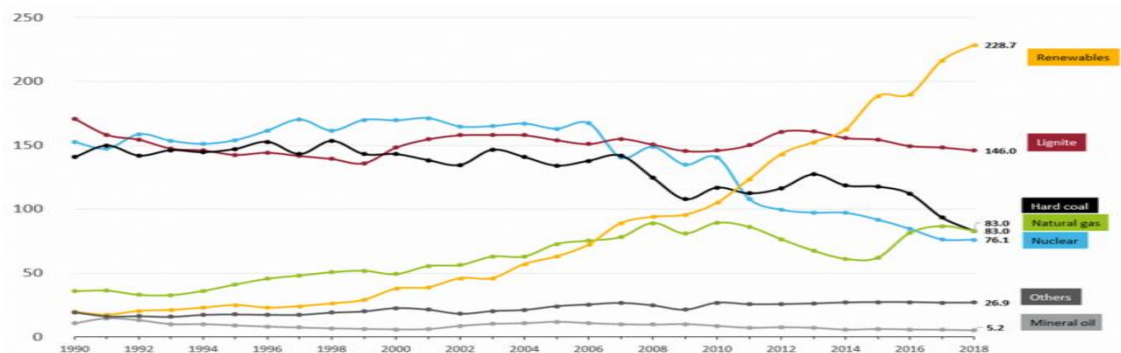


Figure 10: Electricity generation in Germany from 1990 to 2018 in TWh
Source: Clean Energy Wire (2018)

The electric power consumption in Germany was estimated to be about 528 TWh in 2013 (Brunekreeft et al., 2015). The variation between gross electricity generation and consumption can be accounted for in the following; power plants' consumptive power use, from the export of electricity to neighbouring countries, and transmission line losses.

Industries remains the major consumer of electrical power and this accounts for approximately 46 % of national electrical power consumption (Brunekreeft et al., 2015). The residential sector follows suit and its consumptive use is about 26 % while the commercial and public sectors consume about 14 % and 10 % respectively. The transport and agricultural sectors play no more than minor roles and consume just approximately 2 % (Brunekreeft et al., 2015). The resultant load curve is therefore characterized by peaks and valleys patterns but gas-fired power plants are in place to provide the needed ancillary services to maintain imbalances that occur with such load curve patterns. The increasing share of electrical power generated from wind and PV raises the question of how power consumption can adapt to fluctuating generation with flexibility during operation. The potential for load shifting is in the industrial sector with its large electricity consumers because it can be at a reasonable cost. Figure 11 presents the maximum power disconnected negatively or positively connected for a short duration in the residential, commercial, and industrial sectors; the numbers are attributed to the German overall peak load of 80 GW.

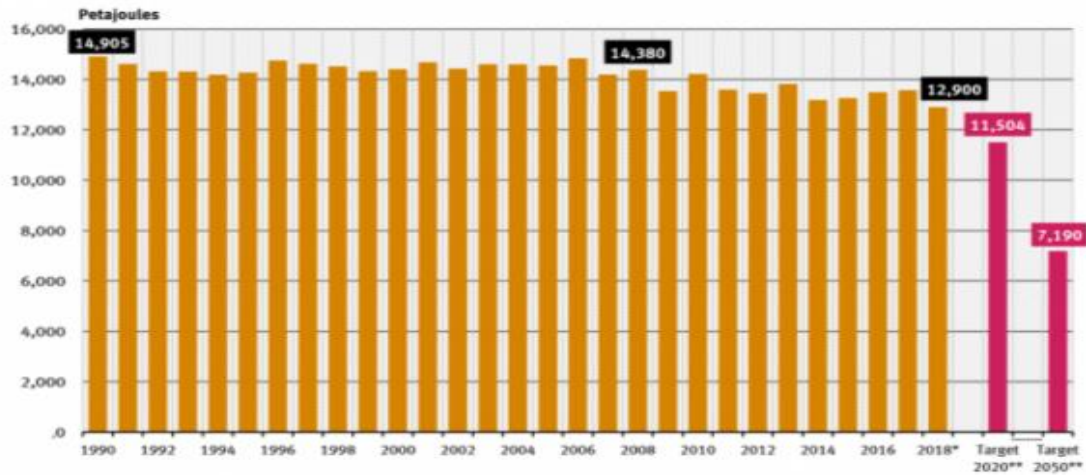


Figure 11: Energy Consumption in Germany Source: Umwelt (2019)

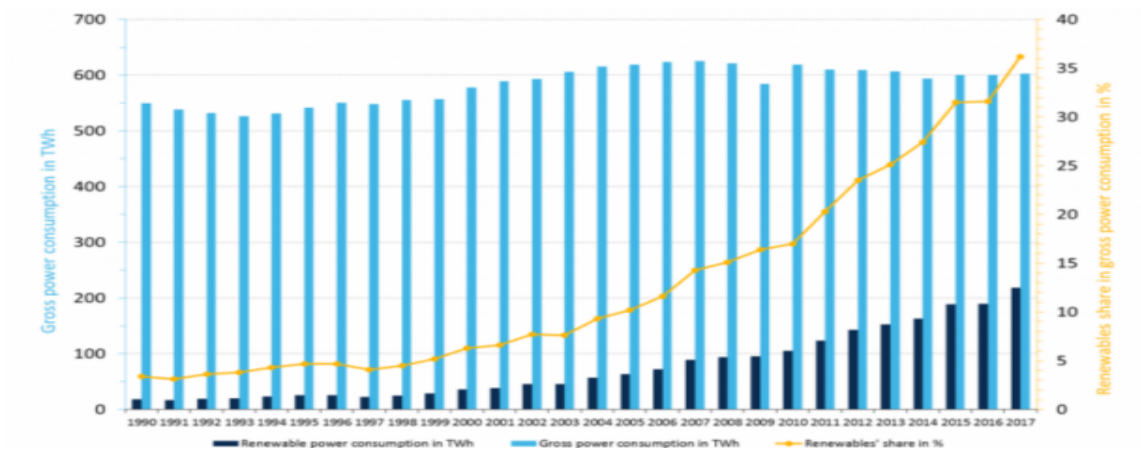


Figure 512: Energy Consumption Mix in Germany Source: Clean Energy Wire (2018)

Residential	Commercial	Industrial
-68 GW (pos.)/28 GW (neg.)		
20 GW	-	2.8 GW
7-32 GW	2.4 GW (pos.) 14.3 GW (neg.)	3.9 GW (pos.) 6.5 GW (neg.)
5.0 GW (pos.) 6.3 GW (neg.)	3.0 GW (pos.) 18.1 GW (neg.)	0.9 GW (pos.) 11.2 GW (neg.)

Figure 13: Demand side management potential Source: Brunekreeft et al. (2015)

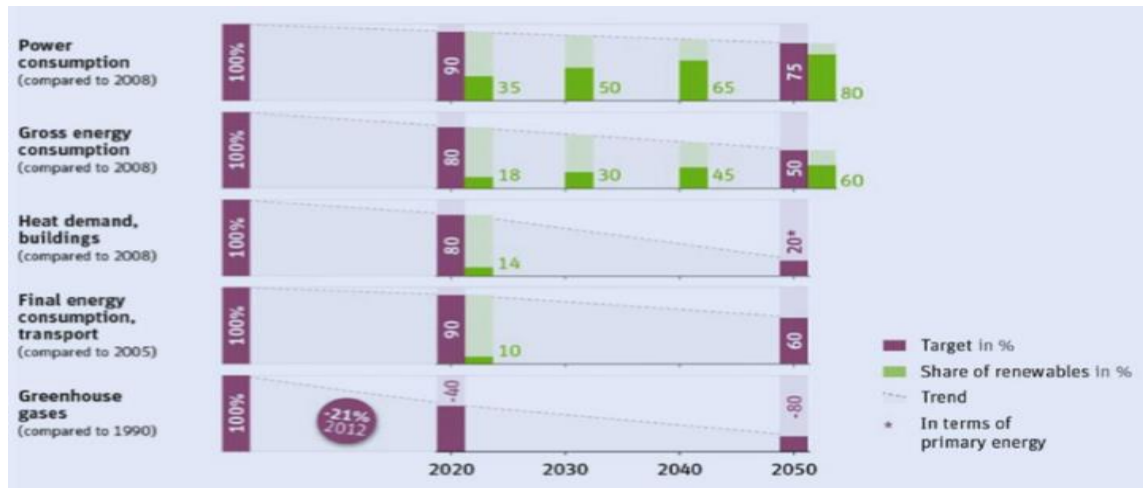


Figure 614: Long-term targets for Germany's energy Source: Gert et al. (2014)

Power Logistics in Germany and German Grid Infrastructure

In Germany, there is an uneven distribution of power generation and consumption. Due to their robust industrial basis, Germany's load centers are concentrated in the country's west and south. When nuclear and coal-fired power plants in these areas are unable to provide enough electricity, it becomes impossible to avoid constantly importing electricity from other sections of the nation or even from neighboring nations. On the other hand, because of their enormous wind resources, the country's northeast and east consistently produce more electricity than they can need. Therefore, Germany's north and east regions transfer electricity to the southern and western regions of Germany regularly. The electrical power grid in Germany is divided into four different groups, which are; extra high voltage grids between 220 kV - 380 kV in the transmission grids of Germany. They are in charge of the electricity feed-in of big generators such offshore wind farms and coal- and nuclear-fired power plants, in addition to the transmission of electricity.

The transmission grid is suspended and has visible electricity pylons as well as surface cables. Currently, there are over 35,000 km of transmission systems in Germany that have 1,100 electrical transformers (Brunekreeft et al., 2015). High voltage grids between 35 kV - and 110 kV are the highest voltage distribution grid levels. It is a redistribution of electrical power systems at the regional level. Furthermore, this type of high-voltage grid supplies electrical power to large industrial consumers and also feeds in electrical power from small power plants, wind farms, and large PV parks. There are relatively 95,000 km of high voltage grids and 7,500 electricity transformers at this level in Germany (Brunekreeft et al., 2015). Medium voltage grids between 10 kV - 30 kV fall to the subordinate grids distribution level. It distributes electricity to the connected low-level voltages. It also supplies electricity to connected bulk consumers and feeds in electricity from small PV parks and single wind turbines. They are underground cables and it is roughly 507,000 km in length with 560,000 local substations (Brunekreeft et al., 2015). Low voltage grids in the range of 230 V - 400 V are typically identified by underground cables, which distribute electricity from local substations to households and collect electricity from PV

modules mounted on rooftops. Its length is approximately 1,150,000 km (Brunekreeft et al., 2015). Increased network congestion during peak generation periods is a result of small distributed rooftop PV installations on the low voltage level and growing feed-in from large wind farms at the high voltage level. The rapid build-up in renewables generation capacities, renders grid capacities to be insufficient to absorb the produced energy at once. This necessitates high rates of grid curtailment from renewable penetration significantly within the last few years. A good example is Schleswig-Holstein, a windy region in the north of Germany in which 3.5 % of the total wind generation in 2012 was curtailed (Brunekreeft et al., 2015). Renewable energy curtailment during peak generation can reduce the need for network investments. Curtailing 30 % of PV peak production and 20 % of wind peak production could lower the cost of infrastructural investments by 10 % between now and 2030 while only 2 % of the annual electricity production from renewables would be curtailed (ECOFYS Germany GmbH, 2012; Gert et al., 2014; Brunekreeft et al., 2015; Deutsche, 2020).

Structure of the German Energy Market

Germany's regulations on the electric power system, through a favourable policy and well-grounded institution are paramount to the further development and successful penetration of renewables into the energy market. The Federal Government's Policy on Energy concept to achieving a 100% environmentally friendly, reliable, and affordable energy supply of September 2010 is a step forward that shows political commitment. The road to the energy of the future that is safe, affordable, and environmentally friendly as highlighted in the Key elements of energy policy concept of June 2011 (ECOFYS Germany GmbH, 2012; Gert et al., 2014; Deutsche, 2020), contains guidelines and objectives relating to Germany's future energy system. In particular, the inclination towards more environmental protection is demonstrated by government plans to cut down CO₂ emissions to 60 % based on the 1990 benchmark by 2020 and subsequently, it is planned to continue until 2050 (Gert et al., 2014). This CO₂ reduction mission is to be realized by cutting down energy utilization in the transport and heating sector, for instance, the energy consumption for heating purposes is expected to be reduced by 20 % between 2008 and 2020 and 80 % by 2050 (Gert et al., 2014). According to the government's targets, the power sector is expected to generate 35 % of electricity from renewable sources in 2020 and increase the share to 80 % by 2050 (ECOFYS Germany GmbH, 2012; Bundesnetzagentur et al., 2013; Deutsche, 2020) as shown in Figure 34. Meanwhile in the meantime, because of the nuclear disaster in Fukushima, the government decided to phase out completely power generation from nuclear energy sources by 2022 (Gert et al., 2014). There are other objectives with specifics about the development of the power system in Germany as a complement to the general goal of achieving more sustainability and increasing the importance of renewable sources.

The plan is to expand transmission grids in the north-south regional direction, which makes easy and effective transportation of electrical power from wind in the north to the load centers in the southern part of Germany.

Additionally, such goal to improve energy efficiency and promote energy storage technologies and electric vehicles is synonymous with the government's plan to create a sustainable power system. However, the general governance structure for the energy system in Germany includes various ministries and independent institutions. Currently, two ministries are at the center of the governance structure of the German electricity system Ministries with energy policy mandate. These ministries are responsible for legislative laws and ordinances that independent institutions must obey and adhere to. What this means in essence is that the legislating bodies are not allowed to interfere with daily activities nor expand or obstruct the competencies of these institutions. (BMWi) the Federal Ministry for Economic Affairs and Energy whose task is to formulate and implement energy policies that include renewable energy. The ministry is also obligated to monitor associated issues with the security of supply and competition policy. The Federal Ministry for the Environment, Nature Conservation, Building, and Nuclear Safety (BMUB) is the second body that has a responsibility towards energy policy that has a direct relation with environmental protection, e.g. energy efficiency of the building sector and cutting down on CO2 emissions. Therefore, BMWi and BMUB shoulder the duty for the design of the market for the power (electricity) sector. There are other important ministries in the context of energy and electricity sector policy and smart grids, such as the Federal Ministry of Transport and Digital Infrastructure (BMVI) whose major work is in the transportation and mobility sectors and for the digital communication infrastructure expansion, as standard reference for smart grids. As well as the Federal Ministry of Labour, Social Affairs and Consumer Protection (BMAS) whose main duty is on social issues associated with energy.

Furthermore, the three following government authorities have specific mandates in the regulation of the electric power system of Germany. They are, the Federal Network Agency for Electricity, Gas, Telecommunications, Post and Railway (BNetzA) whose obligation is in the regulation of such networks with natural monopolies, with the inclusion of electricity grid. The existence and competencies of BNetzA are been detailed in Acts such as EnWG and the Grid Expansion Acceleration Act for Transmission Networks (NABEG). While BNetzA is in control of national, and interstate regulations, at the same time works closely with regulatory counterparts at the federal and state levels. The regulators at state levels have responsibilities towards distribution network operators (DSO) with customers under 100,000 and BNetzA has an obligation towards all transmission system operators (TSO) as well for DSOs with more than 100,000 customers or with operators from many states. The Federal Cartel Office controls competition levels in case there is any difficulty coming from competition associated with natural monopoly networks, the Federal Cartel Office has the jurisdiction to authorize BNetzA to manage the emergence of such challenges. The details about the existence and competencies of the Federal Cartel Office can be found in, the Act against Restraints of Competition (GWB). The Monopoly Commission can counsel on matters that have to do with competition and monopoly matters but such services are non-binding and as well have no

power to decide the process. However, the Monopoly Commission plays a major part in scrutinizing and assessing what the regulators have done or proposed. Monopoly Commissions' responsibilities are found in (the GWB) Competition Act.

Market Structure in Germany for Renewables Integration

In the supply chain of Germany's electric power industry, the vertical and horizontal market structure phases are still far from being completely unbundled. This is so because fully unbundled businesses that are separate from other supply chain components are owned and run by the transmission grids. To prevent the exchange of commercially sensitive information between power grid operators and other micro elements in the supply chain downwards within the same utility, distribution grid operators are legally separated from generation and retail enterprises. The announcement of the first EU directive on electricity initiated a tremendous increase in Germany, the competition for power generation. Before 1996, four major companies, namely RWE, E.ON, Vattenfall Europe now LEAG, and EnBW monopolized power generation. Meanwhile, these four companies together represent only a fractional market share of approximately 44 % of the total installed electricity generation capacities (Gert et al., 2014).

The decreasing rate in the market share of the former monopolists is because of the phasing out of nuclear power and the increasing share of distributed generation from renewable sources. The market share of the four former monopolists has drastically and continuously decreased from 50 % in 2008 to 45 % in 2011 (Gert et al., 2014). One of the main factors driving competitiveness in the power production industry is the increasing importance given to renewables in particular. Even though investing in conventional power facilities requires a large amount of capital, feed-in tariffs have made investments in renewable energy attractive for small investors. Because of this, there are currently 300 or more smaller generation businesses with capacity ranging from one megawatt to hundreds of megawatts. A like situation has also been observed in the retail industry. Greater portions of these retail businesses focus on the local area and aim to capture a large market share within their defined service areas. The rate at which consumer switches to other retailers is still relatively low because end consumers tend to always remain with the incumbent regional suppliers. However, in 2012 about 7.8 % of all households in Germany changed their electricity supplier (Gert et al., 2014). Moreover, the ownership structure on the transmission and distribution level plays an important role in the market structure for power supply. On the transmission level, four TSOs own the infrastructure, and 900 DSOs own parts of the distribution grid (Gert et al., 2014). In as much, as electricity networks are a natural monopoly, there is no room for competitive markets for customers between the different grid operators because BNetzA regulates network charges. However, the emergence of new market actors and the unbundling of the energy market is a process that has legally enjoyed reinforcement toward more competition.

In the electricity sector, new market structures and actors have emerged as a result of the reinforcement brought about by the shift to smart grids and renewable energy sources. The structure of the German power market has undergone significant change in recent years due to their increasing relevance. The supply chain of the electric power system now includes a sizable number of new participants. The number of businesses engaged in the energy sector, which includes the provision of heat, gas, electricity, and other services, is substantial. Has grown from 15,666 in 2006 to 48,292 in 2011 (Gert et al., 2014). This represents a percentage increase of over 200 % in the last five years (Wang & Nehrir, 2008; Guo & Li, 2018). Especially Innovative start-up companies with few employees as energy service providers have contributed to this increase whose number has increased from 14,545 in 2006 to 46,967 in 2013 (Gert et al., 2014). The high rate of the penetration of renewables into the German energy grid calls for a meticulous approach to the restructuring of the energy market. Renewable generation influenced power generation by creating a platform for renewable operators to be recognized in the energy market. More so, power plants were traditionally owned solely and operated by large utilities but because of the financial support structure in EEG Sect. 4.4.3 not less than 1,500,000 renewable power plants as onshore wind, PV, and biomass plants, have been so far (Blanco & Faaij, 2018). Small medium-sized companies and households operate the larger part of these power plants. In 2013 6 % of all German households were proud to have their renewable generation units, and small rooftop PV installations in their buildings (Burkhardt & Busch, 2013). Companies in the manufacturing industry sector also started building their renewable generation units and by 2005, about 5 % of all manufacturing companies in Germany owned renewable. This number increased within a few years to approximately 18 % in 2012 (Jee et al., 1987). Though the first cooperative tradition was formed in Germany at the start of the 20th century with the aim of creating the first power supply systems, this also gave rise to newer energy cooperatives in recent times. These organizations established the framework that allowed private persons or civil society to pool their financial resources to form alliances and jointly invest in power system components. Up to 2012, an estimated 650 energy cooperatives with over 130,000 members had invested over one billion euros in renewable energy-based power facilities (Nishimura et al., 1992).

Grid operations service provider companies are an important fraction in designing market structures for renewables because they understand the dynamics in power logistics. They function mainly by specializing in providing services to operate smart grids for small-sized or municipally owned by German DSO. The business model for services is usually termed efficient since the small DSO does not need specialized personnel, for such grid operation (there is no need for very sophisticated knowledge of ICT capabilities and with the required level of grid automation knowledge). A single grid service provider may be able to operate the smart grids of several small DSOs. VPP operators are responsible for power trading and retailing as part of the unbundling of the power sector. A virtual power plant (VPP) is a network of decentralized, small to medium-scale power generating units such as biomass plants, combined heat and power (CHP)

units, wind farms, and solar parks. The coupled generation units are partially been operated through central control of the virtual power plant although each part remains independent in its operation and ownership. Virtual power plants (VPP) are responsible for the delivery of electricity products, as a balancing power medium for the traded electricity market front. For VPP to fulfill its function, product requirements must be satisfied because the minimum volume of power delivered has restrictions and a single small-scale power plant cannot supply it, e.g. a single wind farm. VPP puts together several other small-scale power plants as well as includes other generation capacities or flexible loads, to meet the product requirements of the energy marketplaces. The power generation of the units in the virtual power plant becomes aggregated (sum as an entity) which is now been sold by a single trader on the energy exchange or other energy marketplaces (as a market for power balancing). In consequence, VPP has the potential to assume the role of traditional power plants by selling its output power in the wholesale markets. In Germany today, around 20 medium-sized companies carry out their operations based on VPP (Gert et al., 2014). Furthermore, specialized marketplace operators are market actors who operate in marketplaces for ancillary service providers or electricity from well-defined sources.

The concept of specialized marketplaces is detailed in several research projects of the German E-Energy (smart energy made in Germany) program. Power traders or brokers refer to a body or a person who trades energy-related commodities and services over the counter (OTC) or in an organized electricity market (also known as an electricity or power exchange). Power traders provide power providers with specialized wholesale electricity services or larger end users (Companies with intensive energy consumption) who are also market actors. The complexity involved in electricity markets requires that well knowledgeable personnel with expertise, comparable to financial service providers, should do the trading. Certain 50 companies in Germany observe trading services (Gert et al., 2014; Brunekreeft et al., 2015; Deutsche, 2020). Finally, on energy generation, the energy market liberalization culminated in the creation of medium-sized power retail companies that are independent of the established utilities called independent retailers in Europe. They entice their customers through numerous energy-based retail products that range from regional tariffs, time of use pricing, or electricity with a low CO₂ footprint. These products are been accepted both by the entire populace and by enterprises generally.

Power Consumption is another factor to consider when talking about the structure of the market for renewables. It is vital to setting market values for renewable energy integration into the power grid. The amount of power generation and consumption influence the size of storage needed to be designed to guarantee grid stability as well as have an influence on market sizing dynamics. Smart appliance contractors take responsibility for households as well as enterprises that make use of or operate quite a lot of power-consuming appliances such as heating equipment, cooling devices, or home electricity storage (smart appliances). Smart appliance contractors render services for

individuals in financing, installation, operation, maintenance, support, and appliance replacement for their clients. In addition, other contractors who provide services such as volume-based heating, cooling, or load management services include prosumers and energy management service providers. The term prosumer is an abbreviation term for producer and consumer. Apart from power consumption, they can also deliver surplus power to the grid through small-scale rooftop PV or combined heat and power (CHP) plants. Large commercial enterprises and the industrial sector can also benefit from the energy monitoring and control services provided by energy management service providers. They contribute to the ongoing development of energy procurement and usage grids based on their service capability. On the other hand, energy efficiency consultants oversee typically small-sized businesses and examine energy usage patterns of individuals, businesses, industries, and government agencies to find areas where energy efficiency can be enhanced. They also provide clients with advice on how to use power more wisely. The cost for such consultation is taken care of or paid from the share of the savings generated from energy efficiency improvement services, roughly about 12,500 companies observed over 400,000 consulting projects in 2011 (Ancona et al., 2016).

Market Design for the Integration of Renewables

The overall market electricity wholesale market design brought together about 300 power generation companies, 50 power-trading companies, and approximately 1,110 power retail companies (Gert et al., 2014) in Germany. Maintaining a high level of liquidity shows that electricity wholesale markets are functioning and thriving as well (Gert et al., 2014). Wholesale markets in Germany are currently been divided into two major energy markets; (a) The European Energy Exchange (EEX) allows spot for two products, which are (short-term), and future (long-term) markets for electricity. Regardless of power source, the age of power plants in construction, and production technology, Germany still maintains a uniform wholesale price for electricity. The market price for electricity irrespective of when for all generators is determined by the marginal costs of the previous power plant needed to satisfy total electricity demand. The result of such a national integrated market is that, at any given time, only the power plants with minimum marginal costs of production will be able to sell their electricity on the market. (b) The over-the-counter (OTC) market provides suppliers and buyers of electricity the freedom to trade electricity bilaterally and mutually. They have the opportunity to negotiate contracts and prices irrespective of standardized contracts or prices at the power exchange. Additionally, OTC contracts provide opportunities for spot and future trades just like EEX. Therefore, on both market's products there are similarities, in that short-term contracts with direct physical fulfillment is been traded through an exchange directly negotiated with another member on the OTC spot market (Gert et al., 2014; Brunekreeft et al., 2015; Deutsche, 2020).

Moreover, in particular, electricity trading is observed in Germany bilaterally between the generation and retail companies. About 7,000 TWh worth of electricity were traded in OTC transactions in 2012, but just roughly, 1,200 TWh were traded at the EEX (Gert et al., 2014; Mayer et al., 2014; Deutsche,

2020). The OTC transaction results are more attractive because the OTC products have more flexibility in design based on the specific needs of the parties involved. Nevertheless, the prices from EEX are very vital because they are the take-off reference value for OTC trading. However, generation and retail companies use the power exchange medium to trade electricity for short-term contracts (physical fulfillment) in particular, but the majority of the trade carried out at the power exchange has a target on the future exchange. The goal of electricity traders in choosing power exchange is mainly on financial exchanges and obtaining their profits through arbitrage between different future periods. The retailing companies are responsible for paying the generators for the costs of electricity produced and the grid operator for the transportation of the produced electricity. The generation company must notify in advance TSO Company the precise volume of electrical power that its facility can produce at a given period and where (e.g. power retail companies) the produced electricity be transported to (Harald & Xiaoshu, 2017; Gert et al., 2016).

Motivation for the promotion and integration of renewables

To support the development of renewables continuously, a fixed feed-in tariff that is above market prices is been paid to every renewables owner or investor. The EEG became the regulating tool for the promotion of renewables. It became law in 2000 on account of the previous act on the feed-in of electricity from renewables into the Public Grid, enacted in December 1990. The EEG regulative jurisdiction of a feed-in system functions under these four key elements. (a) A Fixed feed-in tariff scheme means, every kWh amount of electricity produced and fed into the grid attracts a fixed paid price that is more than the price of electricity for the wholesale market. (b) The take-up obligation approach simply indicates that grid operators have the statutory to purchase electricity from renewable sources at all times and the payment of feed-in tariff should be done separately from the current market prices. (c) Renewable Energy Source's priority simply means the generation and feeding into the grid of renewables has precedence over every other source different from renewable sources if there is congestion or network overload. (d) Renewable Energy Sources curtailment as a last resort means if the network is overloaded or congested, the curtailment of conventional power supply should be observed before renewables curtailment.

A Quick Overview of Feed-In Tariffs

The generation of electricity from these energy sources hydropower, landfill gas, gas from purification plants, mine gas, biomass, biogas, geothermal power, onshore wind, offshore wind, small-sized rooftop PV installations, and large-scale PV parks attracts typically the payment of feed-in tariffs. Feed-in tariffs are designed to address specifically the occurrence of these three situations: (a) if there is variation in tariffs application considering the source of power (b) the feed-in tariffs for installations with similar power sources depend constantly on installed capacity with higher feed-in tariffs applying to smaller installations. (c) Feed-in tariff payments are for 20 years and payment made for each installation at the commissioning time over the same period is certain. The implementation of EEG in 2000 portrays a gradual decline in the costs of renewables and notable technical progress recorded because feed-in tariffs for

new installations have been drastically adjusted. However, feed-in tariffs for installations before the adjustments maintain their initial guaranteed level. The reductions of the feed-in tariff for the future have been determined today and recorded in specific reduction schemes as part of governmental supplements to the EEG as a way to ease the planning process for renewables investors. The following ranges of feed-in tariffs for these power sources based on highest relevance were paid in 2012 depending on their installation capacities and other characteristics; (a) Hydro 0.034 €/kWh – 0.127 €/kWh (b) Onshore wind 0.0893 €/kWh – 0.0991 €/kWh and Offshore wind 0.15 €/kWh – 0.19 €/kWh (c) Biomass 0.06 €/kWh – 0.143 €/kWh (d) PV 0.1794 €/kWh – 0.2443 €/kWh (Bundesministerium et al., 2011).

The feed-in tariffs from electricity generated using energy sources from renewables created a financial burden. This financial burden can be traded on the wholesale markets regardless of the feed-in tariffs. Electrical energy from renewable sources penetrates German wholesale markets in the following way; the electrical energy generators get a feed-in tariff from their respective distribution grid operator while the distribution grid operator receives an equivalent compensation from the transmission grid operator. The transmission grid operator, therefore, on the wholesale market sells electrical energy from renewable sources. Thus, transmission grid operators receive constantly a price that is quite lower than the feed-in tariff fixed by the government. However, to prevent and ease the financial burdens created for transmission grid operators because of such practices. The difference between the market prices for electricity and fixed feed-in tariffs is paid fully to the transmission grid operator. The source of this compensation emanates from the surcharge payment from electricity consumers or end users for promoting of renewables on their electricity bill referred to as renewable energy surcharge. The type of consumer dictates the amount of the surcharge to be paid with high discounts with consideration for industrial consumers. The surcharge payment has no geographic location limitation on consumers. In consequence, the financial burden created through such compensation in recent years has witnessed a significant increase. Almost one billion euros was needed to resolve the cost differences of feed-in tariffs from renewables in 2000 (Gert et al., 2014). The amount jumped to about sixteen billion euros in 2012 and roughly twenty billion euros forecast was expected in 2014 (Gert et al., 2014). According to the increasing rate in the share of renewables in the electricity mix in Germany, the surcharge for renewable energy increased from 0.0008 €/kWh in 2000 to 0.0528 €/kWh in 2013 (Bundesverband et al., 2014). Germany has already set up a system through feed-in tariffs financed by surcharge irrespective of location. The goal here is to redirect the purchasing power from areas that demand high loads to areas with high levels of renewable capacities. Additionally, in Berlin for instance with more than 3 million inhabitants approximately 4.1 % total population in Germany gets just 0.1 % of all connected payments from renewables, meanwhile in Schleswig-Holstein, a federal state in the Northern part of Germany with less than 3 million inhabitants that is about 3.5 % of the population, received 7.0 % of all connected payments from renewables (Bundesverband et al., 2013). This does not mean, therefore, that

the people in Berlin pay less than people in Schleswig-Holstein to finance the renewables funds. In contrast, the purchasing power because the financing mechanism of renewables was indirectly redirected from Berlin to Schleswig-Holstein.

Effects of Renewable Energy Sources on the Price of Wholesale Electricity

The marginal costs of the last power plant determine the prices on the wholesale electricity market. The marginal costs of the last power plant are criteria needed to fulfill total electricity demand by setting the price that is applied to all generators. The ranking of power plants based on their electricity generation and marginal costs is called merit order. The power plants with the least marginal costs are to meet the demand dispatched first while the power plants with the highest marginal costs are to meet the dispatching demand last. Thus, TSO companies have the legality and priority to make sure that energy sources from renewables are fed - in before the feeding in of other conventional generation energy sources. Once the installation and the integration of energy sources from wind and PV installations to the grid are ensured, electricity production can be done nearly at zero marginal costs, while the costs of electricity generation from fossil fuel-fired power plants depend predominantly on the price of the combustible fuel used (fuel costs). The generated power from renewables goes to the wholesale markets from the onset of the merit order or at zero marginal costs with the first dispatch. The aftermath effect is a decrease in the average wholesale prices as the generation technologies that possess higher marginal costs are replaced by the increasing volume of electrical energy from renewable sources. Hence, large-scale integration and penetration of renewables keep control of the prices (suppresses) of wholesale electricity, it is referred to as the merit order effect Figure 15. Owing to the trading of large volumes of electrical energy from renewables, wholesale prices become quite low on the wholesale markets on days with high amounts of wind and sunny days. In a situation in which high feed-in electricity from renewables is similar to low demand concerning consumption that is usually on Sundays, electricity prices may record nearly negative values. At such times, the unconsumable power is occasionally exported to neighbouring countries and has to reward these countries for absorbing the German electricity. About 80 hours of negative spot market prices were recorded in 2013 and these prices took place in ten out of twelve months (Mayer, 2014).

In summary, an increase in the share of renewables penetration to the energy market decreases significantly the volatile prices on the wholesale markets. As wholesale market prices decrease, gas-fired (conventional energy sources) power plants with high marginal costs have less dispatch constantly discouraging investors. Its flexible application coupled with fast ramp times, made gas-fired power plants to be seen as part of a power system with a high share of variable renewables. On this ground, the modification of the EEG and possible support strategy and incentive process for investments in conventional power plants are currently been discussed in Germany (Gert et al., 2014).



Figure 15: Wholesale markets for electrical energy in Germany. Source: (Gert et al., 2014)

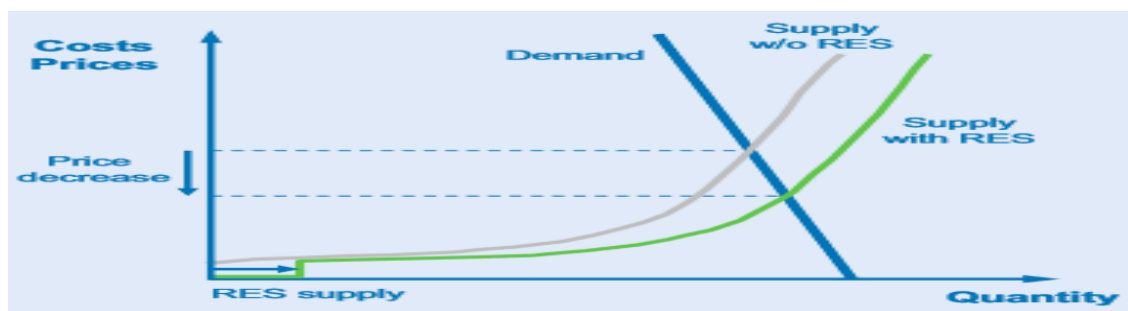


Figure 16: Effects of RES supply on the wholesale electricity prices. Source: (Gert et al., 2014)

Stability Creation in Generation and Consumption for Renewables Integration

Maintaining a balance between power generation and consumption for renewables integration into the grid as part of sector coupling would be a sustainable process for the power grid both for long-term coordination and for short-term balancing in generation and consumption. In recent decades, electricity generation and consumption have experienced a complete transformation. Such policies that focus on enhancing long-term coordination for electricity generation capacities and the development of electricity consumption were not a primary concern. However, the increasingly fluctuating nature of electricity generation in Germany due to the integration of renewables, positions the policymakers to seek out means through policy on how to ensure that electricity generation and consumption in the short term are balanced. This research focuses on using power-to-gas technology as a sustainable solution to storage problems in Germany for sector coupling.

The TSO companies play an important role in ensuring a balance between generation and consumption in the short term. Before the commencement of the unbundling process, companies were allowed to make decisions on power plant dispatching but in recent times wholesale and retail markets are now responsible for coordination and decision making. Sometimes, maintaining a balance in generation and consumption, and dispatching of power plants controlled through market forces is not achievable because of restrictions from power grid infrastructural limitations. TSOs are, therefore, charged with the

duty of balancing between generation and consumption to ensure the stability of the system. TSO has a mandate specifically to take measures and establish adjustments process in the following ways. (a) The balancing market functions are independent of EEX and OTC trading. They have the permission to adjust generation and consumption in a very short term, as provided in 12 EnWG, and can tender the requested balancing power using a common internet platform.

There are three different reserve approaches to tendering, which are primary reserve, which should be available within 30 seconds and tendered on a regular monthly basis. The secondary reserve has to be available within 5 minutes and is usually tendered every month. The tertiary reserve is the last approach, which is to take over from the secondary reserve every 15 minutes, tendering is daily. (b) An Ordinance on Disconnectable Loads (AbLaV) was enforced in 2013, which lets TSO tender, every month with an approximate load of 3GW. It can be disconnected within 15 minutes in case there is an urgent need for consumption adjustment downwards. Similar to balancing markets, the loads can be tendered on the internet platform. (c) In situations where it is difficult to balance generation and consumption in balancing markets or through load disconnecting based on the provision in AbLaV. TSO has the right to repeal market outcomes by forcing power generators to regulate their generation. Such occurrence warrants that the affected generation companies will receive compensation for financial losses with immediate effect but BNetzA should be informed on time before such measures. However, the main function of electricity prices was the coordination of electricity generation and consumption in the end by incentivizing investments in generation capacities, grid capacities, and end-use devices (Deutsche, 2011; ECOFYS Germany GmbH, 2012; Gert et al., 2014).

CONCLUSIONS AND RECOMMENDATIONS

This study rigorously examined the integration of renewable energy sources into the German power grid, focusing on the use of Power-to-Gas (PtG) technology to address the challenges posed by the intermittent nature of renewable energy. By exploring Polymer Electrolyte Membrane (PEM) electrolysis for hydrogen storage and biological methanation, we identified viable pathways for enhancing methane production efficiency and reactor performance. Our findings underscore PtG technology's potential as a critical enabler for sustainable renewable energy integration, offering an effective solution for energy storage and optimization. The successful application of PtG technology not only facilitates the transition towards a more sustainable energy system in Germany but also contributes significantly to the stability and reliability of the power grid amidst increasing renewable energy penetration. Based on the facts in this research, recommendations were made. There is a clear need for continued investment in research and development to further enhance the efficiency of PtG technologies, including PEM electrolysis and biological methanation processes. This will help to reduce costs and improve the scalability of these technologies. Also, governmental and regulatory bodies should implement supportive policies and incentives to encourage the adoption of PtG technology. This includes

subsidies for PtG installations, tax incentives for research and development, and streamlined regulatory processes for new PtG projects. Investment in the necessary infrastructure to support the widespread adoption of PtG technology is crucial. This includes the expansion of hydrogen storage facilities and the development of pipelines for transporting hydrogen and synthetic natural gas. Strategies for the effective integration of PtG technology into the energy market should be developed. This involves creating market mechanisms that recognize and compensate for the value of energy storage and grid stabilization provided by PtG systems. Lastly, efforts should be made to increase public awareness and understanding of PtG technology and its benefits. Educational campaigns can help to build public support for renewable energy projects and encourage community involvement in sustainable energy initiatives.

ADVANCED RESEARCH

In writing this article the researcher realizes that there are still many shortcomings in terms of language, writing, and form of presentation considering the limited knowledge and abilities of the researchers themselves. Therefore, for the perfection of the article, the researcher expects constructive criticism and suggestions from various parties.

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