Renewable Energy and Electricity Security: Smart Grid development prospects for Azerbaijan

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Abstract

This study focuses and analyzes whether the current traditional electricity system of Azerbaijan is ready to absorb and incorporate a large share of intermittent and non-dispatchable renewable sources, assesses current reforms in country's electricity sector and determines the challenges in the prospect of smart grid development. Azerbaijan has almost 200 GW of technical potential in developing renewable energy sources, however, the penetration of renewables to the current conventional grid will rise another big issue of electricity security. The development of a smart grid system is considered as a solution to renewable energy transition. The study evolves interviews with industry experts as a primary source to get the complete picture of the existing electricity system and comparative analysis of the international best-case scenario as a secondary. The findings show that the legislative background and grid infrastructure are far behind the vision of the government in the prospect of green energy transition. Current grid may integrate up to 1,5 GW of renewables, however, problems may occur even with lesser volumes. There is uncertainty arising from management of variable renewable energy sources within existing electric system which may bring to high number of power shortages in Azerbaijan upon its integration.

Keywords: Renewable Energy; Electricity Security; Azerbaijan; Smart Grid; Market Reforms; Energy Transition.

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List of Abbreviations

ADB	Asian Development Bank
AERA	Azerbaijan Energy Regulatory Agency
AREA	Azerbaijan Renewable Energy Agency
CBAM	Carbon Border Adjustment Mechanism
CCGT	Combined cycle gas turbine
DSO	Distribution System Operator
EBRD	European Bank for Reconstruction and Development
GHG	Greenhouse Gas
HPP	Hydro Power Plant
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
MoE	The Ministry of Energy of Azerbaijan Republic
NIST	National Institute of Standards and Technology of the U.S.
OECD	Organization for Economic Co-operation and Development
RE	Renewable Energy
RES	Renewable Energy Sources
SCADA	Supervisory Control and Data Acquisition
TPP	Thermal Power Plant
TSO	Transmission System Operator
VRES	Variable Renewable Energy Sources
WPP	Wind Power Plant

Introduction

The global electricity supply is in the process of expanding its infrastructure and capabilities due to growing demand coming up from increased industrialization, urbanization, and digitalization. To catch up with rapidly increasing electricity demand and to meet its commitment to the Paris Agreement on cutting CO_2 emissions, the global electricity sector rely upon renewable energy sources (RES) (Sarhan et al., 2021; IEA, 2021). Transitioning to RES will support energy security by diversifying energy and power portfolios and reducing dependence on finite fossil fuels (Cox et al., 2019). Electricity demand increases by roughly 50% in 20 years, and this trend will likely continue to grow further to the point electricity will surpass oil as the main energy source by 2040 across the globe (IEA, 2021).

94% of electricity in Azerbaijan was generated by natural gas-fired power plants in 2021 (MoE, 2022). Even if works are being carried out for the modernization and refurbishment of regional power plants, agreements were reached towards the development of RES in Azerbaijan ("*President Ilham Aliyev Inaugurated*," 2020), the fact that more than 90% of the electricity supply is coming from gas-fired power plants reveals the vulnerability of electricity sector of Azerbaijan. The prominent case which verified this fact was the accident at the Azerbaijan Thermal Power Plant on 3rd July 2018 in Mingachevir city. The Mingachevir catastrophe became the turning point in re-organizing the energy security and electricity supply system in Azerbaijan since the accident at one station had a countrywide impact. Electricity was cut off in 39 regions of Azerbaijan, including the capital city Baku and the second largest city Ganja (Aydin, 2019). The causes of the accident were identified as weak security measures, false risk assessment, and mainly a high imbalance between the plant's outdated equipment, infrastructure and the workload that resulted from high electricity demand during summertime (Aydin, 2019). It is worth mentioning, at that time no renewable energy-generated power plants were there to compensate for the imbalance between high local demand and existing traditional infrastructure. Referencing the IEA review on Azerbaijan's energy policy (2021), in 2019 the share of renewable energy in electricity generation was 7% when the world average from 2018 was 25%. Nevertheless, according to the last update from the Azerbaijan Renewable Energy Agency (AREA) for the year 2021, the share of RES in the total electricity installed capacity was roughly 17%, however eventually, only 6% was utilized in the power grid.

OECD reports (2021) that even if Azerbaijan's energy sector is equipped with better quality infrastructure, the electricity transmission and distribution systems underperform compared to neighboring Georgia. The Azerbaijani electricity grid has a loss rate of 9,7%, while Georgia's grid accounted for losses of 7,3% (OECD, 2021; as cited in IEA, 2019). It's worth mentioning that the study of Yusifbayli and Nasibov advocates (2021) that since 2013 electricity security of Azerbaijan was gradually worsening due to the deterioration of generating and electric grid equipment which led to the Mingachevir catastrophe in 2018. After that accident, some refurbishment works were carried out which led to some electricity security recovery in 2019. In 2019, the output of electricity security in Azerbaijan was 72.1% (Yusifbayli & Nasibov, 2021).

The share of the installed capacity of renewables must achieve the target of 30% by 2030. At the end of 2021, the RES share of electricity capacity in Azerbaijan constituted 17,3% (AREA, 2022). This notwithstanding, Azerbaijan has a huge potential in the development of RES, both onshore and offshore. According to the MoE (2022), the total potential of RES is estimated at 27 GW, which is apportioned as 23 GW of solar energy, 3 GW of onshore wind energy, 520 MW of mountain rivers and 380 MW of bioenergy. According to the World Bank's assessment (2022), Azerbaijan's offshore wind technical potential is 35 GW in shallow waters and 122 GW in deep waters. As reported by AREA (n.d.), the preliminary estimation of RE potential in the liberated territories of Azerbaijan is nearly 10 GW of solar and wind energy. Thus, it makes 10 GW plus 27 GW onshore power and 157 GW offshore potential for Azerbaijan, in total almost 200 GW of technical potential. Based on the estimation of the World Bank's offshore roadmap for Azerbaijan (2022), the country can install 7GW of offshore wind energy potential, which under a high growth scenario will supply up to 37% of the country's electricity demand by 2040.

The initial step in the direction of renewables development was taken when the MoE signed two pilot RE projects in January 2020. The first project was the construction 240 MW Khizi-Absheron Wind Power Plant by ACWA Power of Saudi Arabia and the second project was the construction of a 230 MW Garadagh Solar Power Plant by Masdar of United Arab Emirates. Currently, these projects are in the phase of construction. Moreover, in June 2021, the MoE and bp signed a cooperation agreement for the joint implementation of a 240 MW solar power plant in the Jabrayil region. Azerbaijani government intends to establish a Green Energy Zone in the liberated territories by 2050. In addition, Azerbaijan has already signed relevant deals with Fortescue Future Industries (FFI) and Masdar with a total capacity of 22 GW. Australia's FFI will develop a total 12 GW capacity of renewable energy and green hydrogen ("*The MoE and FII signed*", 2022). An exclusive concession was also agreed upon between Azerbaijan's MoE and Masdar to develop a 10 GW renewable energy program, which will incorporate onshore wind and solar projects, and offshore wind and green hydrogen projects ("*Masdar Partners with Azerbaijan's SOCAR*", 2023). The first phase of the program will encompass the construction of 4 GW capacity (1 GW onshore wind, 1 GW solar and 2 GW integrated offshore wind and hydrogen) with the right to develop an additional 6 GW as a second phase.

Yet, solar and wind power, being the most prevalent energy sources in Azerbaijan, are also known as variable renewable energy sources (VRES), meaning, these sources "are not continuously available at the same levels" (Timmons et al., 2022, p.8). Noting the fact of ongoing renewable energy projects in Azerbaijan and the intention to develop high RE capacities, the question of whether the current traditional electricity system of the country is ready to absorb and incorporate new sources of energy comes out. Especially, ensuring balanced supply and demand is the greatest challenge when utilizing VRES (Timmons et al., 2022), and hence, there should be a smart electric grid to respond to fluctuations in power generation and to support an uninterrupted supply of electricity and quality and reliability of the system (World Bank, 2019).

Significance of the project

The electricity sector in Azerbaijan is vulnerable due to its high reliance on the natural gas-generated power system and there is a need for energy diversity. Therefore, several RE projects are ongoing in Azerbaijan. Yet, another reason for the urge towards green sources of energy is as per the statement of President Ilham Aliyev at the 75th Session of the UN General Assembly Debate, Azerbaijan's commitment to the Paris Agreement and the target of 35% greenhouse gas (GHG) emissions reduction by 2030 compared to the base year 1990. Increasing the share of natural gas consumption in the total energy mix at the expense of oil reduction has a true impact on reducing CO2 emissions, however, it will not be sufficient to attain the 35% goal for Azerbaijan (Gurbanov, 2021). Yet, electricity demand is expected to rise year by year due to the electrification of every aspect of human life and the growing population, and in fact, existing equipment cannot keep up with the peak demand. Moreover, Azerbaijan cannot further increase the share of gas in the electricity system. The share of gas is almost 94%, and a further step should be a smooth decrease in the share of natural gas and an ever-increasing share of RES. Yet, ever-increasing domestic electricity consumption will put another challenge for Azerbaijan in terms of natural gas exports, therefore, to keep the threat of export shortfalls down, renewables are killing two fowls with one stone (O'Byrne, 2020). Based on the IEA assessment of Azerbaijan's energy policy (2021), "investments are required in new and more efficient generating capacity and electricity grids" and it is recommended to develop or upgrade the grid to integrate a large share of RES.

To sum up, this project is important because of the following reasons:

- Renewable energy projects are gaining momentum in Azerbaijan since the power sector is poorly diversified being highly dependent on natural gas. Yet, the second pushing factor is the goals set in Paris Agreement urging for the rapid energy transition in electricity generation.
- RES are variable and there is a need for a country-wide smart grid to manage the variability of energy sources and the penetration of renewables in the power supply. The existing electric grid is not designed in a way to balance the variability and penetrate RES in the right way. In particular, to unlock Azerbaijan's offshore wind capacity, investments are required in smart grid technology, storage, management system, and interconnectors to manage the challenge of variability (World Bank, 2022).
- Ever-increasing electricity demand and electrification will require more efficient transmission and distribution systems, prompt restoration of supply after power disturbances and it will require large-scale renewables integration in a cost-effective,

resilient, and secure manner (IEA, 2021). The smart grid will enable policymakers to address all three aspects of this integration.

- The accident at one power plant caused a country-wide outage showcasing vulnerable energy and electricity security issues, system communication problems and technical shortcomings. One of the aims of the project is to prevent the Mingachevir catastrophe and the entire electricity grid outage from happening once again.
- IMF study advocates (2022) that further delay in the energy transition of electricity generation would apply higher macroeconomic costs associated with energy security, growth, and inflationary pressures, especially for fossil-fuel producers. If the steps towards a smooth transition to clean electricity during the remaining seven years are already undertaken, the costs will remain manageable. Thus, the faster Azerbaijan decarbonizes the power sector, the better it is for the nation's economy.
- The EU's Carbon Border Adjustment Mechanism (CBAM) is a tool to tax carbon-intensive imports from non-EU countries and support the decarbonization of their industrial production through carbon pricing. CBAM will enter into force in its first transitional phase as of 1 October 2023 and it will apply to certain carbon-intensive goods, such as iron and steel, aluminum, cement, fertilizers, and electricity (European Commission, n.d.). Starting in 2026, the carbon border mechanism will apply, and gradually all companies that have green certificates will be able to enter the market without border taxation. Azerbaijan should create an equal competition environment for its exports and not be a back burner because of an additional carbon tax. This argument certainly pushes Azerbaijan towards industrial decarbonization as soon as possible.

Project Goal

Renewables are already in the process of integrating into the power system of Azerbaijan; therefore, we need to take a step forward and find a solution to an efficient and resilient power system which will incorporate VRES. The development of a smart grid system is one of the options to adopt VRES in the power supply and to address the issue of energy and electricity insecurity, energy efficiency and saving in the country.

This study will be conducted to evaluate the current electricity sector of Azerbaijan based on the analysis of the best-case scenario. The aims are the following:

- To assess the current condition of the electricity sector in Azerbaijan and what steps are undertaken to reform it.
- To understand the feasibility of renewables integration into the existing conventional grid.
- To evaluate Azerbaijan's potential in the prospect of smart grid development.

Methodology and Limitations

The main method of this study is a qualitative analysis of the smart electricity system with a case study. Our main case study is the electricity system in Azerbaijan and by referring to the success story of Denmark, one of the leading countries in the deployment of smart grid system and penetration of RES, comparative analysis is carried out. The path of Denmark in the implementation of a smart grid is studied and analyzed and afterwards, the prospects and challenges of Azerbaijan in this regard are investigated. Primary data is collected via semi-structured interviews with local and foreign experts from the energy and electricity sector. In total, 10 interviews have been carried out for this study, as per the information given in the table (see appendices). All interviews are audio-recorded and transcribed with the consent of the interview participants.

Due to a lack of publicly available technical information and literature on the condition of the electric grid in Azerbaijan and industry insights, interviewing was chosen as the primary data collection method. Therefore, this study may contain biases. In addition, this study does not delve into the technical feasibility of the project and only examines the administrative part of the topic in question.

Roadmap

As Chapter 1 gave a short introduction on the topic and importance of this project, further the paper is arranged as follows. Chapter 2 discusses electricity security and the smart grid as concepts. The smart grid technology areas are identified, and the global application of smart grid is represented together with the success story of Denmark. Chapter 3 describes the current condition of the electric grid in Azerbaijan and summarizes the latest reforms in the electricity sector. Chapter 4 presents the study results, and the paper ends with the concluding remarks and further implications.

Conceptual Framework

Smart Grid

The literal meaning of electricity security is "keeping the lights on" or saying differently "the electricity system's capability to ensure uninterrupted availability of electricity by withstanding and recovering from disturbances and contingencies" (IEA, 2021). Sarhan et al. (2021) state that even though electricity security has been studied as a part of energy security, many studies have evaluated it from the fossil fuels perspective, however, right now electricity security is greatly reliant on RES. Some factors such as network stability, excess capacity at peak demand, system resilience, and transmission and distribution losses are critical for electricity security. Johansson (2013) concludes in terms of security the main advantage of RE is the fact it is based on energy flows instead of depletable stocks and increases resource diversity in the system, nevertheless, RE heavily depends on weather patterns and an efficiently functioning technologically equipped system. Furthermore, Varaiya et al. (2011, p.41) argue the existing grid was built when "generation was concentrated in a small number of large generators" with passive load demands and controllable output, therefore, the high penetration of variable RE and interactive supply-demand response will impose a great concern to the operation of the traditional grid.

It can be argued that once Azerbaijan starts switching from natural gas to renewable energy sources, its power sector will remain vulnerable and face a variety of challenges. Traditional frameworks for ensuring electricity security, such as fuel availability and unexpected plant outage, will not be sufficient in the face of emerging trends and structural changes in the power system (IEA, 2021). The traditional grid should be modernized and updated based on current market conditions and technological advancement, to become somewhat "smarter".

So, what is commonly mentioned *smart grid*? There are plenty of concepts and practices referred to as smart grids and related to transportation and utility services. In general terms, *smart* means integration of computer science and new technologies or in other words digitalization of existing traditional infrastructure grids. Hence, this gave rise to such concepts as smart cities, smart houses, smart transport and so on. In the same way, *smart grids* started to be used concerning innovative electricity infrastructure networks. So said, a combination of computer technology and traditional power system. Smartening of the system is done via smart technologies, which ‘span the entire grid from generation through transmission and distribution to various types of electricity consumers’ (IEA, 2011, p.17).

IEA describes (2007, p.6) the smart grid in the following way:

“*A smart grid is an electricity network that uses digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end-users*.”

The US National Institute of Standards and Technology (NIST) defines (2014, p.33) the smart grid as:

> *“The addition and integration of many varieties of digital computing and communication technologies and services with the power-delivery infrastructure.”*

European Commission in its directorate “Smart Grid Mandate” defines (2011, p.2) as:

> *“A Smart Grid is an electricity network that can cost-efficiently integrate the behavior and actions of all users connected to it – generators, consumers and those that do both – in order to ensure economically efficient, the sustainable power system with low losses and high levels of quality and security of supply and safety.”*

The objective of the Mandate is to set complete and consistent standards for the implementation of different level Smart Grid services into the European internal market. The U.S.'s NIST and EU Smart Grid Coordination Group (SG-CG) have collaborated to ensure that Smart Grid standards on both continents have as many as possible common points and that the system is designed similarly. This was out into NIST Framework and Roadmap for Smart Grid Interoperability Standards in the U.S. and a Smart Grid Mandate in the EU ("*USA, Europe collaborate on smart grid standards*", 2011). That is said, the scope of the smart grid is large and requires a coherent response to the deployment challenges starting from comprehensive standardization and integrated communications strategies between its actors to infrastructure updates and application of digital computing and communication technologies.

Although smart grid can be defined and construed in different ways across countries and institutions, we can conclude that the smart grid is a digitalization of the electricity sector through the application of computer science techniques and technologies with the aim to improve its function in response to rising electricity prices, supply disturbances and environmental sustainability (Lovell, 2022).

Moreover, today electric grid is no more about economic growth through energy generation. It is about environmental sustainability and energy security and efficiency. Today we face the problem of global energy trilemma, which is a complex interrelationship between energy security, climate change and energy affordability (Bradshaw, 2013). Can we have *secure and affordable* supplies of power which are also *environmentally harmless*? As noted in the above-given definitions as well, the smart grid is seen as a solution to all emerging issues under the weight of progress and as argued smart grid enables policymakers to simultaneously respond to all three aspects of the trilemma – economic (affordability), environmental (sustainability) and social (security) (Oliver & Sovacool, 2017; Poudineh & Jamasb, 2012).

Table 1. Smart Grid against each aspect of Energy Trilemma

Note. Adopted from Poudineh, R. & Jamasb, T. (2012). *Smart Grids and Energy Trilemma of Affordability, Reliability and Sustainability: The Inevitable Paradigm Shift in Power Sector*.

Energy Trilemma	Smart Grid's Solution
Energy security (reliability)	Smart grid provides the capability to diversify power supply through different energy sources, such as wind turbines, solar panels, biomass, etc. This trend of diversification and penetration of a high volume of RES requires automation of the monitoring and the overall system which will match the differing energy flows and utilize distributed energy resources efficiently without any faults. This is possible through advanced smart power devices in the transmission and distribution lines which can detect the emerging problem, provide real-time information, automatically detect the pick hours of high demand and insufficient supply, and prevent or minimize consequences.
Climate change (sustainable)	To be sustainable, the energy should be derived from sources which have minimum environmental hazard. A shift to renewable energy is proven to be effective in addressing climate change and CO2 emission reduction. However, as said RES are variable sources of energy, therefore, the development of the smart grid and incorporation of storage technologies will help to absorb the gap in RES variations.
Energy affordability (affordability)	It is a known fact that the application of smart technologies and their deployment requires a large investment, and it is supposed to be reflected in the electricity bills of consumers. Therefore, the utilization of the smart grid needs to gain public support by proving to be financially appealing. It is expected that the smart grid will have decreasing effect on electricity bills in the long run through such prominent possibilities as AMI, Customer empowerment opportunity and Demand response tariff.

Smart grid boosts energy efficiency by minimizing the waste from electricity production and the distribution losses thanks to the decentralized generations and its proximity to the consumers. Energy efficiency refers to the use of less energy to produce the same result. The major benefit of energy efficiency has been energy savings – elimination of energy waste and energy conservation. Different review studies confirmed (Sun et al. 2011; Lamnatou et al., 2022) that smart grids facilitate energy efficiency, primarily, energy savings as well as considerable reduction in CO2 emissions. It is argued that energy efficiency also strengthens energy security by reducing the need for imports of additional sources of supply (Widuto, 2022). This way smart grid accelerates the efficient use of energy, which simultaneously responds to energy affordability, energy security and climate goals for economies.

Grid modernization and the incorporation of distributed energy sources and new technological means have raised the challenge of interoperability. Smart grid interoperability describes the system's "ability exchange information in a timely, actionable manner" (Gopstein et al., 2021, p. 1) and "the capability of two or more networks, systems, devices, applications, or components to work together, and to exchange and readily use information – securely, effectively, and with little or no inconvenience to the user" (p.3). Grid architecture is the demonstration of the complete grid, which defines numerous interactions, energy flows, complex data exchange and communication flow that exist in the electricity system. It is necessary to reinforce coordination among diverse technologies. Recent research by O'Fallon and Gopstein (2021) has demonstrated that utility-based interoperability investments enhance system resilience, with the potential to save lives and generate billions of dollars in economic benefits during natural disasters. Figure 3 represents the most updated conceptual model developed by NIST which demonstrates the overall composition of the grid and interaction between seven main domains as described in Table 2. This is a high-level visualization that can be understandable by many stakeholders. The full potential of the system will not be realized by just installing various technologies for renewables and the smart grid while maintaining the traditional operating paradigm of the grid (Varaiya et al., 2011). As the grid changes with the integration of technologies and new generating capacities, the paradigm should be updated as well.

Figure 1. Updated Smart Grid Conceptual Model developed by NIST.

Note. Adopted from NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 4.0, 2021.

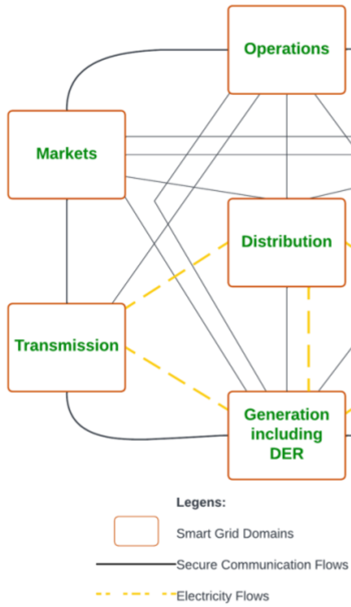


Table 2. Domains and roles/services in the Smart Grid Model as per NIST Framework

Note. Adopted from NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 4.0, 2021.

	Domain	***Roles and services in the domain***
1	**Customer**	This domain includes Commercial, Residential, and Industrial customers who can consume electricity, manage it, generate energy and sell it to the grid as prosumers.
2	**Markets**	The domain where grid assets and services are bought and sold, and supply and demand within the grid are balanced.
3	**Service Provider**	Service Provider manages billing, customer management and customer services, home energy generation installation and management.
4	**Operations**	The domain responsible for the smooth operation of the overall power system and supervision (monitoring and control) of the network. Most frequently it is the responsibility of the regulatory body.

5	**Generation including distributed energy resources (DER)**	This composes bulk generators of electricity from a variety of sources (non-renewable, variable renewables, and non-variable renewables) including DER, which are smaller generation units, such as rooftop solar panels and EV chargers for example, and provision of storage capacities to manage variability of RES.
6	**Transmission**	The bulk carriers of electricity from generation sources to the distribution domain. The transmission-owning operator manages the high-voltage lines, controls substations and may have its own storage infrastructure. The primary responsibility is to maintain system reliability and stability and ensure a balanced supply to meet market demand. The transmission network is monitored and controlled through the SCADA system.
7	**Distribution**	This domain is the interconnection between transmission and customer domains. The final stage distributes electricity to end users: commercial, residential and industrial customers.

Smart grid technologies

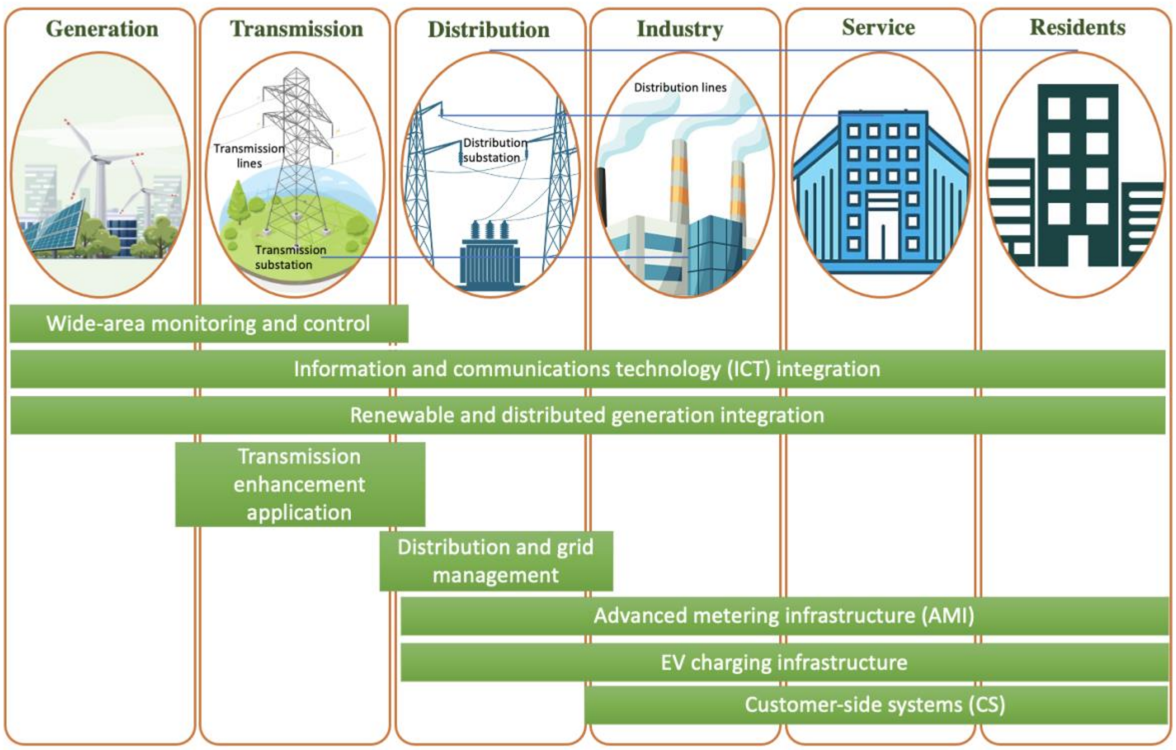
Integrating VRES into the power system will always lead to insecurities in a stable electricity supply because in this scenario uninterrupted supply requires technological expertise and investment in renewable energy technologies (Coester et al., 2020). Smart grid technologies are vital in transforming the traditional electric grid towards a resilient, sustainable, and reliable power grid. According to IEA (2011, p.19), smart grid technologies fall into eight broad technology areas:

1. Wide area monitoring and control.
2. Information and communication technology integration.
3. Renewable and distributed generation integration.
4. Transmission enhancement.
5. Distribution grid management.

6. Advanced metering infrastructure.
7. Electric vehicle charging infrastructure.
8. Customer-side systems.

Figure 2. Smart grid technology areas.

Note. Reprinted from "*Smart Grids Technology Roadmap" published by* International Energy Agency. (2011). Retrieved from https://www.iea.org/reports/technology-roadmap-smart-grids



The electric grid is a system which delivers power from where and how it was generated to the point where and how it is consumed. Technological innovations are ever-expanding, variety of grid equipment is growing to maximize grid functionalities. As the grid system evolves, the ability to update, adapt or reconfigure the technology to meet power system needs and the ability of the end users to understand, interact with and apply this technology are critical. IEA describes (2011, p. 6) the "smartening" of the electricity system as an evolutionary process since even if most of the technologies exist and are being currently deployed, many more require continued development and strengthening.

Figure 4 demonstrates the fully optimized electric grid with smart technology deployment areas, however, not all technology areas need to be installed to smarten the grid (IEA, 2011).

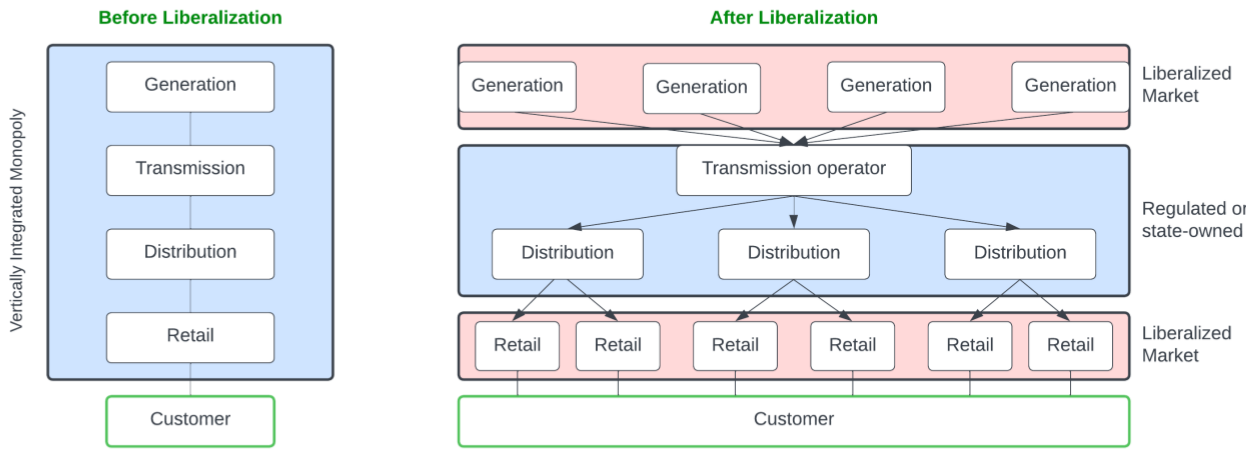
Modern Grid

According to IEA (2022), global electricity grid investment has reached about USD 309 billion in 2021, but it needs to more than double through to 2030 to be on a trajectory with the 2050 Net Zero Emissions Scenario. Estimations show that electricity network expansion and modernization require USD 0.5 trillion of annual investment to achieve the 2030 Agenda (IRENA, 2023). Grid modernization and digitalization are expensive overhauls. For instance, the European Commission (2022) has released an investment plan to build a smarter electricity system with a reliable electricity supply at affordable prices. The estimation is that EUR 584 billion will be required by 2030 for electricity infrastructure investments such as rapid installation of RE capacities on commercial and residential buildings, heat pumps and electric vehicles infrastructure, particularly, in the efficient distribution system.

In what ways modern grid is smarter than the conventional grid, which was deemed to be the critical instrument of the states and served well to the public for many years (Mah, 2014)? As Poudineh & Jamasb (2012) concludes, the power sector is transforming into an "information-intensive" and competitive electricity market. Before the electricity was supplied by mostly state-owned monopolies, which controlled the generating power plants, transmission lines and distribution. But now the power sector has been substantially reformed through liberalization and unbundling policies, meaning breaking up these vertically integrated monopolies and allowing independent power producers (IPPs) to enter the newly established electricity market. Liberalization describes the “introduction of competition into the generation and supply sub-sectors”, shifting the decision-making power from the state to the market and giving consumers the right to choose (IEA, 2000, p.9). Simply put, opening the energy and electricity market to free competition. Unbundling here means disbanding the grid ownership: separation of vertically integrated monopoly from the other segments of the system where competition can be enforced through regulation (Morrison, 2022, p.477). Thus, vertical de-integration is defined as *unbundling*. The main idea is that generation owners should not be able to limit competition and fair pricing mechanisms whilst owning the transmission grid as well. Implementation of regulatory reforms and establishment of securitized law and strong regulatory institutions must occur prior to privatization to guarantee transparency, support mechanisms, credibility and stability for foreign investors' participation. Generally, there are four types of unbundling distinguished: accounting, functional, legal and ownership, being the ultimate form of separation. Nevertheless, there is no country in the world with a fully liberalized energy system. Most of the time the incumbent vertically integrated utility remains within the system as a transmission system operator (TSO) and sometimes distribution system (DSO) is maintained within state regulation as well (Morrison, 2022). Transmission can be either a state-owned natural monopoly or privatized with regulatory oversight (*Regulated Entity*) to ensure overall system security and supply reliability and fair market conditions.

Figure 3. Before and After Liberalization.

Note: Own figure.



Electricity generation is moving from the traditional grid, where large generating facilities are located far away, to the means of efficiency and reliability of many small units located closer to end users. This is one of the most important features of the smart grid system, where many small power units including DER are utilized instead of large-scale facilities (Ackermann et al., 2001, as cited in Aghaei & Alizadeh, 2012). These large power plants were built decades earlier for a different grid, demand load and operating conditions. In addition, the location of generating facilities away from end-users may increase operating costs and energy and electricity losses. Placing generating units closer to the consumers is expected to reduce overall costs and physical losses while ensuring the electricity supply (Gopstein et al., 2021). The main challenge is that most of the conventional grid infrastructure is ageing or has reached its designed operating lifetime and in combination with unutilized capacity possess greater risks (Gopstein et al., 2021).

Before there was a simple one-way power flow, however, now there is a two-way electricity and information flow with multiple stakeholder interactions. Smart meters enable a two-way communication capability for consumers to manage their electricity usage and supply and at the same time provide information to the service providers to set up real-time pricing (Salkuti, 2020). This is known as a demand response tariff. Demand response is described as "the changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time" (Albadi & El-Saadany, 2007, p.1). In other words, "the management of customer consumption of electricity in response to supply conditions" (Varaiya et al., 2022, p. 41). Under traditional grids, some average electricity rates do not showcase the true cost of electricity production and the impact of energy supply and demand variations. By contrast, a demand response tariff will change this pattern of energy use, making it more efficient and valuable for customers and allowing higher quality service from the suppliers'/producers' side.

The biggest challenge for any power system is storage technology. As RES are dependent upon climate conditions intermittent and non-dispatchable, storage technology is critical for uninterrupted power supply, guaranteeing the continuous balance of the grid and matching electricity demand with corresponding generation. Therefore, the need for backup power capacity remains during the low availability of electricity generation from RES (Pepermans, 2019). Electricity cannot be easily stored, as it stands out as the most difficult energy to be stored (Noussan, 2022). Generating electricity from RES will require the operation of distributed storage capacities coupled with distributed energy systems which are viable via smart grids. Here a new concept was created – Prosumager – a "prosumer" who has made additional investments in distributed storage, usually in the form of batteries (Woodhouse & Brown, 2022, p.621). Below given Figure 6 demonstrates the before and after visualization of the grid and Figure 7 compares the traditional grid to the smart grid.

Figure 4. Before and After Grid.

Note: Adopted from Bertam & Primova, 2018, Energy Atlas 2018.

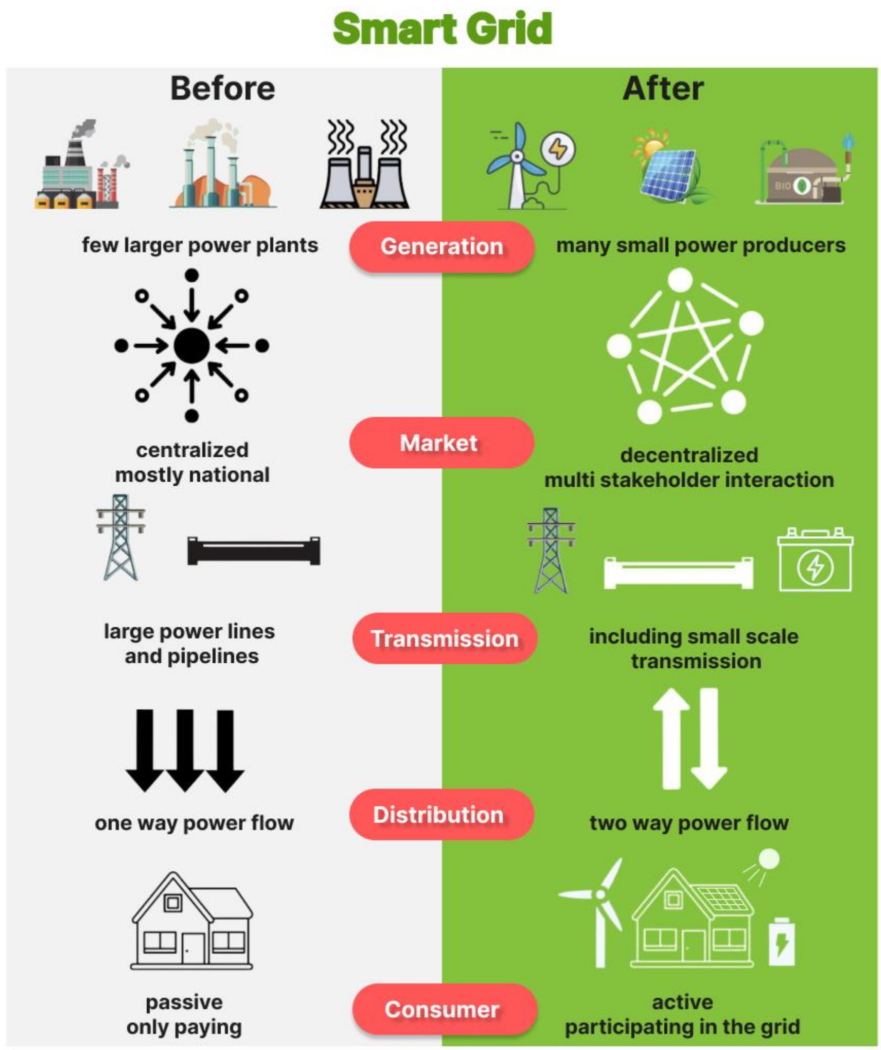


Figure 5. Comparison between Traditional Electricity Grid and Smart Grid

Note. Adopted from Sovacool & Dworkin (2014) as cited in Oliver & Sovacool (2017) and Sifat et al. (2023). Own figure.

Traditional Grid		Smart Grid
Operators respond manually to prevent damage. Self-healing is not possible. System fault requires high restoring time and creates economic losses. Focus is on assets protection after system faults.	***System Resilience and Efficiency***	System is self-healing. It automatically detects and responds to the network problems. Focus is on the fault prevention and reduced system losses.
One-way communication. Consumers are uninformed and non-participative in the network.	***Information flow***	Two-way communication. Consumers are informed, active and involved.
Focus is on preventing power outage.	***Service Quality***	Focus is on power quality patterns and improved customer services. Energy services is matched to consumer demands.
The system relies on large-scale, centralized power plants.	***Diversification***	The system relies on many small independent power producers and distributed energy sources Focus is on integration of renewables and interconnection of vehicle-to-grid systems.
Traditionally monopolistic and government-controlled sector.	***Competitive market***	Open transparent competitive market with fair pricing. Increased competitions result in efficiency gains and investment in innovative technologies.
Limited operational data, manual monitoring and electrically operated mechanical devices. Time-based maintenance of the system.	***Optimization of grid operations***	Deeply integrated technologies (as smart meters and SCADA) allow transmission of enormous amount of data to coordinate timely and stable operation of the grid. Automatized operation with minimized remoted control. Condition-based maintenance.

This is to say, there are two ways the smart grid is smarter (Mah, 2014):

1. Smart grids enable two-way electricity and information flow. Smart grid consolidates data from the overall grid performance and provides price signals (real-time pricing rates) based on the current supply and demand metrics and allows consumers to shift energy usage to off-peak hours (Poudineh & Jamasb, 2012). Consumers can monitor and manage their electricity use, make their energy savings, produce renewable energy at home and sell the excess back to the grid. Play the role of the prosumers.
2. Smart grids allow the integration of a variety of RES from many small power producers. The electric grid is significantly affected by the integration of a large share of RES due to their variability and limited predictability, and challenges such as energy storage management, grid stability, demand management systems, voltage control and forecasting issues arise (Eltigani & Masri, 2015). Smart grids can effectively coordinate all these components.

The countries that complete their energy transition through successful renewables accommodation via smart grids and energy storage capacities, will be one step ahead in strengthening their energy security and reducing dependence on fossil-fuel imports (Bertam & Primova, 2018). Allowing competition creates a decentralized marketplace for firms to invest in innovative technologies (Pepermans, 2019) and large solar and wind projects via auction mechanisms (Bolton, 2021). The competition also redirects the focus on consumer experience and offers consumers an opportunity to choose (Morrison, 2022). Smart grid development is not only dedicated to improving the efficiency and quality of system operation and facilitation of RES integration but also enabling end-users' participation by transforming consumers into prosumers (Chen et al., 2023). The smart grid objective is to turn the traditional electric grid into a sustainable, reliable, and intelligent grid of the future, where consumers, industries, government, regulators, and private actors will have an impact on the economy, environment, and efficiency of energy consumption.

Case of Denmark

This paper takes the smart grid experience of Denmark as the best-case scenario for analysis. Denmark is a small country which is known for integrating large amounts of wind power into the energy system in a relatively short time. According to the Ministry of Foreign Affairs of Denmark (n.d.), the global reputation as a leading renewable energy nation came to Denmark because of the:

- Denmark integrated one of the highest levels of renewable energy sources in the electric grid – more than 50%.
- This is one of the most reliable grids in the world with an up-time of 99,8%.
- The Danish government committed itself to 70% GHG emissions reduction by 2030 and towards net zero by 2050 by passing The Climate Act.
- The first commercial and the largest of that time wind turbine, the Tvind, was erected in 1979 in Denmark and in 2002 the world’s then-largest offshore wind farm Horns Rev 1 (80 turbines) was established in the North Sea and connected to the Danish grid.
- Additionally, as Eurostat reports, Denmark ranked third among EU member states based on RES-generated electricity consumption. In 2020, RES made up 65% of electricity consumption in Denmark.

An interesting event to note, on 15th September 2019, the wind turbine production exceeded the Danish national electricity demand for 24 hours by an impressive 60% and excess electricity was exported, as reported by national transmission system operator Energinet.dk (2019).

The first wind turbine that produced electricity in Denmark was built in 1891 for rural development and modernization of farming practices (Johansen, 2021). At that time, Danish electricity was generated mainly from fossil-fuel-based power plants and the system was operated in a traditional manner. Even if wind power was a local energy source amid a scarcity of imports, oil and coal were still the most prioritized sources because the price of electricity generation from wind turbines was double the price of oil and coal (Johansen, 2021). Oil was inexpensive and required minimal investments in comparison with wind turbines. In the 1970s, due to the oil crisis, which exposed Denmark's critical dependence on oil imports, environmentally polluting traditional systems and ever-increasing electricity demand, the solution was found in favor of wind power generation (Xu et al., 2009; Pallesen & Jacobsen, 2018). At that time, 90% of the total national energy consumption was based on oil imports from the Middle East and the 1973 energy crisis revived the locally harvested energy resources (Johansen, 2021). As Johansen (2022) concludes, societal trust, low levels of corruption and the memories of the energy crisis adding to growing environmental awareness have contributed to the widespread community support for the surge of large-scale energy infrastructures. In 1987, Denmark connected to the grid the largest wind farm in Europe at that time, called Vordingborg, generating a maximum of 3.5 MW. And in 1991, the very first offshore wind farm in the world named Vindeby was connected to the Danish grid. At this point, the Danish Government has provided an attractive incentive for large power companies and investors to construct wind farms and produce wind power (Ding et al, 2014). Over the next ten years, only a few more offshore wind farms were constructed in the world (Ørsted, n.d.).

Behind the successful evolution of the renewable energy industry in Denmark were proactive energy policies and regulatory frameworks. In the mid-70s, during the oil crises, Denmark imposed energy taxes on electricity prices to spread the costs of R&D for RE development among all electricity consumers. According to Est (2022), the political choice to halt the construction of coal-fired power stations, the support for the anti-nuclear movement and the focus on variable energy sources, led to the decision to convert the electricity network from a one-way system to a two-way system. At that time wind power was too costly to afford, and the concept of local wind cooperatives emerged – where people jointly invested in shared wind turbines to meet their own electricity consumption with the right to connect and sell the excess to the grid (Grobbelaar, 2010 as cited in IRENA-GWEC, 2013). This made Denmark possibly the first country in the world to abandon the traditional distribution system and begin the transition to the two-way communication system, which was conceived to be an "effective collection grid" (Est, 2022). Moreover, the Danish government started to offer tax incentives to local communities to generate RE power for their own needs, and as a result, more and more wind cooperatives were established. By 1996, there were 2100 cooperatives throughout the country, and by 2001 more than 100 000 families owned 86% of all turbines in Denmark (IRENA-GWEC, 2013).

With a new energy plan, the government started to provide subsidies for the construction and operation of wind and biomass farms and imposed taxes on oil and coal to give impetus to RE market development. In addition, some grants were available for replacing old wind turbines and for R&D purposes. Denmark started the liberalization process of the electricity market in 1996 in order to create competition in the energy sector. The essential shift during this process was the transition from subsidy systems to fixed feed-in tariffs - a system which guaranteed a fixed price of 85% of the local retail price of electricity net of tax with ensured priority grid connection (Danish Energy Agency, 2020). Although there was an energy tax, once a carbon tax was introduced in 1992, this made RE more economically viable compared to oil and coal (Danish Energy Agency, 2020). In 1999 with a comprehensive law reform for the electricity sector established a new regulator. The electricity and gas transmission grid became owned and operated by a state-owned Transmission System Operator (TSO), Energinet.dk, which was established in 2004. The distribution grid was controlled by companies either owned by cooperatives or by municipalities. At that time there were more than 200 distribution companies, by 2019 this number was reduced to 43 via mergers and in 2020 there were 38 suppliers with a total of 295 various contract types e.g., a fixed electricity price for a period, a variable price, and many more combinations thereof (Danish Energy Agency, 2020).

Later green market reforms have been adopted so that by 2003, 20% of electricity consumption is derived from green RE (excluding waste and hydropower). Fixed feed-in tariffs were intended to be replaced with a cost-effective and flexible green certificate system for market-determined long-term prices and to avoid over-subsidization (Odgaard, 2000). In 2002, Horns Rev 1, the then-largest offshore wind farm, was commissioned in the North Sea west of Denmark. This farm was a significant technological milestone, which gave a baseline for utility-scale wind power utilization and became the first to have its own designated offshore substation (Ørsted, n.d.). According to International Renewable Energy Agency (IRENA) and Global Wind Energy Council (GWEC) (2013), wind energy has priority access to the Danish grid, including small-scale distributed energy resources. By 2003 all existing wind generators were connected to the Danish grid.

The variable nature of wind power raised the issue of energy and electricity security. The studies have confirmed that the operation of offshore wind plants has shown relatively more power fluctuations than the power derived from the onshore wind farms perhaps due to their higher concentration in Denmark (Akhmatov et al., 2008; Sørensen et al., 2008; as cited in Ding et al, 2014). In 2010, Danish Ministry for Climate, Energy and Building come up with the Smart Grid Network initiative that would allow the system to integrate 50% of wind power by 2020. The EU Electricity Directive 2009/72 required each member state to perform a cost-benefit analysis for the massive smart meter roll-out and if assessed positively, to achieve at least 80% intelligent metering penetration by 2020. At the same time, the Danish Parliament decided to reach 100% smart metering installation for households and enterprises by that time to enable flexible electricity consumption and new services. This was also a government pre-requisite for achieving the net zero goal in 2050. Denmark reached its EU-wide set target by the end of 2017, one of the highest penetration rates at that time (Alaton & Tounquet, 2020), and achieved its 100 % roll-out target by December 2020 (Danish Energy Agency, 2021).

The same EU Directive encouraged the introduction of smart grids with a decentralized generation and promoted energy efficiency. In 2012, the Danish Energy Association and Energinet. dk built their smart grid concept in their report (2012, p.9):

> *"An intelligent power system – a Smart Grid – would see consumers interacting with the power system and production by means of automatic and intelligent control of their electrical appliances, thereby realising socio-economic benefits."*

According to the working report of the Danish Energy Agency (2015), electricity supply security in Denmark had reached almost 99,99%, which means that increasing VRES's share in the electricity system did not affect the security of supply. Today Denmark has one of the highest levels of VRES generation with a strong grid integration and this is possible due to major modifications to the power grid (Est, 2022). Today, Denmark is home to two of the top five wind turbine producers in the world – Vestas and Siemens Gamesa, the world's largest wind turbine rotor blade manufacturer – LM Glasfibier, and the world's largest developer of offshore wind – Ørsted (Est, 2022). Moreover, it should be mentioned that Denmark's grid is synchronously connected to the Nordic power market (Norway, Sweden, Finland) and Germany, which helps to export excess in times of high wind production and import in times of scarcity and in this way stabilize the grid. Denmark is ranked second in the world across all three Energy Trilemma dimensions based on World Energy Council's "World Energy Trilemma Index 2022" and among the highest in environmental sustainability and energy efficiency. It can be argued that the establishment of a smart grid was effective in this regard. This is one of the main reasons for considering the Danish smart grid system successful.

Overall, the case of Denmark provides the following lessons to be considered:

1) As Mah et al. (2014, p.133) conclude, "to fully capitalize on the potential benefits of smart grid deployment, it requires not only technological advancement but also a good understanding of the regulatory barriers". The Danish regulatory base is continuously updating, and the focus right now is the legal framework for monopolies and the retail market. All regulations and tariffs have been amended several times once deemed inflexible and inefficient e.g., from 1 January 2023, Energinet is supposed to collect a producer feed-in tariff and a new grid connection tariff which are geographically differentiated contributions for the establishment of the grid connection.
2) Policies need to be customized to the type of energy.
3) Danish experience demonstrates how dependency on fossil fuels can be reduced without negative consequences for economic development through effective energy policy and technological enhancement.

4) Liberalization and unbundling are long processes, which may take decades to implement. The Danish liberalization process started more than 20 years ago. Yet, 100% unbundling has still not been achieved in any country.

5) In Denmark, the early drivers for liberalization of the power sector were EU requirements and the ongoing liberalization process in neighboring Nordic countries. Domestically, there was no strong political desire for electricity market liberalization (Danish Energy Agency, 2020). However, this process may lead to easier integration of renewables, cutting state costs, and attracting more foreign financing. The Danish Energy Agency stated (as cited in Trong and Limann, 2009) that previously regulated monopoly companies were over-staffed and some questionable spending was revealed.

6) A competent, active, and independent Regulator is needed in a free market for strong and effective supervision of the utility sector. Danish Utility Regulator has existed since traditional operation times but rather played a passive role. The Law on the Danish Utility Regulator of 2018 reorganized and expanded the competencies of the Danish Utility Regulator to supervise the electricity, natural gas, and district heating sectors. The purpose of the regulator is stated as "*securing consumer interests in the utility sectors by striving for a higher level of efficiency, the lowest possible costs in the short and long term, a stable and secure supply, and a cost-effective development in technology and climate-friendly initiatives*" (Forsysningstilsynet.dk, 2018).

7) R&D is an important impetus for successful transformation. Throughout the Danish power history, spendings on R&D were part of any policy and grants. For instance, in 2017, the government allocated 24.6 million EUR for research on smart grids and systems (Danish Ministry of Climate, Energy and Utilities, 2019).

8) Setting goals and defining strategies is crucial for government to have a clear vision in drafting plans and policies, and consequently meet its objectives.
9) Repowering of old infrastructure is an integral part of the RE strategy. Denmark has gone through three repowering incentive programs, and as a result by the end of 2017 more than 84% of turbines installed before 1994 and 56% of turbines installed before 2000 had been dismantled (Lacal-Arántegui, Uihlein & Yusta, 2020) and new turbines were installed for enhanced energy production.

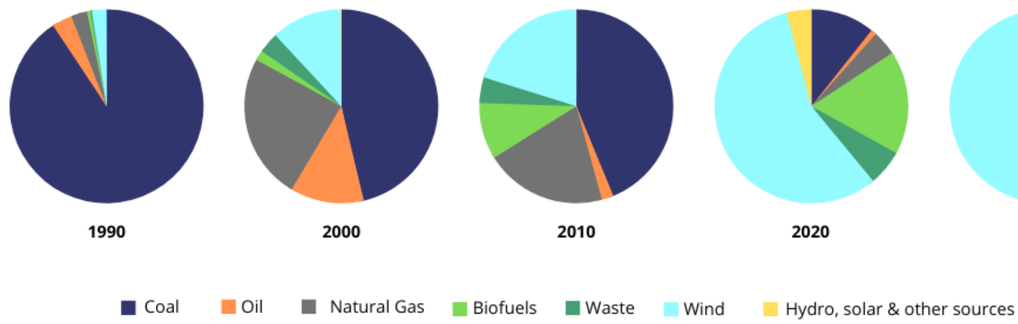
Figure 8 outlines the Danish liberalized electricity sector and Figure 9 showcases the renewables penetration trend and breakdown of electricity generation by source. Figure 10 provides a basic illustration of the smart grid system in Denmark.

Figure 6. Overview of the Danish electricity sector liberalization: before and after

Note. Adopted from Danish Energy Agency (2020).

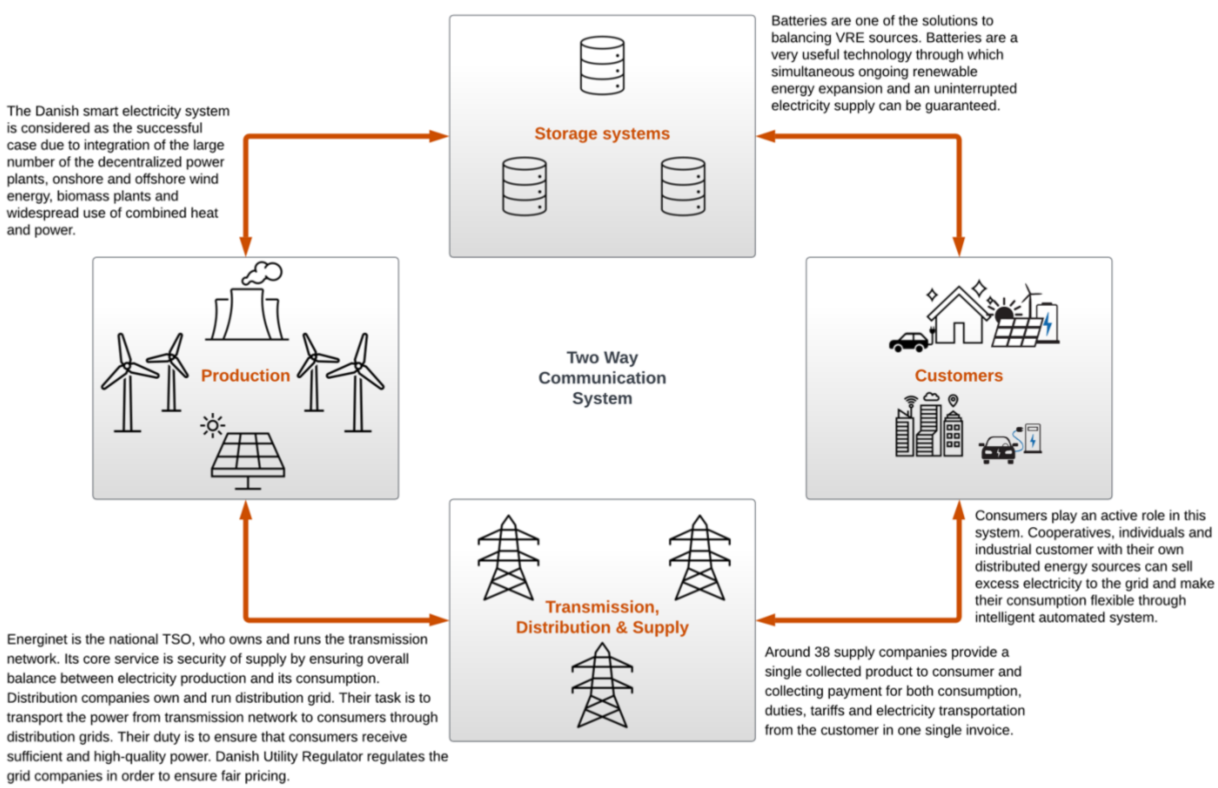
<table>
<tr><th></th><th colspan="2">Pre 1996</th><th colspan="2">Status for 2020</th></tr>
<tr><th></th><th>Structure</th><th>Price-regulation</th><th>Structure</th><th>Price-regulation</th></tr>
<tr><td>Production</td><td rowspan="3">Local monopoly
Vertically
integrated</td><td rowspan="3">Non-profit
Only necessary costs
included in prices
Monitored by Regulator</td><td>Commercial</td><td>General antitrust regulation
EU Regulation on Wholesale
Energy Market Integrity and
Transparency (REMIT)</td></tr>
<tr><td>Transmission</td><td>Monopoly</td><td>Non-profit
Only necessary costs</td></tr>
<tr><td>Distribution</td><td>Monopoly</td><td>Cost-caps
Monitored by
Regulator</td></tr>
<tr><td>Suppliers</td><td>—</td><td>—</td><td>Commercial</td><td>General antitrust regulation
EU Regulation on Wholesale
Energy Market Integrity and
Transparency (REMIT)</td></tr>
</table>

Figure 7. Danish electricity generation by source.
Source: IEA, *Electricity generation by source* https://www.iea.org/countries/denmark



Note: According to Energy Statistics provided by Danish Energy Agency (2022), in 2021, electricity from renewables accounted for 71.9% of Danish domestic electricity supply, compared to 68.0% in 2020. Wind power accounted for 43.6%. Biomass accounted for 22.0% and solar energy, hydro and biogas accounted for the remaining 6.2%. The share of wind energy decreased from 47% in 2020 to 43,6% due to a poor wind year with 10% fewer wind resources (IEA Wind TCP, 2021).

Figure 8. Danish Smart Grid System.
Note. The data is taken from the Danish Ministry of Climate, Energy and Building (2013) and Danish Energy Association & Energinet.dk (2012).



Current condition of the electricity sector in Azerbaijan

The existing grid in Azerbaijan dates to the 19th century, when the first 550 kW oil-fired power plant was built in Baku by the Nobel brothers in 1897. By 1913, Baku produced 110 MW of electricity, of which 95% was used by the oil industry and only 5% for the country’s lighting (MoE, 2020). By the 1970s the installed capacity of local power plants had reached 2882 MW, however, Azerbaijan had to import significant amounts to meet the growing electricity demand (MoE, 2020). To reduce dependence on imports, Shamkir HPP and Azerbaijan TPP were built and the capacity rose to 5000 MW. At the same time, the electricity grid was also systematically updated to include new generation capacities. Right now, Azerbaijan TPP is considered the largest thermal power plant in the South Caucasus with a generating capacity of 2400 MW. Commissioning the Azerbaijan TPP is assumed to be the foundation for the energy security of Azerbaijan (MoE, 2020).

Today 100% state-owned companies continue to dominate the electricity sector. Two vertically integrated monopolies – Azerenergy and Azerishiq – are the main market players. In 1996, Azerenergy Open Joint Stock Company was established following the Executive Decree of the President of the Republic of Azerbaijan No.423 of 17 June 1996, and all energy enterprises became subordinated to it. Currently, Azerenergy is the main grid operator and as well as the main generator of electric power in Azerbaijan. Azerenergy owns around 85% of the country’s generating capacity, including Azerbaijan TPP and Mingachevir HPP in Mingachevir city, the key generation units (IEA, 2021). In total, 98,5% of all installed capacity belongs to state-owned companies and 1,5% is owned by the private sector (*from interviews*). Azerenergy operates all existing power plants, except for small RES capacities under Azalternativenerji LLC and Balakhani Bioenergy Plant. There are also three independent thermal power plants owned by BP Azerbaijan (517 MW, off-grid), SOCAR (134 MW, off-grid) and Azersun Holding (32.8 MW). As mentioned, several pilot projects in the direction of renewables are in the stage of development, Masdar's solar project in the Garadagh region with a capacity of 230 MW as well as ACWA Power's project with a capacity of 240 MW in the Khizi region. The main role of Azerenergy here is purchasing the power under the Power Purchasing Agreement which will be generated at these power plants, as well as their connection to the transmission grid and preparation of technical data which is required for these power plants to be connected to the grid. Meanwhile, Azerishiq OJSC is the distribution network operator, supplier, and service provider (metering and billing) at the same time. Azerishiq was established in 2015 by the Presidential Decree dated 10 February 2015, which passed distributional assets of Azerenergy to Azerishiq (formerly Bakielektrikshebeke OJSC). This decision was the first step towards unbundling and market reforms in Azerbaijan. It should be noted that the Nakhchivan Autonomous Republic has its own State Energy Service, which is a vertically integrated monopoly responsible for the generation, transmission, distribution, and supply of the electricity across republic. Currently, the government aims to attract foreign investment to develop up to 1,5 GW of renewable projects in Nakhchivan and transform it into a green energy zone.

Following approval of the 2016 Strategic Roadmap for the Development of Utilities Services (electric energy, heating, water, and gas), the Azerbaijan Energy Regulatory Agency (AERA) was established in December 2017 under the MoE. European Bank for Reconstruction and Development (EBRD) has shown support to establish local regulatory mechanisms and legislation in line with international requirements and training experts for this project. By Presidential decree, AERA carries out regulatory and supervisory activities in the field of electricity, heat, and gas supply. The agency's functions include the preparation of draft laws, supervision of enterprises' activities, consumer protection and accessibility of services, dispute resolution and consideration of complaints, licensing, and participation in the formation of tariffs. Moreover, AERA plays a critical role in attracting investment in these sectors, financing power plants and privatization of non-strategic production units. The precise roles and responsibilities of the AERA will be clarified once the "Law on the Regulator in the field of energy and utilities" is adopted. This law has been modelled based on the EU Third Energy Package and it was submitted to the Cabinet of Ministries in July 2019. Since that time the law is pending its approval. During the interview, one of the experts argued that powerful actors in the energy sector are blocking the law since it will empower AERA and grant it a key role in the electricity market.

In 2020, Azerbaijan Renewable Energy Agency was established under the MoE, which is involved in the formation and execution of policies related to RE and energy efficiency. AREA just like AERA also focuses on attracting foreign investors and the private sector to participate in RE projects. The main objective of the agency is to meet Azerbaijan's target under Paris Agreement by 2030. Azalternativenerji LLC, the owner of small RE generation units, operates under the subordination of the AREA. However, during a personal conversation with an adviser from the public entity, it was stated that Azalternativenerji LLC will be abolished soon due to internal issues (most probably, ineffectiveness and inability to manage assets properly). What will happen with the ownership of these small power plants is unknown but assumed they would be transferred under the control of Azerenergy for the time being and perhaps later privatized.

Table 3. Key electricity market actors in Azerbaijan and their roles.

Azerenergy OJSC	- A vertically integrated state-owned monopoly. - Produces around 90% of the country's electricity consumption. - TSO which owns transmission lines with a voltage of 110 kV and above (220, 330 and 500 kV), their substations, and dispatch control facilities. - Carries electricity import-export activities. - Sells electricity to a limited number of large consumers directly. - Purchases electricity from private generators based on PPA.
Azerishiq OJSC	- A vertically integrated state-owned monopoly. - Distributor and supplier of the electricity. - Provides customer services (connection, metering, and billing). - DSO which owns power distribution lines up to 110 kV and associated substations and control rooms. - Azerishiq pays the Azerenergy wholesale tariff for electricity generation and its high-voltage transmission lines.
Tariff Council	- Sets electricity prices for generators and consumers. - Proposes changes to legal framework related to pricing.
AREA	The agency involved in the formation and execution of RE policies.
AERA	Market regulator; main supervisory body.

In the early 2000s all oil-fired capacities began to be replaced with gas-fired generation and currently country's electricity supply relies on increased domestic natural gas resources, evidencing a 94% share of gas in electricity generation today. The use of alternative sources for gas and oil in Azerbaijan dates to the construction of Mingachevir HPP (424 MW) in 1953, following Varvara HPP (17 MW) in 1956. The current share of hydropower in electricity generation is almost 5% (see Figure 9); this is the second biggest source of power. However, long-term reliance on hydroelectricity is deemed to be unsustainable, as in fact and based on interviews with government officials, in recent years Azerbaijan is experiencing a water shortage crisis and it has implications on the workload of HPPs. The high natural gas proportion in the country's electricity generation threatens its security and the subsequent increase will further erode the current situation. Hence, the development of alternative RES is inevitable and the need for energy sources diversification is explicit for Azerbaijan. Among VRES generation capacities in Azerbaijan, there is a modern Yeni Yashma Wind Power Plant (WPP) with a capacity of 50 MW under Azerishiq OJSC. There are seven small solar PV plants, a hybrid wind power plant, a bioenergy plant, and a hydro plant under the operation of Azalternativenerji LLC with a total capacity of 17 MW. In addition, Balakhani Waste-to-Energy Plant with 37 MW biopower generates roughly 1% of electricity. This plant is a project implemented by French CNIM S.A. with a 20-year "Design-Build-Operate" contract.

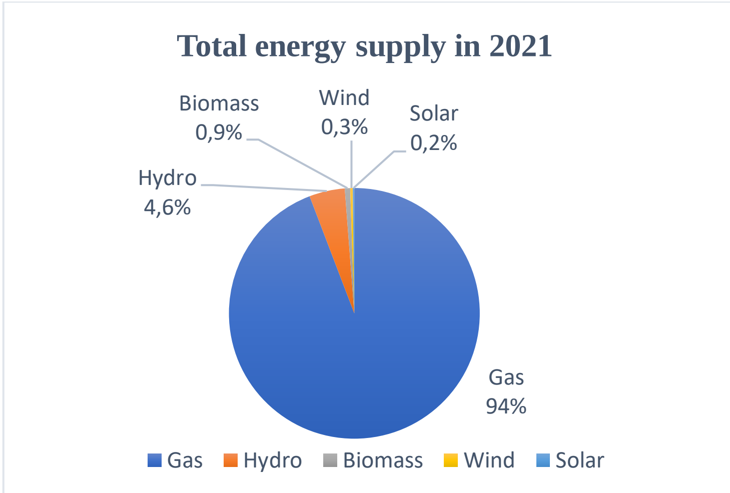
During the interview, one of the experts from private companies argued that the capacities of these numerous small units and Yeni Yashma WPP are negligible and do not have any impact on the electric grid. Two other experts stated that if we turn off these units, decommission them and build new ones, it will be more effective than keeping these capacities.

Table 4. TPPs & HPPs included in the energy system of Azerbaijan (> 10 MW).

Source: Ministry of Energy (2022). *List of thermal and hydropower plants included in the energy system of Azerbaijan and operating independently*.

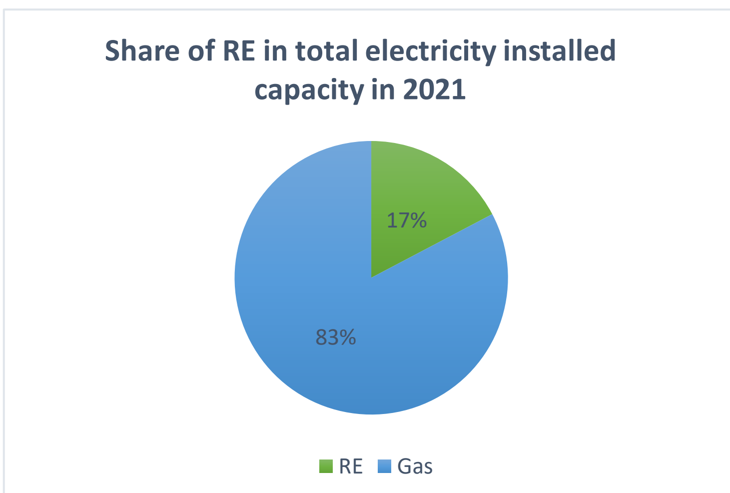
POWER PLANT	SOURCE	OPERATOR	INSTALLED CAPACITY AS OF 2022 (MW)	YEAR OF COMMISSIONING
AZERBAIJAN TPP	Gas	Azerenergy	2400	1981-1989
MINGACHEVIR HPP	Hydro	Azerenergy	424	1953
VARVARA	Hydro	Azerenergy	17	1956
ARAZ	Hydro	Nakhchivan SES	22	1971
SEMKIRCHAY	Hydro	Azerenergy	24	1982
SHAMKIR	Hydro	Azerenergy	380	1983
YENIKEND	Hydro	Azerenergy	150	2000
BAKU POWER PLANT	Gas	Azerenergy	107	2001
BAKU CENTRAL TEC	Gas	Azerenergy	104	2001
SHIMAL CCGT	Gas	Azerenergy	809	2002
ASTARA	Gas	Azerenergy	87	2006
SHAKI	Gas	Azerenergy	87	2006
KHACHMAZ	Gas	Azerenergy	87	2006
NAKHCHIVAN ES	Gas	Nakhchivan SES	87	2006
NAKHCHIVAN CCGT	Gas	Nakhchivan SES	60	2006
SUMGAYIT CCGT	Gas	Azerenergy	525	2008
SANGACHAL ES	Gas	Azerenergy	299	2008
SHAHDAG ES	Gas	Azerenergy	105	2009
BILEV	Hydro	Nakhchivan SES	22	2010
FIZULI	Hydro	Azerenergy	25	2012
JANUB CCGT	Gas	Azerenergy	780	2013
TAXTAKORPU	Hydro	Azerenergy	25	2013
ARPACHAY	Hydro	Nakhchivan SES	20	2013
LERIK	Gas	Azerenergy	17	2018
QOBU ES	Gas	Azerenergy	385	2020

Figure 9. Total Energy Supply in 2021 in Azerbaijan.



Note. Adapted from the MoE (https://minenergy.gov.az/en/statistika/elektrik-stansiyalarinin-novune-gore-elektrik-enerjisinin-istehsali_1282)

Figure 10. Share of RE in Total Electricity Installed Capacity in 2021 in Azerbaijan.



Note. Adapted from the official statistics provided by the Azerbaijan Renewable Energy Agency under the Ministry of Energy of the Republic of Azerbaijan (https://area.gov.az/en#demo-376)

According to IRENA (2019), Azerbaijan has a 100% electrification rate, meaning the whole population has access to electricity, and all cities and villages are electrified and connected to the grid. In 2016, Azerishiq implemented a metering program to rehabilitate power distribution networks across Azerbaijan and increase the availability of electricity for consumers. Asian Development Bank (ADB) allocated a loan in the amount of USD 750 million to improve the Azerbaijani electricity supply. Currently, almost all consumers are metered in Azerbaijan. Supervisory Control and Data Acquisition system (SCADA) was installed in Azerishiq and Azerenergy. In addition, energy management systems, telecommunications and energy accounting systems were implemented within the framework of the "Electricity Transmission System Development" project in 2007-2011. According to the interview with the head of the department in one of the government entities, total installed electricity capacity currently exceeds 8 GW and the system's peak demand was around 4.5 GW in 2022, meaning electricity consumption is self-sufficiently covered by local production and there is excess generation capacity. During the nighttime, the demand is below 2 GW, and some power plants are kept on a low working load. It is a known fact that conventional power plants can be switched off easily, but some of them (especially with outdated equipment) cannot be turned off entirely, operating inefficiently on minimum loads. Investment expert told that the 2018 blackout in Azerbaijan happened during nighttime peak demand when plants operated on lower loads, and once demand soared, outdated equipment could not resist huge loading.

Moreover, further capacity additions are on the way. In February 2023, the President attended the groundbreaking ceremony for a 1280 MW TPP, the second largest in Azerbaijan, to be built in the city of Mingachevir. The project will be implemented by Azerenergy in cooperation with Italian company Ansaldo Energia. As the new power plant will be meeting modern standards, it will enable significant energy savings and consume less carbon dioxide ("*Ilham Aliyev attended*", 2023). There are also plans to build a combined cycle gas turbine (CCGT) power plant with a capacity of 920 MW in Yashma village with the attraction of private investments. These projects will add 2200 MW to the installed capacity in 2025.

Efficient and modern gas-fired power plants will allow balancing the grid once RES are connected. There is a need to decommission old conventional power plants and replace them with new ones based on new technologies which enable switching on/off capacities at any time.

Whilst interviewing the government entities, it was confirmed that the latest loss rate in the transmission grid is 2% and in the distribution grid the losses are around 8%. Some works have been carried out to reduce transmission losses to 2% and it is believed to be a good achievement. In the distribution grid, the loss rate is higher and needs to be reduced to 5-6%. As the reason for high distribution losses experts mentioned that the distribution lines were longer than required in some regions. These lines were developed during Soviet times and most of them have passed their lifetime. The same issue with the transformers, being not appropriate for the demand load of some remote areas with a small number of residents. Yet, in addition, the geographic distribution of the power plants in the region during the Soviet Union time led to the main TPP being built in Mingachevir city. The gas field is in Baku and extracted gas is sent to Mingachevir, and all cables supply power back to Baku again, to the main demand peak point. Back-and-forth transmission perhaps causes not only electricity losses but also energy and money losses. One of the experts mentioned that no detailed study was conducted to understand where these losses come from. Azerenergy and Azerishiq need to conduct a technical audit and figure out where is the root problem. Second, it was argued that they ran away from innovations. Unbundling is necessary since when one entity is responsible for transmission and distribution; it is not within its interest to develop and integrate innovations. It is hard to move forward with the large complex structure.

Azerbaijan started gradual market reforms to establish a wholesale electricity market with enhanced competition, and this way attract foreign companies for RES projects. So far, there is limited competition due to existing state-owned monopolies. The Law on Electricity promoting liberalization was approved recently during the third parliamentary reading (The Milli Majlis of the Azerbaijan Republic, 2023). It provides a three-phase roadmap for the unbundling of the electricity sector in five years as shown in Table 5 and Figure 11.

Table 5. Timeline of the three-phased liberalization of the electricity sector in Azerbaijan.[1]

Phase 1	From the adoption date until June 30, 2023	Legal and Administrative unbundling of Production and Transmission (already separated from an accounting and functional point). Accounting and functional unbundling of Distribution and Supply.
Phase 2	From July 1st, 2025, to June 30, 2028	Legal and administrative unbundling of Distribution and Supply.
Phase 3	From July 1, 2028	The entry and operation of Independent Manufacturers and Supply entities into the market.

From the day the new law entered into force, the Law on Power Industry dated April 3, 1998, was repealed. The 1998 Law provided the legal basis for the electricity sector and allowed Azerenergy to purchase electricity from third-party generators. However, it still did not meet modern market standards and neither envisaged private sector participation in the system. Under the Law on Electricity government's main goal is to reduce its financial burden by allowing many private producers to enter the sector, privatizing current Azerenergy's power plants, abolishing subsidies, and establishing a free market economy. World practice has shown that generation is an excellent candidate for the liberalization and privatization of state-owned assets. Independent market operator purchases electricity from private producers and

[1] Four types of unbundling are distinguished in the Law:
Accounting unbundling – separate audit and annual accounts reports are produced; however, this form of unbundling does not imply independent decision-making power.
Functional unbundling – operational and managerial independence, however, still part of vertically integrated monopoly
Legal unbundling – a newly created legal form with independent decision with own management board, however still under supervision/ownership of the former vertically integrated monopoly.
Administrative unbundling – a separate independent entity is created with own task but shared operational activities within one central holding company.

sells it to various suppliers and only then suppliers will provide their service to customers. At the same time, the ideal plan is to maintain the transmission and distribution functions within state regulation.

New Law stipulates the following players in the Azerbaijani future electricity market:

- Electricity producers (elektrik enerjisinin istehsalçısı)
- Transmission system operator (ötürücü sistem operatoru)
- Distribution system operator (paylayıcı sistem operatoru)
- Market operator (bazar operatoru)
- Suppliers (təchizatçılar)
- Prosumer (aktiv istehlakçı).
- Consumer (istehlakçı)
- Regulator (tənzimləyici)

At present, the prices of utility services are determined by the Tariff Council. At this point, the uniform tariff is applied for residential consumers and different tariffs for commercial and industrial applications. The Tariff Council is also authorized to set tariffs for any kind of renewable energy. During the market liberalization phases, this mechanism will be maintained for all utilities, including the price of electricity. After 2028, electricity prices are assumed to be formed based on the market supply and demand principle. Valid tariffs are represented in Table 6 below. On the other hand, after the adoption of the Law on Regulator, AERA will be given certain powers to adopt normative documents. Among those powers will be regulating tariffs. The regulator has already prepared a tariff methodology plan and submitted it to the Cabinet of Ministers.

In May 2021, the Law on the Use of Renewable Energy Sources in the production of electricity was enacted. The long-awaited law provided certain incentives for foreign investors to develop RES projects in Azerbaijan, as well as the introduction of the “prosumer” concept for the domestic electricity sector. Draft regulations on prosumers have been prepared following EU and Turkish experience and submitted to the Cabinet of Ministers for consideration. The attractive incentives for foreign investors comprise guaranteed grid connection and guaranteed offtake (take-or-pay provision guarantees that the buyer either will take the good or pay regardless of the good was not taken), which by default means priority will be given to these generators in the transmission line. The law also prescribes two methods of selecting private generators: auction or direct bilateral agreements between the government and the company in question. The two RES pilot projects in the process of development were selected through a closed tender and bilateral agreements were signed. Azerbaijan does not have an auction mechanism yet in work, but it was argued to be in the process of development.

Table 6. Electricity tariffs set by the Tariff Council

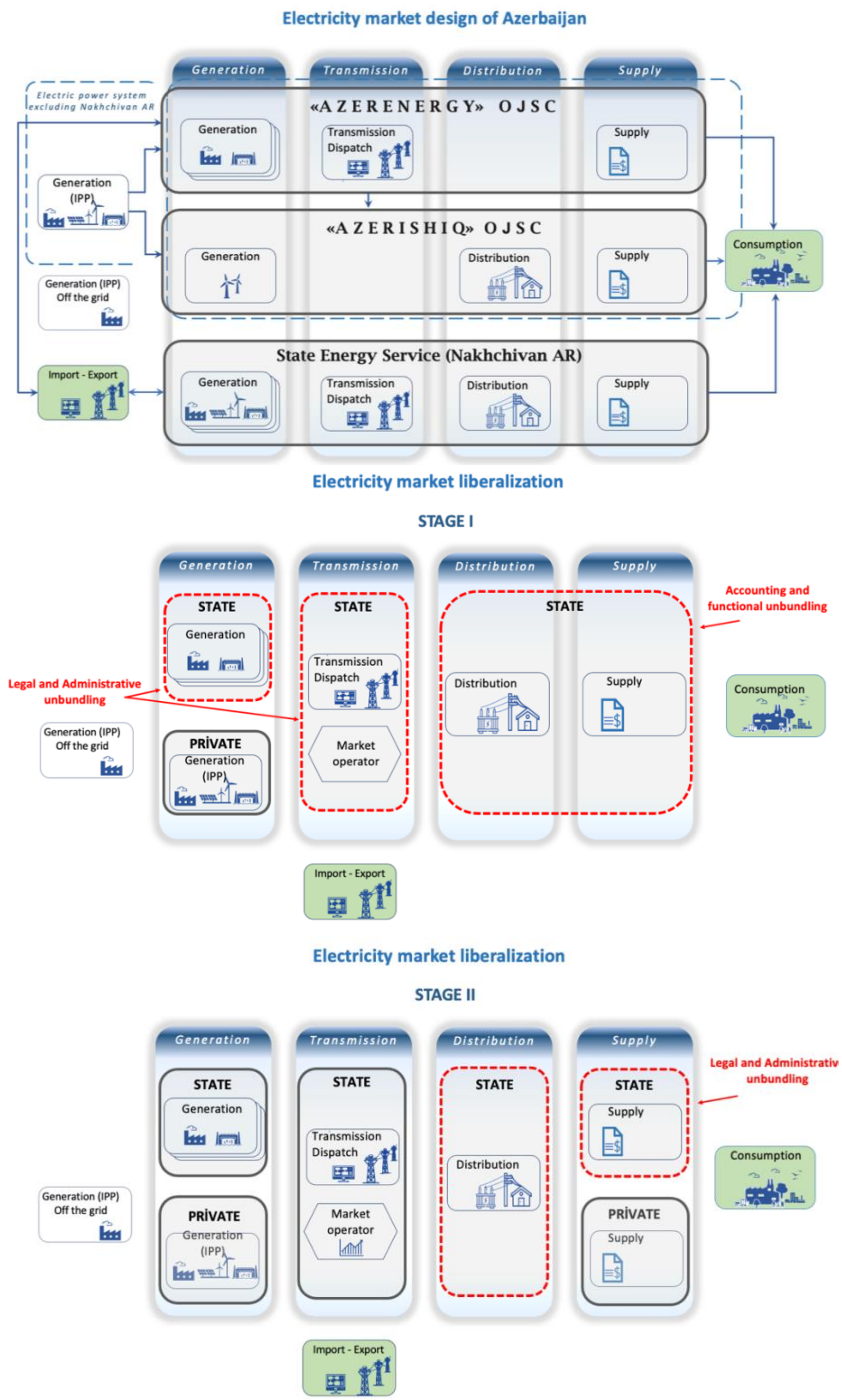
Source: Tariff Council, http://tariff.gov.az/?/az/content/70/

	By service	Tariffs for 1 AZN/kWh (VAT incl.)
I	**Wholesale (**Purchase from the producer)	
	Private generation of small hydropower plants	0,05
	Wind power plants	0,055
	Other renewable sources	0,057
	Alternative sources	0,06
II	**Wholesale (except for consumers specified in Clause 8 of this Decision)**	0,066
	Aluminum industry with direct power supply via 35 and 110 kV transmission lines and has a stable daily load demand and has monthly average energy consumption for production purposes of not less than 5 million kWh	
	Daytime (from 08.00 to 22.00)	0,064
	Nighttime (from 22.00 to 08.00)	0,031
III	Transmission tariff	0,002
IV	**Retail**	
	Residential	
	Monthly consumption up to 200 kW (including 200 kW).	0,08
	Monthly consumption volume from 200 kW to 300 kW (300 kW included)	0,09
	Monthly consumption volume exceeding 300 kW	0,13
	Non-residential (except for consumers specified in Clause 8 of this Decision)	
	Trade and service	0,11
	Others	0,10

Note: Tariffs are approved by decision No. 14 of the Tariff Council of the Republic of Azerbaijan dated October 16, 2021.

Figure 11. Three phases of electricity market liberalization in Azerbaijan.

Source: Provided by the public entity during the interview.



Interpretation of Interview results

Smartening of the electricity system is a continuous process which may take a long time. It actually never ends. According to an expert from an international advisory institution, the legal and regulatory part is just a tool to enable smart grid development. The commercial part like a business model is also a tool for this overhaul. And in every country, it will be different. Every grid is unique; there are no similar grids in the world. The engineering approach and the concept may be the same (like power generation), but legal and regulatory amendments vary based on the existing normative framework in each country.

Azerbaijan has been targeting developing renewable energy for several years and only 3 years ago it started making amendments to the legal environment and this way attracting foreign investors to implement the projects. RES are a new direction for Azerbaijan and requires massive capital investments. Azerbaijan, being a net energy exporter of crude oil and natural gas, did not require alternative energy sources before, hence there is an excess capacity from conventional energy sources right now. This means, the system was built to transmit electric power from a variety of distributed larger power plants in a passive controllable manner.

Certainly, Azerbaijan is and will be facing challenges in the prospect of RES penetration and grid modernization, however, there is no single project which is smoothly implemented. To be ready for drastic changes, the electricity system must be assessed and upgraded according to new penetrations. Overall, the outlook for RE development and smart grid implementation was deemed positive among interviewed public entities. The government has a strategy and priorities, one of which is to make sure smart technology is being utilized. The expected timeline for the efficient integration of smart technologies is at least 5 years. World practice has shown that market liberalization has taken at least 10 to 15 years. As one of the entities argued, it took them 5 years to get the Law on Electricity approved.

Quoting the interview with one of the public entities, it was noted that:

"Considering that more than 90% of the GDP falls on the share of countries with a liberalized energy market. That is, 73-74% of the world's population already obtains electricity from the liberalized market. The non-liberalized markets are mainly in the islands where there is no need, or it is impossible to create competition. It is also in underdeveloped African countries and several authoritarian states."

Investment expert has highlighted that:

"*The world club has approved electricity reforms and a new market strategy, and we need to start moving towards it, otherwise, Azerbaijan will stay much behind*."

This master thesis aimed to figure out challenges, the bottlenecks, and evaluate Azerbaijan's prospects for smart grid development. Interviews with experts from 10 various entities were conducted to collect their exclusive insider knowledge and industry expertise and identify the focus areas for successful smart grid development in Azerbaijan.

6 out of 10 experts mentioned currently applied **tariffs** as being one of the main problems or hindering factors in the prospect of RE development. These tariffs are too low, which brings insufficient incentives for foreign investors to come and implement projects. Azerbaijani tariffs for utilities are much lower than in the world, which means they are heavily subsidized. This is done to take off pressure from the citizens. However, the world standard is market-driven price creation. With the current tariff system, the process of unbundling is being prolonged and before unbundling is not in effect, it is impossible to adopt the market pricing approach. In addition, the current tariff methodology is not suitable for RES. One of the experts assumed that the method used for RES was the same as for thermal energy, and this is a wrong approach.

RES is different; you do not pay for sun and wind, but you have high capital and operational costs. Today, wind energy is purchased for AZN 0,055 ($0,0323) and other RES for 0,057 AZN ($0,0335) in Azerbaijan and these tariffs have been fixed since 2016. Time passed, but the tariffs have not changed, and the cost of raw materials has risen due to inflation. There is no differentiation between onshore and offshore wind, for example. The project expert has argued that there was three times project cost difference between them, the latter being the most expensive. In addition, there is no publicly available information on how these numbers were construed. There are two systems relevant for providing impetus to RE development: feed-in tariff and auction. Azerbaijan does not have any of them. To have an auction, you need unbundling to be in place (a liberal market, in which every bank and investor has an opportunity to assess the market risks). Second, a feed-in tariff is when an investor has a guaranteed return. Everything starts from a feed-in tariff and is then smoothly replaced by different mechanisms and then an auction system.

5 out of 10 experts pointed out **internal balancing issues** due to several existing deficiencies in the grid components. The capacities, Azerbaijan has right now, have been so negligible that discussions about challenges and larger volume integrations have not been even raised at all till recent days. *First*, overhead lines, transformers, and substations, which are the main parts of the transmission, that were built during the Soviet period, are quite old and pose limits to connecting RES. *Second*, renewables need a good planning system and network dispatch centers. SCADA system is applied at Azerenergy and Azerishiq, however, how well the scope of the software is adopted and how well people are trained is the big question. The grid is partially manual and partially automated, therefore, controlling the electricity flow is still predominantly done by manpower. Lack of experience in the planning and operation of the mixed generation portfolio may bring substantial problems. It was stated that new software tools should be acquired for forecasting and planning scenarios, and real-time measurement systems, and the existing metering and telecommunication links should be upgraded for successful operations of RE facilities. The establishment of control centers was stressed as well. *Third*, there are plenty of old power plants which cannot work in line with RES. There are overall three ways to balance the system: 1) Hydropower; 2) Storage capacities; and 3) CCGT plants, which are always ready to balance the system once RES share drops in the power generation. Due to the current situation with water resources, Azerbaijan is targeting the construction of new CCGT power plants. Two more projects have been already approved. It can be argued that Azerbaijan's electricity system is dominated by relatively new CCGTs, however, they are highly underutilized. Based on IEA's review of Azerbaijan's energy policy (2021), prioritizing the use of the most efficient power plants and, correspondingly, avoiding the use of the least efficient ones, would raise fleet-wide plant efficiency. Development and integration of the large share of VRES depend on the system's ability to balance the power system, meaning the capability of conventional power plants to change their power output based on the variability of the RE output in real time. According to the project expert from a private entity, in 2019, before the Azerbaijani government announced a closed tender for the RE project, a world-renowned advisory company DNV assessed the electric system and the management model, and based on their report *the system could integrate up to 1,5 GW*. They could not make a detailed assessment, but they came to this conclusion based on information provided by Azerenergy. In their report, it was also noted that most of the conventional power facilities in Azerbaijan have flat active power output diagrams and they run on technical minimum during the lower demand hours. Now imagine, 1.5 GW is suddenly integrated into the grid. Take-or-pay contracts with ACWA Power and Masdar will provide them with the priority offtake and on the other side there are inefficiently used power plants running on their minimum. There is high uncertainty about how to correctly manage the network, and where and how the system operator needs to switch on or switch off the power plants. This uncertainty will bring a high number of blackouts in Azerbaijan. It might be that Azerbaijan can experience problems even with 1,5 GW incorporation or even less. It is not known how the grid will react to this additional VRES capacity.

The other side of the balancing issue is the **external interconnection** with neighboring countries. *Four experts* have stressed this moment. Azerbaijan's power system is interconnected with those of Russia, Georgia, and Iran, and with Turkey on the Nakhchivan border. However, the electricity system is synchronized only with Russia's, as Azerbaijan was previously part of the USSR's grid. Currently, Azerbaijan is not able to stabilize its grid constantly without a connection to Russia. To have a stable grid, you must connect to another bigger grid. This is one of the critical challenges, which was mentioned by public agencies. The expert even noted that this situation might be the only difference between European countries and Azerbaijan. In Europe, every country is connected to another one via ENSTO-E cooperation, thus, they don't have the challenge of grid stabilization even in connection with renewables.

One of the experts from a private entity highlighted that the **geographical location** of Azerbaijan also poses a risk in the unbundling process, and it was a wise decision to keep it in the hands of the government. Azerbaijan's energy security is the most critical aspect. Nobody knows what will happen if the government allows private companies to take over the electricity sector.

Three experts have noted the **limited role of the regulator** as being a hindering factor for RE field development. After the Law on Regulator will be adopted, it will grant AERA executive powers. As it was highlighted before, this law is pending approval for a long time.

Another issue is that the regulator remains closely overseen by the MoE. In all the countries of the world, this is an independent institution or under subordination of the parliament. Most rarely under the ministry. Experts from financial and academic institutions agreed that AERA should be fully independent. If Azerbaijan is serious about the RE sector and wants to send a sort of message to foreign investors, AERA needs to be fully independent. The regulator has some sort of independency right now, but still reporting to the MoE. If the regulator remains within the government structure, it will create problems in attracting investors to the country. In general, the goals and objectives of the regulator are to ensure the reliability of the service, the accessibility of the consumers and prosumers to the utility services, monitor trading strategies and punish market manipulation, create an attractive investment environment, shape the competitive environment by regulating the relations between producers and transmitters, transmitters and distributors, distributors and suppliers, suppliers and consumers, protect the rights of all. Regulation of these relationships is deemed necessary by an independent regulator. Experts from the public entity noted that the main issue is not the status of the regulator but its empowerment. It does not matter under whom the regulator is given authority if it allows it to achieve those goals. On the contrary, the MoE's supervision provides AERA with partner support.

Investment expert noted that the **government was not aligned for liberalization reforms**. During the approval of the Law on Electricity, several parliamentarian representatives raised constraints about liberalization and came out against the law. It shows that inside the government there is separation of interests and forces. Especially, Azerenergy is against such reforms. They have argued that market liberalization would result in a several-fold increase in electricity prices and raise social discontent. The tariffs are set at a level that keeps services affordable for the population and the first affected by increased prices will be the poor class.

Some parliament members even offered to invite representatives of relevant state institutions to the law hearing for professional discussion ("*Deputatlar qanun layihəsinə yenidən baxılmasını təklif edib*", 2023). Another private sector expert additionally stated that there was a lack of coordination and communication between government agencies. Altogether this may present an obstacle to smart grid development.

Regarding **two-way electricity flow**, the experts responded that it was not economically feasible now. An analyst from the research center complained that one household must spend from 10 000 to 17 000 AZN to install 10 KW of solar power on the rooftop of his house. In addition, one financial institution has conducted a study on small-scale distributed energy sources where the focus was making a cost-benefit analysis and understanding whether prosumers could get any profit. The study showed that it was not economically feasible for people to adopt green energy sources as the tariffs were very low and the payback was almost negligible. There is no motivation from the government side, moreover, it is very expensive for the local population. The government has only one way and this is a subsidy, but again the government cannot cover it from its budget when it decided to abandon subsidies and create a market economy. Public entity representatives shared that they expect the prices to drop only after the adaptation of prosumer legislation. It's have been said for a long time but in practice no steps yet are observed.

Generally, the above-mentioned challenges show us that the legal base and physical grid infrastructure are far behind the vision of the President and the government. For example, detailed and accurate Network Code for connection to the grid has not been issued and necessary legislative frameworks are blocked or pending for a long-time. However, it is said to be sorted out gradually by responsible entities and the government. The point is that in the current situation, Azerbaijan's risk is greater because all investments are made by the state budget. For instance, in 2018, after a country-wide blackout, the state allocated a lot of funds for the rehabilitation of the Azerbaijan TPP. On average, the service life of a power station is 15-20 years. But this autumn, a new decision was made, the units of the station were demolished, and new ones were built, so after 3 years, the entire investment was lost. But in 2018, it was proposed to the government to consider a public-private partnership. That proposal did not pass. This is the risk; the state lost that money. The investment was going to be in the cycle for 25 years, but it disappeared after 3 years.

During the interviews, experts were asked about the roles of Azerenergy and Azerishiq in the liberalized market. There is a plan that structurally Nakhchivan will be connected to Azerenergy. Although there is no technical connection, the generating part will be connected here. The distribution lines will also be part of Azerishiq. It is planned to divide DSO into regions and make around 9 companies in Azerbaijan. There, too, supply can be separated from distribution. But liberalization is expected in Azerishiq. Some of the Azerenergy-owned generation capacities are planned to be privatized. However, privatization has not been carried out yet, maybe a law should be passed to create a legal base. For sure, this cannot be done without involving private investment. The transmission system will remain unambiguously within the state. It was argued that Azerenergy will be split into two new entities: TSO and market operator. Also, it was noted that Azerenergy was also part of the state's privatization program under Azerbaijan Investment Holding, which carries out diagnostics (of loss-making companies working on subsidies), transformation (to become profitable with corporate governance enforced), and finally privatization of the state entities. The work in Azerenergy has not even started there yet, and it is not known when and how it will be privatized.

State regulation is necessary. Electricity and energy security are a matter of overall security and reputation of the country. Especially, due to the neighboring countries, this is a very risky political issue. The state should attract investment, support entrepreneurship, a competitive environment, the principle of fairness and develop the market given the geopolitical situation.

Conclusion and Policy Implications

This master's thesis compiles the challenges related to the smart-grid application in Azerbaijan and the shift out of fossil fuels toward renewables in electricity generation. Even though the government has an ambitious outlook for smart grid adaption to the current electricity system in Azerbaijan, the following challenges have been identified as a result of interviews conducted with the experts. The research identifies that the main hindering factor is the current tariff mechanism and electricity rates that are not suitable for renewables, and this fact prevents the attraction of foreign investors. Furthermore, major legislative backgrounds, such as The Law on Regulator and Prosumer Regulations, have not yet been passed. One prosumer must spend up to 17 000 AZN to install 10 KW of solar power on a rooftop in Azerbaijan. This is economically inefficient for households, as for families of four persons the annual electricity bill will make around 600 AZN. The payback from rooftop green energy will not be achieved even in 15 years, all factors being the same. Especially, it is worth mentioning, the study outcomes demonstrated that market regulator should be empowered and independent. The regulatory environment application of market principles is envisaged, and network codes are being prepared by AERA. The electric grid project codes and 11 market monitoring rules have been drafted, however, they cannot be entered into force, since the Law on Regulator is not enacted. The same situation applies to the adoption of the prosumer regulation. Finally, the balancing issue is critical for Azerbaijan. Based on interview results, Azerbaijan's electricity sector will be vulnerable due to high uncertainty arising from the limited predictability of the

VRES which may result in frequent power outages. Nevertheless, it was argued that the integration of three pilot projects (total 710 MW) will not pose a problem but further additional variable capacities of mentioned 4 GW and higher are not visible. The adequacy of the offshore technical capacity of 157 GW should be considered separately. If these capacities are joined to the grid, the bigger will devour the system. Considering all these challenges, the policy implications of this study are the following:

- The process of legislative background of the “prosumer” should be accelerated to facilitate consumers’ transition to prosumers. The lack of any initiatives from the government side and high initial investment costs are major obstacles that impede the local community’s switch to distributed RES. Therefore, the long-lasting pending of necessary legislation should be sorted out gradually to promote the transition to two-way electricity and information flow.
- AERA should be empowered to establish proper market monitoring rules and Network connection codes. Ideally, regulatory authority must be independent with separation from the government administration, for example, as the Central Bank of Azerbaijan. The independence of the regulator guarantees that the decision-making and market conditions are also independent of stakeholders’ interests.
- The government does not want to be the main producer and investor anymore; therefore, the process of unbundling and introducing feed-in tariffs should be reinforced to attract private investors. All around serious investments are required: technical assessments and grid simulation should be conducted, new substations should be built, and transmission lines must be checked. Most importantly, control and research centers should be established, software should be updated, and people should be trained accordingly to

mitigate forecasting moments. Inefficient power plants should be either decommissioned or privatized for further modernization works.

A paradigm shift is critical. The mindset should be changed from a conventional unidirectional electricity paradigm to a bidirectional and distributed smart grid system. Establishing the smart grid facilities in the same operating paradigm will not allow for to achieve systemwide efficiency. Everyone may understand the same smart grid in different ways. Smart grid is not only about conventional market liberalization and regulatory framework; it is more about technical engineering art: consumers, prosumers, demands and management, and DDD – decentralization, decarbonization and digitalization changing the power infrastructure.

As every study, this study has also limitations due to a small number of experts and its restricted scope. Further research may go deeper and analyze the current condition of the electric system in Azerbaijan from a technical perspective. Moreover, policymakers can address the prospects for the development of an integrated energy system in Azerbaijan. As Azerbaijan has an excess installed capacity, this surplus electricity may be directed to other energy systems such as heating and cooling through systems coupling. Finally, a future study can be conducted on the visibility of Azerbaijan's export of offshore wind energy to Europe through the Black Sea Energy submarine cable project.

Appendices

Table 7. List of interview participants.

NO.	ORGANIZATION	EXPERT POSITION	INTERVIEW METHOD
1	Private Company	Senior Manager	Face to face
2	Private Company	Country Manager	Face to face
3	Research Center	Analyst	Online
4	Public Entity	Deputy Director and chief adviser	Face to face
5	Public Entity	Head of the department	Face to face
6	Public Entity	Head of the department and two advisers	Face to face
7	International Research & Advisory Institution	Senior Adviser	Online
8	Financial Institution	Energy sector investment expert	Face to face
9	Academic Institution	Instructor, previous consultant in Financial Institution	Face to face
10	Public Entity	Head of the department and senior adviser	Face to face

List of Interview Questions

1. Private Company

What have been the major obstacles in renewable energy project implementation in Azerbaijan?
When large scale RE projects will be penetrated to the grid, what impact will they have on grid?
How will your project be connected to the electricity grid?
If Azerbaijan starts electric system upgrade today, at what fact should we focus at first sight?
Unbundling in Azerbaijan. What is your vision of this?
In your opinion, what are the reasons of losses in the grid?

2. Private Company

What steps have been done to update the electric grid for RE projects?
What have been the major obstacles in renewable energy project implementation in Azerbaijan?
Unbundling in Azerbaijan. What is your vision of this?

What will be challenges in implementing smart grid?
In your opinion, what are the reasons of losses in the grid?
What is your opinion regarding electricity tariffs set by Tariff Council?

3. Research Center

In your opinion, is the cost of solar and wind energy in Azerbaijan lower than the wholesale prices set by the Tariff Council?
What are obstacles for the smart grid development in Azerbaijan?
What are the deficiencies in the electric grid of Azerbaijan?
In your opinion, why the power disturbances happen so frequently across Azerbaijan?
Law on Electricity, how do you foresee liberalization of electricity market in Azerbaijan?
Do you think it is possible for Azerbaijan to have prosumer system?

4. Public Entity

In your opinion, what are the major causes of power disturbances in Azerbaijan?
What can be the problem during penetration of renewable energy sources to the current electric grid system of the nation?
What steps have been done to update the electric grid for RE projects?
How do you foresee liberalization of electricity market in Azerbaijan?
Do you think it is possible for Azerbaijan to have prosumer system?
What can be the hindering factor if we start smartening the grid right now?

5. Public Entity

Please explain how current electric grid is working? (From what time it is on, has there been any updates?)
What is your organization's strategy for the upcoming years regarding electricity security and RES penetration?
In my previous interviews, it was noted that grid can integrate up to 1,5 GW of RE. Is that fact true? Is it known how the grid will react to this 1,5 GW of RES?
Please elaborate, what is the common reason of the blackout accidents in Azerbaijan?
What are the reasons of losses in the grid?
Unbundling process, how do you foresee it? What will be the role of your organization in new system?
What do you think will be the main challenges for Azerbaijan specifically during liberalization process?
What can you say about potential of Azerbaijan towards smart grid development?

6. Public Entity

We understand that the integration of larger volume of RES will require update/modernization of the current electric grid of Azerbaijan and also setting up different technologies and storage capacities. Could you please share what steps are undertaken on this matter? What works are planned/performed in this area?
Unbundling process of the electricity industry, how do you foresee its realization in Azerbaijan?
What is your organization's vision of the future liberalized grid architecture?
How do you foresee electricity market regulation after its liberalization? What will be your role there?
Your entity makes proposals on the formation of tariff policy in the field of electricity. Could you please elaborate on the formation of the tariffs for wind and solar energy? How they will be determined and who determines it?
In your opinion, which areas of electric grid system of Azerbaijan need to attract more investment?
Is there regulation related to prosumers? Please elaborate.

7. International Research & Advisory Institution

From your experience, what should be the first step in the route of grid update and smart grid development?
What is the important component of successful smart grid development?
What should be the focus for Azerbaijani government right now?

Could you please provide some technical timescale and financial estimations for Azerbaijan?

8. Financial Institution

Do you a potential in the renewable energy development in Azerbaijan? Could you please first elaborate on this topic?
What are expected or already agreed project investments of your institution in Azerbaijan's electricity sector? Specifically, any project for grid enhancement?
Unbundling process of the electricity industry, how do you see its realization in Azerbaijan?
Do you expect any risks or challenges for Azerbaijan after electricity sector liberalization?
What is your forecast about security of electricity supply of the country once larger share of renewable energy sources are integrated to the grid?
And in overall what do you think will be the major challenge for the smart grid development in Azerbaijan?

9. Academic Institution

What do you think will be the major challenges during electricity grid update in the country to integrate larger volume of RES?
What do you think about electricity sector liberalization law?
What is your opinion regarding prices set by tariff council?
What are the current problems in energy/electricity sector of Azerbaijan which may hinder the process of RES penetration?

10. Public Entity

What can be the problem during penetration of renewable energy sources to the current electric grid system of the nation?
What measures have been taken to update the current electric grid of Azerbaijan?
Why the power disturbances happen so frequently across Azerbaijan? Please list all known reasons, and whether any measures have been taken to address the issues?
Do you have any idea what is the percentage of current transmission and distribution losses in the grid? Could you please elaborate what kind of works have been done to reduce losses in the grid?
Law for liberalization of the electricity sector was recently adopted. How does your organization foresee the electricity industry liberalization? What is the vision of the grid architecture?
What is your forecast about electricity security of the country once larger share of renewable energy sources are integrated to the grid?
Is there regulation related to prosumers? Please elaborate.

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