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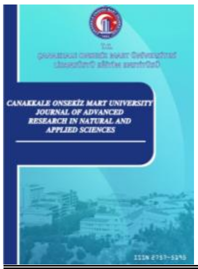

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Flexibility in Power Systems of Integrating Variable Renewable Energy Sources

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Research Article

Abstract –The issue of energy security is addressed in many publications and by specialists in many fields. None of the researchers has any doubts that renewable sources have an impact on the functioning of the power system, in particular on its reliability. The intermittent nature of renewable energy sources introduces a new type of uncertainty to the operation of power systems. The aim of the article is to present an important research problem in the relationship of a smart power grid - network flexibility - optimization models. This study focuses on the analysis of the short-term (operational) and long-term (investment) aspects of providing flexibility with sources of fossil fuel generation, storage, and demand response. The authors discussed the role of power system flexibility at the stage of generation and planning. Paying special attention to the simplified optimization and load profile effect. The proposed optimization model was implemented using the MATLAB optimization engine. The research results indicate the key role of both the identification of energy flexibility and the factors affecting it in terms of renewable development and in terms of savings in investment and operating costs. The recipients of the research may be public and local government units that plan to increase the share of renewable energy in their energy systems in the future. To ensure energy stability and reduce energy production costs.

Keywords − *Flexibility, investment, optimization models, power system, profitability, renewable energy*

1. Introduction

In recent years, much attention has been paid to energy security in the available literature on the subject (Bird et al., 2013; Deng & Lv, 2020; Sinsel et al., 2020). This topic appeared in many legal acts, reports, studies, and conference materials. Considering the enormity of investments related to the need to modernize the energy sector, i.e. the need to increase the production capacity of electricity, as well as the introduction of a significant share of renewable energy sources in electricity generation, it can be concluded that the demand for energy investment funds will be a big challenge (Impram et al., 2020). Thus, it can be concluded that electricity prices will continue to increase in the coming years, as the energy sector will be forced to seek funds for the necessary investments (Schaber et al., 2012). Simultaneously with the energy efficiency improvement program, opinions appear that the energy and climate policy, i.e. the fight against global warming, and the growing share of - unfortunately - unstable sources of renewable energy mean that the effect of these measures is likely to increase energy prices. And this leads to negative consequences both for industry and residents. Questions arise as to whether the flexibility of the electricity system is appropriate as a result of the increase in the share of energy generation from renewable sources (Papaefthymiou & Dragoon, 2016).

Already at the beginning of the considerations, it should be noted that in the last decade, the traditional structure of energy systems has entered a process of change due to the increasing share of renewable energy sources in the total installed power of countries (Kapitonov & Voloshin, 2017). To cope with the volatility and uncertainty

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that renewable energy production brings to the system, prevent energy constraints caused by renewable energy, and provide consumers with the desired energy at all times reliably; it becomes possible by using all kinds of flexible resources in the network.

For an energy system to be considered flexible (Langevin et al., 2021; Schulze et al., 2019):

- It should have the capacity to meet peak loads and net peak loads.
- It should always maintain the balance of supply and demand, ensure that sufficient capacity is available during increasing or decreasing load changes, offer working capacity even in case of low net load, and be able to respond quickly to changes.
- It should have the sufficient storage capacity to fulfill its balancing service during high renewable energy generation or low renewable energy generation in the face of high demand.
- It must be able to manage the demand side to respond to periods of supply shortage or overproduction.
- It must be able to maintain its ability to mitigate potential events that could destabilize the energy system by ensuring that ancillary services are always adequately supplied.
- It should operate in a well-designed market environment where the available flexibility is not hampered by market inefficiencies.

In this article, the authors made an attempt to explain the links between intelligent energy grid - grid flexibility - optimization models. The authors then outlined the need for balance and flexibility in a renewable energy system, using the definition of flexibility on an operating time scale in an hour or a day. Emphasize the importance of flexibility with regard to planning time.

Therefore, the article below has many important political, economic, and practical implications. Considering that the aim of the research is to gain extensive knowledge on a significant research problem in the relation between intelligent energy grid - grid flexibility - optimization models. At the same time, it is a new opening to research the said relationship in relation to renewable sources. This study examines the short-term (operational) and long-term (investment) aspects of providing flexibility using fossil fuel generation sources, storage, and demand response.

The article is organized as follows. Chapter 1 gives information about the author's view of smart grids and what it's all about the reliability and integrity of the power system. Chapter 2 describes keeping the power system in balance and the need for flexibility at the operational time scale. Chapter 3 describes power system flexibility at the planning stage. Chapter 4 describes flexibility and how it is deployed flexibility with the resources. Also, the section explains flexibility in the planning time scale when it has the opportunity to build more resources. Chapter 5 presents the final conclusions of the research, indicating their limitations, practical application, and future directions of research in this field.

1.1. Reliability and integrity of the power system

A grid-tied mini-grid using renewable power sources offers customers benefits that increase overall system flexibility (Tsai et al., 2020). The grid connection strengthens the use of solar PV and wind energy throughout the system. Integrated energy infrastructure based on distributed power generation creates local mini-grids. Although normally autonomous, they can also be connected to the main grid. Installing the system in the desired region increases flexibility by reducing transmission losses (Duran & Sahinyazan, 2021).

The first thing to worry about in a power system is to provide a reliable supply; but there's something else running a power system, it's incredibly expensive (see Figure 2). The running of a traditional power system kind of balances greed and fear. The greed is the grid operator doesn't want to spend more money on operation and management; the fear is consumers can have a blackout. Over many years public services learn how to do such operations. There are monopolies with vertically integrated utility; they have satisfactory reliability and can do so at a very low cost. The technology is also relatively mature; there were not a whole lot of big changes happening there. No real need for innovation therefore in the situation for quite a number of years not much was happening in this field.

But then in a recent year, something else happened. The share of energy consumed from renewable sources in the EU and the world in 2020 was 22.1% and 12.55%, respectively (Mehedintu et al., 2021). Despite the high level of dependence on fossil fuels in the current situation, the use of renewable energy has been increasing over the years. People and governments want to be green, which means integrating renewable energy sources like wind and solar in this context. Therefore, instead of dealing with the fear that has just been decided, it is now necessary to deal with a third aspect, namely, that everything is desired to be green, to have renewable energy sources (see Figure 1).

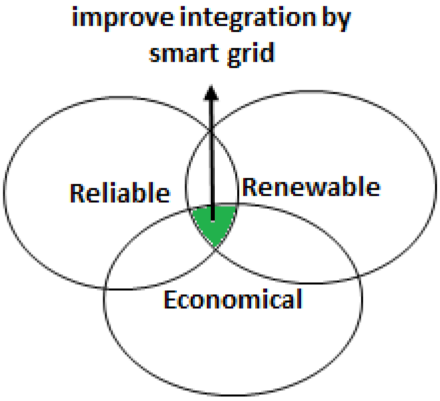

Figure 1. The relationship between the flexible development of energy and the reliability, renewable and economical.

As shown in Figure 1 the three goals should all be taken into account and are commendable, but they go in different directions. Namely, it's easy to be reliable and cheap but it won't be green. It may be environmentally friendly and reliable, but it will not be economical, or it may be cheap and green but not reliable. This is the conundrum about the power system operation trying to satisfy these three goals.

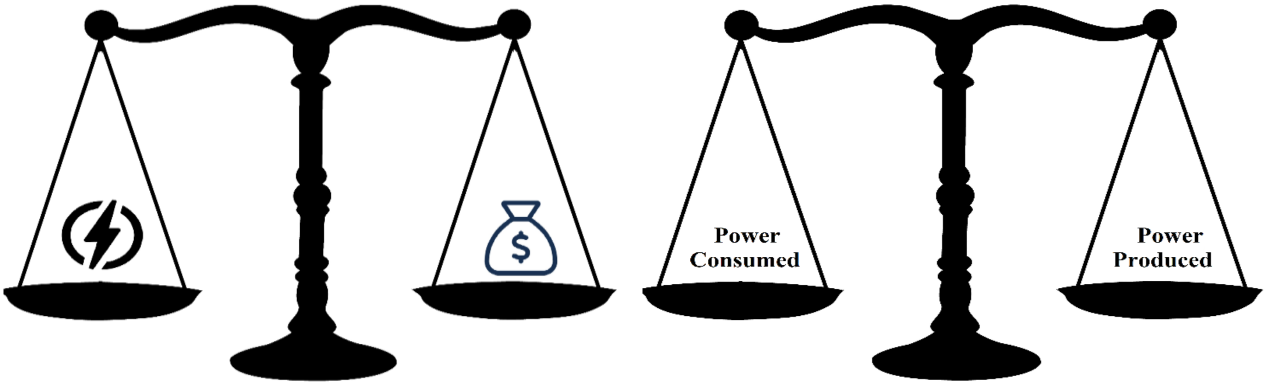

Figure 2. Energy economy and energy balance

There must be a physical balance between the power produced and the power consumed (see Figure 2). These two need to be kept equal, essentially on a second-by-second basis. This balance has to be maintained in the face of fluctuations in the load.

1.2. The Role of Smart Grid

The smart grid is about trying to use new technologies like communication technologies, computing technologies, and control technologies which are a lot cheaper than traditional power technologies; because it doesn't involve a lot of copper steel and concretes (Bouffard, 2010; Gungor et al., 2011). These new technologies must be used to better achieve these three goals simultaneously. There have lots of different definitions of the smart grid (Ardito et al., 2013; Colak et al., 2014; Jenkins et al., 2015; Shabanzadeh, M. Moghaddam, 2013); mainly it is the use of communication control and computer technologies to enhance the operation of the grid. One thing to know about the power system is that the power generation must always be increased to the power consumed and this balance must be maintained. In the old days, this meant having to adjust the generation as low changes throughout the day. A typical load curve and load duration are shown in Figure 3 and Figure 4 respectively. The data shown in Figure 3 represent the average aggregate U.S. hourly load by day of the week indicated between 2018 and 2021 (U.S. Energy Information Administration, 2022). There are very slow variations in demand, and also quite predictable unless the weather changes drastically.

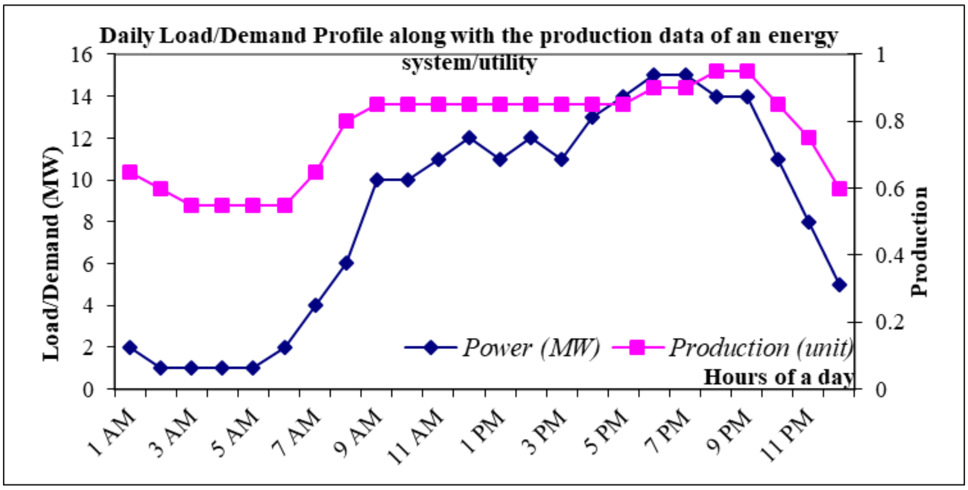

Figure 3. Typical load curve

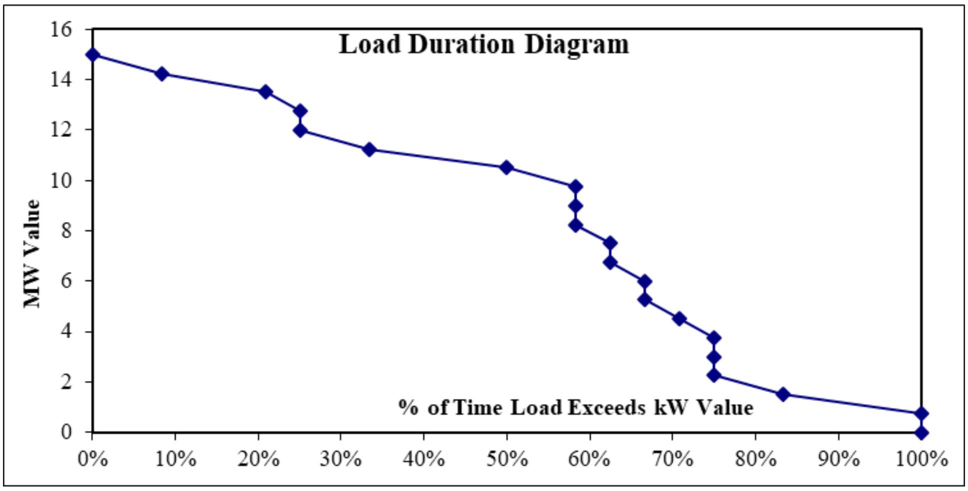

Figure 4. Load duration diagram

When the data set is examined closely, the changes in the hourly consumption values are clearly seen. There may be a remarkable difference between the consumption values and type on weekdays and weekends (see Figure 8). While the peak consumption during the day is in the afternoon on weekends, this is in the morning hours during the weekdays (Bissey et al., 2017). This is because people engage in different activities on weekdays and weekends. While consumption during the week is affected by activities such as lunch breaks, shift changes, and working hours, many different reasons can be considered for the weekend. When the weekly consumption changes are examined closely, seasonal effects can also be noticed (see Figure 8). Different consumption levels caused by the effect of temperature lead to the conclusion that seasonal changes directly affect consumption. Likewise, the difference in consumption values for weekdays and weekends, and the consumption curve corresponding to a day, day and night, give rough information about how different household consumption and industrial consumption are. Therefore, the consumption values for the holiday period are used to calculate the household consumption value. As a result of the seasonal effect, both the difference between day and night and the difference between general consumption amounts increase. One of the important points that make modeling difficult is these changes.

Also in a conventional power system, the low change is relatively slow and they're predictable with good accuracy; conventional generators can be programmed to balance this load. Thus, coal-fired, gas-fired conventional production facilities can be planned to balance this load. But when renewable energy sources are added to the system and here are a few graphs showing the output of a photovoltaic system installed on the university campus that the authors used in their project work on different days. In addition, data were collected with a device called SM206 Solar Power Meter. The curve obtained in solar radiation as a function of time during a day in the Ardahan University campus is shown in Figure 5. As demonstrated in the study of (Bou-Rabee et al., 2015); if it's a clear day, it can get a pretty, smooth curve that's pretty predictable, just as the astronomer tells us when the Sun rises, sets, and rise high. But as it is known, we get the sun under the clouds and as the clouds pass in front of the solar panel, the fluctuations occur in the output and occasionally there may even be a major storm that brings the brightness to near zero. The movement of the clouds and the thickness of the clouds are unknown parameters. Therefore, this brings with it a lot of uncertainty.

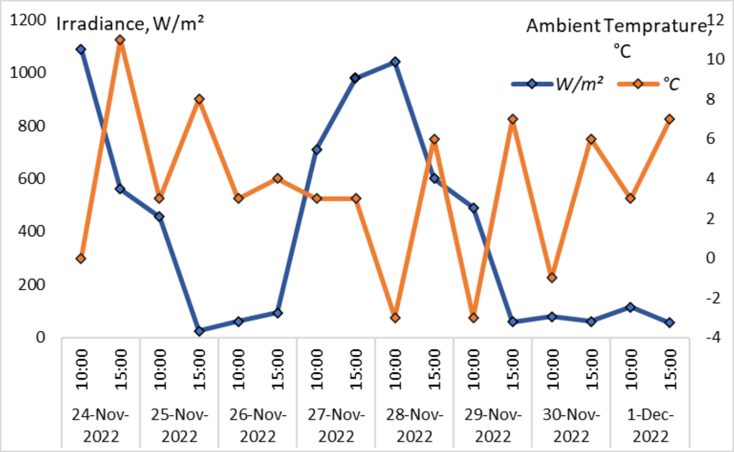

Figure 5. Typical solar irradiance and its fluctuations

In wind energy; the wind speed curve on June 27 (*Turkish State Meteorological Service*, 2022) is shown in Figure 6 and it can be seen there are quite a few fluctuations. Statistically the fluctuation of wind power they quite different from the fluctuations in solar irradiance and therefore PV power. In the wind it may not be so dramatic; wind fluctuations are a bit slower but still, there are significant changes here.

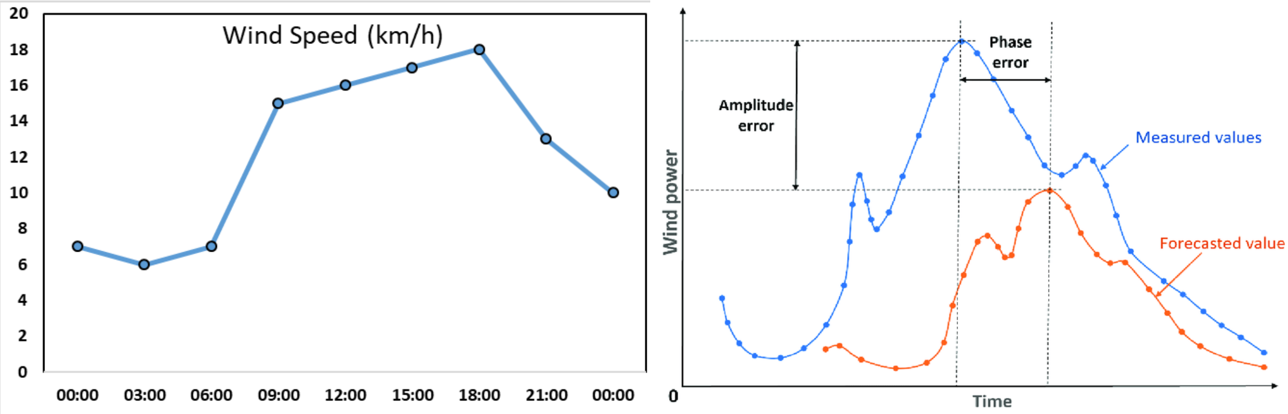

Figure 6. Wind speed for Ankara city and wind power prediction error (Hanifi et al., 2020)

In both cases, however, the fluctuations are quite large and difficult to predict. Another thing is wind strength and direction can be predicted, but the error increases. It can be observed that wind generation and energy demand are in the reverse phase. In many parts of the world, there are places where the wind blows at night and not much energy is used, and consumption peaks during the day. There is good wind around 3:00 AM along the Columbia Gorge (Windfinder, 2022), where most of the wind farms are located.

From a flexibility perspective, hydro is a controllable resource, so it's a traditional manufacturing facility (Gjorgievski et al., 2021). As viewed by power systems, electric vehicles (EVs) can be both a very good thing and a very bad thing (Zhang & Kezunovic, 2016). The bad side is if a lot of people buy EVs and plug them in at 9:30 pm when they get home, it goes to fluctuate very fast. Therefore, great flexibility is needed to prevent the wind from falling. The good side is EVs are a godsend; users can meet their electricity needs when and where it is needed. That is if they can control the charging of EVs that provides resource flexibility. But in order to do this, the owners need to be persuaded with the incentive of EVs. In terms of batteries, storage is known to be very expensive. Thus, free storage space is obtained when the electric vehicle is purchased. Intelligent charging of electric vehicles adapts the charging cycle to events in the power system, allowing vehicles to be integrated into the power system in a grid and user-friendly manner. Vehicle-to-grid (V2G) technologies can bring even more flexibility to the system by providing power to the grid as needed (Clement-Nyns et al., 2011; Noel et al., 2019).

Large storage systems based on batteries can help integrate high shares of solar and wind power, providing the flexibility needed to manage resource variability. Small-scale, localized battery capacity helps integrate solar and wind power from multiple locations around the power grid. Home-level battery storage, with the right incentives, could unlock demand-side flexibility and facilitate system integration for electricity from these variable renewable energy sources.

In an energy system with a large number of renewable energies, only the load is not considered. The so-called net load should be taken into account, that is, the production of renewable energy sources is subtracted from the load (Equation 1.1). The net load needs to be balanced by the conventional generators which are the hydro generators that are controllable. Because typically the wind and the PV generators are not controllable. Therefore, the net load is subject to much bigger fluctuations than the actual load. As renewables are introduced into the system, the amplitude and uncertainty of these fluctuations will change considerably and are likely to increase significantly. These fluctuations can be much higher than predicted fluctuations in net load.

$$NL = L - RG \tag{1.1}$$

Where;

NL – net load;

L – load;

RG – renewable generation.

To respond to these uncertainties and fluctuations, it is necessary to make the energy system more flexible, but providing the flexibility is costly. Where generators are desired to be more flexible, they must be built to have this flexibility or use smaller and less efficient generators that can be started and stopped more frequently and quickly. Also, how much flexibility is needed should be defined.

What is the best mix of flexible resources? Because it can be obtained this flexibility in generation either through conventional generators possibly and operators provide flexibility or it might be able to get some flexibility from the demand essentially convincing consumers to adapt their demand to the availability of renewable energy sources.

Several utilities and pilot programs implemented to try to solve that. In some cases, flexible storage is used where store renewable energy when we have too much of it and then discharge it from the storage when it is needed. Finally, it can be created virtual flexibility which is simply at that thing the rules according to operating the power system, or the rules of the electricity market, and the market itself provides this flexibility.

But how to optimize the capability in the existing power system to have the necessary flexibility is the main objective of this article. Then, if 40% or more of production is from renewable energy sources over the next 20 years, it must be decided how much flexibility will be needed and what needs to be built to meet them.

Pump-hydro is still the most common economical way of storing energy. The problem with pump storage is that the required investments are huge and the environmental impact is significant. Naturally, there should be two lakes; and there's not a lot of room to put pumps and pipes. But it's a matter of technology at a reasonable cost. Also, since the efficiency is around 70%, there is a cost every time it is pumped, it costs a lot of money.

2. Power system flexibility at the generation stage

How to balance a system using renewable energy sources is to say that the rest of the system will need to be more flexible. But providing flexibility costs money (Figure 2), which is a very important thing to keep in mind because that flexibility will have to come from traditional power plants. To keep these conventional power plants operational, fossil fuels must be burned. If it is necessary to operate more of these traditional production facilities, it will be less efficient. If it could predict what would happen, then it would have to have this reserve to go up and down as the sun and wind change.

Essentially the operational timescale has to be taken into account. The power system operators think about what is going to happen the next day that they want to be ready, they don't want to improvise. But they have to improvise, inefficient and coal-fired power plants can take several hours to get started. Therefore, it cannot be decided at the last moment how big is the demand. How much uncertainty will be faced the next day, and therefore production should be planned for the next day so that you can have the right amount of flexibility when needed. It is a problem of balancing startup costs and variable costs. When a large production is planned, a certain amount of fuel must be used to start it, and then once started, it needs to use more fuel to generate a certain amount of power. Thus, some units may have a low initial cost and a high variable cost, while other units may have the opposite; therefore, both need to be balanced in order to reach the optimal solution.

Estimate how much flexibility will be needed the next day on the operational time scale. We do this based on some statistical analysis we have done using some real data from Ankara city. It was known hourly how much renewable energy is produced in the city and the net load. In Figure 7 it is depicted that there are times when it needs energy. That's why they are called resilience events and a resilience event is characterized by three things. The first is the capacity needed to meet this resilience event, and how high a ramp goes. The next characteristic is the ramp rate of how fast it goes from zero to maximum and the third one is the time; how long has this ramp lasted.

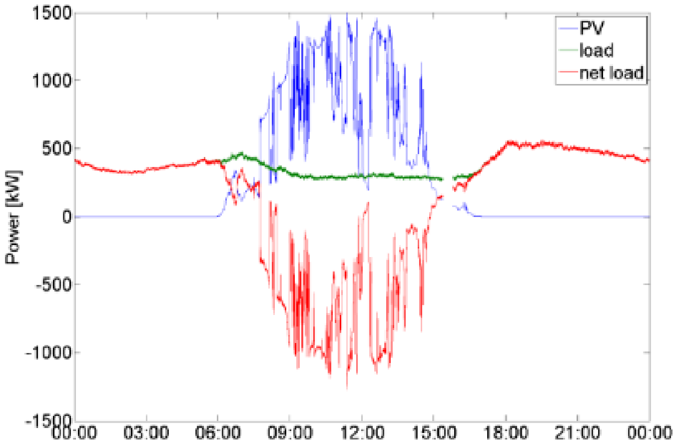

Figure 7. PV generation, load, and net load (Stein et al., 2011)

Since a standard parametric probability distribution function does not work, a non-parametric approach was applied to this problem to represent events, and flexibility requirements can be figured out. What is going to be needed tomorrow in terms of capacity ramp rate and ability to sustain these ramps. The goal is to put a frame around enough of these flexibility events to run a power system or the system operator can be confident that they will have the flexibility they need to meet these expected flexibility times the next day. Therefore, all one has to do without playing with the system is to find the reasonable one.

If it is known how much flexibility is needed; where does this flexibility come from? Typically, it will be from conventional fuel generators, it can ramp them up and down. In addition, consumers can be asked to adjust their consumption according to their needs. If the wind is blowing hard, users can guess and the laundry can be washed; if the wind is not blowing, the dishes can be washed later.

2.1. Refining the requirements: season and day

Some improvements have to be made first, one thing the operators do is define the frame's boundaries. The second improvement is to observe the need for flexibility will vary with the season and day of the week. The day of the week is due to the fact that the electricity demand changes differently on weekends as well as on weekdays. The extent to which the wind speed changes seasonally is important, so it is not necessary to have the same amount of flexibility every time of the year and every day of the week. The third improvement is that it doesn't need the same amount of flexibility of the same type around the time of the day. It can be predicted when the load increases, thus the demand can compensate. There are also times of the day when the wind tends to change very quickly, the wind is a little more stable, or there is no wind at all, as everything else is relatively stable. Thus, the requirements can be adjusted according to the time of day. These flexibility requirements are then used by the optimization solver to determine which conventional generation operators will use the next day.

3. Power system flexibility at the planning stage

The question of how big flexibility will be needed to deliver the expected rate of renewable energy in the coming year should also be taken into account at the planning stage. The idea is to minimize the overall cost of providing this flexibility which has an operating component and an investment component. The following Equation (3.1) shows the form of the modified objective function that minimizes generation costs and investment costs:

$$min\left(\sum_{n=1}^{N} C_{inv}(n) + \sum_{n=1}^{N}\sum_{t=1}^{T} C_{OM}(n,t)\right) \tag{3.1}$$

Where;

C_{inv} - the investment cost;

C_{OM} - the operating and management cost;

N - the number of power plants;

T - the time period.

There can be a lower operating cost if more investment is made in flexibility, but increases the investment cost. If no investment is made, the investment cost is saved, but then the cost is paid daily because it no longer has to provide this flexibility in a more complex and inefficient way. It's a very difficult and huge optimization problem for the operational time scale; following simplifying assumptions needs to be made.

- Centrally planned system: It is assumed a centrally planned system; many parts of the country operate electricity markets where you don't decide that but it's the first step.
- Compare the different types of power plants: The investor decides whether to invest in the more flexible and more expensive option or the opposite.
- Flexibility provided by generating units only: In this case, it is assumed that flexibility is provided only with units of production, and is not sufficient for any flexibility on the demand side or storage.

4. Optimization Model

The objection function of the optimization model is designed to schedule power plants for one or a few days the minimize the total costs (Equation 3.1). It considers a fixed set of available generation units; a set of production units is entered into the program that it can work with to optimize and achieve this minimum cost.

The model enforces dynamic constraints on the scheduling of units because some of the constraints are related to flexibility. For example, each generating unit has an up-ramp rate and down-ramp rate which indicates how quickly the system can get it to increase or decrease its output. Also, each unit has a minimum uptime and a minimum downside which affect the flexibility.

These constraints can be more easily met in this optimization problem when more flexible production units are in place. Therefore, it can achieve a lower operating cost. But this is an operational tool, this is not a planning or investment tool because it ignores the investment cost. This generation schedule is realized by mixed-integer linear programming.

To answer or plan flexibility the optimization tool is developed. The idea of this tool considers not just the operating cost but also the investment costs and it also considers a variable set to optimize not just for a week but at least a set of years where it has a different amount of renewable generation and different fluctuations in wind and solar generation. In Figure 8, the load profiles used for various seasons are shown.

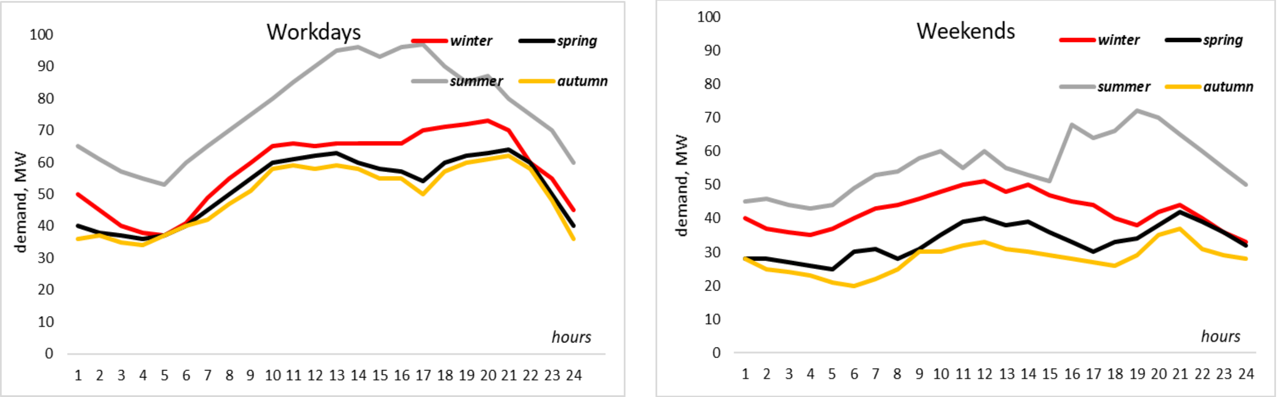

Figure 8. Hourly load profiles of four seasons

Therefore, the seasonal variations have to take into account. The main decision variable in the optimization program was to have the information for each generating unit whether this generating unit is active at this time and how to connect to the network. There is a binary decision variable every hour for every generating unit and it is a very challenging mixed integer linear programming problem. Because much more decision variables can be obtained and optimization takes into account a long time.

In the objective function, the number of days in the season is used to calculate each month's operational expense. Based on this, the solutions to the optimization issue show how many power plants are required to reduce overall costs over the year. It must be taken into account that there can be days with severe changes in load and intermittent renewable generation every few years. It's possible that the ideal level of flexibility determined using typical sample months won't be enough to deal with the cases successfully. The optimization can be performed using a composite load profile of 7 days per year reflecting exceptional circumstances to account for this possibility.

After all, data is entered into the system, only the representative weeks, namely winter, spring, summer, and autumn weeks, are optimized. It also introduced an extreme weather week because those are typically the ones to apply the largest amount of flexibility. Some clustering techniques are used to identify these most representative extreme weeks in each season.

4.1. Simplifying optimization and the load profile effect

It's a very difficult optimization problem, so a way must be found to limit the amount of CPU time. The Monte Carlo method is used to reduce the number of decision variables. The Monte Carlo method is a large class of computational algorithms that rely on repeated random sampling to produce numerical results (Coban & Sauhats, 2022). The underlying concept is to use randomness to solve problems that might be deterministic in principle. The system should not be presented with too many choices, because the more choices it is given, the longer it takes to find the best solution. This priority ordering considerably reduces the amount of time required. Therefore, in order to test a program, firstly, the generation power plants to be ideally created for different load profiles are summarized in Table 1. Investment costs were initially obtained from the Energy Information Administration (EIA) (*Annual Energy Outlook*, 2022), and it is assumed that the lifetime of each power plant is 30 years. The second thing is to reduce the number of decision variables. It is assumed that some of the power plants are already built. The third thing should be built from a reasonably adapted system.

If the peak load is known, it is unnecessary to have three times as many facilities as this peak load, as this provides a lot of flexibility. Therefore, one should get a rough idea of how much capacity should be considered before starting the optimization. Another thing; in power systems, there are many units with essentially the same characteristics, and treating them all as stand-alone units will turn into many combinations that are the same. Therefore, instead of trying all possible combinations, basically, the same units were used in the same order.

Table 1.

Cost and performance characteristics of power plants used in the optimization

Power Plant	Fuel type	Power min (MW)	Power max (MW)	Investment ($/kW)	No-load cost ($/MW)	Start-up cost ($/MW)	O&M cost ($/kW-yr)
1	Natural Gas	10	20	971	264	9	7.34
2	Natural Gas	30	50		251	9	
3	Natural Gas	60	100		225	9	
4	Natural Gas	50	150		210	10	
5	Coal	20	40	2925	280	30	31.18
6	Coal	40	70		340	300	
7	Coal	50	100		300	400	
8	Coal	80	200		260	900	
9	Nuclear	100	500	5501	590	0	93.28
10	Oil	20	75	915	340	710	13.17

A system with 10 power plants was created for the analyses. Some of these units are called peak units very flexible but rather inefficient ones. Some units are called big coal, and nuclear units, they are very efficient but very inflexible. Finally, there are some units that are somewhere between the two.

This resulted in a base load profile, a softer load profile, and a sharper load profile. With the basic load profile, it can be concluded that the 2nd power plant should be out of these 10 power plants, when there is a soft load profile, the best way to do it is to have all 10 power plants, when there is a sharper load for 6th and 7th power plant should be out. Table 2 demonstrates the model outcomes that are in line with these predictions. While only 8 power plants are required to handle the softer valley efficiently, the profile with a sharper valley necessitates the availability of all 10 power plants.

Table 2.

Results for various generation profiles

Scenario	Total Cost	Investment Decision
Soft	266 M.$	Power plants 7 and 8 are not needed.
Sharp	354 M.$	All power plants are needed.

4.2. Wind generation and flexibility

To see the impact of wind generation on flexibility in more detail, there are 4 different things to look at:

1. Thanks to wind turbines, the need for traditional fossil fuel production units is reduced (Equation 4.1). It is relocated producing units and that will be an effect.

$$\sum_{i=1}^{I} P_i(t) = P_{dmnd}(t) - P_w(t) \tag{4.1}$$

Where;

P – the amount of generated power;

P_{dmnd} – total power demand;

P_w - predicted wind power;

i – power plant index;

t – time period.

2. Because renewable resources are less predictable (stochastic nature of renewable energy sources), more reserves are needed and it needs to be taken into account and modeled in the program. Through the demand for spinning reserves, the uncertainty resulting from the wind forecast errors (see Table 2) is taken into account in this study. Here, it is assumed that wind energy is generated by a large number of various wind turbines. To be able to handle both the unexpected loss of the biggest generating unit and a concurrent error in the wind power, the spinning reserve requirement, *sr(t)*, must be increased. This reserve must be large enough to cover the majority of the wind prediction error (Equation 4.2), therefore an extra reserve equal to 3.5 times the wind forecast error's standard deviation is chosen (Black & Strbac, 2007).

$$sr(t) \geq \max(P_i(\max)(t)) + 3.5\sigma_w(t) \tag{4.2}$$

Where; $\sigma_w(t)$ is the standard deviation of wind forecast error.

3. The fact that even if fluctuations in wind speed are predicted correctly, it will require more ramps up and down and turning units on and off.

4. Each generating unit should be operated at the minimum stable production and maximum capacity (Equation 4.3).

$$P_i(max) \geq P_i(t) \geq P_i(min) \tag{4.3}$$

4.3. Test cases

The objective function is to improve this unit commitment by considering both the operating cost and the investment cost. The idea is that not only will a fixed set of power plants available be considered, but a variable set of power plants will be considered. Therefore, the decision variables will decide not only whether this unit will generate at a given hour, but also whether this facility will exist (deciding whether to invest in the generating unit).

The proposed optimization model is implemented using the function “*intlinprog*” in the MATLAB optimization engine. Excluding renewable power plants, tests were conducted for scenarios consisting of 10 conventional power plants. The characteristics of test cases are summarized in Table 3. In the first case, there is no wind power and no forecast error. In the second case, there is 10% wind but no fluctuation, so it just needs to be unloaded and doesn't need much reserve. Case-3 has wind power and no fluctuation, there are some forecast errors to see the effect of this. In the last case, there is wind power and volatility but predictability.

Table 3.

The test cases and investment decisions

	Case-1	Case-2	Case-3	Case-4
Renewable forecast	No renewable	10% wind, without fluctuations	10% wind, without fluctuations	10% wind, with fluctuations
Forecast error	No error	8%	15%	8%
Investment decision	Power plants 3, 8, and 10 are out	Power plants 7, 8, and 10 are out	Power plants 7, and 10 are out	Power plants 7, and 8 are out
Total cost	251 M€	227 M€	246 M€	241 M€

The first scenario offers greater flexibility and generating capacity than the base scenario which consists of all 10 power plants. The overall cost is decreased by forgoing the build of some power plants. Case-2 demonstrates part of the base-producing units is replaced with wind generation, which further lowers the overall cost. However, in Scenario-3, it is decided to construct power plant 8, demonstrating that variations in wind power improve the ideal level of flexibility. Case-4 demonstrates more flexible generating power facilities are required to have the lowest overall cost and the reserve need is raised for larger uncertainty in the wind prediction.

These test findings demonstrate that the linear programming algorithm can maximize the flexibility of the generating mix for various wind penetrations. More power plants are needed to give greater flexibility due to fluctuations in wind power and wind forecast errors. Constant wind integration (as in Scenario 2) can be treated as a negative demand, which reduces the need for conventional fueled power generation facilities.

4.4. Effect of the renewable generation

The results for comparing these various scenarios are shown in Table 3. According to these results, in the basic case, three power plants are not needed. When wind turbines are added to the system, and although there is a forecast error, it becomes clear that even fewer units are needed because fossil fuel-generating units have been replaced by wind-generating units. In another scenario, when the wind is added and there are some fluctuations, the 7th and 10th power plants will not be needed. However, some of the other production units will be needed to provide the necessary flexibility. In the other scenario, when fluctuations and estimation errors are added to the system, the results change; it turns out that the 10th power plant should be used instead of the 8th one.

5. Conclusions, discussion, and future study

None of the contemporary researchers (Göransson et al., 2014; Syranidou et al., 2020; Zappa & van den Broek, 2018) dealing with the research issues mentioned by the authors have any doubts that energy efficiency is an important aspect taken into account when it comes to energy security. Improving the efficiency of energy use can significantly reduce the need to build new energy sources. Therefore, additional challenges need to be prepared in the coming years; The reason for this is the projected increase in demand for electricity with the simultaneous shutdown of older generating units. That is why, for several years now, attempts have been made to define a new model of the energy mix which, on the one hand, would take into account the needs of consumers, and on the other hand, would respond to the challenges posed by environmental protection. The answer to these needs, as emphasized by other researchers (Syranidis et al., 2018; Zsiborács et al., 2019), may be renewable energy sources. A case has been presented that requires a precise quantification of the flexibility needed by the power system and likely to be required as the share of renewable energy generation increases is a sure answer. The authors will confirm with other researchers that these requirements depend on the type and amount of renewable energy (Niekurzak et al., 2022; Ryberg et al., 2019). What it needs for wind will not be exactly the same as for solar energy. It also depends on the system. Renewable energy sources behave differently depending on the location of the source. In addition, studies have confirmed the thesis of other researchers (Chakraborty et al., 2019) that the amount of flexibility needed also depends on the time of day, day of the week, and season of the year. By adapting these requirements, significant savings can be made. At the same time, if the flexibility you need is invented; it can be optimized for savings in investment and operating costs.

Like other research, these also have their limitation in the form of imprecise definitions and integration of optimization with the planning of electricity production over a longer period of time. The aim of future research is to create a model of integrated optimization with production planning covering all determinants that affect both the efficiency of the system and its reliability. As the amount of renewable energy production increases, it will be possible to measure how these requirements will change and what they will be. Their effects on the energy system. In the opinion of the authors, the problems and planning should be combined, and the functioning of the power system must be better represented in planning models. Another important issue requiring a solution will be the integration of flexibility and generation units in the smart grid system.

Summing up the presentation of the research on flexibility in power systems of the integration of variable renewable energy sources, the authors are aware that they do not fully exhaust the essence of the presented considerations. This topic certainly requires further analysis and research in an interdisciplinary approach, which will certainly be conducted by the authors along with the increasing importance of renewable energy in energy systems and the role of individual factors in this process.

Author Contributions

Hasan Huseyin Coban: Methodology, Data curation, Software, Writing-original draft, Writing – Review & Editing, Visualization, Investigation, Validation, Supervision, Conceptualization.

Wojciech Lewicki: Writing-original draft, Writing – Review & Editing, Visualization, Investigation, Conceptualization.

Conflicts of Interest

The authors declare no conflict of interest.

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