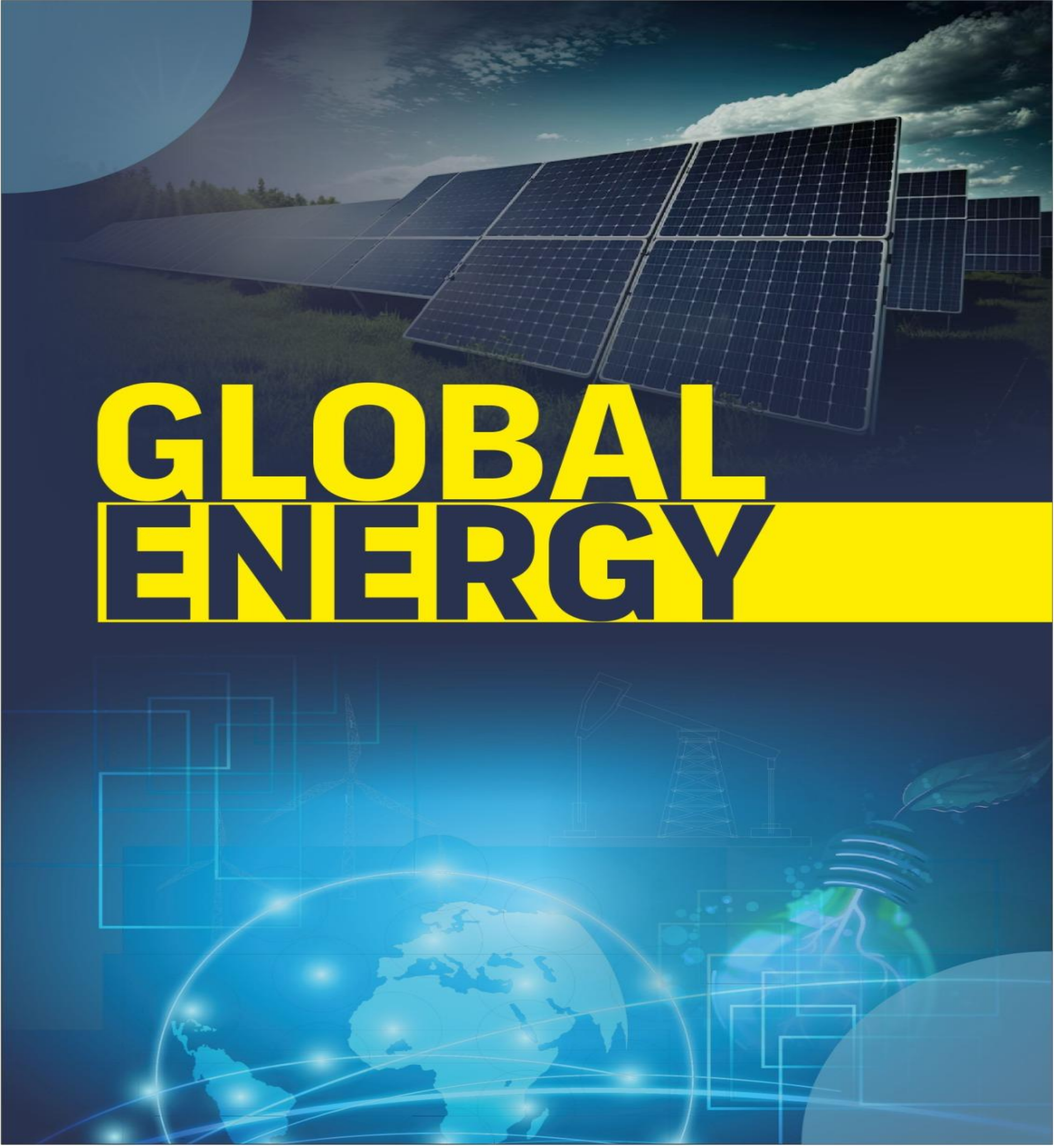

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Natural Geological Resources Used in Nuclear Energy Production: A Mining Perspective

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ABSTRACT

A nuclear reactor requires components like enriched uranium or thorium that come from natural geological sources (rock, mineral) in order to generate energy. Nuclear reactors run on uranium, a radioactive actinide metal. Uraninite, carnotite, or thorite minerals are used to make uranium, which is found in deposits in Africa (Congo), Canada, and the United States (Colorado and Utah). In-situ leaching combined with uranium mining is known to supply 57% of global production, while traditional underground or open pit mining accounts for 43%. The principle behind ores in the traditional mining industry is to grind the ore to a single grain size before using a chemical leaching process to extract uranium. The natural "yellowcake" of uranium, which is currently marketed as U_3O_8, is ground into a dry powder. The top three producers of uranium are Canada, Kazakhstan, and Australia. Nuclear power plants use the uranium that is taken from the earth. In addition to being an essential strategic resource for national growth, uranium is a major supplier of raw materials for energy globally. In the upcoming years, nations are strongly searching for new energy sources and a shift to green energy as part of the "carbon footprint" targets and agreed practices. Growing geopolitical risks and economic worries appear to have raised awareness of the need for nuclear energy, and eventually its usage as a backup energy source.

1. Introduction

Utilizing nuclear reactions to generate electricity is known as nuclear power. Nuclear fission, nuclear decay, and nuclear fusion reactions can all produce nuclear electricity. Currently, nuclear power plants use nuclear fission of uranium and plutonium to generate the great bulk of nuclear-powered electricity. Elements like enriched uranium (U) or thorium (Th), which are present in natural geological resources (rock, mineral), are required in nuclear reactors to generate energy. Nuclear power plants use uranium, a radioactive actinide metal, as fuel. The most significant uranium ore mineral in nature is uraninite, also known as pitchblende, which is an oxide of uranium. Understanding the natural geological origins of the uranium ore used to create uranium is a crucial precondition for the long-term usage of nuclear energy. In addition to its widespread use as fuel in nuclear power plants, uranium is a naturally occurring geological resource that is highly sought after. Cold War ideas in the energy sector, rising geopolitical risks, nuclear reactor building, and energy production activities with enormous potential for countries are all on the rise today. The main purpose of this study is to provide a general perspective in terms of uranium geology, data characteristics and uranium mining within the scope of the increasing nuclear energy potential.

2. Natural Geological Resources

Uraninite (pitchblende) is used for the macrocrystalline, more or less euhedral UO^{2+x} variety that typically occurs in higher P-T metamorphic grade rocks (amphibolite grade and higher, contact-metamorphic), igneous rocks such as granite, and is also found in pegmatite and also vein and vein-like type deposits.

Pitchblende is used for the micro or cryptocrystalline, colloform (collomorph, botryoidal, spherical) UO^{2+x} variety that typically occurs in lower grade metamorphic and non-metamorphic rocks such as greenschist facies metasediments and more or less sandy sediments, and has been identified in most vein and vein-like type uranium deposits. It is understood that both varieties crystallize in the same crystallographic system, the cubic system, but have certain distinctive physicochemical properties [1] [2].

The term pitchblende was first used for black uranium oxide minerals in 1565 and is particularly common in Europe. Uraninite is a term commonly used in American literature for all types of uranium oxide. Worldwide, both terms are applied variably and overlappingly by many authors. The criteria used by various geologists to distinguish between uraniite and pitchblende are sometimes contradictory and can lead to confusion.

2.1 Uranium

Uranium is a silvery-grey metallic weakly radioactive chemical element. Its chemical symbol is U and its atomic number is 92. The most common isotopes in natural uranium are ^{238}U (99.27%) and ^{235}U (0.72%). All uranium isotopes found in natural uranium are radioactive and fissionable, and ^{235}U is fissionable (will support a neutron-mediated chain reaction). A radioactive isotope of uranium (U), thorium (Th), and potassium (40 K) and their decay products are the main contributors to natural terrestrial radioactivity [3]. Cosmogenic radionuclides are of lesser importance, but unlike the primordial radionuclides mentioned above, which date back to the formation of the planet and have been slowly decaying since then, they are replenished at roughly the same rate as their decay by the Earth's bombardment with cosmic rays.

Uranium has the highest atomic weight of any naturally occurring element, being about 70% denser than lead, but not as dense as tungsten, gold, platinum, iridium, or osmium. It is always found in combination with other elements. Along with all elements with atomic weights higher than iron, iron only occurs naturally during supernova explosions (Figure 1). Yellowcake (also known as Yellowcake: uranium) is a type of uranium concentrate powder obtained from leach solutions as an intermediate stage in the processing of uranium ores. It is a step in the processing of uranium after its extraction but before fuel production or uranium enrichment. Yellowcake concentrates are prepared by various extraction and refining methods, depending on the type of ore. Typically, yellowcakes are obtained by grinding and chemically treating uranium ore; It forms a coarse powder containing about 80% uranium oxide, with a pungent odor, insoluble in water, and melting at about 2880 °C (Figure 1).

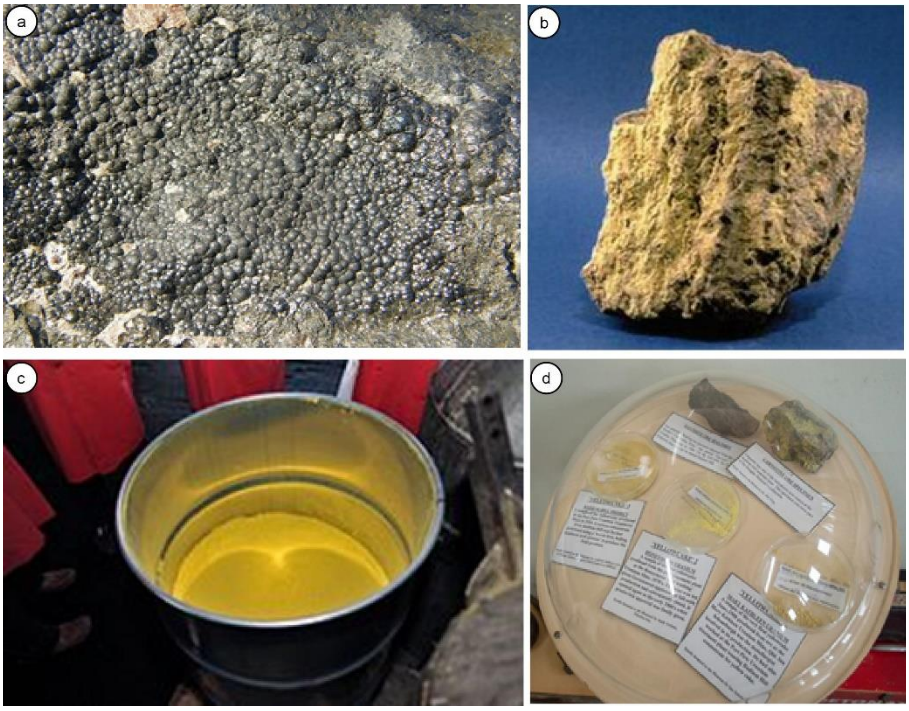

Figure 1. a) Natural photo of Pitchblende mineral, b) Natural rock photo of Uranium (Public Domain, 2005), c) Yellowcake d) Ore rock and yellowcake exhibited at Radium Hill Heritage Museum (https://creativecommons.org/licenses/by-sa/4.0)

3. Uranium Mining

Many different types of uranium deposits have been discovered and mined on Earth (Figure 2). Furthermore, large parts of Canada, Greenland, Siberia and Antarctica are currently unexplored due to permafrost and may contain significant undiscovered reserves. The world's known uranium reserves are 5,718,400 tons. The area with the largest reserves is Australia with 2,049,400 tons (Figure 3). This is followed by Kazakhstan, Canada, Russia and Africa. Geologically, there are three main types of uranium deposits, including unconformity-type deposits, namely paleoplacer deposits, and roll-front-type deposits, also known as sandstone lithology. Uranium deposits are classified into 15 categories according to their geological environment and the type of rock they are found in. This geological classification system was determined by the International Atomic Energy Agency (IAEA) (World Nuclear Association, 2016). Uranium is also found in seawater, but according to current prices in the uranium market, costs would need to be reduced by a factor of 3–6 to make its recovery economical [4].

Uranium deposits in sedimentary rocks include sandstones (Canada and western USA), Precambrian unconformities (in Canada), phosphate deposits, Precambrian quartz-gravel conglomerates, collapse breccia pipes (e.g., uranium neomineralization within breccia pipes in Arizona), and limestone-type rocks (Figure 4). Hydrothermal uranium deposits include vein-type uranium ores. Vein-type hydrothermal uranium deposits typically represent epigenetic concentrations of uranium minerals that fill breccias, fractures, and shear zones [5]. The South China Block is an example of a region that has relied on vein-type hydrothermal uranium deposit demand for the past half century [5]. Breccia uranium deposits are found in rocks that have been fractured by tectonic faulting or weathering. Breccia uranium deposits are common in Australia, India, and the United States [6].

Uranium exploration is similar to other mineral exploration methods except for some specialized instruments for detecting the presence of radioactive isotopes. Ionization chambers and Geiger counters were first adapted for field use in the 1930s. Airborne gamma-ray spectrometry is now the accepted leading technique for uranium exploration, with worldwide applications for geological mapping, mineral exploration, and environmental monitoring. In Australia, the Shuttle Radar Topography Mission (SRTM) developed the Weathering Intensity Index based on elevation and airborne gamma-ray spectrometry images [7].

A uranium deposit discovered by geophysical methods requires sampling to determine and evaluate the amount of uranium ore that can be extracted from the deposit at certain costs. The amount of uranium reserves is also the amount of ore that can be recovered excluding costs. As prices rise or technology allows the cost of recovery known, previously uneconomic deposits to decrease, reserves increase. This effect is particularly pronounced for uranium, as the largest currently uneconomic reserve, seawater uranium recovery, is larger than all known terrestrial uranium resources combined [8] [9].

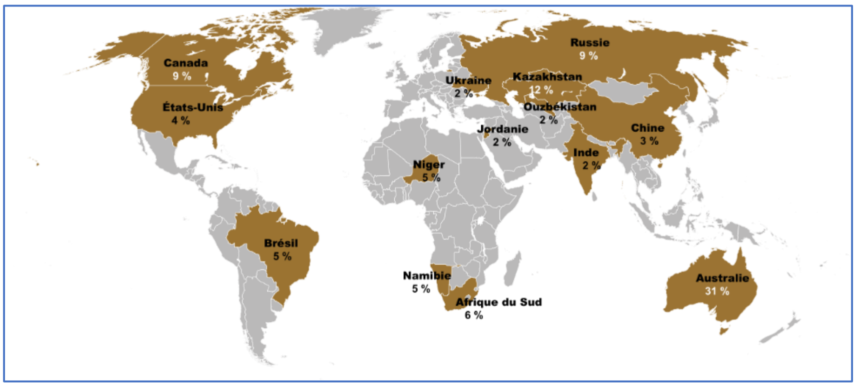

Figure 2. Map showing the areas where the World's uranium reserves are located

Figure 3. Ranger uranium open pit mine (Australia, www.getty images.com)

Figure 4. Red, white, and green sandstone layers in the Mi Vida Moab (Utah, USA) uranium mine (https://imgur.com/gallery/YfsLV4B).

3.1 Uranium Production

Since the 1950s, uranium has become an important commodity in parallel with the rise of nuclear energy. This is especially true for countries that are highly dependent on nuclear energy to meet their domestic energy needs. Global uranium production was approximately 48,888 metric tons in 2022. Kazakhstan, with approximately 21,227 metric tons of production in the same year, is the world's largest single uranium producer by a significant margin. Other leading uranium producers include Canada, Namibia, and Australia [10]. The world's largest uranium-producing mine is Puro Lake in Canada, where approximately 7,983 metric tons of uranium were mined in 2023. The second largest mine is Husab in Namibia, where 5,613 metric tons of uranium were produced that year. Approximately 56 percent of the world's uranium that year was produced by in-situ leach mining. Kazakhstan’s KazAtomProm National Atomic Corporation became the world’s leading uranium miner, producing about 21,100 metric tons in 2023. Canadian Cameco and French Orano came in second and third, respectively, that year. Just 10 companies accounted for 91% of global uranium mining in 2022. More than half of the world’s uranium production comes from Canada, Australia, and Kazakhstan. An increasing share is produced by on-site leaching. After a decade of decline when mining ended in 1993, production has since increased overall and now accounts for 61% of electricity demand. Canada produces the largest share of uranium from mines (25% of the world’s supply from mines), followed by Australia (19%) and Kazakhstan (13%). However, production in Australia and Canada decreased in 2006.

Data from 2021 to the present are shown in Table 1. Today, according to the German Institute of Geosciences and Natural Resources BGR, Kazakhstan has become the largest producer of the radioactive metal. This Central Asian country produced approximately 24,600 metric tons of this substance in 2016. This value constitutes a share of almost 40 percent of the worldwide production. Australia is third with 6,300 metric tons. However, in terms of total resources, Australia has the largest resource. It has approximately 1.1 million tons of uranium reserves, but it is not possible to excavate all of them at reasonable costs today. We can say that there are approximately 3.5 million tons of uranium resources known worldwide, and therefore there is no foreseeable decrease in reserves.

Table 1. World Nuclear Association (2021)

Rank	Country	Uranium Production (tonnes U)	Percentage of World Production (%)
1	Kazakhstan	21.819	45.14
2	Namibia	5.753	11.90
3	Canada	4.693	9.1
4	Australia	4.192	8.67
5	Uzbekistan	3.500	7.24
6	Russia	2.635	5.45
7	Niger	2.248	4.65
8	China	1.885	3.90
9	India	615	1.27
10	Ukraina	455	0.94

Kazakhstan is the world's largest uranium producer, with a production volume of 21,227 metric tons in 2022. Canada follows with a production volume of 7,351 metric tons. In comparison, the United States produced 75 metric tons of uranium that year. However, the country has seen a significant decline in production in recent years, compared to the 1,919 metric tons produced by the United States in 2014. To date, the United States remains the largest consumer of uranium, consuming 18,200 metric tons in 2016, compared to 5,300 metric tons in China. However, with 21 of the 61 reactors built in 15 countries worldwide located in the People's Republic, China's uranium needs are likely to increase in the future. In Namibia, in southwestern Africa, the Chinese-operated Husab Mine could begin production in 2016, making it the world's single largest uranium production facility. The world's resources for uranium minerals are relatively small. The United States produces uranium from carnotite extracted from deposits in Colorado and Utah. Uranium is currently mined in Saskatchewan, in northeastern Canada, where it is extracted from the mineral taurite. Some uraninite (pitchblende) is obtained from Cornwall and Australia, but the main source is the Republic of Congo in Africa. The main uranium minerals are Pitchblende, Torbernite, Autunite, and carnotite. Uranium is also found in Samarskite, a mineral with a highly variable composition; it contains uranium, iron, lime, and several rare earth elements. In the microcosmic bead, uranium compounds impart a light mossy green color in the oxidizing flame, both hot and cold. Uraninite or pitchblende is an oxide of uranium and is the most important ore of uranium worldwide.

Mining companies generally consider concentrations greater than 0.075% (750 ppm) economical to mine at current uranium market prices as ore or rock (Table 2) [11]. There are approximately 40 trillion tons of uranium in the Earth's crust, but most of it is dispersed at low parts per million concentrations over its 3×1019 ton mass [12] [13].

Table 2. Concentration-based grade classification of uranium ore resources (World Nuclear Association, 2008).

Uranyum ore grade	
Resources	**Concentration**
Very high quality ore – %20 U	200.000 ppm U
High quality ore – %2 U	20.000 ppm U
Low grade ore – %0,1 U	1.000 ppm U
Very low grade ore – %0,01 U	100 ppm U
Granite	4–5 ppm U
Sedimentary rocks	2 ppm U
Continental crust of the Earth (average)	2.8 ppm U

4. Conclusion

The nations that use nuclear energy the most are the world's top users of uranium. About 18,300 metric tons of uranium were consumed in 2020 by the US, China, and France. Over the past 20 years, the world's nuclear energy consumption has stayed constant despite worldwide trends toward other energies. This implies that uranium will remain a valuable commodity for many years to come. Nuclear power plants use nearly all of the uranium that is mined worldwide. In addition to being a crucial strategic resource for national growth, uranium is a major supplier of raw materials for energy worldwide. The nuclear energy market sold 64,832 tons of natural uranium in 2020, accounting for around 98% of the organization's annual sales. Countries all around the world are actively looking for new energy source alternatives and green energy transitions as part of the "carbon footprint" targets. Furthermore, current geopolitical threats and the world's rising energy needs have increased demand for nuclear energy globally and elevated its use as a backup energy source.

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Energy Management Simulation Of a Plant in Batman Province with Multiple Renewable Energy Sources

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ABSTRACT

In this study, the environmental, economic and technical optimization of multiple renewable energy sources synchronously connected to the grid of a facility consuming 2.5 MWH electrical energy in Batman province was simulated. Grid connection-wind turbine (WT)-photovoltaic panels (PV) were preferred in the simulation inputs. Homer Pro 3.16.2 software was used in the research. Homer software can retrieve twenty years of meteorological data from NASA for Batman province and use variable parameters such as inflation, which is difficult to predict for the future, within the scope of sensitivity analysis. Electrical energy unit price is taken from EPDK data. In the simulation results, where 1.362 different configurations were tested in the background, it is understood that the most optimal solution can be realized with the grid-WT-PV array. Technical findings showed that PV production was 21.6% on an annual basis, WT production was 76.1%, and grid usage was 2.31%. It has also been observed that the renewable contribution can reach 97.5% and the maximum renewable contribution can reach 316%. In the economic results, it was calculated that $3.616.205,85 of income could be obtained from the electrical energy produced. In the environmental results, it was revealed that CO2 emissions could be 3,807,336 kg/year, SO2 emissions 16.506 kg/year, and NO emissions 8.073 kg/year.

1. Introduction

Electrical energy starts with the definition of ‘an electromotive force is generated in the conductor moved in a constant magnetic field’ and is consumed by its transformation into another energy in the final receiver. This brief information on the production and consumption of electrical energy does not show what mankind has sacrificed to produce electrical energy. In our country, fossil fuels and coal are mostly used in the production of electrical energy. The CO2 emission of these fuels is 0.872 to 1.279 t/MWh. In other words, for each MWh of electricity produced with coal fuel, our atmosphere is polluted with 0.872 to 1.279 tonnes of CO2. A similar situation is 0.376 tonnes/MWh for natural gas production (http://enerji.gov.tr/bilgi-merkezi-enerji-elektrik).

In today's world, where energy demand is at its peak, the supply of new power resources is not only related to our energy needs, but also to technical, economic, and especially environmental and health issues.

It is known that system design in basic engineering is defined by the ability to design the most optimal solution in technical and economic categories. For this reason, it is important to analyze the efficiency of these resources in terms of technical, economic, environmental, and health aspects. It is necessary to design a system that can generate electrical energy by using wind turbines and solar radiation, which are the leading renewable energy sources and leave almost no waste. The installation of a renewable system, the effectiveness of which is not efficient enough, will not bring any technical benefit and may cause losses from economy to sociology and even psychology. Due to all these situations; predicting the effectiveness of the technical and economic benefits of these systems has become essential as a strategic function.

The importance of software-assisted research in renewable energy systems cannot be overstated in today's era of sustainable energy transition. Software tools, like HOMER, have become pivotal in designing and optimizing renewable energy systems by simulating and assessing the technic-financial feasibility of various power configurations. These tools enable researchers to model complex hybrid systems incorporating solar, wind, battery storage, and other renewable sources, ensuring that solutions are both efficient and cost-effective. By supporting detailed simulations, they help optimize energy output, minimize environmental impact, and reduce the reliance on fossil-based energy sources. Moreover, the ability to conduct these simulations with diverse input scenarios allows researchers to assess the most viable renewable energy options for specific regions or applications, which is crucial in advancing worldwide efforts to mitigate climate change. Such software-driven methodologies not only improve the precision of energy system designs but also promote innovations in the renewable technologies' integration into existing infrastructure. Therefore, these tools play a critical role in accelerating the renewable energy's adoption, fostering energy independence, and contributing to the global shift towards a greener future.

In 2006, American scientists Tom LAMBERT, Paul GILMAN, and Peter LILIENTHAL wrote a simulation program (HOMER) that can minimize installation disadvantages in the design of renewable energy systems, receive data from NASA's meteorological data banks for each location in the world, and show the optimal solution with different configurations and different resources. [1]

In this study, the environmental, technical, and economic optimization of multiple renewable power sources synchronously connected to the grid of a 2.5 MWh electrical energy-consuming plant in Batman province is simulated. Grid connection-wind turbine (WT)-photovoltaic panels (PV) were preferred as simulation inputs. Homer Pro 3.16.2 software was used in the research. Homer software can extract twenty years of meteorological data from NASA for Batman province and can use variable parameters such as inflation, which are difficult to predict for the future, within the sensitivity analysis's scope. In this study, the unit price of electricity energy is taken from EPDK data.

2. Literature

Some detailed researches on Homer software in the literature are as below.

Agyekum et al. endeavoured to generate electric power in Northern Ghana using HRES with the objective of assessing environmental impact, agricultural activities, fertiliser and H2 generation, land irrigation and employment potency. They simulated five different scenarios to explore the optimal configuration, incorporating Shannon entropy weighting and MCDM. According to the results of the Homer simulation programme, they found that the highest production can be achieved in the battery and hydro category, producing 1,095,679 kWh of electrical energy per year. They measured the system's operating cost as 18.318 $ and the production expense of electrical energy as 0.06 $/kWh. They calculated the total amount of hydrogen that can be produced per year in the optimal configuration as 8.816 kg and its cost as 4.47 $/kg. They also stated that a small amount of low carbon fertiliser will be produced during the hydrogen production phase. With their analyses, they also concluded that four people can be employed for a twenty-five-year production. In addition, the team also saw that 383.49 tonnes of CO2 and equivalent greenhouse gas emissions could occur annually within the scope of environmental impact.[2]

Ekren et al. investigated the case of a hybrid power charging station with wind turbine and solar energy mechanism by means of Homer simulation programme. They have declared that its applicability can be suitable for any place in the world. In such a Hybrid system, they concluded that the optimal solution will be obtained from 55.6 percent solar energy and 44.4 percent wind energy.[3]

Khosravani et al. analysed the technical and economic structure of HRES to generate electrical energy at four different sites in the USA and collected the necessary institutional data from the US institutions. In the simulation results of the Homer programme, which runs 495 different configurations in the background, it is shown that the use of HRES can contribute 34% to 48% for New York, 55% to 75% for Milwaukee, 0% to 34% for San Diego and 21% to 65% for Texas in the bracket of $0/ton - $30/ton carbon tax. They also declared that a total contribution of 5.26% was achieved in terms of health benefits. [4]

Hassane and his research team carried out techno-economic studies on four rural villages in Chad within the scope of multiple renewable power mechanisms. In their studies, they used Homer pro software with multi-criteria evaluation technique. The simulation results with six different scenarios showed that the most appropriate solution can be configured for the village of Etena with a net present value of $328,146 and a battery-PV system. The village with the lowest suitability is Mandelia village with PV-WT-DG-Battery configuration. On the basis of the levelised energy cost, they calculated that the lowest cost with PV-WT-Battery configuration could be in Koundoul site with 0.236$/kWh and the highest cost could be in Linia village with PV-Battery configuration and 0.363$/kWh. [5]

Panhwar and colleagues, aiming at cost analyses of PV systems, investigated the economic and technical feasibility of grid-connected PV mechanisms in Pakistan. In their analyses using Homer pro software, they calculated that the grid-connected PV mechanisms' net current costs with the same demand load can be more economical than the net current costs of off-grid PV systems that can meet the same demand load. They stated that the primary reason for this is the cost of battery packs used in off-grid PV system scenarios.[6]

Chaurasia et al. investigated the environmental and techno-economic aspects of WT/PV/Diesel generator (DG)/Battery and DG/PV/Battery HRES at different loads and performed designs with Homer simulation programme. Using 50 kW DG, 197.38 kW PV, 80.61 kW converter and 599.76 kWh battery as Homer pro data input, the team found that the most economical and advantageous performance in HRES can be realised with PV/DG/Battery. In a new simulation with 599.76 kWh battery, 50 kW DG, 234.70 kW PV, 1 kW WT, and 73.49 kW converter under load, they showed a 17% reduction in greenhouse gas emissions. They determined that 93% energy contribution can be achieved with this configuration. Homer software with sensitivity analysis function proved that the PV/DG/Battery array significantly reduces the levelised GHG emissions and energy costs.[7]

Afif et al. examined the technical and economical structure of hybrid renewable systems and took the electrical energy needs of the Al Karak governorate building in Jordan as a reference. They simulated a hybrid energy system consisting of a biogas plant, a wind turbine, PV panels and battery packs, synchronous or disconnected from the grid, using Homer software. As a result, they discovered that battery-connected wind and PV systems are the most suitable in terms of techno-economic benefits while minimising CO2 emissions and energy cost.[8-10]

Table 1. Summary of some research using Homer software

Focus	Study	Key Focus	Year	Ref.
Sustainable energy transition	Simulation	Microgrid optimization, renewable energy sources integration, energy cost reduction	2019	[11]
Residential microgrid energy management	Simulation	Energy efficiency modeling and cost analysis of building systems	2020	[12]
Hybrid renewable systems	Simulation	Comparison of HOMER with other software tools for microgrid energy system design	2021	[13]
Solar and wind energy systems	Simulation	HOMER's role in renewable energy integration, hybrid systems design	2020	[14]
Microgrid design for green campus	Case study	Optimization of hybrid systems (solar, wind, battery) for off-grid applications	2018	[15]
Sustainable energy solutions in developing countries	Simulation	HOMER for smart city projects, renewable energy systems integration	2021	[16]
Solar PV optimization	Simulation	Case studies on HOMER's applications in green and sustainable building projects	2019	[17]
Battery storage for renewable energy	Simulation	Integration of HOMER with smart grid and energy storage systems	2020	[18]

Hybrid energy systems in remote areas	Case study	Sizing and simulation of renewable energy systems for residential and commercial buildings	2018	[19]
Hybrid energy systems in remote areas	Simulation	Techno-economic feasibility analysis of renewable energy microgrids	2022	[20]
Building integrated energy systems	Simulation	Energy storage, generation system optimization for commercial buildings	2020	[21]
Residential microgrid energy management	Simulation	HOMER's role in sustainable energy transition for island communities and remote areas	2017	[22]
Hybrid renewable systems	Simulation	Energy management optimization in residential microgrids	2018	[23]
Solar and wind energy systems	Case study	Hybrid energy mechanisms' optimization for residential and off-grid implications	2019	[24]
Microgrid design for green campus	Simulation	Cost-effectiveness analysis of renewable energy sources using HOMER	2020	[25]
Sustainable energy solutions in developing countries	Simulation	Microgrid energy storage optimization for campus buildings	2021	[26]
Solar PV optimization	Simulation	Sustainable energy solutions for developing countries using HOMER	2020	[27]
Battery storage for renewable energy	Case study	Optimization of large-scale solar PV systems using HOMER for commercial and industrial projects	2021	[28]
Hybrid energy systems in remote areas	Simulation	Battery storage sizing and renewable energy integration with HOMER software	2020	[29]
Building integrated energy systems	Simulation	Hybrid system design for remote and off-grid energy applications using HOMER	2020	[30]
Sustainable energy transition	Simulation	Cost reduction in building energy systems through HOMER simulations	2021	[31]

Table 2. Research on Turkey with Homer software

Objective	System Type	Findings	Source
To analyze stand-alone hybrid mechanisms using wind and solar to power a remote apartment in Istanbul.	Stand-alone	Demonstrated cost-effective and environmentally viable solutions for off-grid systems.	[32]
Design on-grid and off-grid systems to optimize energy costs and reduce emissions for rural electrification in Sivas.	On-grid and off-grid	On-grid systems were economical, while off-grid systems had lower emissions.	[33]
Develop hybrid systems to electrify a 100-household area, optimizing economic and environmental impacts.	Grid-connected and stand-alone	Grid-only solar was the most economical; stand-alone systems were more environmentally friendly but costlier.	[34]
Evaluate hybrid systems combining solar, wind, and diesel generator for educational campus energy supply.	Off-grid	Provided insights into optimal energy generation and storage systems for campus demands.	[35]
Assess feasibility of hybrid systems incorporating micro-hydro, wind, and solar power to meet energy demand sustainably.	Off-grid	Highlighted the potential of hybrid systems to provide reliable and sustainable energy in remote regions of Turkey.	[36]
For rural electrification, evaluating on-grid and off-grid renewable energy mechanisms	Stand-alone	Cost-effective and environmentally friendly hybrid systems designed with PV, wind turbines, and battery storage	[37]
Designing renewable hybrid systems for sustainable EV charging stations	Stand-alone	HOMER enabled the integration of solar and wind resources, significantly reducing environmental impact	[38]
Assessing the economic feasibility of rooftop PV installations	Stand-alone	Results highlighted significant energy cost savings and reduced carbon emissions	[39]

3. Homer Pro 3.16.2 Software

Homer software has been operating in the market with many versions since its production. The 3.16.2 version is the latest version, but it can offer the design and optimisation of grid-synchronous or off-grid multiple and renewable electricity generation systems with different scenarios. In this study, the HOMER software was employed to design and optimise sustainable power systems. HOMER is a robust tool developed through the National Renewable Energy Laboratory to simulate and evaluate hybrid energy systems that combine renewable power resources with conventional technologies. The methodology is divided into three main stages:

Modeling: HOMER simulates energy systems based on user-provided input data, including energy demands, resource availability (solar, wind, biomass, etc.), equipment characteristics, and costs. Input data included:

-Meteorological data: Variables like wind speed, solar irradiance, and temperature. These parameters are typically sourced from reliable databases or local measurements.

-Energy consumption profiles: Daily and seasonal variations in load demand, accounting for peak and base loads.

-Technological parameters: Capacities, efficiencies, lifespans, and costs of components like solar panels, batteries, wind turbines, generators, and power converters [40, 41].

Optimization: HOMER optimizes the energy system by evaluating various configurations and selecting the most cost-effective and technically feasible solution. It uses key performance indicators such as:

-Net Present Worth: The total economic benefit of the system over its lifespan.

- Energy’s Levelized Cost: The expense of generating power, accounting for investment, maintenance, and operation.

-Reliability metrics: Measures such as unmet load or renewable penetration percentages [42].

Sensitivity Analysis: HOMER includes a powerful sensitivity analysis feature that allows users to test system performance under different scenarios. For example, users can vary parameters like fuel prices, renewable energy potential, or load demand to assess their impact on system design and cost [41].

Scalability and Applications: HOMER is versatile and scalable, making it suitable for:

-Remote or off-grid communities: Designing systems that integrate solar, wind, and diesel to meet isolated energy needs.

-Urban microgrids: Optimizing renewable energy adoption within grid-connected systems.

-Policy and financial planning: Assisting policymakers and investors in evaluating the long-term benefits of renewable energy projects [40-42].

This approach provides a comprehensive framework to design power mechanisms that are economically viable, technically robust, and environmentally sustainable. The workflow of the HOMER software (Figure 1) illustrates the stages of system modeling and optimization [40, 42].

Figure 1. The workflow of the HOMER software

4. Results and Discussion

The simulation results of the synchronous operation of the energy needs of a facility in Batman province with multiple renewable energy sources, accompanied by Homer Pro 3.16.2 software, are shown below. A quadratic equation supplying the information of voltage versus revolutions-per-minute was created using the curve-fitting approach after the motor voltage was raised linearly from 1 V with 1 V increments, the number of revolutions being measured for each value and fed into the Matlab application. Using a microcontroller, this equation employed voltage data obtained from the tachogenerator to determine instantaneous revolutions.

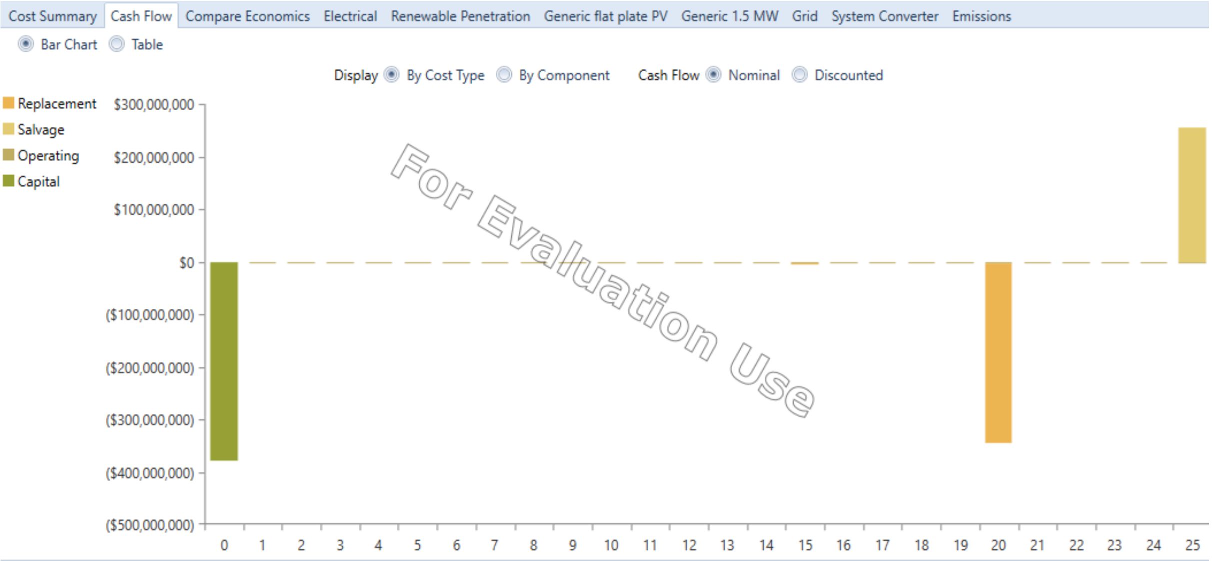
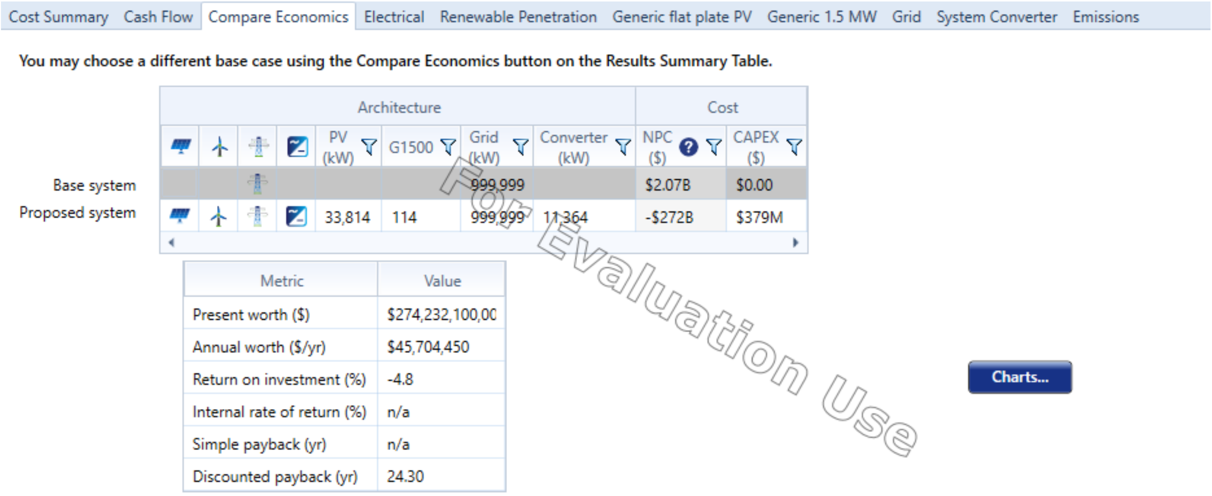


Figure 2. Cash Inflow

In Fig.2, the component and maintenance costs specified in the simulation inputs are shown in dark green colour. Since the life expectancy of the PV system is twenty-five years and the life expectancy of the WT system is twenty years in the inputs section, the component replacement costs are plotted between these years.



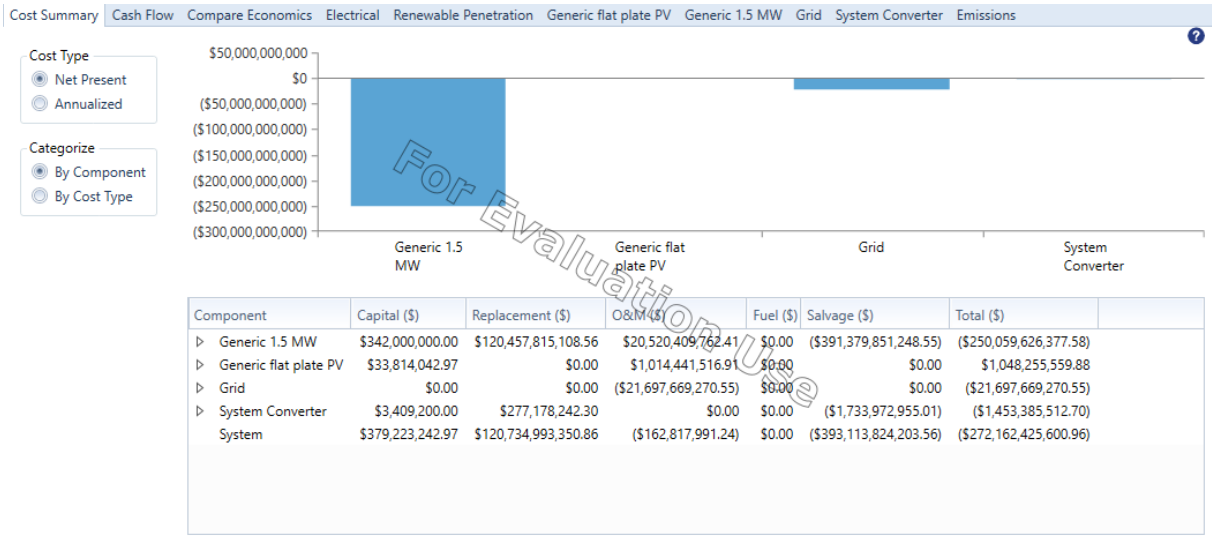
You may choose a different base case using the Compare Economics button on the Results Summary Table.

	Architecture								Cost	
					PV (kW)	G1500	Grid (kW)	Converter (kW)	NPC ($)	CAPEX ($)
Base system			●				999,999		$2.07B	$0.00
Proposed system	●	●	●	●	33,814	114	999,999	11,364	-$272B	$379M

Metric	Value
Present worth ($)	$274,232,100,00
Annual worth ($/yr)	$45,704,450
Return on investment (%)	-4.8
Internal rate of return (%)	n/a
Simple payback (yr)	n/a
Discounted payback (yr)	24.30

Figure 3. . Economic Comparisons

Figure 3 displays the comparative economic outputs of the existing mechanism and the proposed system.



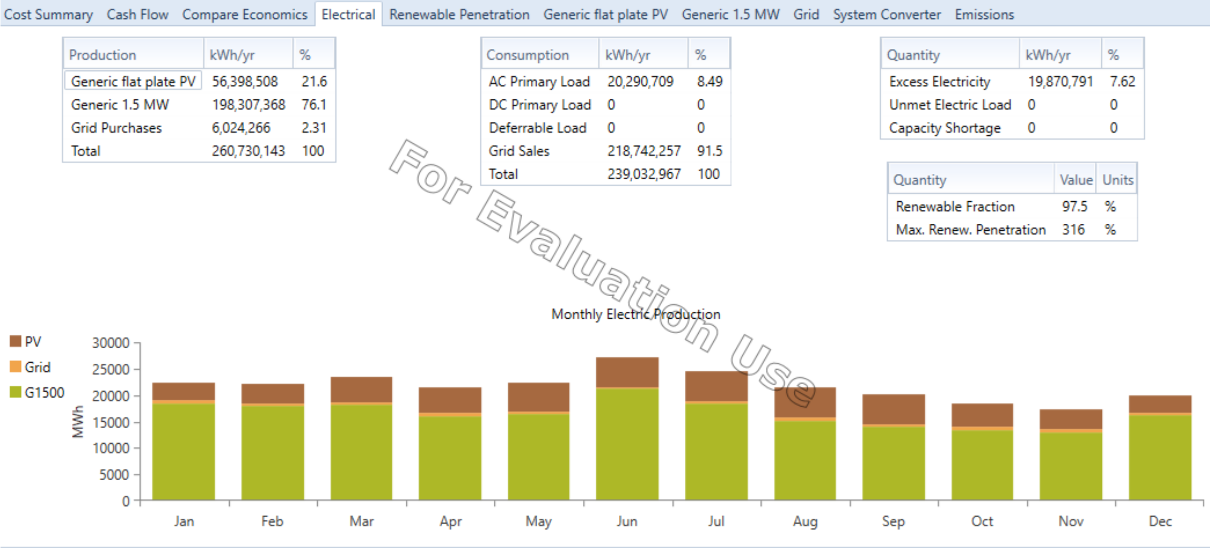
Cost Type: ● Net Present ○ Annualized

Categorize: ● By Component ○ By Cost Type

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
▷ Generic 1.5 MW	$342,000,000.00	$120,457,815,108.56	$20,520,409,762.41	$0.00	($391,379,851,248.55)	($250,059,626,377.58)
▷ Generic flat plate PV	$33,814,042.97	$0.00	$1,014,441,516.91	$0.00	$0.00	$1,048,255,559.88
▷ Grid	$0.00	$0.00	($21,697,669,270.55)	$0.00	$0.00	($21,697,669,270.55)
▷ System Converter	$3,409,200.00	$277,178,242.30	$0.00	$0.00	($1,733,972,955.01)	($1,453,385,512.70)
System	$379,223,242.97	$120,734,993,350.86	($162,817,991.24)	$0.00	($393,113,824,203.56)	($272,162,425,600.96)

Figure 4. . Cost Summary

In Figure 4, the cost summary of all components included in the planned mechanism is shown.



Production	kWh/yr	%
Generic flat plate PV	56,398,508	21.6
Generic 1.5 MW	198,307,368	76.1
Grid Purchases	6,024,266	2.31
Total	260,730,143	100

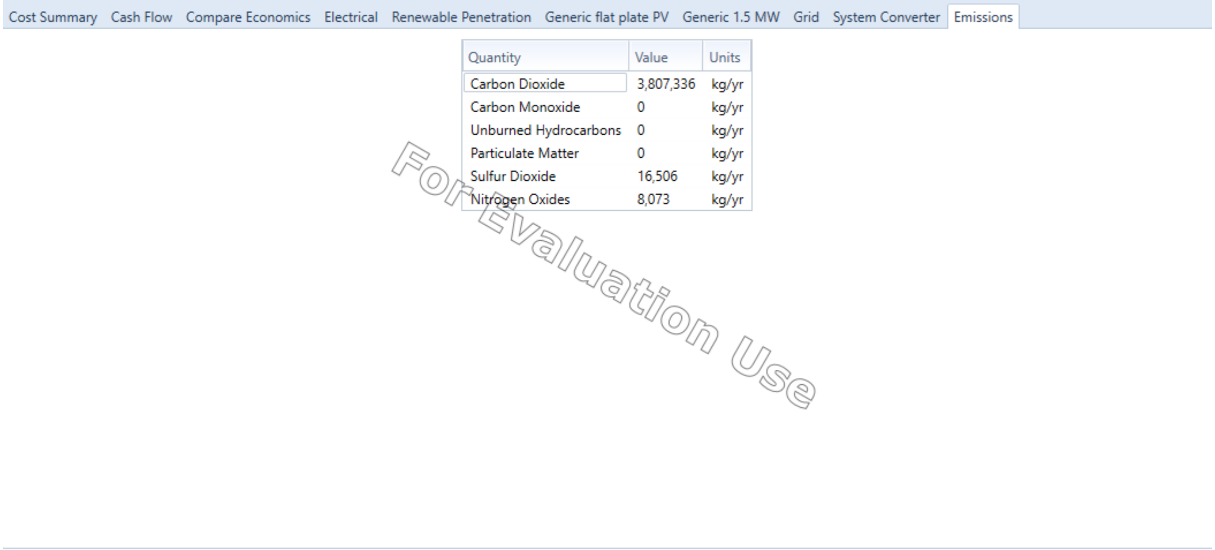
Consumption	kWh/yr	%
AC Primary Load	20,290,709	8.49
DC Primary Load	0	0
Deferrable Load	0	0
Grid Sales	218,742,257	91.5
Total	239,032,967	100

Quantity	kWh/yr	%
Excess Electricity	19,870,791	7.62
Unmet Electric Load	0	0
Capacity Shortage	0	0

Quantity	Value	Units
Renewable Fraction	97.5	%
Max. Renew. Penetration	316	%

Figure 5. Electrical Outputs

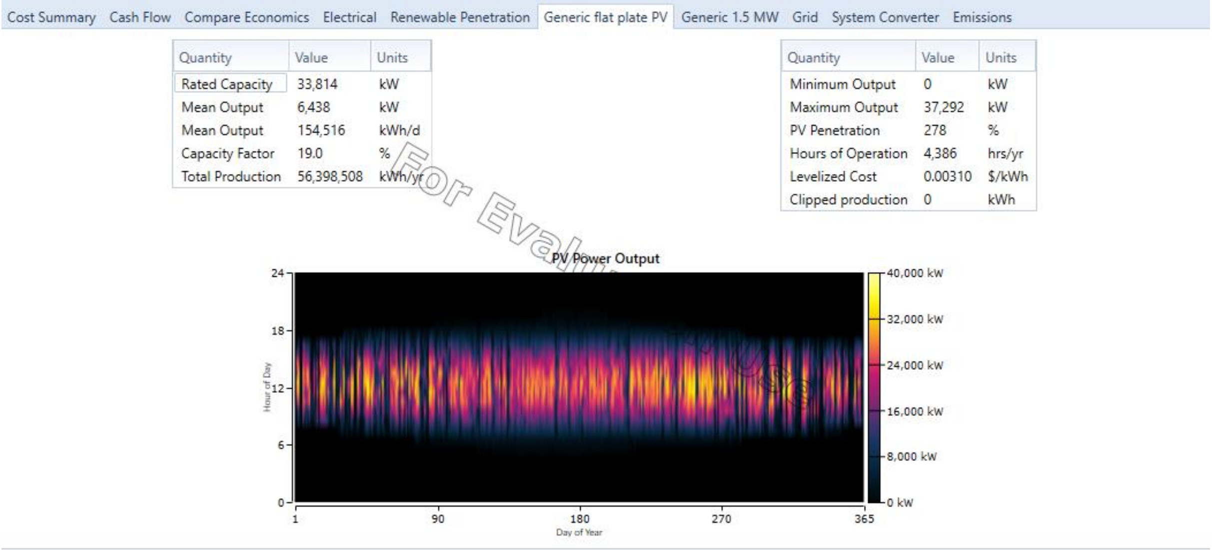
Figure 5 shows the graphs of the electrical outputs that the system components can produce. The highest values show June for WT and PV components. The lowest production shows November for these components. The other months are stable without much variation. On a yearly basis, 56,398,508 kWh of electricity power can be generated with a 21.6% share in PV production and 198,1307,368 kWh of electricity power can be generated with a 76.1% share in WT production. In exceptional cases and targeted to be used at the lowest level, the electrical energy received from the grid is 6,024,266 kWh/year with a share of 2.31%. Renewability contribution is measured as 97.5% in the simulation graph. It is foreseen that the maximum renewability can reach up to 316% in any time period.



Quantity	Value	Units
Carbon Dioxide	3,807,336	kg/yr
Carbon Monoxide	0	kg/yr
Unburned Hydrocarbons	0	kg/yr
Particulate Matter	0	kg/yr
Sulfur Dioxide	16,506	kg/yr
Nitrogen Oxides	8,073	kg/yr

Figure 6. Emision Outputs

The emission amounts of environmental pollution caused by the designed system are shown in Figure 6. As of the end of the year, carbon dioxide emission can be measured as 2,652,798 kg, sulphur dioxide emission as 16,506 kg and nitrogen oxide emission as 8,073 kg.

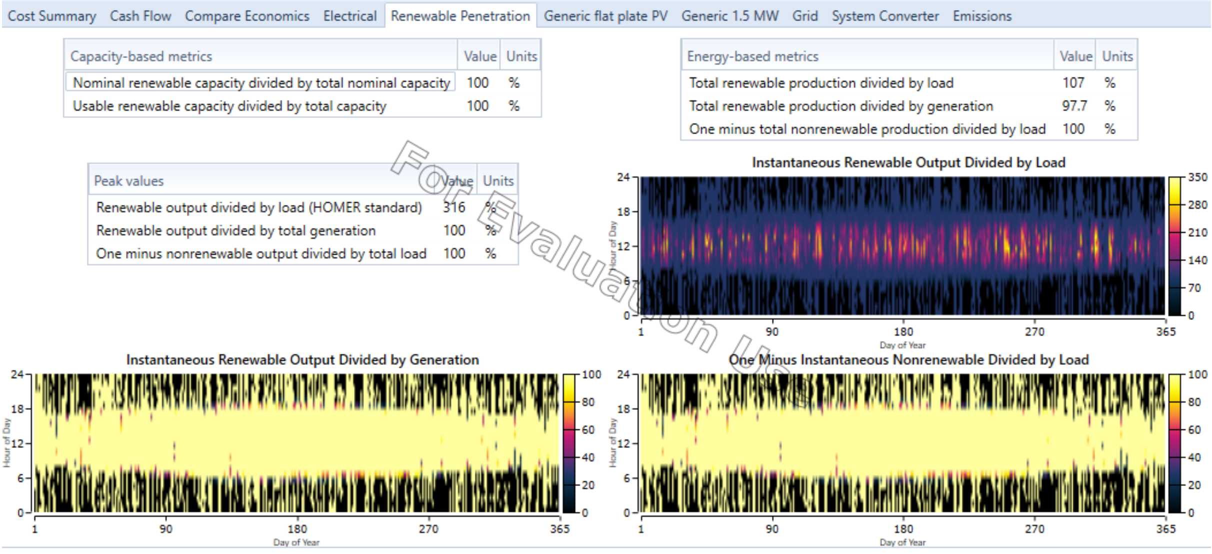


Quantity	Value	Units
Rated Capacity	33,814	kW
Mean Output	6,438	kW
Mean Output	154,516	kWh/d
Capacity Factor	19.0	%
Total Production	56,398,508	kWh/yr

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	37,292	kW
PV Penetration	278	%
Hours of Operation	4,386	hrs/yr
Levelized Cost	0.00310	$/kWh
Clipped production	0	kWh

Figure 7. PV Production Outputs

The production colours of Batman province for 365 days and every hour are shown in Figure 7. The intervals where the yellow colour is the brightest indicate the times when production is the highest. The black colour depiction shows the time intervals when there is no production. According to the modelled graphical outputs; with an average of 154,546 kWh per day, 56,398,508 kWh of electrical energy can be produced at the end of the year. In these outputs, the operating time of PV panels is determined as 4,386 hours in a year.



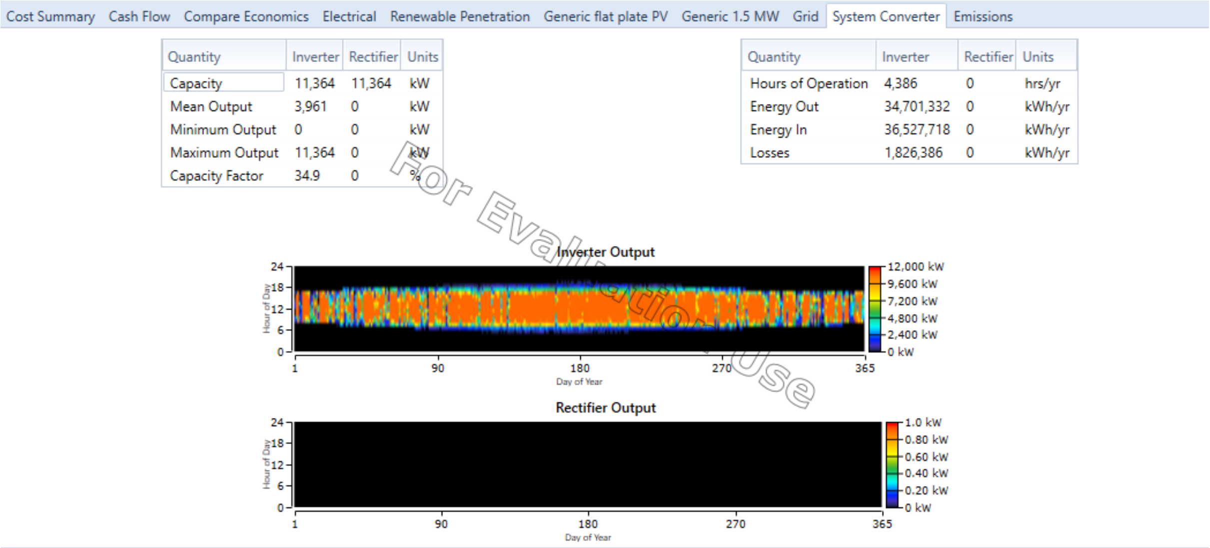
Capacity-based metrics	Value	Units
Nominal renewable capacity divided by total nominal capacity	100	%
Usable renewable capacity divided by total capacity	100	%

Energy-based metrics	Value	Units
Total renewable production divided by load	107	%
Total renewable production divided by generation	97.7	%
One minus total nonrenewable production divided by load	100	%

Peak values	Value	Units
Renewable output divided by load (HOMER standard)	316	%
Renewable output divided by total generation	100	%
One minus nonrenewable output divided by total load	100	%

Figure 8. Renewability Contribution

The different renewable outputs through instantaneous generation can be seen graphically in Figure 8 for 24 hours a day for one year. In the instantaneous renewable output split by generation graph, the regions shown in yellow colour model the highest renewable output through generation, and the regions shown in black shifting colour model the lowest renewable output through generation. In the instantaneous renewable output split by load graph, blue colours indicate the load used and orange colours indicate the generation. Accordingly, the ratio of accumulated renewable generation to load is 107%. The negative valence of the instantaneous non-renewable split load graph is modelled in yellow. In this case, the electrical energy required by the demanded load can be met with a rate of 97.5%, excluding exceptions.

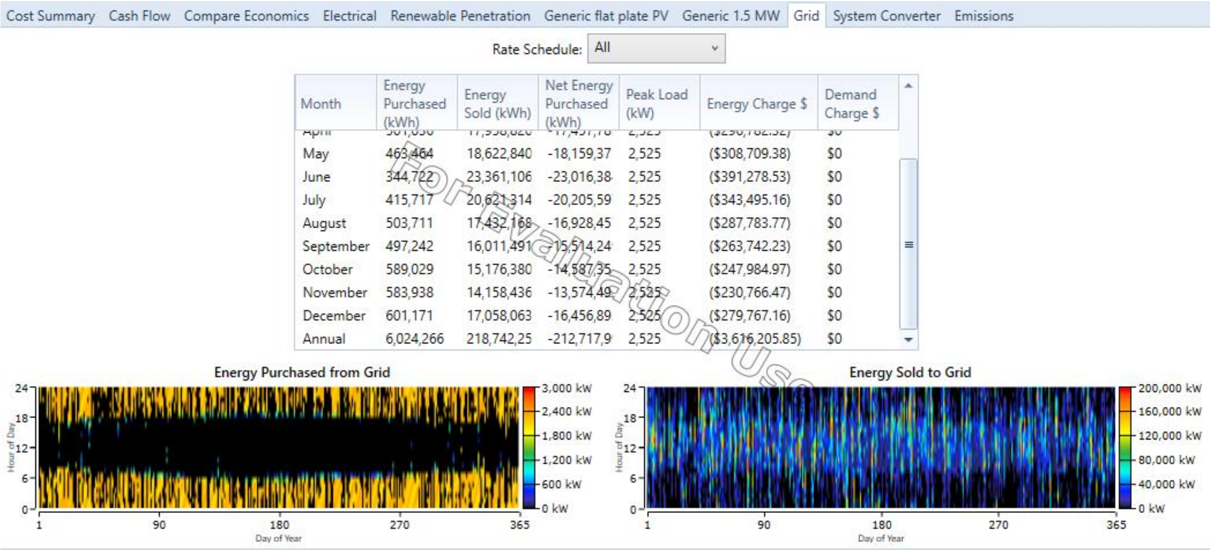


Quantity	Inverter	Rectifier	Units
Capacity	11,364	11,364	kW
Mean Output	3,961	0	kW
Minimum Output	0	0	kW
Maximum Output	11,364	0	kW
Capacity Factor	34.9	0	%

Quantity	Inverter	Rectifier	Units
Hours of Operation	4,386	0	hrs/yr
Energy Out	34,701,332	0	kWh/yr
Energy In	36,527,718	0	kWh/yr
Losses	1,826,386	0	kWh/yr

Figure 9. Inverter Graph

In Fig.9, the outputs of the inverter units converting direct current to alternating current are modelled with graphs. The operating time of the inverter is 4.386 hours per year. In the system component inputs, the input power of the inverters converting the electrical energy generated by the PV system via direct current to alternating current is 36,527,718 kWh per year, while the output power is 34,701,332 kWh. The loss of 1,826,386 kWh is due to the losses in the electronic circuits of the inverters and the transmission line. In the graph modelling the inverter output, the blue shifting areas indicate the days when the output power and therefore the PV generation is the lowest.

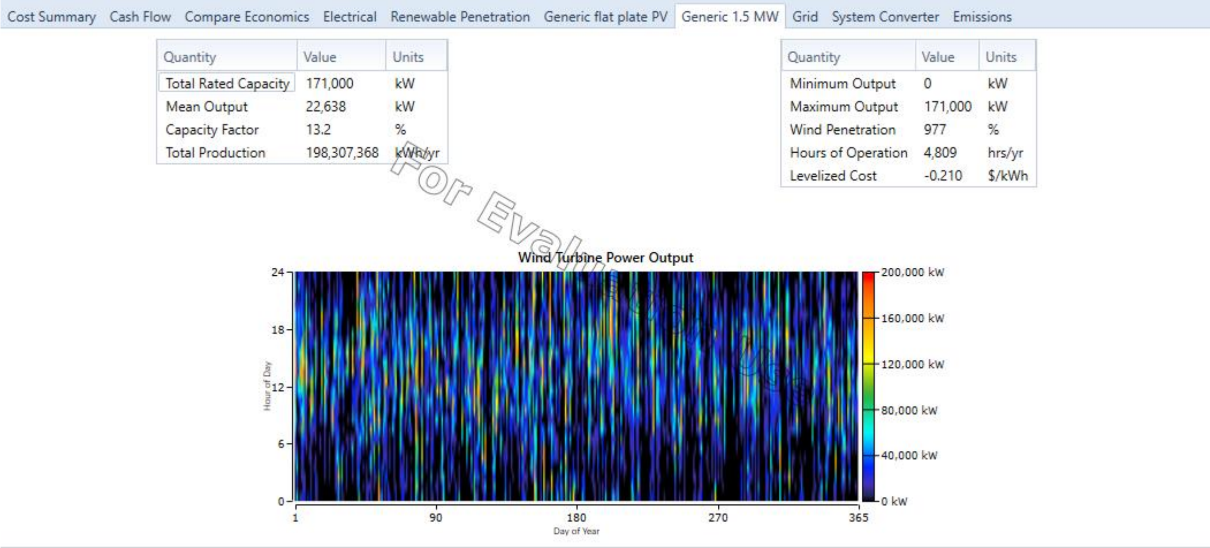


Rate Schedule: All

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Load (kW)	Energy Charge $	Demand Charge $
May	463,464	18,622,840	-18,159,37	2,525	($308,709.38)	$0
June	344,722	23,361,106	-23,016,38	2,525	($391,278.53)	$0
July	415,717	20,621,314	-20,205,59	2,525	($343,495.16)	$0
August	503,711	17,432,168	-16,928,45	2,525	($287,783.77)	$0
September	497,242	16,011,491	-15,514,24	2,525	($263,742.23)	$0
October	589,029	15,176,380	-14,587,35	2,525	($247,984.97)	$0
November	583,938	14,158,436	-13,574,49	2,525	($230,766.47)	$0
December	601,171	17,058,063	-16,456,89	2,525	($279,767.16)	$0
Annual	6,024,266	218,742,25	-212,717,9	2,525	($3,616,205.85)	$0

Figure 10. Grid Graph

Figure 10 shows the values of electricity sold to and purchased from the grid for each day and hour of the year in a year. The black colours in the grid-purchased electricity graph model the electricity sold to the grid and the red shifting colours model the electricity purchased from the grid. In addition, according to the grid unit price assigned in the simulation inputs, it is also revealed that the energy revenue sold to the grid can be a total of $3,616,205 per year.



Quantity	Value	Units
Total Rated Capacity	171,000	kW
Mean Output	22,638	kW
Capacity Factor	13.2	%
Total Production	198,307,368	kWh/yr

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	171,000	kW
Wind Penetration	977	%
Hours of Operation	4,809	hrs/yr
Levelized Cost	-0.210	$/kWh

Figure 11. Wind Turbine Graph

The energy output obtained through the wind turbine is shown in Figure 11. In the graph where every day and hour of a year is modelled, the blue shifted regions model the electrical energy produced, while the red shifted regions model the times when the electrical energy production is the lowest. In the output, for the maximum and minimum output values, the electricity generation input from wind, annual operation hours and minimised cost values are shown. Accordingly, a total of 198,307,368 kWh of electrical energy can be generated at the end of the year with an average production of 22,638 kWh per year.

5. Conclusion

Homer Pro 3.16.2 software can show which generators should be commissioned and which size should be used in the system design phase with the most appropriate results. The sensitivity analysis function of this software can also be used in the design of many variables that are difficult to predict. The software offers the most optimal configuration according to cost, technical outputs and environmental factors. During the simulation, any requested changes can be made and the results can be displayed in a very short time. The main capabilities include simulation, optimisation and sensitivity analysis.

In this study, the environmental, technical and economic optimisation of multiple renewable power sources synchronously connected to the grid of a plant consuming 2.5 MWH electrical energy in Batman province is simulated. Grid connection-wind turbine (WT)-photovoltaic panels (PV) were preferred as simulation inputs. Homer Pro 3.16.2 software was used in the research. Homer software can extract twenty years of meteorological data from NASA for Batman province and can use variable parameters such as inflation, which are difficult to predict for the future, within the sensitivity analysis's scope. The unit price of electricity energy is taken from EMRA data. In the simulation results where 1,362 different configurations are tested in the background, it is understood that the most optimal solution can be realised with the grid-WT-PV array. Technical findings show that PV generation is 21.6%, WT generation is 76.1% and grid utilisation is 2.31% on an annual basis. It is also seen that the renewable contribution is 97.5% and the maximum renewable contribution can reach up to 316%. In the economic results, it is calculated that an income of 3.616.205,85 $ can be obtained from the generated electrical energy. In environmental results, it was revealed that CO2 emission 3.807.336 kg/year, SO2 emission 16.506 kg/year, NO emission 8.073 kg/year can be benefited.

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Examining the Impact of Cyber-Physical System Security on Sustainable Smart City Management

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ABSTRACT

As smart cities increasingly rely on Cyber-Physical Systems (CPS) for critical infrastructures like energy, public safety, and healthcare, cybersecurity threats become a major concern. This study assesses the vulnerabilities of CPS in smart cities, with a focus on energy management, public safety, transportation, healthcare, and water systems. Using risk analysis and threat modeling, we identified significant security gaps in these systems.

Our findings show that energy management systems face a 65% chance of DDoS attacks and 45% chance of ransomware, leading to up to 80 hours of downtime and impacting 55% of users. Public safety systems have 50% DDoS attack likelihood, with 40% ransomware risk, affecting 45% of services. Healthcare systems exhibit a 38% probability of data breaches, threatening sensitive medical data. These results highlight the urgent need for robust cybersecurity measures in CPS.

We recommend deploying AI-driven threat detection to reduce detection times from 3 hours to 2 hours, and implementing multi-layered security, including next-generation firewalls (NGFW) and intrusion detection systems (IDS). Such solutions are critical as 60% of attacks target energy and public safety sectors. Additionally, regular cybersecurity audits and policies should be enforced to protect vital infrastructures.

In conclusion, securing CPS is essential for the operational sustainability of smart cities. Future research should focus on AI and machine learning solutions to further enhance CPS resilience against evolving cyber threats.

1. Introduction

As smart cities have emerged as sustainable urban models that leverage advanced technologies and Cyber-Physical Systems (CPS) to address the challenges posed by increasing population, rising energy demands, and environmental pressures. In these cities, critical services such as transportation, energy management, water resources, and public safety are optimized through CPS and Internet of Things (IoT) technologies. These systems enable smart cities to become more efficient, environmentally friendly, and user-oriented. However, the expansion of digitalization and technological infrastructures has made urban systems more vulnerable to cyber threats. The security of critical infrastructure is a significant concern, as it is essential to ensure the continuous operation and long-term sustainability of these systems.

CPS systems integrate physical infrastructure with digital networks, making them susceptible to various cyberattacks. Energy grids, smart transportation systems, water management networks, and healthcare services all depend heavily on the security of CPS. A cyberattack targeting a CPS could result in power outages, transportation disruptions, or threats to public safety. For instance, a cyberattack on energy systems could not only cause power failures but also disrupt industrial processes, leading to severe economic and social costs. Similarly, a security breach in public safety systems could weaken the city's emergency response capabilities.

Therefore, CPS cybersecurity is critical for ensuring sustainable management in smart cities. Securing these complex systems is of utmost importance not only for technology providers and city administrations but also for the communities that rely on them. The growing number of threats targeting CPS could hinder cities from achieving their sustainability goals. The future success of smart cities depends on how CPS security is managed and how potential threats are mitigated.

The aim of this study is to analyze potential cyber threats to CPS in smart cities and examine their impact on critical urban infrastructures such as energy management, transportation systems, and public safety. The study seeks to demonstrate that CPS security is not only vital for ensuring operational efficiency but also crucial for long-term sustainability. By focusing on critical urban components like energy, transportation, and public safety, this research evaluates the risks posed by security vulnerabilities in CPS and how these risks impact sustainable urban management. Additionally, the study explores which security strategies might be most effective in mitigating these threats.

This research aims to fill the gaps in the understanding of CPS security in smart cities while addressing several fundamental questions: What are the most common cyber threats to CPS systems in smart cities? How do these security vulnerabilities threaten the sustainability of urban energy management and public services? How effective are cybersecurity strategies in preventing these threats? By answering these questions, we aim to clearly highlight the critical role CPS security plays in urban governance and its contribution to sustainability.

2. Literature Revıew

The security of Cyber-Physical Systems (CPS) in smart cities has become a prominent research area in recent years, particularly as cities undergo a digital transformation. The use of CPS has rapidly expanded in critical components of smart cities, such as energy management, transportation, water, and waste management. While these systems have the potential to enhance urban sustainability, they remain vulnerable to cyber threats. Studies conducted between 2020 and 2024 have highlighted the critical importance of ensuring CPS security for maintaining operational efficiency and sustainability in cities.

Numerous studies have examined the impact of CPS on smart cities and analyzed how security vulnerabilities in these systems affect urban management. According to the paper of M.A. Jabbar and his friends, Technological advancements in ICT and the global trend of urbanization, with an expected 60% of the population living in urban areas by 2030, have made the development of smart cities inevitable. Cyber-Physical Systems (CPS) play a critical role in supporting day-to-day activities within these cities. This study highlights the concept of CPS and the challenges associated with its implementation in smart cities, while also providing future research directions for CPS integration [1]. Fernando Almeida in his study of smart cities said the interconnected infrastructure of smart cities presents numerous opportunities for cyberattacks, potentially compromising critical urban infrastructures. This study analyzes security risks in smart cities by reviewing 62 European cybersecurity research projects (2022-2027) and identifies 7 dimensions and 31 sub-dimensions of cybersecurity risks, along with 24 mitigation strategies to address these challenges[2]. In one another paper of Gang Xiong and his friends the situation determined as The integration of Cyber-Physical-Social Systems (CPSS) within smart cities enhances the effectiveness of urban infrastructure by facilitating intelligent human-machine interactions and real-time data flow from various urban elements such as traffic, air quality, and resource status. This study highlights the critical role of CPSS in optimizing transportation systems through continuous monitoring and real-time decision-making, while addressing challenges related to detection, communication, and control]3]. In one another smart City related study indicated that with the emergence of smart cities and the interconnection of critical infrastructures, cybersecurity has become a key focus area in security studies. This research explores cybersecurity issues in smart cities, particularly in critical infrastructures, and proposes a model for enhancing their cybersecurity[4]. The smart city prototype is envisioned as an urban environment with innovative services across multiple sectors such as transportation, energy, and healthcare. Christos G. Cassandras study identifies key characteristics of smart cities as Cyber-Physical Systems (CPS) and highlights the ongoing research challenges related to mobility, security, privacy, and the processing of large-scale data[5]. According to the paper of Onais Ahmad and his friends paper, Cyber-Physical Systems (CPS) serve as the backbone of smart city ecosystems, playing a pivotal role in the transformation of conventional urban environments into more connected and efficient smart cities. This study explores the integration of CPS in the Indian context, focusing on the infrastructure and technological frameworks necessary for upgrading poorly planned, overpopulated cities. It also addresses the security concerns associated with CPS, the technical, financial, and social challenges involved in this transformation, and the opportunities available for governments, businesses, residents, and other stakeholders within the smart city ecosystem. Additionally, the study provides insights into future research directions aimed at overcoming these barriers to smart city realization[6].

Marcin Bernas and his friends in their study said, as urbanization accelerates, modern cities aim to become more technologically advanced by integrating sustainable development with enhanced quality of life. This study highlights the role of Cyber-Physical Systems (CPS) as a key component of digital transformation, focusing on their integration into the physical environment and their increasing presence in daily life within smart cities. CPS, considered a core element of the Industry 4.0 revolution, combine computing, communication, and information technologies with physical processes, enabling interdisciplinary engineering systems. The paper explores current IT concepts, their real-world applications, and the synergies between CPS and the Internet of Things (IoT), emphasizing the future challenges and opportunities these technologies will bring for smart city development[7].

According to the Kiran Deep Singh and his friends study, Integrating Cyber-Physical Systems (CPS) into smart city infrastructures has the potential to enhance urban efficiency, citizen engagement, public safety, environmental management, and decision-making processes. This study explores the application of CPS in smart cities, identifying both their benefits and challenges. While CPS can greatly improve the functionality of smart cities, issues such as privacy and security concerns, scalability, and integration with existing systems remain critical obstacles. The study’s findings offer valuable insights for policymakers, researchers, and practitioners, highlighting the need for addressing these challenges to fully realize the benefits of CPS in smart cities[8]. The study of Antonio Puliafito and his friends indicate that, Smart cities utilize Information and Communications Technology (ICT) to enhance sustainability, improve urban functionality, and elevate citizens' quality of life, viewing cities as interconnected 'objects' within a Cyber-Physical System (CPS). This study explores how CPS enables real-time monitoring of mobility, energy use, and pollution, while addressing urban challenges like transportation and public health. However, the large-scale deployment of Cyber-Physical-Social Systems (CPSS) faces challenges in energy efficiency, architecture, and security, requiring advanced sensing and communication technologies[9]. And also there are valuable reports that could be check about the CPS Cyber Security importance for smart cities[10-11].

3. Dataset And Methodology

This study analyzes the security threats facing Cyber-Physical Systems (CPS) in smart cities and examines the impact of these threats on critical urban components such as energy, transportation, and public safety. The primary objective of the research is to identify the potential risks that cyber threats pose to sustainable city management through CPS systems and to assess the consequences of security vulnerabilities on urban governance. In line with this objective, the analysis in this study is based on risk analysis and threat modeling methodologies.

3.1 Research Method

The overall framework of the research is structured using a mixed-method approach, which combines both qualitative and quantitative data analysis methods. This approach allows for a comprehensive examination of CPS security vulnerabilities and potential threats. In the study, the security risks associated with CPS components used in smart cities are investigated through case studies and scenario analysis focused on existing security threats.

3.2 Data Collection Process

Case Studies: Case studies were chosen as the primary data collection method. Particularly, recent case studies that analyze the effects of cyberattacks on CPS systems were selected. These cases were used to assess the impact of cyberattacks on operational processes in fields such as energy, transportation, and public safety. The study relies on case reports from reliable sources documenting attacks that occurred in different smart city projects.

Literature Review: The literature review focused on current academic studies and reports related to CPS security and cyber threats. These studies form the foundation of the research, playing a crucial role in understanding the vulnerability of CPS components and the impact of cyber threats on these systems.

3.3 Data Analysis Methods

Risk Analysis: Risk analysis was applied as the most effective method in this study. It was used to evaluate CPS security vulnerabilities and assess the severity of potential threats. This method helps us understand how vulnerable critical infrastructure, such as energy and public services, is to cyber threats in urban management. The research analyzed the risk levels of attacks on energy management systems and smart transportation networks. Risk analysis was used to evaluate both the likelihood of these attacks occurring and the potential damage they could cause.

Threat Modeling: Threat modeling was employed to predict the potential impacts of cyber threats in CPS security research. This method focuses on identifying which components of CPS systems are most vulnerable and which types of attacks could cause the most damage to these systems. In this study, the most common threats to energy management and transportation systems were analyzed, and their operational impacts on the city were modeled based on scenarios. For instance, threat modeling was used to analyze the types of disruptions that a DDoS attack on a smart grid system might cause and the potential economic and social consequences of such disruptions across the city.

3.4 Validity and Reliability of the Method

Validity: To ensure the validity of the research, case studies, real-world examples, and data from recent literature were used. The reliance on case studies from credible sources increases the validity of the findings. Additionally, the selection of risk analysis and threat modeling methods ensures that the approach is consistent with existing research on CPS systems.

Reliability: The threat modeling and risk analysis methods used in this study are based on methodologies that are consistent with current research on CPS security, ensuring the reliability of the results. Furthermore, the use of reliable academic and industry sources in data analysis enhances the repeatability and accuracy of the findings.

In light of these methods, the impact of CPS security on critical infrastructures in smart cities has been comprehensively analyzed, and the potential damage of cyber threats to the sustainable management of cities has been detailed. Risk analysis and threat modeling methods have allowed us to identify which security strategies are most effective in protecting CPS systems.

4. Analysis And Findings

This section presents the analysis of cybersecurity threats to Cyber-Physical Systems (CPS) in smart cities, detailing the impacts of these threats and their implications on critical urban infrastructures. The findings are based on risk assessments, threat modeling, and financial evaluations. Additionally, the potential impacts of attacks on critical CPS components such as energy management, public safety, transportation, healthcare, and water management systems are evaluated.

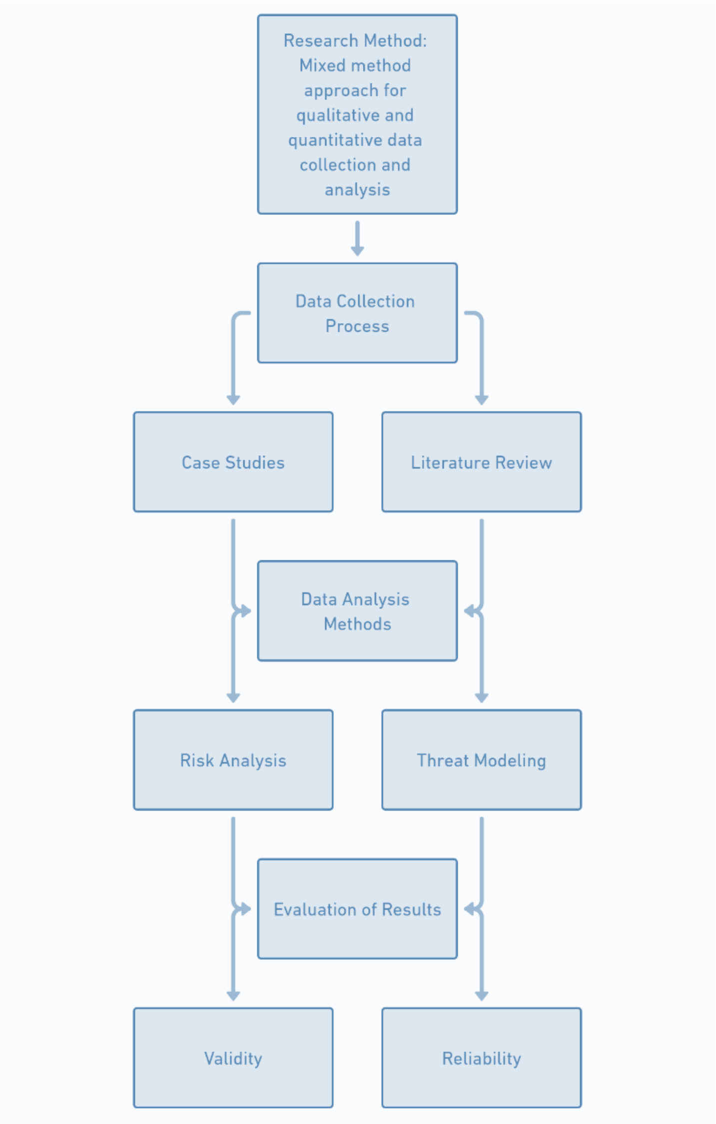

Figure 1. Flow Diagram of the Process

4.1 Risk Assessment and Threat Modeling Results

The risk assessment method used in this study evaluates the severity of cyberattacks targeting CPS systems and the potential damage these attacks could cause to urban systems. The Energy Management System emerged as the most vulnerable system, with a DDoS attack probability of 65% and a ransomware attack probability of 45%. The Public Safety System follows with a 50% probability of DDoS attacks and 40% for ransomware attacks.

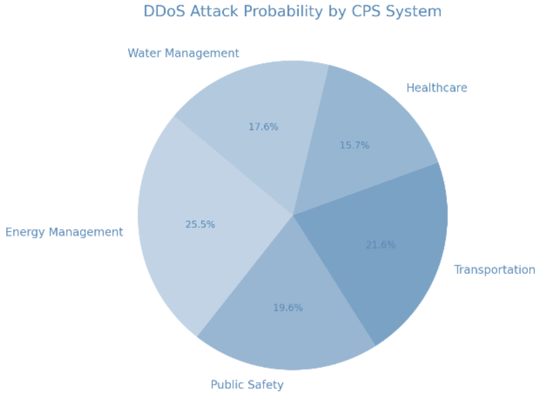

Figure 1. DDoS Attack Probability by CPS System

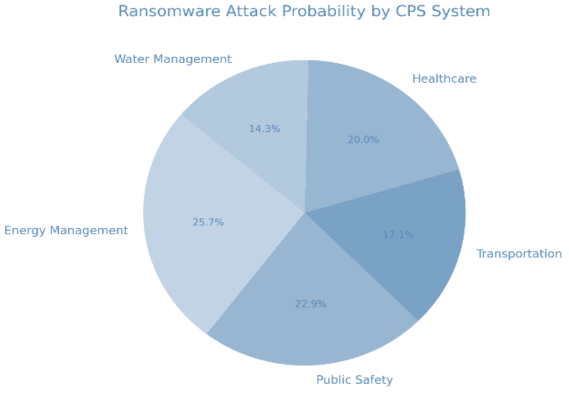

Figure 2. Ransomware Attack Probability by CPS System

In terms of operational downtime, the most affected systems are the energy and public safety systems. The Energy Management System could experience an average of 80 hours of downtime following an attack, while the Public Safety System could experience 65 hours of disruption. Healthcare and Water Management Systems face similar threats, but operational downtimes and productivity losses are somewhat lower in these systems.

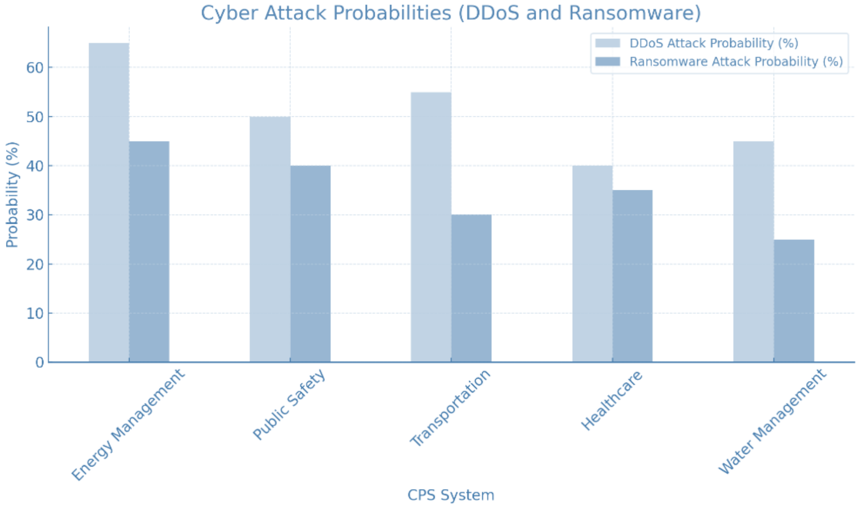

Figure 3. Cyber Attack Probabilities (DDOS and Ransomware)

4.2 Productivity Losses and Recovery Costs

One of the most significant impacts of cyberattacks on CPS systems is the reduction in operational efficiency. Specifically, the Energy Management System experiences a 25% productivity loss following an attack, leading to significant disruptions in operational processes. The Public Safety System sees an 18% reduction in productivity.

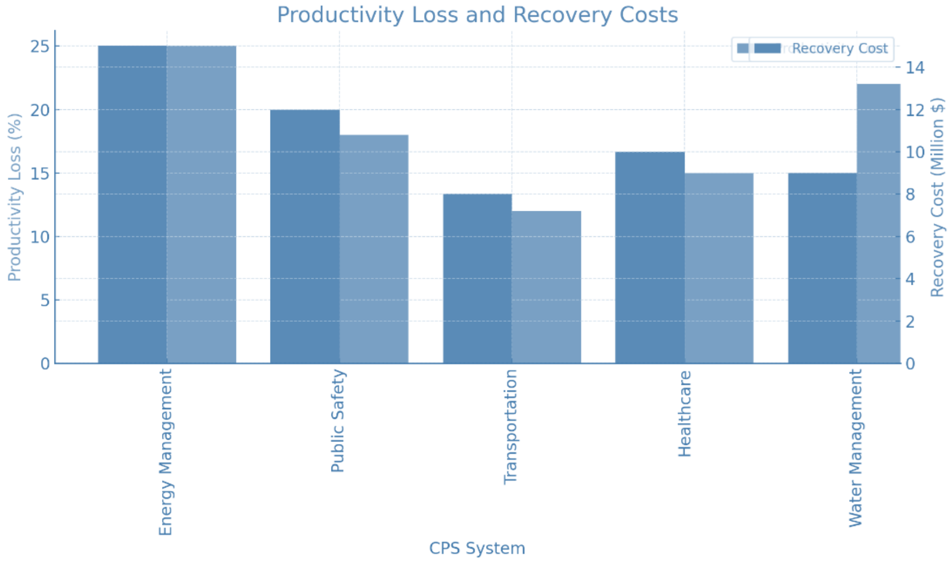

Figure 4. Productivity Loss and Recovery Costs

The recovery costs of these attacks also represent a significant factor. The Energy Management System, as the most affected system, requires an average recovery cost of $15 million following a cyberattack. In the Public Safety System, this cost is $12 million. Other systems, while incurring lower costs, still face significant expenses, with the Transportation System requiring $8 million and the Healthcare System requiring $10 million in recovery costs. These figures emphasize the critical importance of protecting CPS systems from cyberattacks.

4.3 User Impact and Data Breach Probability

The impacts of cyberattacks on smart city systems are not limited to operational downtimes and costs. These attacks also directly affect the city's residents. A cyberattack on the Energy Management System has a user impact of 55%, meaning more than half of the city's residents experience power outages. In the Healthcare System, the user impact is 50%, with critical healthcare services being interrupted as a result of the attack.

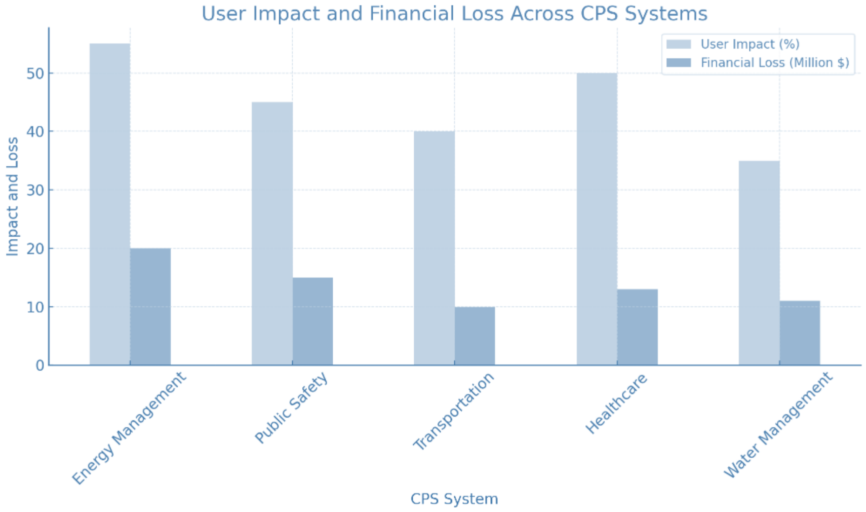

Figure 5. User Impact and Financial Loss Across CPS Systems

In terms of data breach probability, the highest risk is observed in the Healthcare System, with a 38% chance of a data breach. The Energy Management System and Public Safety System have similar risks, with data breach probabilities of 40% and 35%, respectively. These findings highlight the critical importance of protecting sensitive data in these systems.

4.4 Financial Losses and Recovery Times

Cyberattacks on CPS systems result not only in operational disruptions but also in significant financial losses. According to the data gathered, the Energy Management System incurs an average financial loss of $20 million following an attack. In the Public Safety System, this loss amounts to $15 million. Considering recovery times, the energy systems take an average of 8 days to recover, while public safety systems take 6 days.

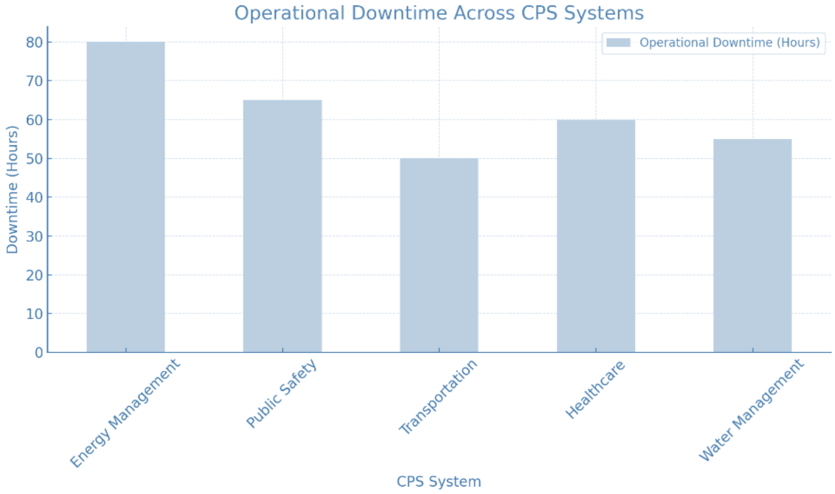

Figure 6. Operational Downtime Accross CPS Systems

On the other hand, the Transportation System and Water Management System, while incurring lower financial losses, still experience considerable impacts, with losses of $10 million and $11 million, respectively.

Table 1. CPS System Values Under Different Conditions

CPS System	DDoS Attack Probability (%)	Ransomware Attack Probability (%)	Data Breach Probability (%)	Operational Downtime (Hours)	Productivity Loss (%)	Recovery Cost (Million $)	Recovery Time (Days)	Attack Detection Time (Hours)	Financial Loss (Million $)	User Impact (%)
Energy Management System	65	45	40	80	25	15	8	3	20	55
Public Safety System	50	40	35	65	18	12	6	2.5	15	45
Transportation System	55	30	25	50	12	8	5	2	10	40
Healthcare System	40	35	38	60	15	10	6.5	3.5	13	50
Water Management System	45	25	20	55	22	9	5.5	2.8	11	35

According to the study's findings, CPS security plays a vital role in protecting critical infrastructures in smart cities. Energy and public safety systems are the most affected sectors in terms of cyberattacks. The disruptions caused by these attacks, productivity losses, and user impact are substantial. The results highlight the necessity of ensuring CPS security for sustainable urban management.

5. Discussion

This study has thoroughly examined how Cyber-Physical Systems (CPS) are utilized in smart city infrastructures and the extent to which these systems are vulnerable to cyber threats. Particularly in critical infrastructures such as energy management, public safety, and healthcare, the need to protect CPS from cyberattacks is of paramount importance for the sustainable management of smart cities. If CPS security is not ensured, the operational efficiency, user safety, and sustainability of urban services are at significant risk.

Security vulnerabilities in the energy management sector can directly affect the energy supply security of cities. The integration of CPS with digital energy grids has made these systems more susceptible to cyberattacks. According to the study's findings, DDoS attacks targeting energy systems have a 65%

likelihood of occurring, potentially affecting 55% of city residents. Such attacks on energy grids could result in serious consequences in terms of both downtime and costs. Similarly, public safety systems must address their cybersecurity gaps to protect critical infrastructures and ensure the uninterrupted operation of emergency response processes.

The risk of data breaches in healthcare and other sensitive infrastructures is also high. The study identified a 38% probability of data breaches in healthcare systems, posing a significant risk to the security of medical data. Similarly, water management and transportation systems have critical security vulnerabilities that could impact the daily lives of urban residents. In both sectors, the user impact of such attacks is estimated to range from 35% to 40%. Protecting these infrastructures is essential for maintaining the overall quality of services and the standard of living in cities.

Protecting CPS infrastructures must be a strategic priority to ensure the long-term security and sustainability of cities. In this context, various cybersecurity measures are needed to safeguard CPS systems in smart cities. First, the integration of advanced threat detection systems can help identify threats at an early stage and contribute to preventing large-scale attacks. In particular, Artificial Intelligence (AI) and Machine Learning (ML) based monitoring tools can learn and analyze abnormal behaviors within CPS systems, allowing potential attacks to be detected more quickly and effectively. This is especially important for reducing attack detection times in energy and public safety systems. The findings indicate that detection times currently range from 2 to 3 hours; integrating AI-based systems could reduce this time even further.

Additionally, multi-layered security solutions are recommended to make CPS infrastructures more resilient. These solutions provide security not only at the software level but also at the hardware and network levels, minimizing the impact of attacks. For instance, Next-Generation Firewalls (NGFW) and Intrusion Detection and Prevention Systems (IDS/IPS) can offer effective defense mechanisms against DDoS and ransomware attacks targeting CPS systems. The study's data show that DDoS attacks have a 60% likelihood of targeting energy management and public safety systems. These types of attacks can be mitigated with NGFW solutions.

Moreover, the integration of cybersecurity policies and standards into CPS systems is crucial. Every smart city should establish its own security policies and protocols to protect CPS systems. These policies should be regularly updated, and routine security audits should be conducted to identify vulnerabilities. The study's findings show that the recovery costs for energy and public safety systems are around $15 million. Implementing strong cybersecurity policies can help reduce these costs.

Finally, collaboration between the public and private sectors is essential for developing more comprehensive security solutions for CPS systems. Particularly in the protection of critical infrastructures such as public safety and healthcare, the integration of security solutions provided by the private sector is important. This collaboration will help integrate technological advancements into urban infrastructures and ensure that cities are protected more rapidly and effectively.

6. Conclusion

This study has demonstrated how critical the security of CPS systems is for the sustainable management of smart cities. The findings reveal that critical infrastructures such as energy, public safety, and healthcare are vulnerable to cyberattacks. These attacks not only cause operational disruptions and financial losses but also directly affect urban residents, threatening the continuity of essential services. Addressing cybersecurity vulnerabilities must become an integral part of cities' long-term governance strategies.

In conclusion, the security of CPS systems is becoming increasingly important as cities continue to digitalize, and it is essential for ensuring sustainable urban management. The growing number of cyber threats targeting CPS systems in areas ranging from energy management to public safety necessitates the implementation of next-generation security strategies. Future research should focus on enhancing CPS security through AI and machine learning-based solutions, making these systems more resilient to evolving cyber threats.

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Legal Dimension Of The Existence Of Distribution Companies In The Electricity Market And Distribution Contracts

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ABSTRACT

Electricity Market; It is a market consisting of the production, distribution, presentation, market operation, wholesale, retail sales, import and export activities of electrical energy and the business and transactions related to these activities. Distribution activity, which is one of the activity areas of the market, refers to the uninterrupted, continuous and high-quality delivery of electrical energy to the end consumer through lines of 36 KW and below. According to the decision dated 12/09/2012 and numbered 4019 taken by the Energy Market Regulatory Board, distribution and retail sales activities must be carried out under separate legal entities by legal entities holding distribution licenses as of 01/01/2013. With this decision taken by EMRA, it is aimed to ensure that the activities of electricity distribution companies are more transparent and open to competition in order to liberalize our electricity market. Efforts to ensure competition in the electrical energy market also bring about the unique characteristics of the market, the increasing need for electrical energy, legal problems and the need for legal regulation. In this study, the existence of the electricity market and distribution companies, their legal aspects, the main contracts in energy management and the processes related to the implementation of the contracts will be explained.

1. Introduction

Generation, transportation (transmission and distribution), trade and trade of electrical energy, which is a basic requirement and indispensable part of our lives, and the services associated with all these processes and their specific characteristics constitute the electricity sector. The electricity market, which has gone through different stages in the historical process and transformed into today's practices, refers to the generation, transmission, distribution, market operation, wholesale, retail, import and export activities of electrical energy and the business and transactions related to these activities. Distribution, one of the most important activities of the market, refers to the uninterrupted, continuous and high quality delivery of electrical energy to the final consumer through lines of 36 KW and below [1].

After 1980, the restructuring of the electricity sector, which was on the agenda in many countries around the world, came to the agenda in Turkey around the same time. With the liberalization of the electricity market, the vertically integrated structure, which was owned by the public sector in the past, is now being transformed into a competitive market structure in which the private sector also plays a role. For this reason, the private sector was requested to take part in the generation, supply and distribution phases of electricity market activities [2]. The main purpose of vertical unbundling is to ensure that all participants have non-discriminatory access to the transmission and distribution networks, which will maintain their natural monopoly characteristics in the electricity system, and that competition is transparent. In this context, the historical adventure of distribution activities carried out by the public sector in Turkey is summarized as follows:

- In 1982, some electricity generation, transmission and distribution facilities owned or used by municipalities were transferred to the Turkish Electricity Authority (TEK),

- In 1993, TEK was restructured into two separate state-owned enterprises, the Turkish Electricity Generation and Transmission Corporation (TEİAŞ) and the Turkish Electricity Distribution Corporation (TEDAŞ).

In 1980 and 1990, various legislative amendments were enacted to encourage private sector participation in the sector in line with the practices in other countries. However, these initiatives have so far failed to yield the desired results as the necessary legal and legislative arrangements have not been developed as a whole.

2.Privatization

Privatization, in a narrow sense, refers to the transfer of ownership and management of public economic enterprises to the private sector. In a broader sense, it involves the transfer of public assets or publicly measurable resources to private ownership, as well as the implementation of regulations that reduce or eliminate the state’s role in economic activities. The concept of privatization is based on the work of Adam Smith, often considered the founder of modern economics, whose 1776 book The Wealth of Nations laid the groundwork for this concept. Generally, privatization can be defined as the transfer or sale of state-owned investments and resources to the private sector in accordance with free-market principles, provided that the oversight and control remain with the state [3].

The privatization process can be realized through various methods, which differ in terms of technique, results, and political and economic impacts. In the context of the Turkish electricity market, the privatization of distribution activities was carried out based on Article 15 of the Law on Privatization Applications No. 4046. This law facilitated the transfer of operating rights (operating rights transfer, IHD) and the sale of shares (share transfer model, IHS Model) in TEDAŞ, which was responsible for electricity distribution in Turkey.

By the 1980s, rapid technological development and globalization led to socio-economic transformations worldwide. These changes, driven by crises and problems within public administrations, prompted many countries to undertake reformist actions [4]. With the rise of free-market economic principles, state-driven models were increasingly questioned, leading to the deregulation of trade and finance. Consequently, privatization emerged as a policy to reduce the state's role in the economy and transfer economic areas to the private sector. In line with these developments, privatization policies were implemented to improve efficiency and address issues within the electricity sector. The goal was to liberalize the sector by increasing competition, and in 2004, the Electricity Market Reform and Strategy Document was published [5].

For many years, electricity distribution in Turkey was handled by TEDAŞ, but following the 2004/3 decision by the High Planning Council, the Electricity Energy Sector Reform and Privatization Strategy Document came into effect, stipulating the privatization of distribution activities. The plan proposed creating a maximum of 21 distribution regions across Turkey. As the first stage of privatization, electricity distribution companies (EDAŞ), each with separate legal identities but fully owned by TEDAŞ, were established in 20 regions as of March 1, 2005. In 2006, to ensure the transfer of operating rights, a Operating Rights Transfer Agreement was signed between TEDAŞ and EDAŞ. This agreement led to the second stage of privatization, where shares of EDAŞ were transferred to the private sector while TEDAŞ retained ownership of the facilities. The share transfers were completed by 2013. Today, TEDAŞ no longer holds a distribution license, and distribution activities are carried out by privatized EDAŞ in the regions specified in their licenses [6].

3.Regulation

Regulation, in a general sense, is a concept that concerns various fields such as law and economics. From a legal perspective, it can sometimes refer to regulation, sometimes to supervision, or in some cases, to both regulation and supervision. From an economic standpoint, regulation involves a broader range of activities than typical regulation and supervision. Therefore, the concepts of regulation and supervision alone do not fully define regulation. The term "regulation" encompasses not only the establishment of rules for a particular activity and ensuring compliance with those rules but also guiding the implementation of laws, assessing complaints about violations, imposing temporary measures to prevent serious and irreparable harm, evaluating notifications about decisions, conducting investigations upon complaints or at the discretion of the regulatory body, providing documentation and information, imposing fines, and showing how the law is being applied in the relevant sector [7].

Since the 1980s, energy production and distribution of primary energies such as natural gas, coal, hydraulic energy, and oil, as well as secondary energy sources like electricity, have gradually shifted from state monopolies to the private sector and/or publicly traded companies with state participation. In Turkey, discussions on this shift began in 1985 and were put into practice during the 1990s. After the publication of the European Union's Directive 96/97, restructuring efforts in the electricity sector were initiated in 1997, and as a result, the Electricity Energy Law No. 4828 was adopted in 2001. With the Electricity Market Law, Turkey aimed to create a competitive electricity market based on private law principles, where the state would assume a purely regulatory role, ensuring a transparent and efficient market [8].

In the electricity sector, there are two stages where competition is not feasible: the high-voltage transmission and low-voltage distribution stages. Furthermore, there are no technological or economic barriers to competition in the production and supply (retail sales) stages. In countries where privatization has been successful, regulation is not deemed necessary in stages where competition is possible. However, in Turkey, where the state has withdrawn from the sector through privatization, the continuity of oversight and control under the regulatory framework remains essential. Therefore, it is crucial for the Energy Market Regulatory Authority (EPDK) to perform monitoring and control impartially and free from external pressures to ensure the success of privatization. If effective regulation and supervision are maintained within the framework of privatization, a transparent and efficient electricity market will be established [8].

4.Legal Aspects of Post-Privatization Distribution Companies

Thomas Edison’s famous quote, “I’ll make electricity so cheap that only the rich will be able to afford to light their homes with candles,” which emerged at the end of the 19th century, aligns with the goal in the Electricity Market Law of 2001: “to make electricity available to consumers at low cost.” In this context, under the Electricity Market Law, distribution companies, under licenses granted by the Energy Market Regulatory Authority (EPDK), are required to provide electricity distribution and connection services to all system users in a non-discriminatory manner and with high quality.

The electricity service, considered a public service, does not have the characteristics of a public good from an economic standpoint. Electricity consumption is both excludable (consumers can be charged for the electricity they use) and competitive (the marginal cost of one person consuming one more unit of electricity is greater than zero). The categorization of electricity services as a public service is based on the universal service logic. The Electricity Market Law includes provisions that aim to ensure the provision of a reliable, quality, continuous, and low-cost electricity service to consumers [9].

Electricity distribution, although not prohibited for the private sector, is still considered a public service due to its monopoly nature. Despite privatization, distribution remains under the public sector's control in Turkey, with private companies holding monopoly power. Distribution services can only be carried out by private legal entities in specific regions, as outlined in the Electricity Market Law. According to the Court of Cassation, electricity distribution is inherently a public service monopolized by the state. This was reflected in a 2004 decision regarding TEDAŞ, which held the monopoly in energy distribution [10].

5.Conclusion

The discovery of electricity is one of the milestones in human history, as it facilitates numerous everyday activities, from transportation to agriculture. Therefore, electricity, along with water and air, has become an essential commodity. Its production, transmission, trade, market operations, and regulations all aim to ensure electricity is supplied at reasonable prices, with a focus on security of supply, environmental sustainability, and a robust market. Electricity is not only of extraordinary value due to its importance but also has unique characteristics not found in any other commodity [14].

For this reason, electricity markets have a unique structure, operational processes, legal framework, and public interest, subject to economic regulation. As a result, the state long managed the electricity sector, but since the 1980s, many countries have initiated restructuring processes, leading to privatization. In Turkey, privatization initiatives in the electricity sector have gone hand-in-hand with liberalization reforms. The first legislative measures were taken in 1984 with the Law No. 2983, and the electricity sector underwent significant changes with the Law No. 3096 that year, marking the end of the Turkish Electricity Authority's (TEK) monopoly and allowing the private sector to engage in electricity production, transmission, and sales.

The Electricity Market Law No. 4628, which came into effect in 2001, laid the legal framework for the restructuring of the electricity industry, aiming to open up the market to competition while maintaining regulation of natural monopolies such as transmission and distribution. The Law's primary goal is to ensure a competitive, transparent, and efficient electricity market while also establishing an independent regulatory body for oversight [15].

The developments in the electricity sector, from TEK to TEDAŞ, and eventually to regional distribution companies, are of great importance to consumers, as distribution and retail sales are the most commonly encountered areas of the market. The privatization and restructuring of the distribution and retail sales sectors have aligned with neo-liberal economic policies. In today's Turkey, with the increasing demand for electricity due to rapid urbanization and industrialization, the private sector's participation is essential for providing the necessary investment and financing, as state resources alone cannot meet these growing needs [16].

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The Emergence, Implementation, Necessity, Factors Affecting The Development, And Legal Framework Of The Capacity Mechanism

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ABSTRACT

Capacity mechanism is a regulation introduced to protect and/or increase electricity supply. This mechanism aims to create and/or maintain sufficient installed power capacity along with spare capacity among legal entities holding electricity generation licenses. In this way, the continuity and security of electricity supply within the country will be ensured in possible negative situations. Due to the importance given to the field, a budget was allocated for serious incentive payments and a legal regulation specific to this field was prepared and published in the Official Gazette on January 20, 2018 (See: Electricity Market Capacity Mechanism Regulation). However, sufficient work has not been done in this field, where large investments are made and serious incentive payments are received in return. The lack of sufficient research and studies on the emergence, implementation and necessity of the capacity mechanism makes it difficult to determine the factors that will have a positive and/or negative impact on the development of the mechanism. It is a serious shortcoming that sufficient studies have not been carried out in an area that is given such high importance. In this study, the emergence, implementation and necessity of the capacity mechanism will be examined and the factors that will affect the development of capacity will be explained.

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1. Introduction

Throughout history, as the economy continuously developed and electricity demand increased, it became evident that existing systems could not meet these needs. Consequently, policies and strategies in the energy sector were devised and improved over time. As a result of these efforts, a system called the capacity mechanism was developed to protect and/or increase electricity production. This capacity mechanism system stipulates that system operators make capacity payments to legal entities holding electricity generation licenses within an annually determined budget to ensure adequate installed power capacity, including necessary reserve capacity, for the security of electricity supply in the market. This mechanism aims to ensure long-term electricity supply security. Due to the significance of this area, a substantial budget was allocated for incentive payments, and a legal regulation specifically for this area was prepared and published in the Official Gazette on January 20, 2018 [1].

The implementation of this capacity mechanism, with substantial payments and intervention in the electricity market, has drawn criticism and raised questions about its necessity. Despite being a highly regarded system, the relatively recent history of its implementation and the insufficient academic studies on the topic represent significant shortcomings. Examining the emergence, implementation, necessity, legal framework, and factors influencing the development of the capacity mechanism is crucial for the system to deliver the expected contributions to the energy sector.

2. Definition

The "Electricity Market Capacity Mechanism Regulation," published in the Official Gazette on January 20, 2018, with issue number 30307, is among the most critical resources for the capacity mechanism. Article 4, titled "Definitions and Abbreviations," subsection (f), defines the capacity mechanism as follows: "Capacity mechanism: A support mechanism annually operated by the System Operator to create or maintain reliable installed power capacity to ensure the security and reliability of the electricity system supply."

Additionally, subsection (k) of the same article states, "System Operator: Refers to the Turkish Electricity Transmission Corporation (TEİAŞ)," indicating that the capacity mechanism system is operated by TEİAŞ.

In summary, the capacity mechanism can be defined as a support mechanism annually operated by TEİAŞ (Turkish Electricity Transmission Corporation) to create and maintain the necessary installed power capacity to ensure electricity supply security in the market.

3. Emergence And Implementatıon Process

Due to the rapid growth of the electricity market in Turkey, a system called the "capacity mechanism" was developed in 2018 to ensure electricity supply security [2]. This system guarantees support payments to power plants if unit production costs fall below market prices [3]. The mechanism aims to make electricity production more attractive, thereby increasing production, and provides certain incentives to real and/or legal entities for investments in non-fossil energy sources [4].

In addition to the capacity mechanism, other incentive systems in the energy sector, such as the Renewable Energy Resources Support Mechanism (YEKDEM) and Renewable Energy Resource Areas (YEKA), have also been implemented. With the regulation introduced in 2018, hydroelectric power plants meeting the specified criteria began benefiting from the incentives provided by the capacity mechanism. Initially, it was determined that the total number of eligible plants was 43, with a combined installed capacity of 24,137 MW [5].

4. Necessity

It is estimated that approximately $300 million in incentive payments were made in 2018, the year the capacity mechanism was introduced. The high amount of these payments and the development of such an interventionist system in the energy sector have led to criticism. While some argue that setting a price cap could result in economic losses for the country and thus defend the necessity of the mechanism, others claim that such interventions hinder competitive markets and advocate for more flexible practices in terms of supply and demand. Consequently, although this mechanism enhances system security, concerns persist about the potential risks being passed on to consumers due to its high costs [6].

In countries with guaranteed fixed prices, the capacity mechanism may be required to support the sustainability of traditional production facilities. To avoid problems in such countries, it is suggested that a gradual transition to market-based models should be implemented. After implementing necessary measures to ensure supply security and system operation, a transition to a green certification model could be considered [7].

Energy supply security holds a prominent place within Turkey’s energy policies and strategies, reflecting its importance [8]. The capacity mechanism contributes to the continuation of operations for power plants that struggle to cover their costs in the long term, ensuring their presence in the system [9]. In cases where the energy market is insufficient, the implementation of capacity mechanisms in the form of capacity payments and/or obligations may be deemed necessary [10]. However, the deliberate reduction of production capacity by producers to increase payable capacity prices represents a significant issue during the application of the capacity mechanism [11]. Therefore, rigorous controls and audits must be conducted meticulously during the implementation of the capacity mechanism system.

5. Factors That May Affect Its Development

The University of Oxford has conducted comprehensive research into the factors that could affect the development of the capacity mechanism. The study revealed that support programs have generously facilitated the integration of intermittent renewable energy sources in some European countries. However, this approach has adversely impacted the energy market, as existing flexible baseload technologies are no longer adequately remunerated, leading to financial losses. It was also argued that the decline in investments in this sector is partially attributable to frequent regulatory changes, the absence of a stable legal framework, and persistent uncertainty over the timeline and conditions for phasing out nuclear energy.

The study emphasized the necessity for governments to prioritize alternative methods to ensure the security of electricity supply, particularly through more efficient electricity market designs that mitigate market distortions weakening supply reliability. The regulatory decision to implement the capacity mechanism as a means of attracting new resources may be perceived as a market intervention adversely affecting existing facilities, as these new resources could suppress prices in the spot market. From a robust economic theory perspective, it has been suggested that existing power plants should also be allowed to compete on equal terms to receive the same remuneration. Ensuring equal treatment for existing and new power plants is deemed essential for delivering an effective long-term signal to expand production capacity.

The research further identified critical factors influencing the development of the capacity mechanism, including the presence or absence of a stable legal framework, clarity in energy policy, and the provision of a level playing field for competition among power plants. Additionally, as incentive payments are made to legal entities holding electricity generation licenses under the capacity mechanism, the economic burden of the mechanism and fluctuations in electricity demand significantly impact its development. Increased or decreased electricity demand directly influences the required supply levels. Since a mechanism with high economic costs—where losses outweigh benefits—is unlikely to sustain over the long term, such dynamics can have both positive and negative effects on the mechanism's evolution.

6. Legal Framework

The legal regulation of the capacity mechanism system is the "Regulation on the Electricity Market Capacity Mechanism," published in the Official Gazette No. 30307 on January 20, 2018. This regulation legally secures the capacity mechanism. It includes detailed provisions on the purpose, definition, participation requirements, budget, calculation of payments, payment methods, and the return of payments. The regulation aims to clarify the capacity mechanism and address potential issues in its implementation. Article 3 of the regulation explicitly states its legal basis as follows: "This Regulation has been prepared based on Article 20 of the Electricity Market Law No. 6446 dated March 14, 2013."

Article 20 of the Electricity Market Law, which serves as the basis for the Regulation on the Electricity Market Capacity Mechanism, addresses the security of electricity supply. This article assigns the Ministry of Energy and Natural Resources the responsibility to monitor the security of electricity supply and take necessary measures. It also obliges licensed electricity generation companies to comply with, contribute to, and share relevant data for initiatives introduced by the ministry concerning supply security.

The regulation stipulates that the ministry, after consulting relevant institutions and organizations, must prepare a long-term National Energy Plan for Turkey, with the first plan to be completed within one year of the regulation's publication and subsequent plans every five years. Based on this plan, the ministry may organize capacity allocation tenders to ensure supply security. To establish and maintain reliable installed capacity for system security, capacity mechanisms prioritizing domestic resources will be created.

Furthermore, the Turkish Electricity Transmission Corporation (TEİAŞ) is authorized to commission new power plants or lease the capacities of existing plants through tenders to meet regional system needs if sufficient capacity is not available to maintain system security.

7. Conclusion

The capacity mechanism is a support system operated annually by the Turkish Electricity Transmission Corporation (TEİAŞ) to ensure the establishment and maintenance of the installed capacity required for supply security in the electricity market. This regulation was introduced to preserve and/or increase electricity supply. By implementing this system, the continuity and security of electricity supply within the country during potential adverse scenarios will be ensured. Due to its critical importance, significant legal regulations have been enacted for its implementation.

Under this system, it is guaranteed that support payments will be made to power plants if the unit cost price falls below market levels. This approach aims to make electricity production more attractive, increase electricity generation, and incentivize real and legal entities to invest in non-fossil energy sources. However, a critical issue with the capacity mechanism is the deliberate reduction of production capacity by producers to artificially inflate capacity prices. This necessitates meticulous oversight and inspections during the system's implementation.

It is essential to note that one of the primary reasons for applying capacity mechanisms is the inability or unwillingness of the demand side—especially residential consumers—to adequately secure long-term electricity supply. Research highlights that factors such as the presence of a stable legal framework, the clarity of energy policies, and whether power plants are granted equal competitive conditions significantly impact the development of the capacity mechanism.

Additionally, since licensed electricity generation companies receive incentive payments under the capacity mechanism, the economic burden of the mechanism and fluctuations in electricity demand are other factors influencing its effectiveness.

The "Regulation on the Electricity Market Capacity Mechanism," published in the Official Gazette No. 30307 on January 20, 2018, legally secured the capacity mechanism. The legal basis of the regulation is Article 20 of the Electricity Market Law No. 6446, dated March 14, 2013, which is a provision related to supply security. Reflecting the importance attributed to the issue, the ministry has been granted significant responsibilities and authorities to ensure supply security.

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