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Economic Optimization of a Hybrid Power Plant with Nuclear, Solar, and Thermal Energy Conversion to Electricity

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Abstract: This research presents a new solution for optimizing the economics of energy produced by a hybrid power generation plant that converts nuclear, solar, and thermal energy into electricity while operating under load-following conditions. To achieve the benefits of cleaner electricity with minimal production costs, multi-criteria management decisions are applied. The investigation of a hybrid system combining nuclear, solar, and thermal energy generation demonstrates the impact of such technology on the optimal price of generated energy; the introduction of nuclear reactors in hybrid systems reduces the cost of electricity production compared to the equivalent cost of energy produced by solar systems and compared to fossil fuel thermal systems. This method can be applied to hybrid energy systems with nuclear, solar, and thermal power generation plants of various sizes and configurations, making it a useful tool for engineers, researchers, and managers in the energy sector.

Keywords: nuclear reactors; energy economics; economic optimization; hybrid energy systems; thermal systems; solar systems; renewable energy

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1. Introduction

While nuclear engineering is about developing and utilizing the power in nuclear power systems, combined with the need to control and operate these systems in conditions of maximum safety and economic feasibility, it is the concern of nuclear engineers for the design, construction, and operation of reactors to the management of the decommissioned reactors [1]. Nuclear technology includes applications of nuclear reactions, such as the use of atomic nuclei for energy generation, the production of radioactive isotopes for medical and industrial purposes, and the propulsion of nuclear vehicles. Two main categories can be distinguished: (a) nuclear reactions that use nuclear fission to generate electricity in power stations, produce energy for heating water and rotate turbines to produce electricity, and (b) applications in medical imaging, cancer treatment, food irradiation, agriculture and industry [2].

Nuclear reactors deliver approximatively the 10% of the world's electricity [3]. All parts of the world are involved in nuclear power development. The majority of nuclear reactors generating units are in North America, Europe and Asia: the U.S. has 94 reactors, France has 56 reactors, China has 57 reactors [3], and is expected to acquire the largest number of nuclear reactors by 2035 [4].

Nuclear reactors produce electricity using the heat generated by nuclear fission reactions. Uranium and plutonium isotopes undergo controlled fission and release energy, which heats water and produces steam, which drives turbines connected to electrical generators, and thus produces electricity [2]. The two types of power reactors are the boiling water reactors (BWRs) and the pressurized water reactors (PWRs). Both BWRs and PWRs use light water as a moderator and coolant and are light water reactors (LWRs). The pebble bed high temperature gas-cooled reactor (PB-HTGR) operates at high temperature and has high efficiency. The fuel within the core includes graphite pebbles containing special coated TRistructural ISOtropic (TRISO) uranium fuel particles. PB-HTGR is cooled by helium gas under pressure, and the inlet and outlet core temperatures are 260 °C and 750 °C, respectively [5,6]. A TRISO particle is a uranium sphere, coated with special ceramic layers, which contain fission products and ensure mechanical and chemical stability during irradiation and temperature changes. Another TRISO-fueled reactor technology combined with low-pressure fluoride salt coolant that uses steam to convert heat from fission into electricity is the small modular reactor (SMR) [7,8].

Hybrid nuclear power plants can improve the reliability, flexibility, and efficiency of power systems while reducing emissions of gases such as CO_2. However, implementation of these systems requires technological innovation, design, and regulatory approval to ensure safety, reliability, and economic viability. Each hybrid system involves a set of technical, operational, and regulatory regulations that must be resolved during design and implementation. Therefore, nuclear power plants produce electricity without emitting gases such as CO_2. On the other hand, fossil fuel-based thermal power plants generate pollution. Thus, electricity generation has been directed towards hybrid systems that include renewable energy sources [9], or hydrogen combined with renewable energy sources and thermal generation, in an attempt to reduce pollution [10]. Such hybrid systems can be built as stand-alone in isolated areas [11] or connected to an infinite grid [12].

While the initial investment capital to build nuclear power plants is large, the lifetime operating costs are lower compared to fossil fuel-based power plants, because nuclear power plants have high output and long lifetimes, which helps distribute the initial investment capital over many years [13–15]. In particular, SMRs can operate continuously for long periods of time, up to 18–24 months without refueling, providing a stable and reliable source of electricity [16–18]. Despite a higher initial capital investment compared to larger nuclear reactors, SMRs offer economic advantages for small systems that are either connected to the infinite grid or in isolated areas.

Due to the rising price of CO_2 emission allowances, the continued operation of fossil fuel power plants is not compatible with European climate policy. The replacement of existing lignite-fired power plants with SMRs of equivalent ratings, while using the existing infrastructure, is described in [19–24]. Techno-economic analysis shows that retrofitting coal-fired power plants and replacing thermal plants with SMRs can reduce the cost of the initial investment capital [21,25]. A technical study of replacing a 460 MW coal plant with a 320 MW SMR unit shows that integrating the SMR unit is feasible [7,8], while the economic feasibility study shows that such a retrofit is more advantageous than new investments without CO_2 emissions, because the net present value is improved, and the discounted payback period is reduced to 10 years [19].

Following the initiatives of other countries [21,26], Greece is exploring the introduction of nuclear reactors, to be added to the existing fossil fuel power plants, in order to diversify the country's energy resources and reduce CO_2 emissions [27]. However, nuclear power is accompanied by concerns about safety and radioactive waste disposal; therefore, it is necessary to develop strong safety measures and related regulatory frameworks. These include reactor design standards, operational procedures, emergency preparation, and international agreements for the control of nuclear facilities [28].

SMRs are distinguished by their ability to operate in a load-following mode. The placement of multiple SMR reactors to facilitate load following can control between 50 and 100% of the rated power generation and, at the same time, improve the economic and environmental aspects [29]. Another situation reported in the literature is load following between 25 and 100% of the rated power [30]. Therefore, control optimization for load-following operations of nuclear power plants is still under investigation.

This research presents a new solution for optimizing the energy economics produced by a hybrid power plant that converts nuclear, solar, and thermal energy into electricity. Within the scope of the work, a case study was elaborated using optimization techniques. The investigation concluded that the cost of coal-based electricity generation is lower than the cost of electricity generation from the hybrid solar–thermal system, and is higher than the cost of electricity generation from the hybrid nuclear–solar–thermal system. The subject matter is of interest to those working in the energy industries, including the nuclear industry.

From the study of methods and techniques for optimizing the economics of dispatch and commitment in hybrid energy systems, economic issues continue to be of interest. Optimal generation scheduling of hybrid nuclear–solar–thermal power plants to minimize electricity costs must take into account the specific characteristics of each power plant and load demand. Due to the involvement of hybrid plants in power generation and monitoring load following, generation planning must fulfill specific requirements. The literature shows that research efforts have been made; however, an accurate mathematical method is needed to show the effects of changing electrical load demands, fuel prices, operation and maintenance costs, solar irradiance variability, and to solve the load-following problem in real time. This research links the above issues with finding an optimal scheduling solution for cost-optimal power generation, and which will follow the electrical load.

To address the issues, in Section 2, the hybrid nuclear–solar–thermal system is described; then, in Section 3, the paper proposes an approach for the economic optimization of hybrid nuclear–solar–thermal generation systems, which applies economic multi-criteria decisions. In Section 4, in selected scenarios, the objective is to control the power generated by nuclear reactors, solar units, and multiple thermal units operating in load-following mode, from full rated power to a target load level, within a 24 h time frame. The results are discussed in Section 5.

2. Hybrid System Description

A hybrid power plant combines nuclear fission reactors with other forms of energy generation, such as solar and thermal, or storage technologies, and creates a more flexible and efficient power generation system that can adapt to changing energy demands and grid conditions and enhances economics and gas emissions

One hybrid thermal–nuclear power plant consists of a nuclear reactor operating at the same time with a thermal power unit. The nuclear reactor produces heat through nuclear fission. This heat produces steam by heating the water in the steam generator or directly in the reactor's cooling system. In parallel, a thermal power plant is installed. The steam produced by the nuclear reactor is fed into the turbines of the power plant, where it drives generators and produces electricity [31]. This concept allows for flexibility in power generation, as the thermal plant can be operated independently of the nuclear reactor, in load following and grid stabilization.

A hybrid nuclear-solar configuration combines a nuclear fission reactor with solar power units. During times of peak sunlight, the solar panels generate electricity, reducing the load demand on the nuclear reactor. When solar power production is low (during night, or cloudy weather), the nuclear reactor can ramp up its output to meet load demand. This setup balances the intermittency of solar power with nuclear energy.

In the load-following mode, the electricity production of the whole hybrid power plant is adjusted to the changes in load demand, while at the same time, the system operator monitors the changes in production according to the system requirements [32–34]. Published reports [35–38] show that SMRs are able to load follow and can vary the generated energy during different time periods, such as between day and night. Also, SMRs are capable of changing the generated energy according to the changes in the power output of renewable energy sources, such as wind or sun [39], or in relation to the placement of SMRs in isolated areas [40].

The nuclear reactor in a hybrid nuclear–solar system would load follow to balance the intermittency of solar power. Even though nuclear reactors are designed to load follow, it is not recommended for a nuclear power reactor to load follow on a daily basis, as it will increase the risk of reactor accidents and reduce the nuclear power plant lifespan.

However, nuclear reactors have technical limitations in terms of operating in load following mode; frequent and rapid changes in temperature cause interactions between nuclear fuel and metal cladding, which can break the metal, resulting in fission products escaping [30,41,42]. For safety reasons, a limited rate of power variation is imposed; the permitted rates of power variation are between 1 and 5% of the rated power per minute. Publications [30,43] show operation at 50–100% of rated power during the day, with a rate of change of 3–5% of power per minute. However, the variation in output of SMRs is not fast enough to compensate for the variations in output from the solar modules. Consequently, in load-following operation, nuclear power plants lose some of their economic efficiency, because they have a high initial capital investment, and to recoup the initial investment they must operate continuously near peak power.

In contrast, fossil fuel power plants are better suited to meet lower loads in load-following operation because they have a lower initial investment capital and lower fuel costs. When SMRs are installed in renewable energy grids, if the capacity factor is reduced, the energy produced increases in cost because the total capital and operating costs are spread over fewer kWh [44]. Therefore, based on an economic evaluation, the operation of SMRs in load-following mode must be carefully scheduled [34,45,46].

The optimization of economic dispatch and commitment of energy generated in hybrid grids such as with thermo–solar units is a complex problem because of the many generators of different kinds and sizes that are interconnected. The generators have different operating constraints and must contribute to optimize objective cost functions [47,48]. The optimization of a thermo–solar plant must take into consideration that the solar energy units depend on solar irradiation, period of the year, geographical coordinates, and weather conditions. A model for a hybrid solar–thermal power system which addressed the energy economic dispatch and commitment optimization is in [48].

Optimizing the economic dispatch and commitment of energy produced by hybrid networks, such as those with thermo–solar plants, is a complex and complicated problem due to the many generators of different types and sizes interconnected in the same network. All generators have operating characteristics, operational constraints, and limits that contribute to the optimization of the objective cost functions to be developed for each grid [47,48].

Figure 1 shows the hybrid energy generation system with the energy management system (EMS), solar power generating units, nuclear power generating units, SMRs, thermal generating units (Th_i), and electrical loads. Specifically, in the case study, a hybrid energy system will be considered that consists of small modular reactors (SMRs), solar units, and thermal generation units based on lignite Th1–Th5, to cover the total load (including constant and variable loads, such as industrial motors, heating–cooling, air conditioning, etc.). The energy management is implemented by the EMS, which controls the distribution of power between generation and load demands during different time periods and under different operating conditions. Thus, the EMS, depending on the detected loads, switches to available options and achieves power balance with respect to time when power resources and load demands vary. Therefore, in this hybrid energy system, nuclear and solar units are involved in meeting electrical load demands. In addition, the EMS controls the levels of nuclear production by SMRs. All power units are considered as operating independently of each other.

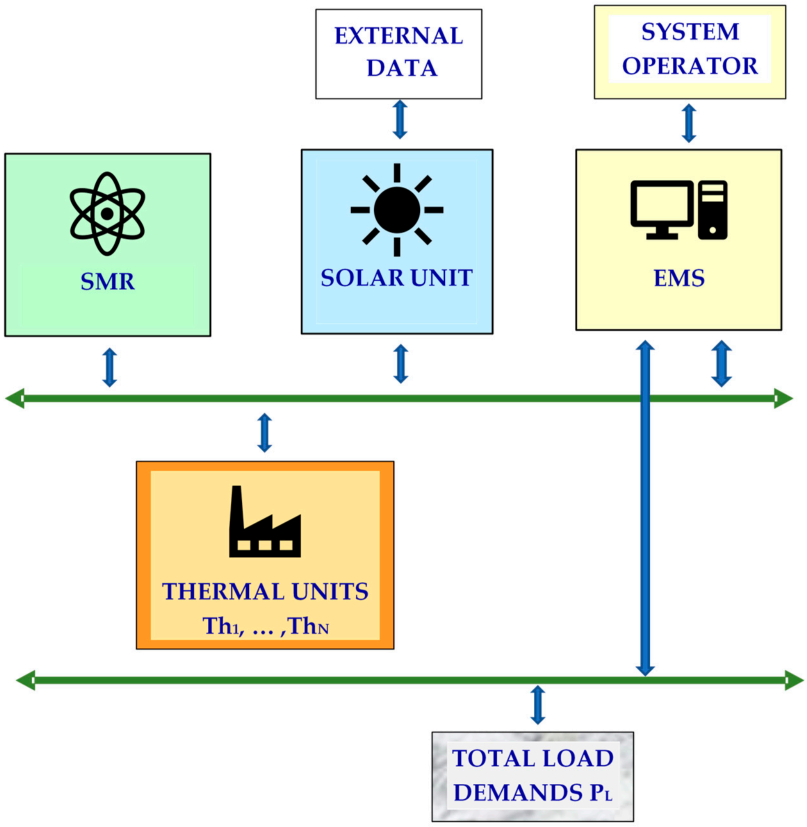

Figure 1. Hybrid nuclear–solar–thermal energy generation system.

The constant electric load is assumed at 55% of the mean value between the total minimum and maximum powers of the thermal units. Their technical data are in Table A3 from Appendix A [49]. An estimation of varying electrical loads versus time during 24 h is shown in Figure 2 [48]. Depending on operating conditions, industrial loads such as electric motors can be connected or disconnected to the system. In our approach, it is estimated that the varying electrical loads at 2.15 MW, between 0.7 and 2.85 MW, represent approximatively the 0.2% of the total committed constant electric load. However, such varying loads could be neglected in a big power system. On the other hand, in small power grids, a load of 2.15 MW can overload the system, with impacts on stability. For reasons of generalization of the model, computer program, and solution, the total load was analyzed separately in a constant component and a varying component.

The hybrid power system must cover the committed loads from the nuclear, solar, and thermal power units. The proposed retrofit by the addition of one nuclear reactor and one solar power unit of equivalent ratings aims at a replacement of one of the existing thermal units, to lower the gas emissions from the firing of lignite. However, when the power generated by nuclear reactors and solar units is lowered, the committed loads are covered by existent thermal units.

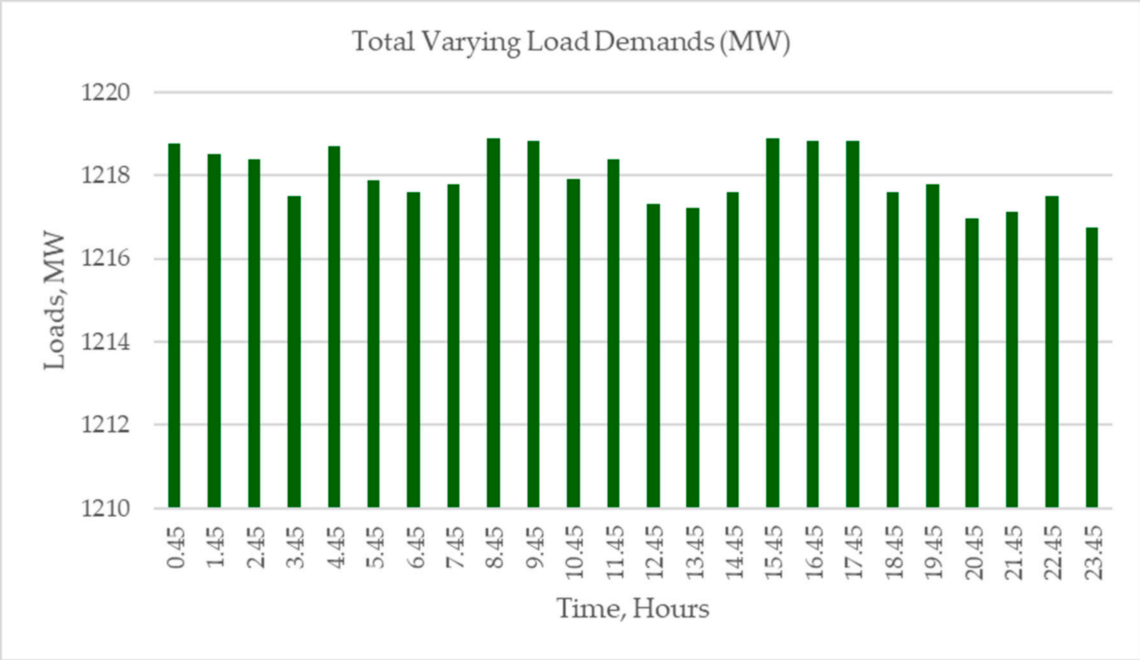

Figure 2. Total varying load demands during 24 h.

3. Economics Model and Optimization

The objectives of the economic dispatch and commitment problem in a hybrid power system are to control the generating units in a load-following mode, with technical and security constraints, and to optimize the total costs [47,50,51].

All nuclear power plant capital costs may be simplified into two major categories: capital and operational costs. Capital costs refer to the upfront costs associated with the plant design, licensing, and construction processes. They are often grouped into detailed design and engineering, overnight capital costs, interest during construction, and contingency costs. Operational costs, on the other hand, refer to the personnel, materials, and equipment required for plant operations. This may be further broken down into operations and maintenance (O&M), fuel, and decommissioning costs.

The cost of connecting power generating units to the grid involves infrastructure investments, transmission upgrades, and system integration expenses. This cost varies depending on the type of generation technology (nuclear, solar, wind, thermal), on the location related to the existing transmission infrastructure, and on the size and ratings of the units being connected. One of the factors of connecting costs is the distance between the generation unit and the grid, as longer distances typically require more expensive transmission lines, especially for connecting wind or solar farms, which often requires new high-voltage transmission lines due to their remote locations and because they include substations, transformers, and interconnection fees charged by utility companies for ensuring grid reliability.

Integration of renewable units involves additional expenses for grid upgrades to manage variability and intermittency of power generation, which increase the total connection costs, while connecting thermal plants, which are usually closer to load centers, incurs lower costs due to existing infrastructure. The cost of connecting power generating units is also influenced by regulatory policies, such as grid access fees, and market structure, where independent power producers face different cost structures compared to state-owned entities [52]. The evaluation of connection costs across different electricity generation types, such as micro-generation and large-scale interconnected systems, tells of significant variations, determined by network demands and infrastructure [53,54]. For the above reasons, the costs of connecting power generation units are considered as belonging to the initial capital investments.

3.1. Economics of Nuclear Reactors

The economics of nuclear power are characterized by high initial capital investment, competitive generation costs, and significant sensitivity to factors such as discount rates, construction timelines, and fuel changes. The levelized cost of electricity (LCOE) serves as a metric, reflecting both accounting and economic costs over the lifecycle of a nuclear plant. Nuclear power often competes with fossil fuels due to low operating and fuel costs; however, high construction and regulatory costs, along with long lead times, can offset these advantages. Studies highlight the disparity in nuclear costs across regions and technologies; for instance, VVER-1000 reactors in Jordan showed a LCOE ranging from 144.81 USD/MWh to 610.09 USD/MWh due to local economic conditions and construction variances [55]. Other studies suggest SMRs have an LCOE typically between 80 USD/MWh and 175 USD/MWh depending on the region, financing, and technology. In Indonesia, an SMR LCOE ranges between 81.10 USD/MWh and 131.0 USD/MWh [56–58].

Configurations like hybrid energy systems and hydrogen cogeneration further enhance SMR economics. Hydrogen production integrated with SMRs can achieve costs at 1.77–3.36 USD/kg and reduce fossil-fuel dependency [59]. Furthermore, SMRs' integration into hybrid systems, including hydrogen production and storage, has demonstrated additional cost advantages, particularly in low-carbon energy transitions [59]. Workforce and operational costs remain substantial, contributing to the lifecycle cost variance, which emphasizes the importance of long-term planning and skilled labor development [60,61].

Once a nuclear reactor is commissioned, it can maintain stable output for long periods of time. This stability helps in grid management by providing a predictable source of energy. Due to their continuous operation and short downtime for maintenance and/or refueling, nuclear reactors have high-capacity factors of 90–95%. Nuclear plants have a long lifetime, 40–60 years, with proper maintenance and upgrades. This contributes to their economic viability and helps to pay back the initial capital investment. The initial capital costs are high, but their operating costs are lower compared to other forms of electricity generation, especially when the nuclear power plant is in operation.

The operating costs of nuclear power plants cover the expenses related to the operation and maintenance of the plant and include the following:

- Fuel costs: nuclear power plants mainly use uranium or plutonium as fuel for fission reactions.
- Operating and Maintenance (O&M) costs cover operating expenses, including employee remuneration, equipment maintenance, and administrative expenses.
- Decommissioning costs include decontamination, dismantling of structures and equipment, as well as disposal of radioactive waste, which are collected in special accounts during the operational life of the station and are available when the station is deactivated.
- Waste Management Costs for the safe management and disposal of radioactive waste, spent fuel and other by-products, including storage, transport, and final disposal in long-term repositories.
- Insurance and Regulatory Compliance and licensing requirements, imposed by regulatory authorities, which include the purchase of insurance coverage against accidents and liabilities related to nuclear operations.

The validity of an economic model of a nuclear power plant without tax treatment on the total cost rate depends on the inclusion and weighting of other key cost factors, such as capital costs, fuel expenses, operation, and maintenance costs. In nuclear power plants, taxes, including income taxes and fixed charges, are a significant component of total costs, where tax treatment influences the overall power costs [62]. However, excluding tax considerations may offer a useful perspective in comparing costs between different reactor technologies. Studies [58,63] suggest that elements such as capital investment, fuel prices, and operational efficiencies play critical roles in the economic viability of nuclear reactors, particularly SMRs and desalination plants. In [63], the study focuses on fuel and operational costs over taxes in efficiency optimization, while ref. [58] highlights the cost breakdown in SMRs, showing the importance of non-tax factors like capital costs.

Without tax treatment, while these models might miss a portion of the financial picture, they can provide valuable insights into cost optimization through technical and operational efficiencies. The impact of taxes on carbon and pollution in nuclear economics needs to be considered; while taxes have environmental and economic implications, their exclusion from models does not invalidate the analysis but limits the generality when assessing net-benefit scenarios, especially when policy and regulatory environments are key to financial sustainability [64]. Thus, the cost rate of nuclear power plants refers to the total cost of producing electricity per unit of output, including fuel costs (procurement and processing of nuclear fuel) and operational and maintenance costs (O&M). Financing costs, like interest during the construction period, and taxes may be neglected from the cost rate.

Thus, taking into consideration the above examination, the cost rate of a nuclear unit j during the time duration t is

$$F_{nj}(P_{nj}) = c_{nj}/t,\ j = 1, 2, \ldots, N_n \tag{1}$$

where N_n is the total number of nuclear units, P_{nj} is the output power of nuclear unit j, and c_{nj} is the total cost (fixed costs and variable costs) of the nuclear unit [65].

Economic analyses indicate that SMRs can achieve cost parity with conventional systems under favorable financing conditions. Notably, modular construction and economies of scale are critical in reducing construction timelines and overall project costs. However, higher discount rates and equity costs can significantly increase the LCOE, risking economic feasibility [61].

The economic competitiveness of SMRs improves in regions with high natural gas prices or carbon taxes, as seen in studies comparing SMRs to coal and natural gas combined-cycle plants. Minimum electricity prices of approximately 175 USD/MWh are often required to ensure feasibility at the higher end of capital costs [56]. Comparative analyses of nuclear versus natural gas reveal that nuclear's competitive edge increases with volatile fossil fuel prices, particularly when construction efficiencies and low discount rates are achieved [66–68]. Additionally, advanced nuclear technologies and optimized financing models can lower costs but require policy support to address uncertainties in fuel preparation, waste management, and decommissioning. To produce 1 MW of electrical energy, it can be considered that a generic value of uranium of 1 g of U-235, fully fissioned, produces about 1 MWd of electricity. But, 1 MWd (day) = 24 MWh, and thus 1000 MWh, or 41.67 MWd, would require the fissioning of 41.67 g of U-235. The following databases and resources track the cost rates and economic performance of SMRs [69–71].

3.2. Economics of Thermal Power Systems

The optimal dispatch and commitment models for thermal units [47] as well as for hybrid solar-thermal units [48] need to be studied and expanded for hybrid energy systems to include nuclear power generation units.

The objective function F_T or the total operating cost rate of the thermal units includes fixed costs (personal, costs non-varying with the output), and variable cost (fuels, energy, maintenance material, etc.). General external costs that arise from electric utilities activities are not considered where these do not fall on the utilities themselves, such as accidents, damages to property or health, environmental damage from air pollutants, discharges of waste heat, etc. [47,50,51]. Also, the initial capital investments are not considered.

The cost rate $F_i(P_i)$ for a duration of one hour, where P_i is the power generated by unit i, $i = 1, \ldots, N$, and C_i are the total costs (fixed and variable), is considered.

$$F_i(P_i) = C_i/t \quad (2)$$

The sum of P_i equals the total load P_L, and, therefore, function Φ_{th} is null.

$$\Phi_{th} = \sum_{i=1}^{N} P_i - P_L = 0 \quad (3)$$

Therefore, the total generated maximum power must exceed the load demand P_L plus the reserve R_L.

$$\sum_{i=1}^{N} P_{i,\max} \geq P_L + R_L \quad (4)$$

All power plants have limits of generating capacity so that their generators can work stably between minimum generation levels, $P_{i,\min}$, and maximum generation values, $P_{i,\max}$ [47,48,50,51].

$$P_{i,\min} \leq P_i \leq P_{i,\max} \quad (5)$$

3.3. Economics of Solar Systems

Sun irradiation levels vary daily and depend on the time of the year and on the location and geographical coordinates [48,72]. In Figure 3, the solar irradiation during 24 h at the selected location is shown.

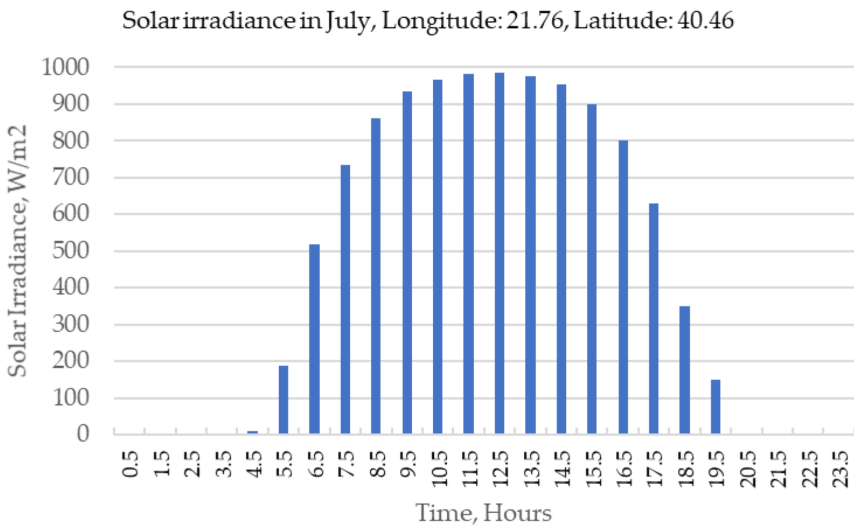

Figure 3. Solar irradiance during 24 h.

The power output from the solar power unit k can be estimated as follows:

$$P_s = \sum_{k=1}^{N_s} P_{sk}(I) \quad (6)$$

$$P_{sk}(I) = \begin{cases} P_{sr}\left(\frac{I^2}{I_{std} \cdot I_C}\right) & for \quad 0 < I < I_C \\ P_{sk,\max} & for \quad I > I_C \end{cases} \quad (7)$$

$$P_{sr} = \eta \cdot S \cdot P_{sro} \quad (8)$$

$$|P_{sk}| \le P_{sk,\max} \tag{9}$$

where N_s is the number of solar collectors, I is the solar irradiation in (W/m^2) [72] (see Figure 3), $P_{sk}(I)$ is the function of conversion the solar irradiation to electric power of the solar unit k, I_{std} is the reference solar irradiation designated equal to 1000 W/m^2, I_C is the cut-off irradiation level designated equal to 1000 W/m^2, P_{sr} the rated equivalent power output of the solar unit, $P_{sk,\max}$ is the maximum power of solar unit k, which depends on efficiency η, area S of the solar collectors, and per unit base value P_{sro} [48,73–76].

Therefore, the total nuclear power P_N output to the hybrid system is constrained by the maximum capacity $P_{nj,\max}$ of each nuclear unit.

$$P_N = \sum_{j=1}^{N_n} P_{nj} \tag{10}$$

$$|P_{nj}| \le P_{nj,\max} \tag{11}$$

Thus, the power balance of the hybrid nuclear–solar–thermal system can be written as

$$\Phi = P_L + R_L - \sum_{i=1}^{N} P_i - \sum_{k=1}^{N_s} P_{sk} - \sum_{j=1}^{N_n} P_{nj} = 0 \tag{12}$$

3.4. The Objective Function

In view of an economic dispatch and commitment applied to a hybrid nuclear–solar–thermal system, which includes N thermal units, N_s solar units, and N_n nuclear units, and covers a total load P_L, the objective function studies the total cost rate function F. The optimization of the objective function is carried out with the constraints regarding the power balance and the power bound.

$$Min\_F = Min\_(F_N + F_S + F_T) \tag{13}$$

$$F_T = \sum_{i=1}^{N} F_i(P_i) \tag{14}$$

$$F_s = \sum_{k=1}^{N_s} F_{sk}(P_{sk}) \tag{15}$$

$$F_N = \sum_{j=1}^{N_n} F_{nj}(P_{nj}) \tag{16}$$

$$F_{sk}(P_{sk}) = t_k \cdot P_{sk} \tag{17}$$

$$F_{nj}(P_{nj}) = t_j \cdot P_{nj} \tag{18}$$

where F_T is the total operating cost rate of the thermal units, which includes fixed costs and variable cost, designed at 150 EUR/MW [47,51]. The function F_s is the direct cost of the solar unit; if solar plants are owned by the utility, then F_s can be neglected, while, if solar plants are not owned by the utility, then F_s is analogue to the output. Therefore, a linear cost function is used for the scheduled solar generation, and t_k is the direct cost coefficient of the solar unit k [73,74,76].

The objective function is

$$F = \sum_{j=1}^{N_n} t_j \cdot P_{nj} + \sum_{k=1}^{N_s} t_k \cdot P_{sk} + \sum_{i=1}^{N} F_i(P_i) \tag{19}$$

The problem of minimization with constraints of objective function F is solved by introducing the Lagrangian function L, equal to the objective function F plus the constraint Φ multiplied by a variable lambda λ, which is an incremental cost rate [47,77].

$$L = F + \lambda \cdot \Phi \tag{20}$$

The optimal solution for objective function F is computed from the partial derivatives of L by introducing the incremental cost rates $\frac{\delta F_i(P_i)}{\delta P_i}$:

$$\frac{\delta F_i(P_i)}{\delta P_i} - \lambda = 0 \tag{21}$$

3.5. Solution

The cost rates $F_i(P_i)$ result from the heat rates $H(P_i)$ multiplied by the fuel costs FC_i.

$$F(P_i) = H(P_i) \cdot FC_i \tag{22}$$

The powers, cost rates, and the heat rates are computed as follows [47]:

$$[P_0] = -[A]^{-1} \cdot [B] \tag{23}$$

$$[A] = \begin{bmatrix} 2 \cdot H_{1,2} \cdot FC_1 & \cdots & 0 & -1 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & \cdots & 2 \cdot H_{N,2} \cdot FC_N & -1 \\ -1 & \cdots & -1 & 0 \end{bmatrix} \tag{24}$$

$$[B] = \begin{bmatrix} H_{1,1} \cdot FC_1 & \cdots & H_{N,1} \cdot FC_N & P_L - \sum_{k=1}^{N_s} P_{sk} - \sum_{j=1}^{N_n} P_{nj} \end{bmatrix}^T \tag{25}$$

$$[P_0] = \begin{bmatrix} P_1 & \cdots & P_N & \lambda \end{bmatrix}^T \tag{26}$$

The optimal solution $[P_0]$ of the objective function (13) minimizes the system without constrains. The values $P_1, \cdots, P_N$ are initial operating points of the powers from thermal units, and λ_1 is the initial incremental cost rate. The lambda iteration procedure introduces small variations $\pm\Delta\lambda$ from λ_1 and the boundary conditions from Equations (5), (9) and (11), obtaining the Equations (27)–(32):

$$[A_\lambda] \cdot [P_\lambda] + [B_\lambda] = 0 \tag{27}$$

$$[A_\lambda] \cdot [P_\lambda] + [B_\lambda] < 0 \tag{28}$$

$$[A_\lambda] \cdot [P_\lambda] + [B_\lambda] > 0 \tag{29}$$

$$[A_\lambda] = \begin{pmatrix} 2 \cdot H_{1,2} \cdot FC_1 & & 0 \\ & \ddots & \\ 0 & & 2 \cdot H_{N,2} \cdot FC_N \end{pmatrix} \tag{30}$$

$$[L_\lambda] = \begin{bmatrix} \lambda & \ldots & \lambda \end{bmatrix}^T \tag{31}$$

$$[B_\lambda] = [L_\lambda] - [B(1:N)] \tag{32}$$

The generated thermal powers are the solutions for matrix $[P_\lambda]$:

$$[P_\lambda] = [A_\lambda]^{-1} \cdot [B_\lambda] \tag{33}$$

The minimal operational costs of each thermal unit are $F([P_\lambda])$; the total minimal costs of the thermal power plant and the total minimal costs of the hybrid nuclear–solar–thermal power plant are computed from Equations (34)–(36), respectively.

$$F([P_\lambda]) = [H([P_\lambda])]\cdot[FC] \quad (34)$$

$$F_\lambda = \sum_{i=1}^{N} F([P_\lambda]) \quad (35)$$

$$F_{opt} = \sum_{j=1}^{N_n} t_j \cdot P_{nj} + \sum_{k=1}^{N_s} t_k \cdot P_{sk} + \sum_{i=1}^{N} F([P_\lambda]) \quad (36)$$

Based on the analysis from Equations (1)–(36), a program for the economic optimization of the hybrid power plant for nuclear–solar–thermal energy conversion to electricity is developed.

4. Case of a Hybrid Nuclear–Solar–Thermal System

In this case study, the power system consists of one nuclear reactor, one solar unit, five thermal units, one constant load at 1216 MW, plus varying loads between 0.7 MW and 2.85 MW.

In Appendix A, in Table A1, are the technical data of the SMR [8]. In Table A2 are the technical and economic data of the solar unit [78]. The technical data and the coefficients of the selected five thermal units Th1–Th5 are in Table A3 [48,49]. The heat/hour of the thermal units are convex functions, while the cost rate is computed according to Equation (22). The selected cost coefficients are lignite at 105 EUR/Gcal, solar cost coefficient at 300 EUR/MWh, and nuclear cost coefficient at 150 EUR/MWh.

In order to select fuel prices, a study was conducted in publications, in stock market rates and for reported inflation rates for Greece [79]. For a combined price of nuclear fuel and O&M, the publications [15,61,80] published values of 14.40 EUR/MW (for Europe), 27.10 USD/MWh and 28.02 USD/MWh (for the USA), 36.42 USD/MWh (for China), and 39.76 USD/MWh (for Japan), respectively.

Also, for the computations of this work, it must be accounted that the growth of the Dow Jones industrial index of the stock market for the period 2014–2024 is of the order of about 180%, while the stock market growth index of uranium processing is of the order of 393%. For the same period 2014–2024, the price of processing the nuclear fuel is considered proportionally increased starting from 27.10 USD/MWh and up to 75.97–133.61 USD/MWh, respectively.

However, because the scenarios must forecast the prospect of the future construction of nuclear power plants, which may take place within the next decade, 2025–2034, by keeping for this decade the same growth rates of 180–393%, nuclear fuel and O&M prices can be forecasted between 213 USD/MWh and 659 USD/MWh, respectively. On the other hand, using other statistical indexes, such as median prices per month, the growth rate of uranium processing during the years 2025–2034 is computed at 840%, while the median price of processing nuclear fuel can be forecasted at 2390 USD/MWh.

Therefore, taking into account the above criteria in forecasting future increases of costs, the nuclear cost coefficient value at 150 EUR/MW was selected for this research. In Table A4 in Appendix A are summarized the cost coefficients for lignite, solar, and nuclear generation used in the economic analysis.

The following scenarios have been studied: Scenario 1, with an activated nuclear reactor, solar unit, and the five thermal units; Scenario 2, with an activated solar unit and the five thermal units; and Scenario 3, with activated the five thermal units. The nuclear reactor is deactivated in Scenarios 2 and 3, while the solar unit is deactivated in Scenario 3.

The operation from Scenario 3 is considered as a base case for study and comparison of results obtained by introducing the nuclear reactor and solar power unit (in Scenarios 1 and 2). The three scenarios are shown in Table 1.

Table 1. The three scenarios studied.

	Power Units	Scenario 1	Scenario 2	Scenario 3
1.	Solar Unit	On	On	Off
2.	Nuclear Reactor	On	Off	Off
3.	Thermal Unit Th1	On	On	On
4.	Thermal Unit Th2	On	On	On
5.	Thermal Unit Th3	On	On	On
6.	Thermal Unit Th4	On	On	On
7.	Thermal Unit Th5	On	On	On

4.1. Scenario 1: Load Following in a Hybrid System with One Variyng Output Nuclear Unit, One Variyng Output Solar Unit, and Five Varying Outputs Thermal Units

The nuclear unit generates at almost rated power from 0:45 a.m. and 6:45 a.m. and from 17:45 p.m. to 23:45 p.m., while from 6:45 a.m. to 17:45 p.m. it generates at 80% of the rated power. This is scheduled in order to balance the increased solar irradiance between 6:45 a.m. and 17:45 p.m.

During 24 h, the optimal values of the generated power by the five thermal units Th1–Th5, the reserves of power, versus λ are obtained using the small variations of λ, from λ = 186.70 to λ = 187.40, according to Equation (33), and are plotted in Figure 4.

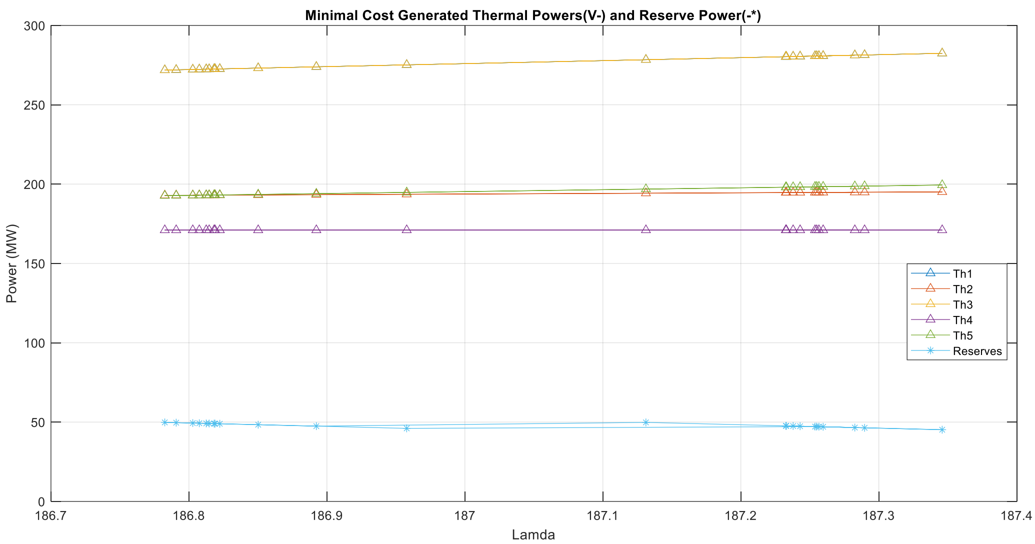

Figure 4. Scenario 1. The minimal cost powers (Th1 blue, Th2 red, Th3 yellow, Th4 magenta, Th5 green) and the reserves of power (light blue with *) versus λ. During 24 h, the optimal value of λ_λ changes from λ_λ = 186.7 to λ_λ = 187.35. The power outputs of Th1 and Th3 are equal and shown superposed.

In Figure 5 are shown the minimal costs of powers generated by Th1–Th5, by the nuclear unit, and by the solar unit during 24 h. In Figure 6 are shown the total minimal costs for the powers from the solar (power unit 1), the nuclear (power unit 2), and the five thermal units (numbered as power units 3, 4, 5, 6, and 7) during 24 h.

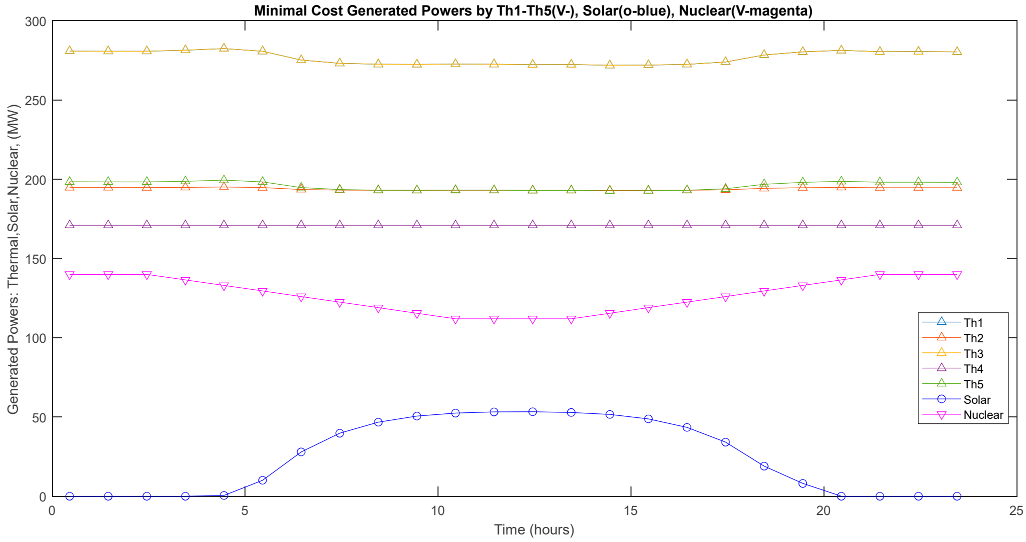

Figure 5. Scenario 1. Minimal cost powers generated by the five thermal units Th1–Th5, by the solar unit, and by the nuclear power unit during 24 h. The power generated from Th1 and Th3 are equal, shown superposed. The power of Th2 is equal to Th5 between the hours of 6:45 a.m. and 17:45 p.m. The power of Th4 is equal to the minimum limit of operation $P_{4,\min}$.

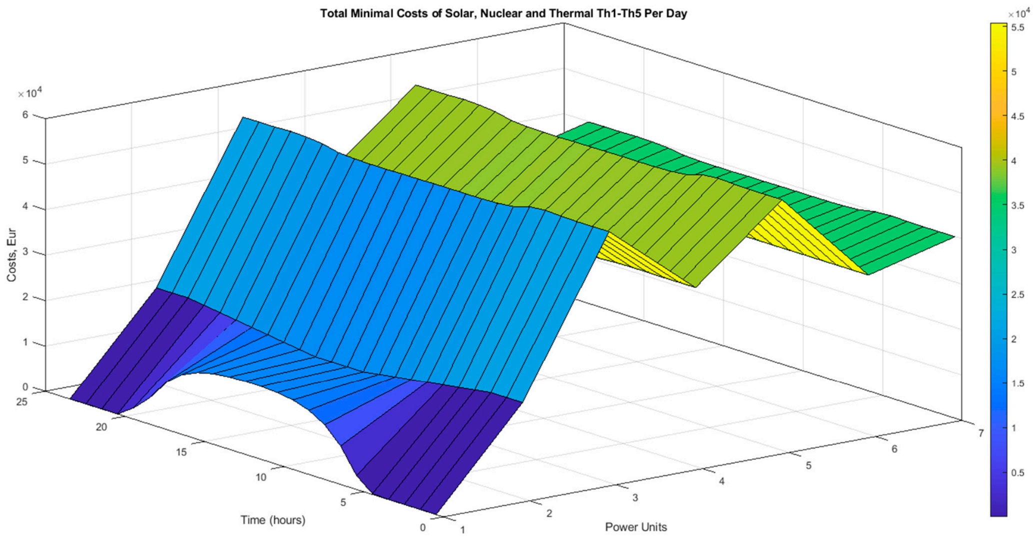

Figure 6. Scenario 1. Total minimal costs of power generated by the solar unit (power unit 1), nuclear unit (power unit 2), and five thermal units (power units 3, 4, 5, 6, and 7) during 24 h.

4.2. Scenario 2: Load Following in a Hybrid System with One Variable Output Solar Unit and Five Varying Output Thermal Units with the Nuclear Unit Disactivated

The minimal cost power generated by Th1–Th versus lambda is shown in Figure 7. The solar unit is enabled. The nuclear unit is disabled. The computed optimal value of λ_λ changes from 188.3 to 189.2.

In Figure 8 is shown the minimal cost power generated by Th1–Th5 and by the solar unit over 24 h. The nuclear unit is disabled. Th1 operates at $P_1 = P_{1,\max}$, Th3 at $P_3 = P_{3,\max}$, and Th4 operates at $P_4 = P_{4,\min}$.

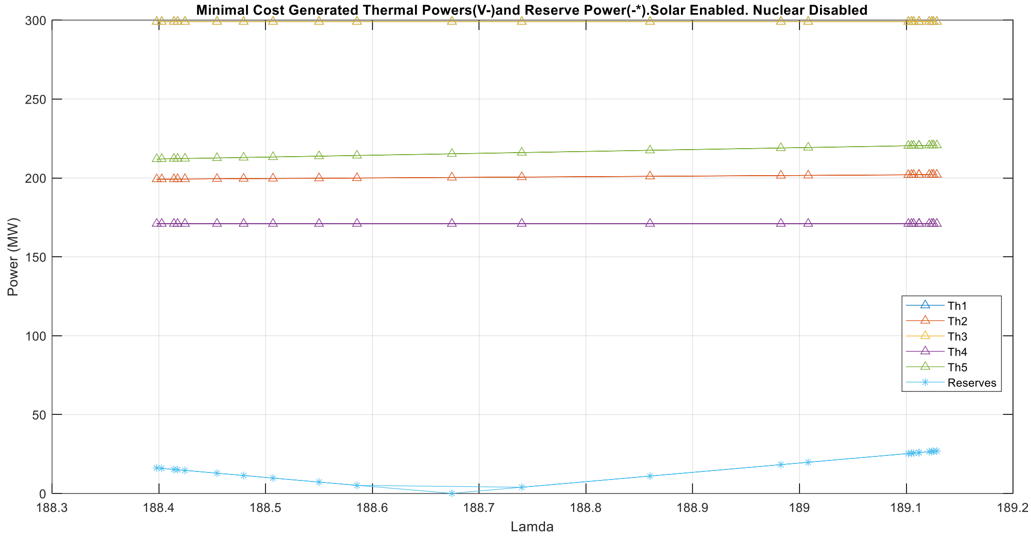

Figure 7. Scenario 2. The minimal cost powers generated by Th1–Th5 versus lambda (Th1 blue, Th2 red, Th3 yellow, Th4 magenta, Th5 green) and reserves of power (light blue with *) during 24 h. The solar unit is enabled. The nuclear unit is disabled. The optimal value of λ_λ increases from λ_λ = 188.3 to λ_λ = 189.2. The power outputs of Th1 and Th3 are equal and shown superposed.

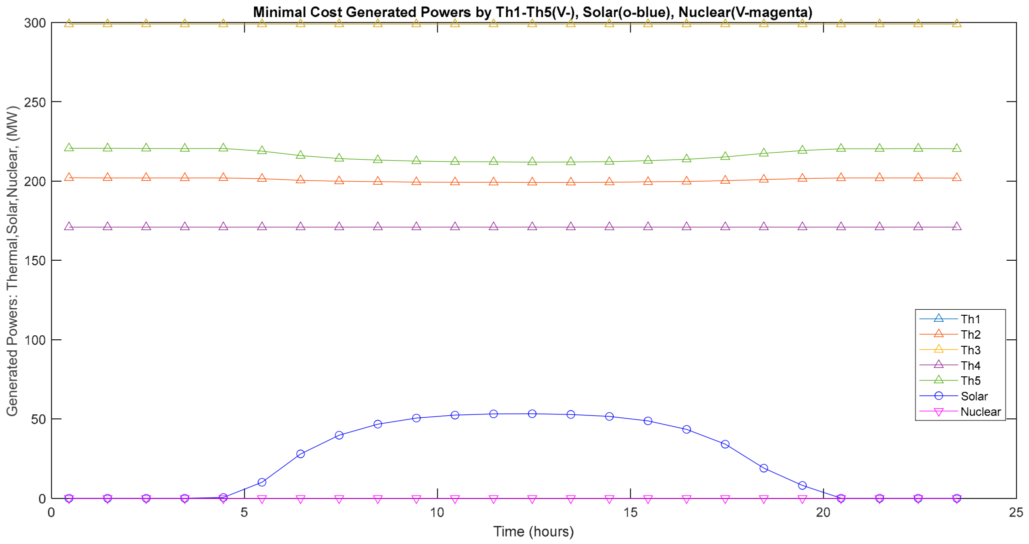

Figure 8. Scenario 2. Minimal cost powers generated by Th1–Th5 and by the solar unit over 24 h. The nuclear unit is disabled. The thermal unit Th1 operates at $P_1 = P_{1,\max}$, Th3 at $P_3 = P_{3,\max}$, and Th4 at $P_4 = P_{4,\min}$. The power outputs of Th1 and Th3 are equal and shown superposed.

In Figure 9 are shown the total minimal costs for generated power from the solar (power unit 1) and the five thermal units (numbered as power units 3, 4, 5, 6, and 7) during 24 h. The nuclear unit (power unit 2) is disabled.

4.3. Scenario 3: Load Following in a System with the Five Thermal Units Activated Where the Nuclear Unit and the Solar Unit Are Disabled

In Figure 10 is plotted the minimal cost power generated by Th1–Th5 and the reserves of power versus lambda. The nuclear unit and the solar unit are disabled.

In Figure 11 is shown the minimal cost power generated by Th1–Th5 during 24 h. The nuclear unit and the solar unit are disabled. The results show that the thermal unit Th1 operates at $P_1 = P_{1,\max}$, Th3 at $P_3 = P_{3,\max}$, and Th4 generates at $P_4 = P_{4,\min}$.

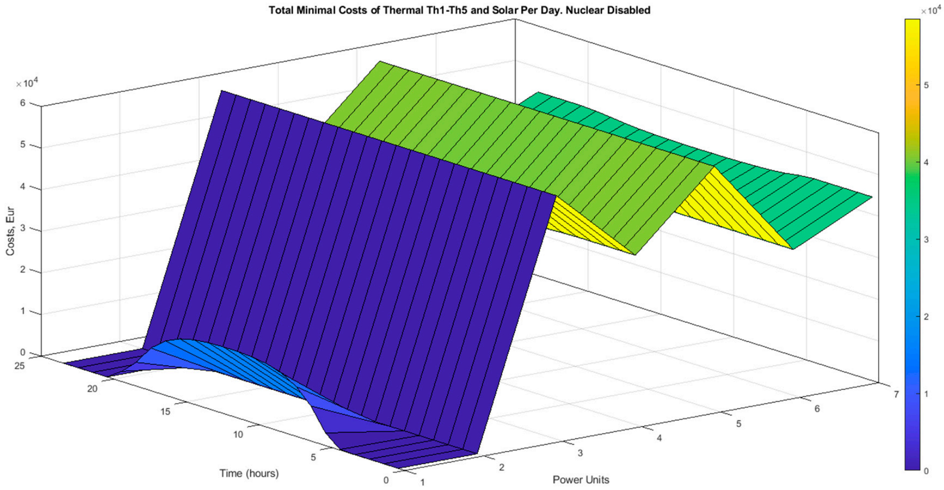

Figure 9. Scenario 2. Total minimal costs of generated power from the solar (power unit 1) and five thermal units (power units 3, 4, 5, 6, and 7) during 24 h. The nuclear unit (power unit 2) is disabled.

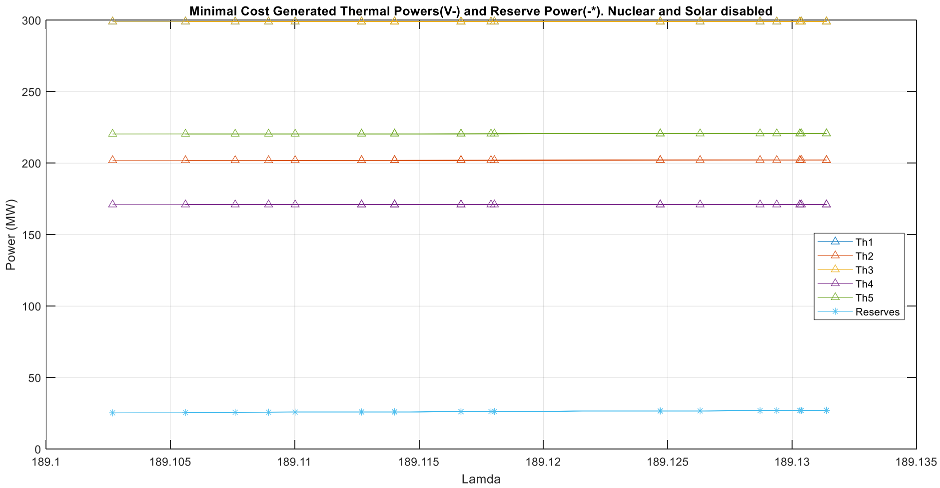

Figure 10. Scenario 3. The minimal cost powers generated by Th1–Th5 and the reserves of power versus lambda (Th1 blue, Th2 red, Th3 yellow, Th4 magenta, Th5 green, reserves light blue with *) during 24 h. The nuclear unit and the solar unit are disabled. The optimal values of λ_λ increase from λ_λ = 189.10 to λ_λ = 189.135. The power outputs of Th1 and Th3 are equal and shown superposed.

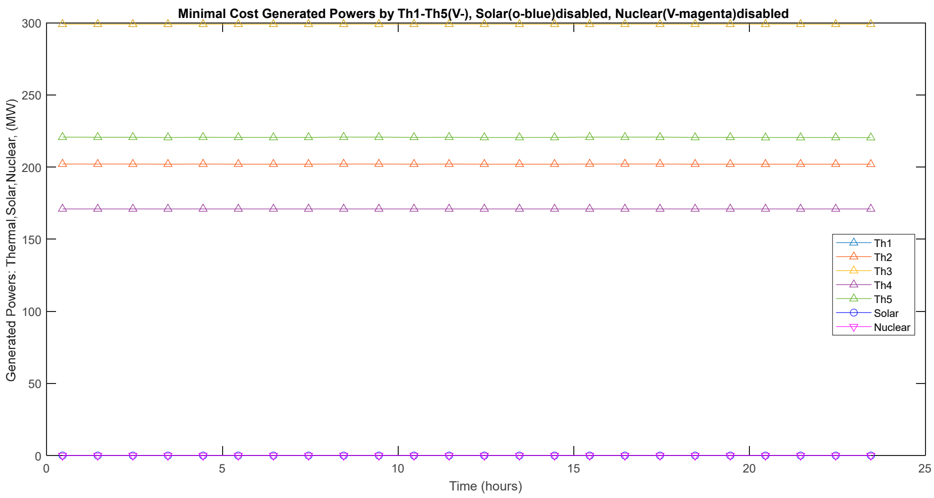

Figure 11. Scenario 3. Minimal cost powers generated by Th1–Th5 over 24 h. The nuclear unit is disabled. The solar unit is disabled. The thermal unit Th1 operates at $P_1 = P_{1,\max}$, Th3 at $P_3 = P_{3,\max}$, and Th4 at $P_4 = P_{4,\min}$. The power outputs of Th1 and Th3 are equal and shown superposed.

In Figure 12 are shown the total minimal costs for the generated power from the five thermal units Th1–Th5 (numbered as power units 3, 4, 5, 6, and 7) during 24 h. The solar unit (power unit 1) is disabled. The nuclear unit (power unit 2) is disabled.

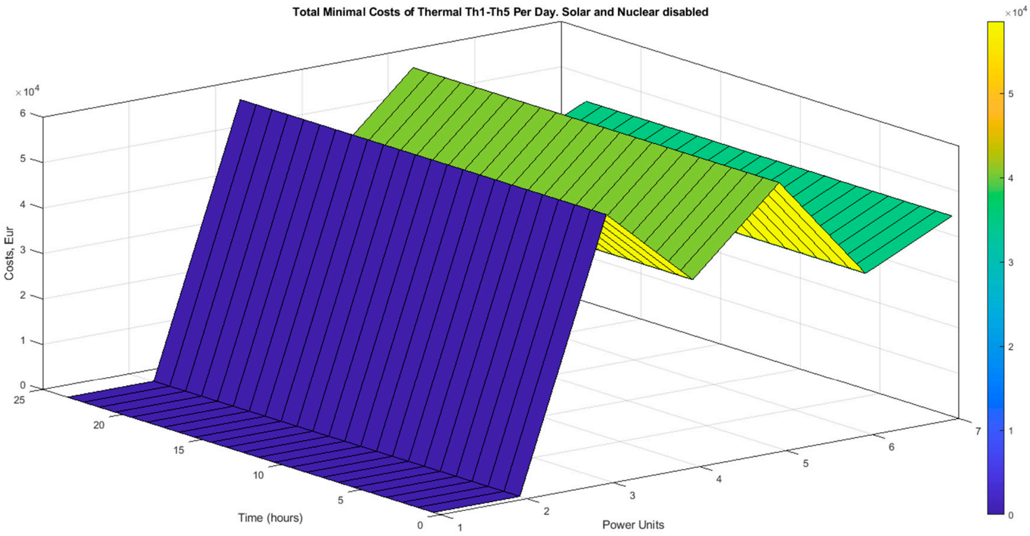

Figure 12. Scenario 3. Total minimal costs of generated powers from the five thermal units (power units 3, 4, 5, 6, and 7) during 24 h. The solar unit (power unit 1) and the nuclear unit (power unit 2) are disabled.

5. Results and Discussion

The three scenarios examined are as follows: in Scenario 1, the hybrid system operates with thermal units Th1–Th5 activated, the solar unit activated, and the nuclear unit activated; in Scenario 2, the thermal units Th1–Th5 are activated, the solar unit is activated, and the nuclear unit is deactivated; in Scenario 3, the thermal units Th1–Th5 are activated while both the nuclear and solar units are deactivated. The operation of Scenario 3 is considered the baseline case for the study, and all relevant results will be compared with those from the scenarios where the nuclear or solar units are activated (Scenarios 1 and 2).

The same data and parameters are used to solve the operational conditions and to compare the results obtained from the three scenarios: the initial data for the thermal units, the data for the solar system, the data for the nuclear system, and the varying load, as examined previously in Sections 3 and 4, as well as the data from Appendix A.

For the three scenarios and the varying electrical loads from Figures 2, 3, 6 and 9 illustrate the minimum cost power produced by the thermal units Th1–Th5 for small variations of λ over a 24 h period. The power output from the solar and nuclear units is unaffected by this regulation. Regarding power generation over time during the 24 h for the three scenarios and the same total variable loads from Figures 2, 5, 8 and 11 show the minimum cost power generated with constraints, respectively, from the nuclear unit, the solar unit, and the activated thermal units Th1–Th5 (Figure 5); from the solar unit and the activated thermal units Th1–Th5 (Figure 8); and solely from the activated thermal units Th1–Th5 (Figure 11).

In Scenario 1, (Figures 4 and 5), the power outputs of Th1 and Th3 are equal. The power of Th2 is equal to the power of Th5 between 6:45 a.m. and 17:45 p.m. The power of Th4 is equal to the minimum limit of operation $P_{4,\min}$. In Scenario 2 and Scenario 3 (Figures 8 and 11), Th1 generates at $P_1 = P_{1,\max}$ and Th3 at $P_3 = P_{3,\max}$, while the power generated by Th4 is equal to the minimum limit of operation $P_4 = P_{4,\min}$.

From Figures 5, 8 and 11, it is clear that in the three scenarios operating under load following, in situations where both the nuclear and solar units are either activated or deactivated, and depending on the variability of solar radiation, the thermal units Th1–Th5 adjust their energy production as needed to follow the electrical load, thereby compensating for the reduction in generation from the nuclear reactor and the solar unit. Furthermore, the application of optimal control to the thermal units situates the thermal unit Th4 at minimal production levels, thus minimizing CO_2 emissions from this energy unit. Figure 13 illustrates the balance of generated power during Scenario 1, from the optimally controlled hybrid system with nuclear–solar–thermal units, along with the generated energy reserves and the total electrical load over a 24 h period.

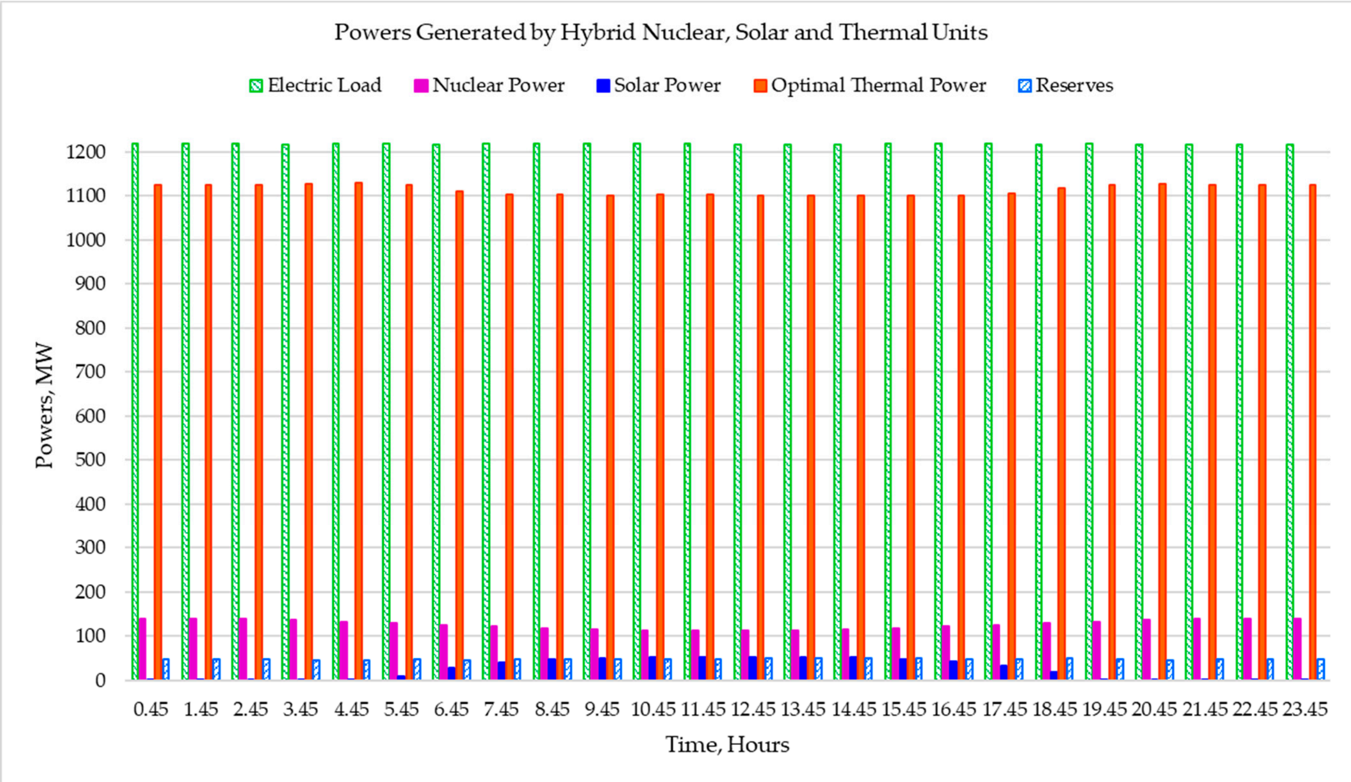

Figure 13. Scenario 1. Powers generated by hybrid nuclear, solar and thermal system during 24 h.

Figure 14 depicts the balance of generated powers over 24 h for the three scenarios. In Scenario 1, a hybrid nuclear–solar–thermal setup; in Scenario 2, a solar-thermal setup with the nuclear reactor deactivated; and in Scenario 3, thermal units with both the nuclear reactor and the solar unit deactivated. Figure 14 shows the complete picture of the power balance of the hybrid system. The three following figures showing the details of the three kinds of power related to Figure 14 are:

- Figure 15: Power generated by the nuclear reactor in the three scenarios during 24 h. Scenario 1, nuclear reactor enabled; Scenarios 2 and 3, nuclear unit disabled. (Details of Figure 14);
- Figure 16: Power generated by the solar unit in the three scenarios during 24 h. Scenarios 1 and 2, solar unit enabled; Scenario 3, solar unit disabled. (Details of Figure 14);
- Figure 17: Power generated by the five thermal units in the three scenarios during 24 h. Scenarios 1, 2, and 3, all thermal units enabled. (Details of Figure 14).

However, the solar plant's power generation capacity of 50 MW and the nuclear reactor's power generation capacity of 140 MW are low compared to the total power generation of the five thermal plants, which vary between 700 and 1510 MW, with an average value of 1105 MW. For the present study, the operating point of the thermal units that must cover the constant electrical load was selected at 1215.5 MW, or at 55% of the average value, plus the variable electric load between 0.7 and 2.85 MW, thus giving a total load demand varying between 1216.2 and 1218.35 MW. It results that the average power output of the both solar and nuclear plants vary between 15.60 and 15.62% of the power output of the five thermal units.

In Scenarios 2 and 3, where the nuclear reactor is offline, the thermal units Th1–Th5 take on the responsibility of generating the necessary energy to meet the electrical load demand. In this operational state, both in Scenarios 2 and 3, the thermal units Th1 and Th3 operate at their maximum capacity, $P_{1,max}$ and $P_{3,max}$, respectively, while Th4 operates at its minimum capacity $P_{4,min}$. The other two thermal units, Th2 and Th5, increase their production to compensate for the amount of power lost due to the shutdown of the nuclear reactor. These quantities of energy generated are detailed in Table 2(1).

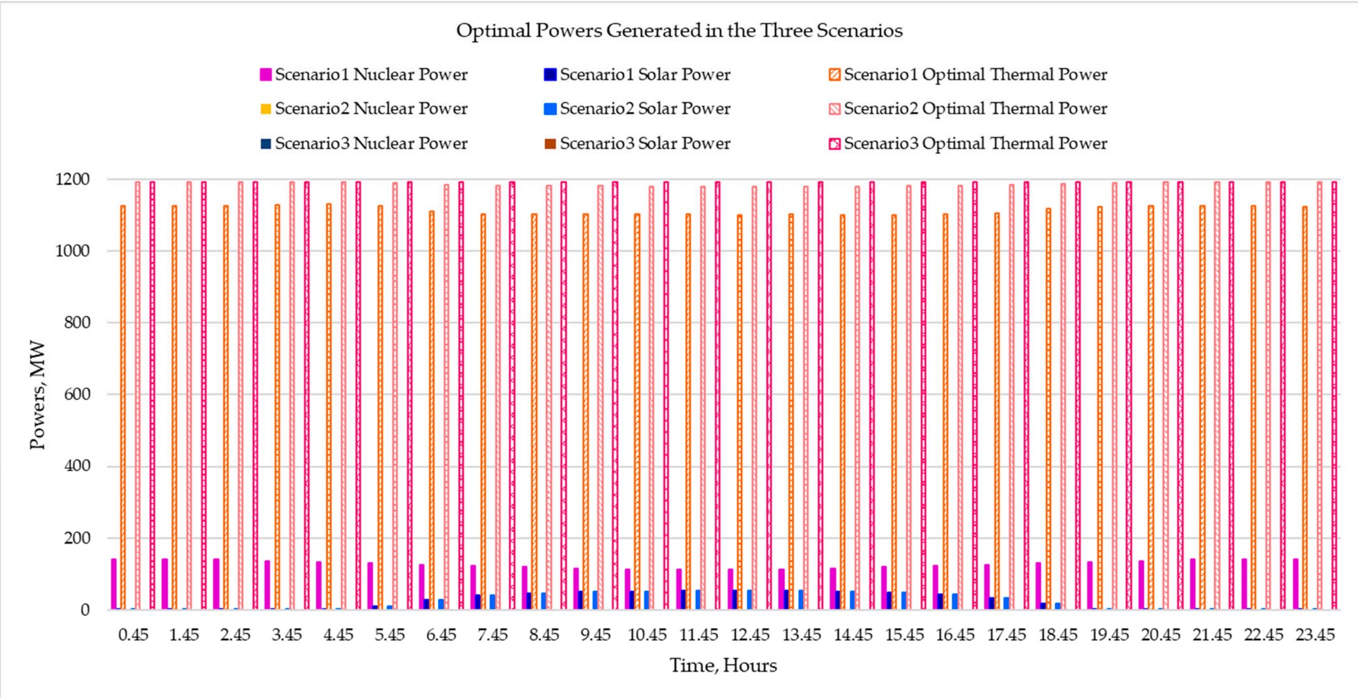

Figure 14. Optimal powers generated in the three scenarios during 24 h.

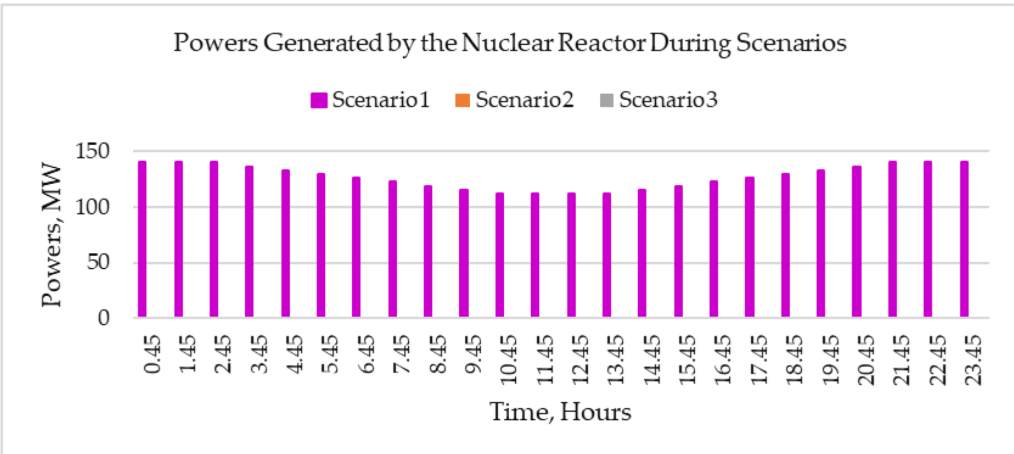

Figure 15. Powers generated by the nuclear reactor in the three scenarios during 24 h. Scenario 1, nuclear reactor enabled; Scenarios 2 and 3, nuclear reactor disabled. (Details of Figure 14).

Table 2. (1). Aggregated results for optimal nuclear–solar–thermal power (Scenario 1), optimal solar–thermal power (Scenario 2), and thermal power (Scenario 3), in load-following mode, during 24 h. (2). Aggregated differences between optimal nuclear–solar–thermal power (Scenario 1), optimal solar–thermal power (Scenario 2), and thermal power (Scenario 3), in load-following mode, during 24 h. The basis for comparison is the optimal thermal power (Scenario 3).

(1)									
24 h	**Nuclear**	**Solar**	**Th1**	**Th2**	**Th3**	**Th4**	**Th5**	**Total Units**	**Total Units %**
Scenario 1. Generated Energy, MWh.	3052	585	6641	4654	6641	4104	4698	30,375	106.21%
Scenario 1. Costs, EUR.	457,800	178,059	130,4574	939,607	1,304,574	840,701	947,334	5,972,647	105.04%
Scenario 1. Cost/Energy EUR/MWh.	150.00	304.34	196.44	201.91	196.44	204.85	201.63	196.63	98.89%
Scenario 1. Operating Constraints.			$P_1 = P_3$	$P_2 = P_5$ 6:45 a.m.–17:45 p.m.	$P_1 = P_3$	$P_{4,\min}$	$P_2 = P_5$ 6:45 a.m.–17:45 p.m.		
Scenario 2. Generated Energy. MWh.	-	585	7176	4818	7176	4104	5200	29,058	101.61%
Scenario 2. Costs. EUR.	-	178,059	1,404,953	970,459	1,404,953	840,701	1,041,525	5,840,650	102.71%
Scenario 2. Cost/Energy EUR/MWh.	-	304.34	195.78	201.43	195.78	204.85	200.31	201.00	101.09%
Scenario 2. Operating Constraints.			$P_{1,\max}$		$P_{3,\max}$	$P_{4,\min}$			
Scenario 3. Generated Energy. Base Values. MWh.	-	-	7176	4849	7176	4104	5294	28,599	100.00%
Scenario 3. Costs, Base Values, EUR.	-	-	1,404,953	976,315	1,404,953	840,701	1,059,403	5,686,325	100.00%
Scenario 3. Cost/Energy. Base Values EUR/MWh.	-	-	195.78	201.35	195.78	204.85	200.10	198.83	100.00%
Scenario 3. Operating Constraints.			$P_{1,\max}$		$P_{3,\max}$	$P_{4,\min}$			
(2)									
Differences	**Nuclear**	**Solar**	**Th1**	**Th2**	**Th3**	**Th4**	**Th5**	**Total Units**	**Total Units %**
Scenarios 1–2. Energy, MWh.	3052	0	−535	−164	−535	0	−501	1317	4.60%
Scenarios 1–2. Costs, EUR.	457,800	0	−100,380	−30,852	−100,380	0	−94,192	131,997	2.32%
Scenarios 1–2. Costs/Energy, EUR/MWh.	150.00	0	0.66	0.48	0.66	0	1.32	−4.37	−2.20%
Scenarios 1–3. Energy, MWh.	3052	585	−535	−195	−535	0	−596	1776	6.21%
Scenarios 1–3. Costs, EUR.	457,800	178,059	−100,380	−36,708	−100,380	0	−112,070	286,322	5.04%
Scenarios 1–3. Costs/Energy, EUR/MWh.	150.00	304.34	0.66	0.56	0.66	0	1.53	−2.2	−1.11%
Scenarios 2–3. Energy, MWh.		585	0	−31	0	0	−95	459	1.61%
Scenarios 2–3. Costs, EUR.		178,059	0	−5856	0	0	−17,878	154,325	2.71%
Scenarios 2–3. Costs/Energy, EUR/MWh.		304.34	0	0.08	0	0	0.21	2.17	1.09%

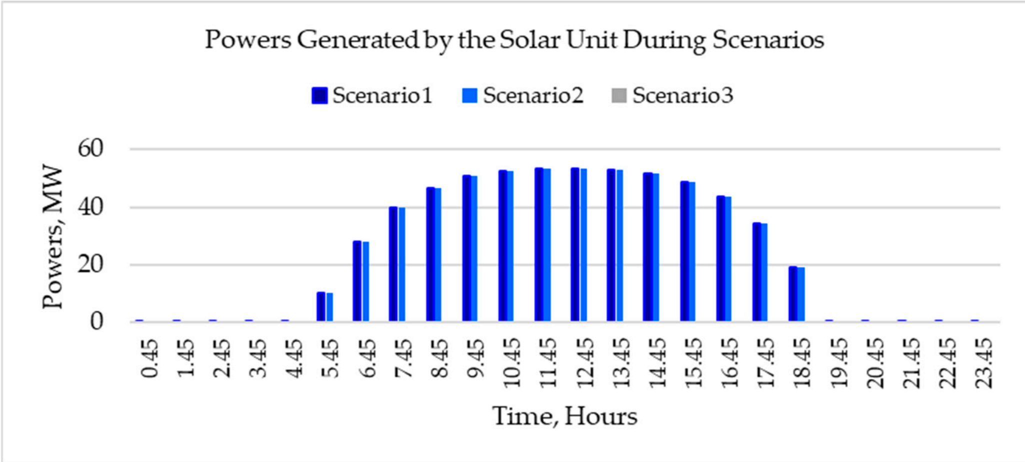

Figure 16. Power generated by the solar unit in the three scenarios during 24 h. Scenarios 1 and 2, solar unit enabled; Scenario 3, solar unit disabled. (Details of Figure 14).

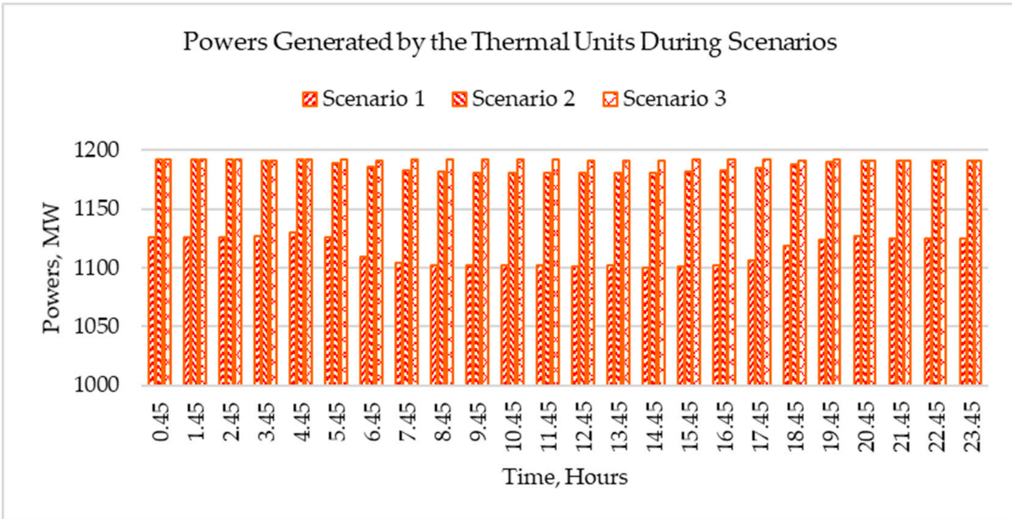

Figure 17. Power generated by the five thermal units in the three scenarios during 24 h. Scenarios 1, 2, and 3, thermal units enabled. (Details of Figure 14).

Table 2(1) shows the aggregated results for optimal nuclear–solar–thermal power (Scenario 1), optimal solar–thermal power (Scenario 2), and thermal power (Scenario 3) in load-following mode during 24 h. The basis for comparison is the optimal thermal power (Scenario 3). Table 2(2) shows aggregated differences between optimal nuclear–solar–thermal power (Scenario 1), optimal solar–thermal power (Scenario 2), and thermal power (Scenario 3) in load-following mode during 24 h. The basis for comparison is the optimal thermal power (Scenario 3). Table 2(1) consolidates the obtained results from the described method for Scenarios 1, 2, and 3 and electric loads during 24 h. Specifically, for Scenario 1, (hybrid nuclear–solar–thermal) the results are shown in the rows titled "Generated Energy, MWh", and "Costs, EUR". The results computed for Scenario 2 (solar and thermal units activated, nuclear reactor disabled) are shown in the rows titled "Generated Energy, MWh" and "Costs, EUR".

The obtained results from Scenarios 1, 2, and 3 are compared, and the differences from enabling/disabling the nuclear reactor and the solar unit for power production and minimization of costs, respectively, are shown in the rows "Differences: Scenarios 1–2", "Differences: Scenarios 1–3", "Differences: Scenarios 2–3" in Table 2(2).

The results in Table 2(1) show that Th4 will operate at the minimum limit of power $P_{4,\min}$, and is not affected by the enabling or the disabling of the nuclear reactor and solar unit. Therefore, the thermal units Th2 and Th5 work at equal levels $P_{2,\min} \leq P_2 \leq P_{2,\max}$ and $P_{5,\min} \leq P_5 \leq P_{5,\max}$, respectively. In Scenario 1 (Figure 5), the power outputs of Th1 and Th3 are equal. The power of Th2 is equal to the power of Th5 between 6:45 a.m. and 17:45 p.m. (with sunshine). The power output of Th4 is equal to the minimum limit of operation $P_{4,\min}$. However, operation of Th4 at $P_{4,\min}$ saves on emissions of CO_2.

The results regarding the minimum average energy cost (EUR/MWh) and the minimum average power cost (EUR/MW) per generating unit for all three scenarios are presented in Table 3(1,2). The average minimum power cost generated by the hybrid nuclear–solar–thermal system is 8.19 EUR/MW (Scenario 1), which is lower than the average minimum power cost generated by the solar–thermal system at 8.37 EUR/MW (Scenario 2), and it is also lower than the average minimum power cost produced by the thermal system at 8.28 EUR/MW (Scenario 3). Thus, the cost of 8.28 EUR/MW for one MW of power generated by the thermal-lignite system is lower than the cost of 8.37 EUR/MW for one MW of power generated by the solar–thermal system, and higher than the cost of 8.19 EUR/MW for one MW of power generated by the hybrid nuclear–solar–thermal system. Correspondingly, the energy cost produced by the hybrid nuclear–solar–thermal system at 196.63 EUR/MWh (Scenario 1) is lower than the energy cost produced by the thermal system at 198.83 EUR/MWh (Scenario 3), and ultimately it is lower than the energy cost produced by the solar–thermal system at 201.00 EUR/MWh (Scenario 2).

Table 3. (1). Minimal Mean Costs of Energy (per MWh) and Minimal Mean Costs of Power (per MW), per each generating unit and per all seven power units for the three scenarios. Load following during 24 h. (2). Differences of Minimal Mean Costs of Energy (EUR/MWh) and Minimal Mean Costs of Power (EUR/MW) per each generating unit and per all seven power units for the three scenarios. Load following during 24 h.

(1)									
24 h	**Nuclear**	**Solar**	**Th1**	**Th2**	**Th3**	**Th4**	**Th5**	**All Units**	**All Units %**
Scenario 1. Mean Cost of Energy per MWh, EUR/MWh	150.00	304.34	196.44	201.91	196.44	204.85	201.63	196.63	98.89%
Scenario 1. Mean cost of power per MW, EUR/MW	6.25	12.68	8.19	8.41	8.19	8.54	8.40	8.19	98.89%
Scenario 2. Mean Cost of Energy per MWh, EUR/MWh		304.34	195.78	201.43	195.78	204.85	200.31	201.00	101.09%
Scenario 2. Mean cost of power per MW, EUR/MW		12.68	8.16	8.39	8.16	8.54	8.35	8.37	101.09%
Scenario 3. Mean Cost of Energy per MWh. Base Values. EUR/MWh			195.78	201.35	195.78	204.85	200.10	198.83	100.00%
Scenario 3. Mean cost of power per MW. Base Values. EUR/MW			8.16	8.39	8.16	8.54	8.34	8.28	100.00%
(2)									
Differences	**Nuclear**	**Solar**	**Th1**	**Th2**	**Th3**	**Th4**	**Th5**	**All Units**	**All Units %**
Scenarios 1–2. Mean Cost of Energy per MWh, EUR/MWh	150.00	0.00	0.66	0.48	0.66	0.00	1.32	−4.37	−2.20%
Scenarios 1–2. Mean cost of power per MW, EUR/MW	6.25	0.00	0.03	0.02	0.03	0.00	0.06	−0.18	−2.20%
Scenarios 1–3. Mean Cost of Energy per MWh, EUR/MWh	150.00	304.34	0.66	0.56	0.66	0.00	1.53	−2.20	−1.11%
Scenarios 1–3. Mean cost of power per MW, EUR/MW	6.25	12.68	0.03	0.02	0.03	0.00	0.06	−0.09	−1.11%
Scenarios 2–3. Mean Cost of Energy per MWh, EUR/MWh	-	304.34	0.00	0.08	0.00	0.00	0.21	2.17	1.09%
Scenarios 2–3. Mean cost of power per MW, EUR/MW	-	12.68	0.00	0.00	0.00	0.00	0.01	0.09	1.09%

Also, a hybrid solar–thermal power system with fossil fuels increases the minimum cost per one MW, and also per one MWh, compared to electricity generation from fossil fuels. The energy costs of the hybrid system can be partially improved if reserves of power are taken into account (as in Figures 4, 7, 10 and 13). These reserves of power could be either stored in battery storage systems and later supplied to consumers or sent to other hybrid grids when there are solar irradiation shortage situations. However, the cost of energy and power generated by hybrid solar–thermal systems is higher than the cost of energy and power generated by hybrid nuclear–solar–thermal systems, Table 3(1,2).

From this comparative study it can be concluded that the cost of producing coal-based electricity is higher than the cost of producing electricity from the hybrid nuclear–solar–thermal system and is lower than the cost of producing electricity from the hybrid solar–thermal system.

Nuclear power is more cost-efficient in reducing CO_2 emissions compared to renewable energy [81]. It is expected that by 2030, renewable energy technologies like wind and solar will offer a lower average cost of producing electricity over the plant's lifetime in G20 countries, making them competitive with nuclear [82]. Furthermore, the external costs related to health, accidents, and waste disposal are typically higher for nuclear energy compared to renewables, which, despite intermittency, have a minimal environmental footprint.

These analyses [56,57] emphasize the sensitivity of SMR economic feasibility to factors like discount rates, market electricity prices, and carbon taxes. Additionally, sensitivity analysis demonstrates that SMR project viability is influenced by financing structures, with higher equity shares increasing the LCOE significantly [61,83].

As expected, recent developments in technologies that generate new knowledge have influenced research and education in energy engineering [84], aiming to develop innovative skills and enhance the future career prospects of engineering graduates and researchers [85,86]. Publications like this one, which combine mathematics, control systems, power systems, and economics, attract readers to seek out new scientific ideas [87,88]. Thus, the new knowledge generated from this research, along with software for solving hybrid energy problems, can become accessible for education and research in the energy sector.

6. Conclusions

The development of this method for the economic optimization of electricity generated by hybrid nuclear–solar–thermal systems creates new knowledge for scientists, which includes the following:

The method optimizes the cost of electricity production from hybrid nuclear–solar–thermal systems, utilizing power units that have different sizes, operational constraints, different fuels, fluctuating fuel prices, and operate in electrical load-following mode.

The mathematical model and algorithm developed determine the optimal economic cost of electricity production. To achieve the optimal operating point, it is necessary to identify the production units that have adjusted their operation to either minimum or maximum power, as well as those operating between their minimum and maximum capacities. As a result, alongside minimizing the operational cost of the hybrid nuclear–solar–thermal energy system, a thermal unit was set to its minimum operating power, which simultaneously led to a reduction in the corresponding carbon dioxide emissions.

Fuel costs influence the minimum cost production of energy and power for all units. The introduction of a hybrid system combining nuclear, solar, and thermal energy results in lower costs compared to the use of fossil fuels, or even a combination of solar and thermal energy. Achieving minimum costs depends on system parameters such as load demand, operational constraints, power balance, solar data, and nuclear data.

For this reason, multi-criteria decision-making methods must be applied to realize the benefits of cleaner electricity with lower emissions, while simultaneously minimizing production costs. This research enhances science and technology in the energy industries and supports researchers in solving economic optimization problems using multi-criteria decision-making and management methods.

Investigating the sensitivity of fuel costs in the economic analysis of hybrid energy systems could be a subject for future research. Additionally, studying the sensitivity of carbon taxes to changes in the overall cost of hybrid energy systems may also be another area for future investigation. Both studies would focus on designing the hybrid system model based on cost sensitivity.

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Appendix A

In Table A1 are the data of the nuclear reactors [8]. In Table A2 are the data of one solar power system [78]. In Table A3 are the data of five thermal units selected from the Greek power system [48,49]. In Table A4 are the cost coefficients used in the economic analysis.

Table A1. Technical data of the SMR [8].

Power:	140 MWe
Efficiency:	45%
Main Temperature:	585 °C
Reheat Temperature	585 °C
Reactor Outlet Temperature:	650 °C
Fuel Enrichment Level:	19.75%
Intermediate Salt:	"Solar"/Nitrate Salt
Refueling Type:	Online

Table A2. Technical and economic data of the solar power unit [78].

Technology	Parabolic Trough
Power Cycle	Steam Rankine
Nominal capacity	50 MW
Generation	97 GWh/year
Latitude/Longitude of Location (°)	39°24′/3°47′
Solar Field Aperture Area	300,000 m^2
Number of Solar Collectors (SCs)/Number of Loops/ SCs per Loop/Modules per SC	360/90/4/12
SC Length	150 m
Total Construction Cost/Specific Cost (2020)	215 M EUR/6070 EUR/kW
PPA or Tariff Period	25 Years
LCOE (2020)	0.27 EUR/kWh
Operation and Maintenance (O&M)	1.5 (% of investment cost per year)

Table A3. Technical data of thermal units Th1–Th5 [48,49].

Thermal Units	$P_{i,\min}$ (MW)	$P_{i,\max}$ (MW)	Heat Rates			Locations [89]
			$H_{i,2}$	$H_{i,1}$	$H_{i,0}$	
Th1	120	300	0.00025	1.64	44.20	Kardia 1–2
Th2	120	300	0.00122	1.31	73.20	Kardia 3–4
Th3	120	300	0.00025	1.64	44.20	Ptolemaida 4
Th4	170	300	0.00022	1.73	31.00	Agios Dimitrios 1–2
Th5	170	310	0.00040	1.63	42.50	Agios Dimitrios 3–4
Totals	700	1510				
Average Value/Operating point (MW)	1105/1215.5					

Table A4. Cost coefficients for lignite, solar, and nuclear generation used in the economic analysis.

Cost rate of lignite	105 EUR/Gcal
Solar unit cost coefficient	300 EUR/MW
Nuclear unit cost coefficient	150 EUR/MW

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