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A New Path towards Sustainable Energy Transition: Techno-Economic Feasibility of a Complete Hybrid Small Modular Reactor/Hydrogen (SMR/H2) Energy System

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Abstract: Small modular reactors (SMRs) are nuclear reactors with a smaller capacity than traditional large-scale nuclear reactors, offering advantages such as increased safety, flexibility, and cost-effectiveness. By producing zero carbon emissions, SMRs represent an interesting alternative for the decarbonization of power grids. Additionally, they present a promising solution for the production of hydrogen by providing large amounts of energy for the electrolysis of water (pink hydrogen). The above hint at the attractiveness of coupling SMRs with hydrogen production and consumption centers, in order to form clusters of applications which use hydrogen as a fuel. This work showcases the techno-economic feasibility of the potential installation of an SMR system coupled with hydrogen production, the case study being the island of Crete. The overall aim of this approach is the determination of the optimal technical characteristics of such a system, as well as the estimation of the potential environmental benefits, in terms of reduction of CO_2 emissions. The aforementioned system, which is also connected to the grid, is designed to serve a portion of the electric load of the island, while producing enough hydrogen to satisfy the needs of the nearby industries and hotels. The results of this work could provide an alternative sustainable approach on how a hydrogen economy, which would interconnect and decarbonize several industrial sectors, could be established on the island of Crete. The proposed systems achieve an LCOE between EUR 0.046/kWh and EUR 0.052/kWh while reducing carbon emissions by more than 5 million tons per year in certain cases.

Keywords: small modular reactors; pink hydrogen; decarbonization

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1. Introduction

In order to combat climate change and pave the way for a society that has a low impact on the environment, the simultaneous use of nuclear energy, renewable energy, and hydrogen is of utmost importance. These three pillars provide complementary approaches to decarbonize different industries and reduce greenhouse gas emissions.

A low-carbon future requires the use of renewable energy sources like solar and wind, since they offer a plentiful supply of carbon-free energy, lowering reliance on fossil fuels and helping to reduce greenhouse gas emissions. Also, electrolysers can be directly powered by renewable sources, enabling the production of green hydrogen. When used as a fuel or energy source, this renewable hydrogen may replace fossil fuels in a number of industries and heating systems, considerably decreasing carbon emissions and assisting in the shift to a hydrogen-based economy [1].

A clear pathway to a sustainable and climate-friendly future is provided by the combination of nuclear energy, renewable energy sources, and hydrogen. The significance of the use of hydrogen is easily understood once one takes into account the challenge of lowering carbon emissions from industrial processes, which are otherwise hard to decarbonize. In particular, green hydrogen or pink hydrogen (produced by nuclear energy-powered electrolysis) can be thought of as a necessary link between renewable and low-carbon energy and heavy or light industry [2]. This all-encompassing strategy not only promotes deep decarbonization but also the construction of a hydrogen economy, opening up fresh possibilities for economic development, job creation, and energy security.

In searching for safer and more environmentally friendly alternatives for energy generation, small modular reactors (SMRs) have come to light as a possible answer to the above-mentioned problems. SMRs are cutting-edge nuclear power facilities that, in terms of size, design, and operating flexibility, are very different from conventional large-scale reactors. The benefits of this new generation of reactors include improved safety measures, lower construction and operating costs, more scalability, and more flexibility in deployment [3,4].

According to Schaffrath et al., the newer SMR designs are such that their major components can be potentially mass-produced in production lines and transported on site more conveniently, decreasing the overall cost arising from the logistics of transportation. PWR designs are also being approached in a way that would lead to their modularization, by optimizing the design of their components and creating integrated systems [5].

Currently, there are many SMR projects under development in countries such as Argentina, China, and Russia, where different technologies will be examined [6]. Potential designs include offshore underwater SMRs which are believed to show a higher degree of safety, since they are better suited against earthquakes and tsunamis and have superior passive cooling systems compared with land-based SMRs [7,8]. Other potential solutions include micro-reactors which have a power output between 1–20 MWe and showcase advantages closely linked to their small size, simple layout, and relatively quick installation process. However, according to Testoni et al. (2021), they also have drawbacks such as limited fuel availability, heightened security, and proliferation process [9].

In order to assess the suitability of SMR–hydrogen systems, there exists the need to simulate how they can be integrated in the context of medium/large grids. As a result, a suitable location for such an endeavor had to be examined, which led to choosing the island of Crete as a case study. Although currently grid-connected with mainland Greece, the island presents an interesting case study as a standalone system and as a result, it was examined as such. This enables easy comparison with similar systems that share common characteristics with Crete. Furthermore, the presence of an abundance of data for this case study played an additional role in choosing it for this analysis.

With a population of 623,065, the case study considered (the island of Crete) is the largest Greek island and the fifth-largest island in the Mediterranean Sea. Due to the inflow of tourists throughout the summer, there is a large rise in population, which raises the need for power. The island has an annual energy consumption of 3.2 TWh and an instantaneous peak demand of 707 MW, and consequently, one could argue that it presents an interesting case study for the installation of an SMR [10]. Additionally, Crete may improve its grid stability, raise energy self-sufficiency, and lessen dependency on imported fossil fuels by using an SMR. More specifically, due to its small size, the reactor can be positioned conveniently close to demand centres like cities or industrial locations. A few benefits of this localization include less transmission loss and enhanced grid resilience. Additionally, an SMR may offer the island a dependable and low-carbon base load power source that at the same time would help in the diversification of its energy sources, enhancing the already-installed renewable energy sources like wind and solar energy to build a more stable and reliable system.

What should also be taken into consideration is the fact that the installation of an SMR would offer certain financial gains for the nearby communities. Construction, operation, and maintenance jobs would be made available, boosting local employment and economic development. At the same time, long-term use of nuclear energy can reduce the uncertainties brought on by changing fossil fuel prices by offering steady and predictable power pricing.

Additionally, the extra heat produced by the SMR may be used for a variety of purposes, including district heating and water desalination. This integrated strategy promotes energy efficiency and lessens the island's dependency on independent energy systems by enabling the efficient and sustainable exploitation of energy resources.

Finally, the construction of a small modular reactor offers a compelling chance to tackle relevant energy issues while advancing sustainable development. In terms of this case study, the installation of an SMR in Crete can increase its energy independence, lower emissions, diversify its energy supply, and promote local economic growth by utilizing the advantages of nuclear energy.

For all the above reasons, the island of Crete was selected as a case study for a techno-economic analysis of a system encompassing both SMR and renewables for the production of hydrogen. This study aims to showcase the techno-economic viability of such systems as well as the potential they have for large-scale decarbonization of energy grids. Also examined in the next paragraphs is the capability of such systems to be integrated into the context of a hydrogen economy, by supplying a large enough quantity of hydrogen to nearby end users.

2. Overview of Small Modular Reactors

SMRs are classified as reactors having a maximum power output usually around 300 MW. Historically, the first SMRs were installed in nuclear submarines in the early 1950s, and since then, a number of different designs have surfaced. Most designs can be classified as integral PWRs, marine-derivative PWRs, BWRs/PHWRs, gas-cooled, lead and lead–bismuth cooled, and sodium-cooled.

Another categorization might split SMRs into two main categories: those for short-term deployment based on established light-water reactor (LWR) technology and those for longer-term deployment based on other, more sophisticated designs [11].

The relatively small size of SMRs may be advantageous in supplying electricity to rural places lacking adequate transmission and distribution networks, but they may also be utilized to provide power locally for larger population centers. SMRs are ideal for supplying electricity to nations with constrained or scattered electric grid systems as well as those with limited financial potential for massive nuclear power plant investments. For industrial complexes, water desalination, and district heating, the majority of the suggested solutions offer a combination of power and process heat.

The most talked-about advantages of SMRs include the following: (1) They seem to be ideal power-generating systems for hard-to-reach areas or areas lacking infrastructure for fuel transportation; (2) their modular concept leads to reduced work on site; (3) they have a long life cycle and reduced need for refueling (possibly every 10–15 years); (4) their design leads to a more straightforward and passively safer operation; (5) a smaller nuclear island and overall footprint; (6) low operating and maintenance expenses, lower initial costs.

What should also be considered regarding SMR safety is the fact that the reduction of the nominal power results in a lower decay power to be removed in a potential accident [12]. An SMRs requires less decay heat to be removed than a bigger reactor, since there is less fuel contained in it. This enhances the possibility of using passive mitigation strategies, contributing also to simplifying the reactor design. Furthermore, SMRs using a passive mitigation method are regarded as an essential design option for deploying nuclear reactor technology, according to the International Atomic Energy Agency (IAEA) [13]. This is because of their built-in safety measures and straightforward designs, which provide benefits such as the potential for streamlined parallel construction, accelerated construction schedules, and lower capital and operating costs [14]. In order to effectively disperse the decay heat over a lengthy period of time following a loss-of-coolant accident (LOCA), certain SMRs are made with natural convection in mind. Consequently, a core meltdown can be avoided even in circumstances of extended station outages, such as those that happened during the Fukushima incident [15].

However, in order for SMRs to be deployable in the near future, the following drawbacks must be eliminated: (1) More research is needed on the economics of SMRs in order to demonstrate potential advantages over LWRs; (2) spent nuclear fuel from SMRs may be situated in isolated locations, making transportation more challenging and additionally, although it is now congregated at a few locations, spent fuel will be dispersed across many more sites; (3) public acceptance of innovative ideas; and (4) obtaining design certification and licensing may take longer than anticipated.

2.1. SMR Economics

Due to the widely held belief that "bigger is better," which is an incorrect application of the economies-of-scale concept, SMRs are typically not seen as being economically competitive with LWRs. According to the principle of economies of scale, the specific capital cost (in terms of EUR/KW_e) of a nuclear reactor decreases with increasing size as a result of the rate reduction of special setup costs in investment activities (such as licensing, siting activities, or civil works to access the transmission network) and the more efficient use of raw materials [16]. Today, however, smaller modular reactors have considerably different designs and properties from their large-scale equivalents, thus, this is no longer the case [17].

In particular, SMRs, by their nature, are designed to be factory-manufactured, transportable and/or re-locatable, and suitable for the production of heat, desalinated water, and other by-products that industrial sectors require [18].

Moreover, small modular reactors (SMRs) are less expensive than bigger reactors, which lowers the financial risks involved in making significant investments, particularly in a market where the price of energy generation from alternative sources may decline [19].

Economy of scale is frequently used to influence the LWR-generating cost structure. Traditional techno-economic assessments demonstrate that as plant size increases, the average investment and operational costs per unit of power decrease. The fact that this finding depends on the phrase "other things being equal" prevents it from being immediately used in investment assessments comparing SMRs to LRs. This notion essentially assumes that SMRs and LRs are identical, with the exception of size. The capital cost of a larger unit is much less than that of a smaller equivalent, even if the design is only slightly altered. Geometrical (volumes grow to the power of 3, while areas and subsequently materials and costs increase to the power of 2) and economic (sharing of fixed or semi-fixed costs, such as licensing for more MW_e) factors are to blame.

Small size and modularity are stated to enable important components to be standardized and produced in sizable quantities on assembly lines, giving the manufacturers greater flexibility in cost learning and control and leading to a sizable reduction in deployment. Small size is said to increase the potential market for SMRs by enabling them to meet much smaller increments of demand and relieving the burden of financing enormous megaprojects. Passive safety design, integration of major systems into a single unit, and below-ground deployment are said to dramatically lower safety concerns and costs. As has already been pointed out, the lower labor costs per MW, which may be addressed by using automation technology, are the main cause of the lower operating costs of bigger power units [20]. Furthermore, in addition to the aforementioned investment benefits, the flexibility provided by the placement and use of SMRs can also help to lower operational expenses.

When cost trends are taken into consideration, the enormous cost disadvantage that nuclear power suffers, regardless of size, is even more obvious [21]. According to certain projections, the fuel costs for SMRs are anticipated to be somewhat higher than those for big reactors [22]. While nuclear prices have escalated and are not anticipated to decrease, renewable technologies have been shown to reduce costs for a few decades [23].

Small reactors are desirable in circumstances when financial resources are constrained or where self-financing is preferable, and they benefit from the idea of "economy of multiples" when constructed consecutively [16]. According to Carelli et al. [24], the integrated design and modularity of small modular reactors (SMRs) can reduce the higher capital, operating, and maintenance costs that are usually connected to the absence of economies of scale. As long as the initial cost of the reactor remains affordable, co-locating SMRs and the anticipated decrease in construction time can also positively affect their economic viability [25].

2.2. SMR in an Integrated System Setting

Currently, the cost of building large storage systems that can handle long-term fluctuations is particularly high. As a result, there is still a need for more controlled sources that can bridge the gap between the supply of renewable energy and the requirement for dynamic load.

Diesel generators are currently the most widely used dispatchable power sources for off-grid areas. High operational expenses are a result of these areas' remoteness and reliance on sporadic roads or water access for fuel delivery. Additionally, there is growing pressure to minimize the use of diesel for the generation of power due to the CO_2, NO_x, and particle emissions from diesel combustion. Hydroelectric systems, natural gas turbines, hydrogen fuel cells, and geothermal systems are dispatchable substitutes for diesel generators in microgrids, and they may have fewer environmental effects than diesel [26].

Due to the SMR market's nascent position and lack of systematic studies, little research has been conducted on the integration of SMRs into renewable energy microgrids. In reality, SMR/renewable microgrids, which offer low-carbon electrical and thermal power, have the potential to replace diesel power sources in isolated communities and mining/industrial applications.

Heavy industry, on-grid applications, and distant settlements are the three possible application areas for SMRs. Due to their small and modular designs, they may be progressively incorporated into a variety of environments and applications, including those that require both electrical and thermal power sources. According to reports, the levelized unit energy cost of diesel ranges from EUR 0.466/kWh to EUR 0.487/kWh, and in certain situations might surpass EUR 0.50/kWh. This cost takes into account capital, operating, and decommissioning expenses.

Due to the high capital cost of facility construction and the cheap fuel cost of large-scale nuclear power plants, these units often run close to their rated output level to sustain the base load. This base load operation means that the power plant operates constantly at its maximum rated capacity, whenever online. However, nuclear power plants have the technological capacity to operate adaptably, enabling them to ramp up or follow loads over time, contribute to frequency control, and maintain operational reserves. There are a number of techniques that may be used to control the electrical output power of the system while keeping the reactor thermal power constant or alternatively to regulate the output power of an SMR in reaction to fast load changes and fluctuations in renewable power. These involve initiating steam bypass, adjusting the feed water flow rate, and adjusting the control rod. The rate of the fission reaction is directly impacted by the control rod motions in terms of thermal power. As many regions transition to low-carbon power networks with higher amounts of variable renewable energy sources like wind or solar power, the significance of flexibility is also growing.

Micro-reactors are described as having an electric power output ranging from one to ten Mwe, according to the US Office of Nuclear Energy [27]. These micro-reactors have been created with the goal of being completely independent, requiring no upkeep, and being portable. They operate as "plug-and-play" devices and are appropriate for localized energy production in isolated communities and commercial locations with modest power requirements. In addition, they may be used to produce hydrogen fuel, desalinate water, and heat districts. Because of their mobility, they can take the place of diesel power generators, which are frequently utilized in off-grid settlements or during emergencies. Additionally, they may be included in micro-grids and used in conjunction with renewable energy sources.

2.3. The Role of Hydrogen Infrastructure

Hydrogen has the potential to be a renewable energy storage solution due to its ability to deliver or store large amounts of energy, provided it is produced in an environmentally friendly manner. A complete energy storage system can be composed of hydrogen production through a hybrid SMR-RES energy system, hydrogen compression and storage, and hydrogen transportation, making it suitable for a broad range of applications across virtually all sectors.

The importance of hydrogen storage and transportation operations is equal to that of production processes and plays a significant role in the hydrogen economy. The primary objective of storing hydrogen energy is to ensure it is safe and efficient for use anytime and anywhere [28].

Just like any other product, hydrogen must be packaged, transported, stored, and transferred from production to final use. The main technological challenge facing a viable hydrogen economy is its storage, and so far, a cost-effective method of storing hydrogen has proven to be an insurmountable challenge. To make hydrogen useful for transportation, it must be made more energy dense, which can be achieved in a number of ways [29].

Achieving high-density hydrogen storage is a significant challenge for stationary, portable, and transportation applications. Currently, available storage options typically involve large-volume systems that store hydrogen in its gaseous form. This is less of a concern for stationary applications where the size of compressed gas tanks is less critical [30].

Compression is a crucial aspect of almost all storage methods for hydrogen and its subsequent usage. Although hydrogen compression is only part of the "hydrogen value chain", it is essential for overcoming the entry barriers to a hydrogen economy. It is widely recognized that significant improvements in the efficiency, durability, and reliability of hydrogen compressors, as well as cost reductions, are needed, especially if the end use is intended for vehicles or fueling stations and involves high hydrogen-purity requirements for transportation and other industrial applications [31–34].

Efficient hydrogen compression is a crucial element in various applications across the hydrogen supply chain, including onsite storage, transport, and dispensing. Moreover, the development of lightweight high-pressure hydrogen storage vessels has resulted in much higher working pressures than before. Currently, diaphragm or reciprocating compressors are typically used at hydrogen fueling stations [35]. However, poor reliability remains a persistent issue, as current design standards assume prolonged operation at peak pressure, which is not representative of forecourt hydrogen compressors' operating conditions. On/off cycling of compressors due to a lack of station demand exacerbates the operating and maintenance costs of in-service compressors. Additionally, the capital cost of commercial hardware remains high due to low production volumes.

An in-depth analysis of the different technological options as well as the state of the art of SMRs, electrolysers, and compressors escapes the scope of this study, which intends to provide an alternative way of approaching large-scale energy systems by combining power systems with hydrogen in order to cover the energy needs of different sectors with as little CO_2 emission as possible. Furthermore, as it will be shown in the following paragraphs, the techno-economic analysis which was conducted does not take into consideration the cost of hydrogen compression. The reason for this is the general approach of the system, which is based on the notion of centralized production of hydrogen. The primary use of hydrogen that demands exceptionally high hydrogen pressure is for automotive applications, which require an elevation of up to 700 bar. Other applications, however, such as industrial uses or its use in fuel cells, require much lower pressure which can be achieved by the electrolyser itself. As a result, it seems unreasonable to internalize the cost of compression to the hydrogen-producing system, just to cover the possibility that the produced hydrogen will be used in vehicles. It thus would make more sense for the cost of compression to burden the hydrogen refueling stations or whoever uses high-pressure hydrogen.

3. Case Study

The analysis presented in the following paragraphs aims to showcase the potential of SMRs for co-generation of power and hydrogen, in the context of a large-scale integrated energy system. The choice of Crete as a case study made sense due to its relatively large energy consumption while being located in an ideal position to become a hydrogen hub. An SMR could play a role in decarbonizing its power grid, while also producing hydrogen by powering an electrolyser. The produced hydrogen could play a role in connecting the power, the industrial sector, and the transportation sector of the island, decreasing greenhouse gas emissions significantly. Also, due to its location between three continents, it could potentially provide an ideal spot for large-scale production and distribution of hydrogen via either offshore pipelines or marine vessels. Furthermore, the abundance of renewable energy sources on the island could mean that hydrogen produced there would be considered green.

Currently, the majority of energy is produced by traditional thermal units, which have high operating costs of EUR 0.15 to 0.20 per kWh due to the usage of costly diesel and heavy fuel oil (HFO) [36].

Up until 2019, the peak yearly energy usage was 676.40 MW. The total installed capacity, which was assessed to be 1076.70 MW, was made up of 0.99 MW of biogas power plants, 200.29 MW of onshore wind, 796.82 MW of thermal energy, and 78.29 MW of solar PV [37].

Crete started using renewable energy sources (RES) in 1998 when the first wind farms were put in place. More than a decade later, in 2010, solar system implementation started. The attained proportion of yearly energy output from RES should be deemed adequate given the limitations imposed by Crete's power system's non-interconnected status prior to June 2021. The permitted installed capacity of RES and the consequent integration of renewable energy into the grid were significantly impacted by these restrictions [38].

It is important to note that the levelized cost of producing electricity in Crete was estimated in 2019 to be EUR 0.127/kWh of variable cost and EUR 0.110/kWh of fixed cost. The particular cost of total power generation in Crete increased significantly to over EUR 0.30/kWh from December 2021 as a result of the sharp rise in the price of fossil fuels on a global scale.

The characteristics of the energy consumption as well as the consumption of fuel in Crete are shown in Table 1 [39].

Table 1. Energy consumption and CO_2 emissions of Crete by sector.

Sector	Annual Energy Consumption (MWh)	Share (%)	CO_2 Emissions (tn)
Electricity Consumption			
Public buildings	237,519	7.43	537,754
Residential buildings	1,064,217	33.28	2,409,441
Primary sector	199,400	6.23	451,453
Industry	220,757	6.9	499,805
Tertiary sector	1,295,020	40.49	2,931,991
Public lighting	55,015	1.72	124,556
Miscellaneous	126,204	3.95	
Sub-total	3,198,132	100	6,954,999

Table 1. *Cont.*

Sector	Annual Energy Consumption (MWh)	Share (%)	CO_2 Emissions (tn)
Fuel used in transportation			
Liquefied petroleum gas (LPG)	51,959	1.3	12,985
Diesel	2,006,359	50.3	582,647
Gasoline	1,929,588	48.4	530,637
Sub-total	3,987,906	100	1,126,268
Heating and other uses in buildings			
Oil burners for indoor space heating	350,687	41.6	101,840
Wood/solid biomass for indoor space heating	60,000	7.1	0
LPG for cooking	272,783	32.3	68,168
Solar water heaters	160,178	18.9	0
Sub-total	843,648	100	170,108

The study which was conducted was separated into three different scenarios. The first examined the use of a grid-connected SMR, which partly serves the electric load of the island, while the system buys and sells power to the grid. The purpose of this scenario is to estimate the economic viability of this system and the identification of instances at which there is the need for additional power in order for the island to have the ability to operate as a standalone system. The SMR is sized at 350 MW of electric power with a capacity factor of 90%. The same is also true for the size and capacity factor of the SMRs in the following scenarios. The second scenario added to the first the possibility of using a renewable energy source in order to achieve an even higher percentage of carbon-free energy sources. More specifically, the examined setups include the use of solar panels, the reason being that most of the wind potential in the mountaintops of Crete has already been exploited, while the installation of offshore wind farms would result in a much more complicated analysis. Finally, the third scenario describes a system which uses a combination of SMR and PV to cover the electric load of Crete, as well as to power an electrolyser in order to produce hydrogen. The electrolyser prioritizes the use of green energy from the PVs in order to produce green hydrogen, and when this is not possible (when the sun does not shine), its power load is covered by the SMR. The produced hydrogen is then stored in tanks or used to cover the daily hydrogen load. The daily hydrogen load has been set to 10 tons per day as a realistic case for the first step towards a hydrogen economy.

The potential uncertainties that can be associated with the systems that are described above are closely linked to the electric and hydrogen loads which will be served. Although the assumptions of slightly higher energy consumption and higher power peaks seem realistic, they are projections and predictions based on the current trends. What should also be mentioned is the fact that the economics of SMRs are not yet fully clear, including capital and operational costs. Furthermore, the complexities which surrounds SMR fuel, more specifically its availability, its fabrication processes, and the waste management strategies, also introduce a number of uncertainties. All the above could lead to significant deviations to the economics of such systems, with direct consequences on their sustainability.

3.1. HOMER Software

The software used for this analysis was HOMER Pro, which provides a tool for the design, optimization, and techno-economic evaluation of energy systems. HOMER gives the user the capability of choosing between a wide range of power production systems, such as wind turbines, solar panels, conventional generators, the grid, and many more, in order to serve the electric load that the system in question aims to cover [40–42].

In addition to electric loads, the software gives the user the capability to serve hydrogen loads, by using electrolysers and reformers, as well as thermal loads by using CHP or other similar infrastructure. HOMER downloads power resource data depending on the site of the system, in order to achieve realistic results regarding how much energy the system can produce. For instance, the solar resource of the system in terms of kWh/m^2/day, as well as the clearness index, is presented in Figure 1.

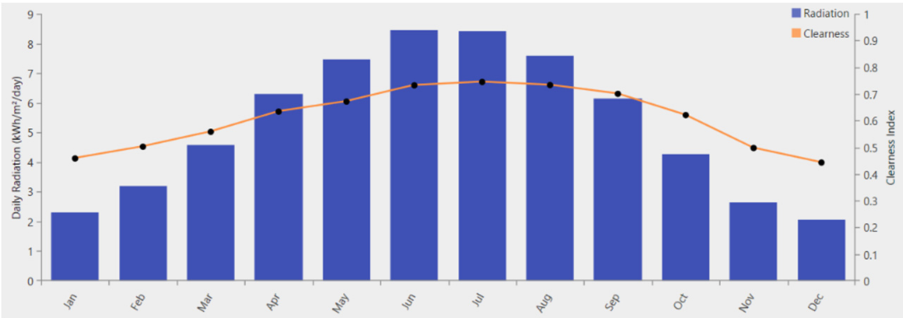

Figure 1. Daily radiation and clearness index of Crete.

Depending on the available resources in the area of installation, HOMER then estimates the power output of the energy-producing units which are installed there. The power output of the *PV* array is estimated using Equation (1):

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}} \right) [1 + a_P (T_C - T_{C,STC})] \quad (1)$$

where Y_{PV} is the rated capacity of the *PV* array (kW), f_{PV} is the *PV* derating factor (%), G_T is the solar radiation incident on the *PV* array (W/m^2), $G_{T,STC}$ is the incident radiation under standard test conditions (i.e., 1000 W/m^2), α_p (%/°C) is the temperature coefficient, T_c (°C) is the *PV* cell temperature, and $T_{C,STC}$ (°C) is the *PV* cell temperature under standard conditions.

The electrolyser output, in terms of kilograms of produced hydrogen per hour, is defined by the efficiency of the electrolyser as well as its rated capacity. While the theoretical efficiency of a PEM electrolyser is over 90%, for the purpose of this study, it was considered to be equal to 80%. This practically means that if 100 kW of power are "given" to the electrolyser, 80 kW will finally be used by it in order to split water molecules into hydrogen and oxygen [43,44].

Since HOMER does not include a nuclear reactor module, the SMR was modelled as a custom component, the characteristics of which are shown in Table 2. The unit produces both electric and thermal energy; thus, it has the ability to serve different loads.

Table 2. Power characteristics of SMR.

Quantity	Value	Units
Nominal power	350	MW_e
Capacity factor	90	%
Thermal output	155	MW_{th}

All three scenarios' techno-economic viabilities were examined by estimating their respective LCOE. HOMER has the capability of determining the system's LCOE by dividing the total annualized costs (capital and operational) by the total electric energy which is produced throughout the year. The optimization of the sizing for the system's components is such that the LCOE is minimized while all the loads are being served.

The algorithm of the operation of the system, in terms of which unit's operation is prioritized, is as follows. The loads that need to be covered are the hourly electricity and hydrogen demands. Hydrogen loads are served by hydrogen produced by the electrolyser or by hydrogen stored in tanks. The electrolyser prioritizes the consumption of electricity produced by the PV panels, and when this is not possible, it consumes electricity from the SMR. If the SMR is occupied in serving the electric load, the electrolyser does not consume grid electricity and the hydrogen load is covered by the stored hydrogen. Electric loads are served first by the SMR and subsequently by the PV panels, while the excess energy that is produced is used to power the electrolyser. If the electrolyser already operates at its rated capacity, the excess electricity is sold to the grid. In case the electric load cannot be served by the installed unit, power is purchased from the grid.

3.2. HOMER Inputs

The following paragraphs describe the process of determining the optimal sizing for a hybrid SMR–renewables energy production system for hydrogen production. The island of Crete is considered as a case study, since it has a large enough power consumption for the installation of an SMR to be justified, while being grid-connected, thus giving the ability to experiment with a broader range of potential system setups. The power consumption characteristics of the island, which were used as input in HOMER, are presented in Table 3 and visualized in Figures 2 and 3. Table 4 sums the cost of each of the different components used in the examined scenarios.

Table 3. Power demand characteristics used in HOMER.

Quantity	Value
Average annual power consumption (GWh)	3198
Daily power consumption (GWh)	8.762
Peak load (MW)	700

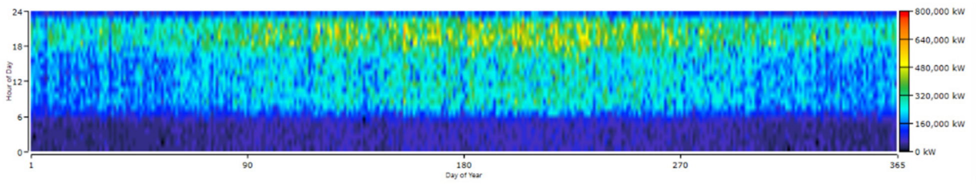

Figure 2. Electricity demand in Crete throughout the year.

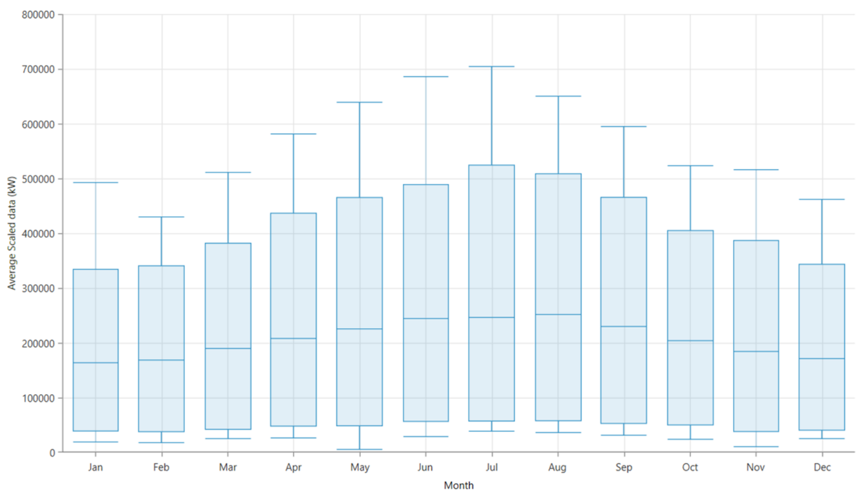

Figure 3. Crete's electricity demand averages and peaks by month.

Table 4. Cost breakdown of the system's components.

Components	Initial Cost	Annual Operating and Maintenance Cost
Electrolyser	EUR 1500/kW	EUR 20/kW
Hydrogen tank	EUR 500/kg	EUR 2/kg
PV panels	EUR 1500/kW	EUR 10/kW
Converter	EUR 300/kW	EUR 2/kW
SMR	EUR 3000/kW	EUR 0.0161/op.hour

4. Results and Discussion

4.1. Grid-Connected SMR System

The first system that was examined was a grid-connected SMR, the architecture of which is shown in Figure 4.

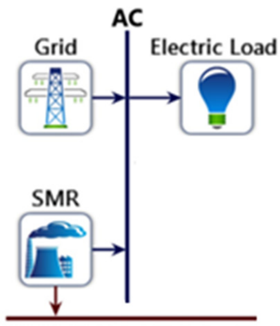

Figure 4. System architecture.

During periods of low energy demand, which for this case study coincide with winter and autumn, the SMR can serve the electric load most of the time. When excess energy is produced, it is sold to the grid. Figures 5 and 6 show heat maps of when energy is purchased and sold from and to the grid.

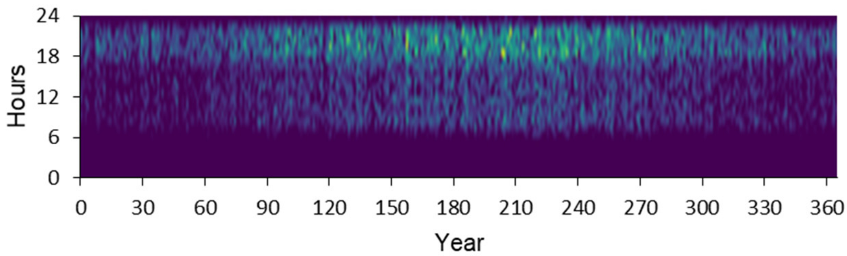

Figure 5. Energy purchased from grid (kW).

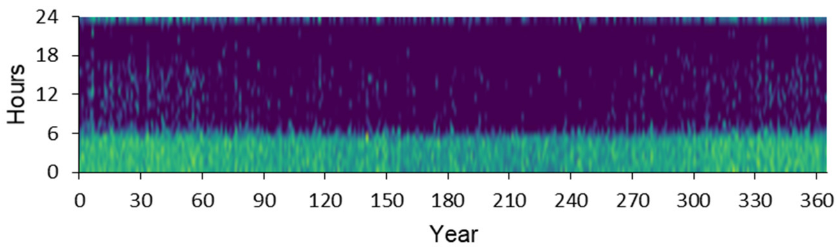

Figure 6. Energy sold to grid (kW).

Thus, it becomes evident that during the night hours when the energy demand is low, there is excess energy to be sold to the grid. During the spring and summer, there is an increase in energy consumption due to the tourist waves on the island, which lead to the need to purchase power from the grid, especially during the evening hours. As shown in Table 5, 74% of the year the electric load of the island can be served by the SMR, while during only 26% of the time is there a need for the grid to provide energy. Similarly, Table 6 shows how the energy that is produced from the SMR is used by the system.

Table 5. System's energy production.

Production	GWh/yr	%
Grid purchases	970.86	26
Small modular reactor	2759	74
Total	3729.86	100

Table 6. System's energy consumption.

Consumption	GWh/yr	%
AC primary load	3198.13	85.7
Grid sales	532.13	14.3
Total	3620.984	100

Table 7 sums the characteristics of the operation of the SMR, which include both the electric and the thermal energy it produces. By comparing Tables 1 and 5 it becomes clear that the SMR has the potential to cover a significant portion of the annual thermal needs of Crete.

Table 7. SMR operation details.

Quantity	Value	Units
Nominal power	350	MW
Mean output	315	MW
Mean output	7.55	GWh/d
Capacity factor	90	%
Electricity production	2759	GWh/y
Thermal output	155	MW
Thermal production	1354	GWh/yr

Although the heat produced for the reactor is more than the demand, it must be stated that since this heat production is centralized, it cannot be transported to users all over the island due to geomorphological reasons. As a result, we cannot assume that the heat produced by the SMR can be used by the whole Cretan population. Regardless, it has the potential to cover a significant heating load for the island. As for the system's emissions, Table 8 shows that by using an SMR, the greenhouse gas emissions of such systems result in large-scale decarbonization of energy grids, since the CO_2 emissions are more than three times lower than the current situation.

Table 8. Annual emissions of the system.

Pollutant	Quantity	Unit
Carbon dioxide	2,043,462,795	kg/yr
Sulfur dioxide	2,660,158	kg/yr
Nitrogen oxides	1,300,953	kg/yr

Finally, the techno-economic indicators of the system are shown in Table 9.

Table 9. Techno-economic indicators of the system.

Indicator	Value
Net present cost	EUR 3.16B
CAPEX	EUR 1.05B
OPEX	EUR 120M
LCOE (per kWh)	EUR 0.048

4.2. Grid-Connected SMR/PV System

The second scenario of the analysis considers an additional power source alongside the SMR, specifically, the inclusion of solar panels as a secondary power production system (Figure 7). In this case, the rated capacity of the SMR is considered equal to the one in the previous paragraph, so the optimization should focus on the optimal sizing of the PV installation. The optimal PV size is determined by the net present value of the system instead of the LCOE, the reason being that as long as the LCOE value of the PV system is lower than the kWh cost for the energy bought from the grid, the LCOE will be reduced with the increase of the total PV installed capacity. A boundary set for the sizing of the PV was the desired renewable energy penetration, which was set to be at least 5%. The optimized PV system sizing as well as its characteristics according to the simulations can be read from Table 10.

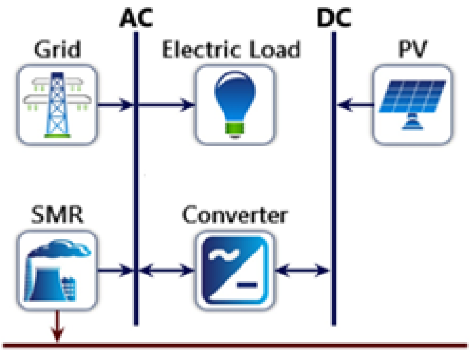

Figure 7. System architecture.

Table 10. PV characteristics.

Quantity	Value
Rated capacity	147 MW
Maximum output	152 MW
Mean output	28 MW
Mean output	675 MWh/d
Total production	246 GWh/yr
Capacity factor	19.1%
PV penetration	7.71%
Max. renewables penetration	32.5%

Like in the first scenario, the details regarding the system's power production are presented in Table 11. It becomes clear that regardless of the installed capacity of solar panels, the SMR produces the same amount of energy, because it constantly (except for its downtime) operates at its rated capacity. Thus, the quantity that is decreased is the energy which is bought from the grid.

Table 11. System's energy production.

Production	GWh/yr	%
Solar panels	246	6.47
Grid purchases	801	21
Small modular reactor	2759	72.5
Total	3806	100

Similarly, due to the excess energy produced from the PV panels, it can be seen in Table 12 that the energy sold to the grid increases. Figures 8–10 present heat maps that show the hourly energy produced from the solar panels, as well as the amount of energy that is bought or sold from or to the grid throughout the year. As expected, there still exists a need to purchase energy from the grid at night time, especially in the spring and summer months.

Table 12. System's energy consumption.

Consumption	GWh/yr	%
AC primary load	3198	84.3
Grid sales	593	15.7
Total	3791	100

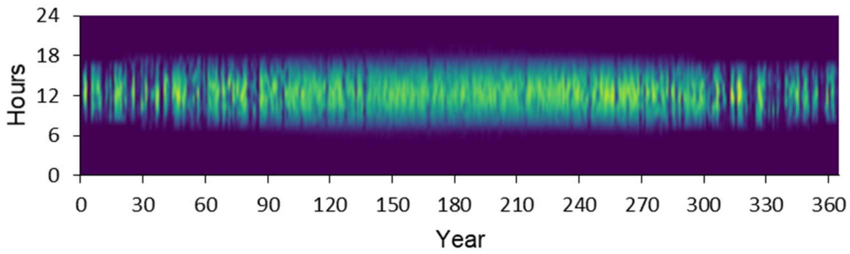

Figure 8. Energy produced by PV.

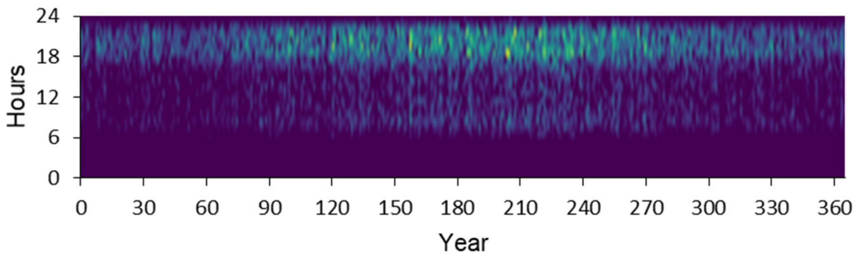

Figure 9. Energy purchased from grid (kW).

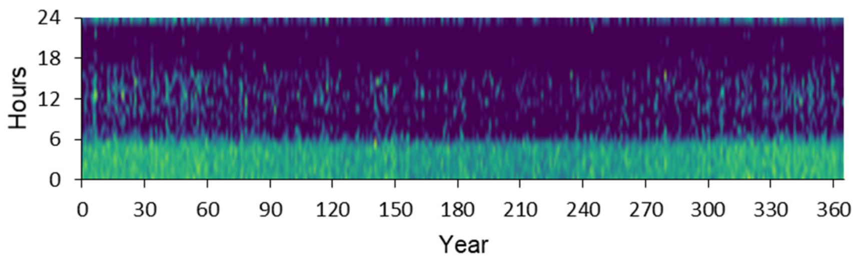

Figure 10. Energy sold to grid (kW).

However, by comparing Figures 6 and 10, it can be seen that when there are PV panels installed, there is an excess of power produced at the times at which the panels operate near their rated capacity, and this power is sold to the grid. Finally, due to the system's decreased consumption of grid energy, the respective emissions appear to be decreased as well, as seen in Table 13.

Table 13. Annual emissions of the system.

Pollutant	Quantity	Unit
Carbon dioxide	1,936,185,794	kg/yr
Sulfur dioxide	2,195,065	kg/yr
Nitrogen oxides	1,073,499	kg/yr

The techno-economic indicators that were presented for the first scenario can be found in Table 14 for the second scenario.

Table 14. Techno-economic indicators of the system.

Indicator	Value
Net present cost	EUR 3.1B
CAPEX	EUR 1.3B
OPEX	EUR 102M
LCOE (per kWh)	EUR 0.046

4.3. Grid-Connected PV/hydrogen Systems

The third scenario of the analysis considers a system that utilizes power by a combination of PV panels, SMR, and the grid, while also generating hydrogen, which covers a daily load for automotive or stationary applications. To do so, the system includes an electrolyser and hydrogen tanks. The system's architecture is shown in Figure 11.

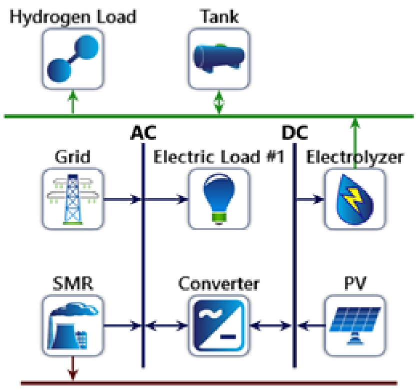

Figure 11. System architecture.

Depending on the size of the hydrogen load, the rest of the system components are sized accordingly, as can be seen in the following paragraphs. It should be noted that the hydrogen load is 10 tonnes per day, which is enough to fuel a fleet of hydrogen-fuelled vehicles on a daily basis or a large portion of the thermal need needs of the island. As already mentioned, the electrolyser prioritizes the use of power from the solar panels, and when this is not possible, it is powered by the SMR. When neither is possible, the hydrogen load is served by the stored hydrogen. In this scenario, the rated capacity of the PV panels was chosen to be equal to the respective capacity of the second scenario in order to compare the two alternatives. The presence of an additional electric load in the form of the power consumption of the electrolyser allocates the resources of the system differently. As a result, as seen in Tables 15 and 16, there is the need for more energy to be bought from the grid, while less energy is sold to the grid.

Table 15. System's energy production.

Production	GWh/yr	%
Solar panels	246	6.44
Grid purchases	820	21.1
Small modular reactor	2759	72.1
Total	3825	100

Table 16. System's energy consumption.

Consumption	GWh/yr	%
AC primary load	3198	84
Grid sales	437	11.5
Electrolyser	174	4.5
Total	3809	100

The details of the electrolyser operation can be seen in Table 17, and the heat map, which shows the power it consumes throughout the year, is presented in Figure 12. By comparing Figures 12–14, the flow of power to the electrolyser is apparent.

Table 17. Details of hydrogen production and storage.

Quantity	Value
Hydrogen production	3729 t/yr
Rated capacity	50 MW
Mean input	19.7 MW
Minimum input	0 kW
Maximum input	50 MW
Total input energy	173 GWh/yr
Capacity factor	39.5%
Mean output	426 kg/h
Minimum output	0 kg/h
Maximum output	1077 kg/h
Specific consumption	46.4 kWh/kg
Hydrogen storage capacity	100,000 kg
Amount at end of year	9.351 t

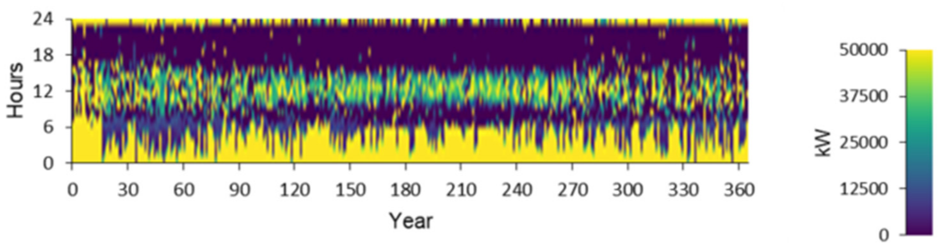

Figure 12. Electrolyser input power (kW).

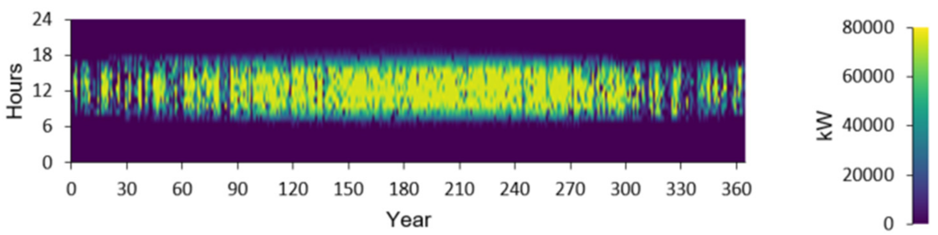

Figure 13. Inverter power output.

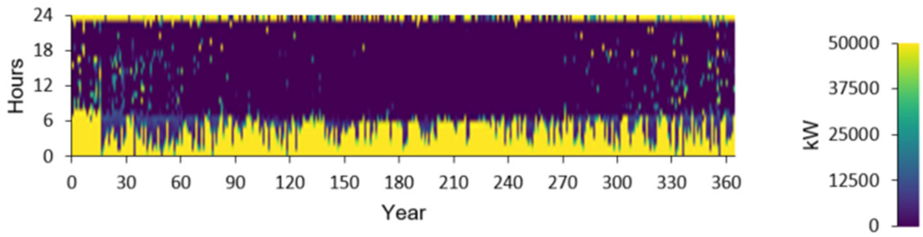

Figure 14. Rectifier output (kW).

The rectifier that converts AC to DC works only when the SMR powers the electrolyser. So, as expected, this happens during the night time, when the SMR produces excess electricity, while there are also instances during the day, especially during the winter months. The fact that the SMR powers the electrolyser also explains the dip in energy sold to the grid in relation to the first two scenarios. The fact that the third scenario is related to more CO_2 emissions (Table 18), according to HOMER, is partly true, due to the fact that there is more energy purchased from the grid, but in this case, the software fails to acknowledge the fact that the hydrogen that is produced will reduce the emissions of the rest of the sectors in which it is going to be used. For example, if the produced hydrogen were to be used in the automotive sector, and considering the fact that 1 kg of hydrogen used in a fuel cell can produce 33 kWh of energy, the useful energy produced is estimated to be 123 GWh per year, which amounts to 3% of the energy used by conventional fuels. So, a rational assumption could be that the system in question has the potential to decrease the greenhouse gas emissions of the island by an additional 3%. Finally, the techno-economic indicators of the system are shown in Table 19.

Table 18. Annual emissions of the system.

Pollutant	Quantity	Unit
Carbon dioxide	1,948,162,651	kg/yr
Sulfur dioxide	2,246,990	kg/yr
Nitrogen oxides	1,098,893	kg/yr

Table 19. Techno-economic indicators of the system.

Indicator	Value
Net present cost	EUR 3.38B
CAPEX	EUR 1.42B
OPEX	EUR 111M
LCOE (per kWh)	EUR 0.052

5. Conclusions

The above analysis focuses on three different scenarios for the integration of an SMR in a large-scale power system, using the case study of the island of Crete as an example. The first scenario examined the use of the SMR for the production of electricity and heat, while the second one had an additional power source in the form of solar PV panels. The third scenario also included the use of an electrolyser for the production of hydrogen. The results from the simulations show that the potential integration of renewable energy sources with SMR for power and hydrogen co-generation could provide a techno-economically feasible solution in the near future, since, for all three scenarios, the LCOE is significantly lower than the current LCOE for the case study that was considered. More specifically, the LCOE of the first scenario is EUR 0.048/kWh, the second EUR 0.046/kWh, and the third EUR 0.052/kWh. By comparing the LCOEs of the three scenarios, it can be understood that a PV/SMR system is the most attractive financially, but this fails to acknowledge the fact that the produced hydrogen of the third scenario will be sold to potential customers, meaning that there is additional revenue to be made within this system. Even if hydrogen were not to be sold, the above analysis leads to the conclusion that it could be an economically viable solution for storing excess energy from solar panels, increasing further the penetration of renewable energy sources. What should be mentioned is that the above results are in close agreement with the existing literature. More specifically, Lokhov et al. (2013) found that LCOE of USD 0.045–0.08/kWh is viable for SMR, while Shropshire (2011) gave a respective value of EUR 0.045/kWh [45,46]. Finally, Boldon and Sabharwall (2014) gave an estimation of an LCOE of USD 0.07–0.084/kWh [47]. The results that concern the net present cost, CAPEX, and OPEX agree with this logic, since they become higher as the complexity of the system increases and additional components are added. A common benefit of the three scenarios is the significant decrease in the carbon emissions of the systems, which as well as providing an environmental benefit has the potential to provide additional economic benefits, since by avoiding carbon emissions, those systems also avoid paying carbon taxes and penalties. The produced hydrogen, even in this case which concerns relatively small-scale production, is enough to establish potential business cases by its usage in either transportation or industry. This particular result shows the potential of such systems, when located in suitable places, to create hydrogen hubs that will boost hydrogen adoption. As a result, all the above hints to the fact that such systems not only have the potential to provide energy stability and security but also to provide an alternative approach to establish the fundamentals for a hydrogen economy.

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List of Abbreviations

CAPEX	Capital expenditure
CHP	Combined heat and power
LCOE	Levelized cost of electricity
LR	Large reactor
LWR	Light water reactor
OPEX	Operational expenditure
PEM	Proton-exchange membrane
PV	Photovoltaics
RES	Renewable energy source
SMR	Small modular reactor

References

1. El-Emam, R.; Zamfirescu, C.; Gabriel, K. Analysis of copper chlorine electrolysis for large-scale hydrogen production. *Int. J. Hydrogen Energy* **2023**, *48*, 22720–22733. [CrossRef]
2. Stamatakis, E.; Perwög, E.; Garyfallos, E.; Millán, M.S.; Zoulias, E.; Chalkiadakis, N. Hydrogen in Grid Balancing: The European Market Potential for Pressurized Alkaline Electrolyzers. *Energies* **2022**, *15*, 637. [CrossRef]
3. Vinoya, C.L.; Ubando, A.T.; Culaba, A.B.; Chen, W.-H. State-of-the-Art Review of Small Modular Reactors. *Energies* **2023**, *16*, 3224. [CrossRef]
4. Hidayatullah, H.; Susyadi, S.; Hadid Subki, M. Design and technology development for small modular reactors—Safety expectations, prospects and impediments of their deployment. *Prog. Nucl. Energy* **2015**, *79*, 127–135. [CrossRef]

5. Schaffrath, A.; Wielenberg, A.; Kilger, R.; Seubert, A. SMRs—Overview, International Developments, Safety Features and the GRS Simulation Chain. *Front. Energy* **2021**, *15*, 793–809. [CrossRef]
6. International Atomic Energy Agency. *Advances in Small Modular Reactor Technology Developments*; International Atomic Energy Agency: Vienna, Austria, 2020.
7. Shirvan, K.; Forrest, E. Design of an Organic Simplified Nuclear Reactor. *Nucl. Eng. Technol.* **2016**, *48*, 893–905. [CrossRef]
8. Lee, K.H.; Kim, M.G.; Lee, J.I.; Lee, P.S. Recent Advances in Ocean Nuclear Power Plants. *Energies* **2015**, *8*, 11470–11492. [CrossRef]
9. Testoni, R.; Bersano, A.; Segantin, S. Review of Nuclear Microreactors: Status, Potentialities and Challenges. *Prog. Nucl. Energy* **2021**, *138*, 103822. [CrossRef]
10. Vujić, J.; Bergmann, R.; Skoda, R.; Miletić, M. Small modular reactors: Simpler, safer, cheaper? *Energy* **2012**, *45*, 288–295. [CrossRef]
11. Mascari, F.; Woods, B.G.; Welter, K.; D'Auria, F.; Bersano, A.; Maccari, P. Small modular reactors and insights on passive mitigation strategy modeling. *Nucl. Eng. Des.* **2023**, *401*, 112088. [CrossRef]
12. International Atomic Energy Agency. IAEA Annual Report 2018. 2018. Available online: https://www.iaea.org/opic/annual-report-2018 (accessed on 3 June 2023).
13. Mascari, F.; Bersano, A.; Ferri, R.; Lombardo, C.; Burgazzi, L. Description of PERSEO Test N 7. Technical Report. Available online: https://www.enea.it/it/Ricerca_sviluppo/documenti/ricerca-di-sistema-elettrico/adp-mise-enea-2015-2017/energia-da-fissione/report-2018-lp1/rds-par2018-122.pdf (accessed on 3 June 2023).
14. Nian, V. The prospects of small modular reactors in Southeast Asia. *Prog. Nucl. Energy* **2017**, *98*, 131–142. [CrossRef]
15. Locatelli, G.; Bingham, C.; Mancini, M. Small modular reactors: A comprehensive overview of their economics and strategic aspects. *Prog. Nucl. Energy* **2014**, *73*, 75–85. [CrossRef]
16. Carelli, M.D.; Conway, L.E.; Oriani, L.; Petrović, B.; Lombardi, C.V.; Ricotti, M.E.; Barroso, A.C.O.; Collado, J.M.; Cinotti, L.; Todreas, N.E.; et al. The design and safety features of the IRIS reactor. *Nucl. Eng. Des.* **2004**, *230*, 151–167. [CrossRef]
17. Dominion Energy Inc.; Bechtel Power Corporation; TLG Inc.; MPR Associates. *Study of Construction Technologies and Schedules, O&M Staffing and Cost, Decommissioning Costs and Funding Requirements for Advanced Reactor Designs*; Dominion Energy, Inc.: Richmond, VA, USA, 2004.
18. Gollier, C.; Proult, D.; Thais, F.; Walgenwitz, G. Choice of nuclear power investments under price uncertainty: Valuing modularity. *Energy Econ.* **2005**, *27*, 667–685. [CrossRef]
19. Dahlgren, E.; Gocmen, C.; Lackner, K.; Ryzi, G. Small modular infrastructure. *Eng. Econ.* **2013**, *58*, 231–264. [CrossRef]
20. Hussein, E. Emerging small modular nuclear power reactors: A critical review. *Phys. Open* **2020**, *5*, 100038. [CrossRef]
21. Pannier, C.P.; Skoda, R. Comparison of small modular reactor and large nuclear reactor fuel cost. *Energy Power Eng.* **2014**, *6*, 82–94. [CrossRef]
22. Cooper, M. Small modular reactors and the future of nuclear power in the United States. *Energy Res. Soc. Sci.* **2014**, *3*, 161–177. [CrossRef]
23. Michaelson, D.; Jiang, J. Review of integration of small modular reactors in renewable energy microgrids. *Renew. Sustain. Energy Rev.* **2021**, *152*, 111638. [CrossRef]
24. Carelli, M.D.; Garrone, P.; Locatelli, G.; Mancini, M.; Mycoff, C.; Trucco, P.; Ricotti, M.E. Economic features of integral, modular, small-to-medium size reactors. *Prog. Nucl. Energy* **2010**, *52*, 403–414. [CrossRef]
25. Boldon, L.; Sabharwall, P.; Painter, C.; Liu, L. An overview of small modular reactors: Status of global development, potential design advantages, and methods for economic assessment. *Int. J. Energy Environ. Econ.* **2014**, *22*, 437–459.
26. McGinnis, E. The BIG Potential for Nuclear Micro-Reactors 2020. Available online: https://www.energy.gov/ne/articles/big-potential-nuclear-micro-reactors (accessed on 3 June 2023).
27. Cevahir, T.; Ali Çil., M. A study on hydrogen, the clean energy of the future: Hydrogen storage methods. *J. Energy Storage* **2021**, *40*, 102676.
28. Niaz, S.; Manzoor, T.; Hussain Pandith, A. Hydrogen storage: Materials, methods and perspectives. *Renew. Sustain. Energy Rev.* **2015**, *50*, 457–469. [CrossRef]
29. Dornheim, M.; Baetcke, L.; Akiba, E.; Ares, J.R.; Autrey, T.; Barale, J.; Zoulias, E. Research and development of hydrogen carrier based solutions for hydrogen compression and storage. *Prog. Energy* **2022**, *4*, 042005. [CrossRef]
30. Gkanas, E.; Stamatakis, E.; Christodoulou, C.; Tzamalis, G.; Karagiorgis, G.; Chroneos, A.; Kuganathan, N.; Khzouz, M.; Stubos, A. Study on the Operation and Energy Demand of Dual-Stage Metal Hydride Hydrogen Compressors under Effective Thermal Management. *Int. J. Hydrogen Energy* **2021**, *46*, 29272–29287. [CrossRef]
31. Li, H.; Wang, X.; Dong, Z.; Xu, L.; Chen, C. A study on 70 MPa metal hydride hydrogen compressor. *J. Alloys Compd.* **2010**, *502*, 503–507. [CrossRef]
32. Galvis, E.A.R.; Leardini, F.; Bodega, J.; Are, J.R.; Fernandez, J.F. Realistic simulation in a single stage hydrogen compressor based on AB2 alloys. *Int. J. Hydrogen Energy* **2016**, *41*, 9780–9788. [CrossRef]
33. Gkanas, E.I.; Grant, D.M.; Stuart, A.D.; Eastwick, C.N.; Book, D.; Nayebossardi, S.; Pickering, L.; Walker, G.S. Numerical study on a two-stage Metal Hydride Hydrogen Compression system. *J. Alloys Compd.* **2015**, *645*, S18–S22. [CrossRef]
34. Witkowski, A.; Rusin, A.; Majkut, M.; Stolecka, K. Comprehensive analysis of hydrogen compression and pipeline transportation from thermodynamics and safety aspects. *Energy* **2017**, *14*, 2508–2518. [CrossRef]
35. Chalkiadakis, N.; Stubos, A.; Zoulias, E.; Stamatakis, E. Pilot autonomous hybrid hydrogen refueling station utilizing a metal hydride compressor covering local transportation needs. In *E3S Web of Conferences*; EDP Sciences: Les Ulis, France, 2022; p. 06002.

36. Caralis, G.; Christakopoulos, T.; Karellas, S.; Gao, Z. Analysis of energy storage systems to exploit wind energy curtailment in Crete. *Renew. Sustain. Energy Rev.* **2019**, *103*, 122–139. [CrossRef]
37. Gkeka-Serpetsidaki, P.; Tsoutsos, T. A methodological framework for optimal siting of offshore wind farms: A case study on the island of Crete. *Energy* **2022**, *239*, 122296. [CrossRef]
38. Gigantidou, A. *Annual Technical Bulletin for the Exploitation of the Electrical System of Crete in 2019*; Technical Private Report; Hellenic Electricity Distribution Network Operator, S.A.: Heraklion, Greece, 2019.
39. Katsaprakakis, D.A.; Michopoulos, A.; Skoulou, V.; Dakanali, E.; Maragkaki, A.; Pappa, S.; Antonakakis, I.; Christakis, D.; Condaxakis, C. A Multidisciplinary Approach for an Effective and Rational Energy Transition in Crete Island, Greece. *Energies* **2022**, *15*, 3010. [CrossRef]
40. Stamatakis, E.; Yiotis, A.; Giannissi, S.; Tolias, I.; Stubos, A. Modeling and simulation supporting the application of fuel cell & hydrogen technologies. *J. Comput. Sci. Vol.* **2018**, *27*, 10–20.
41. Smaragdakis, A.; Kamenopoulos, S.; Tsoutsos, T. How risky is the Introduction of Fuel Cell Electric Vehicles in a Mediterranean town? *Int. J. Hydrogen Energy* **2020**, *45*, 18075–18088. [CrossRef]
42. Tzamalis, G.; Zoulias, E.I.; Stamatakis, E.; Parissis, O.-S.; Stubos, A.; Lois, E. Techno-economic analysis of RES & Hydrogen technologies integration in remote island power system. *Int. J. Hydrogen Energy* **2013**, *38*, 11646–11654.
43. Tzamalis, G.; Zoulias, E.I.; Stamatakis, E.; Varkaraki, E.; Lois, E. Techno-economic analysis of an Autonomous Power System integrating hydrogen technology as energy storage medium. *Renew. Energy* **2011**, *36*, 118–124. [CrossRef]
44. Sifakis, N.; Vichos, E.; Smaragdakis, A.; Zoulias, E.; Tsoutsos, T. Introducing the cold-ironing technique and a hydrogen-based hybrid renewable energy system into ports. *Int. J. Energy Res.* **2022**, *46*, 20303–20323. [CrossRef]
45. Lokhov, A.; Cameron, R.; Sozoniuk, V. OECD/NEA Study on the Economics and Market of Small Reactors. *Nucl. Eng. Technol.* **2013**, *45*, 701–706. [CrossRef]
46. Shropshire, D. Economic Viability of Small to Medium-Sized Reactors Deployed in Future European Energy Markets. *Prog. Nucl. Energy* **2011**, *53*, 299–307. [CrossRef]
47. Boldon, L.M.; Sabharwall, P. *Small Modular Reactor: First-of-a-Kind (FOAK) and Nth-of-a-Kind (NOAK) Economic Analysis*; INL: Idaho Falls, ID, USA, 2014.