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Review

Nuclear-Driven Integrated Energy Systems: A State-of-the-Art Review

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Abstract: Because of the growing concerns regarding climate change and energy sustainability, a transition toward a modern energy sector that reduces environmental effects while promoting social and economic growth has gained traction in recent years. Sustainable energy solutions, which include renewable and low-carbon sources such as nuclear energy and natural gas, could minimize emissions of greenhouse gases, enhance air and water quality, and encourage energy independence. Yet, the shift to a sustainable energy industry is fraught with difficulties, including governmental and regulatory obstacles, technological and economic limits, and societal acceptability hurdles. Addressing these issues would necessitate the development of long-term, durable, and cost-effective energy systems containing nuclear energy and associated with the generation of both electricity and other by-products required by industry. Integrated energy systems (IES) are a novel way to maximize the use of various energy resources and technologies in order to deliver dependable, efficient, and sustainable energy services. IES entail the integration of various energy systems, such as electricity, heating, cooling, and transportation, in respect to energy sustainability and a system's resilience and flexibility. Their development and implementation require the cooperation of several parties, including energy providers and policymakers. This study provides a state-of-the-art literature review of the most creative nuclear-driven hybrid energy system applications and methodologies, from which the research challenges and prospects for effective IES implementation emerge.

Keywords: sustainable energy; nuclear energy; integrated energy systems; resilience; robustness

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1. Introduction

Recent interest in modernizing power systems and creating projects targeted at more effectively employing energy resources has been rekindled by rising fossil fuel costs, rising electricity usage, and worries about the environmental effects of greenhouse gas emissions [1]. Investment in the energy sector needs to be increased and targeted toward greener, more sustainable technologies that will improve climate change resilience and mitigation while also defending the planet's imperiled species in order to achieve carbon neutrality and reduce global warming [2]. The world is currently dealing with the need to refocus and realign investment in the energy industry to handle risks to energy security and environmental issues. The most effective replacement of fossil fuels with alternative energy sources and the enhancement of energy efficiency are the two main methods used to reduce CO_2 emissions, which are released into the atmosphere during the burning of fossil fuels, to address the issue of climate change [3].

Two of the most serious issues facing the globe today are the mitigation of climate change and the security of the energy supply, which may call for a complete overhaul of the global energy infrastructure. To attain net zero emissions, the power sector, which is responsible for 40% of global energy-related emissions, will need to undergo a significant transformation. There will be serious concerns regarding technology, economy, society, and politics if carbon fuels are not replaced with flexible renewable technologies [4]. A major expenditure is required to provide a global fleet of low-carbon generation, grid infrastructure, energy storage, and appropriate flexibility measures. Over the coming decades, the availability and dependability of energy infrastructure will become crucial as the demand for power rises.

Nuclear power may significantly contribute to the stability and security of a fully decarbonized power system and serve as the prime counterpoint to renewable energy sources because it has one of the lowest carbon footprints among energy technologies, is always available, and can operate flexibly [5]. To accomplish this, the concept of merging nuclear and renewable energy sources through the use of energy storage systems has been researched further. These systems can store excess energy generated by renewables during periods of high production and then deploy it when renewable sources produce less electricity. However, in [6], the researchers propose a paradigm-shifting idea by arguing that some industrial facilities may use surplus renewable energy without the need for energy storage. For instance, these facilities might employ extra renewable energy for operating a desalination plant, supplying both the needed electricity and water while reducing the need for separate energy storage devices. The electrification of the transportation, industrial, and construction sectors, combined with the use of nuclear energy to produce alternative energy products, such as hydrogen, can offer a more diverse energy mix as well as a large-scale, independent method of decarbonization to end users at a lower cost. As a result, non-electric operations, such as desalination, district heating, and hydrogen production, may be increased to cut emissions and improve the supply sustainability and security of the global energy system [7].

There is a notable transformation occurring in the electricity industry, moving away from the traditional base load model where a single power source meets the minimum demand and is supplemented by quick-responding resources. Instead, the future power system will rely on a diverse mix of energy resources to satisfy the load. Current indications suggest that the future grid will have fewer operators dedicated solely to base load supply as a combination of variable and dispatchable resources will be used to reliably meet the load requirements [8]. This evolving grid will incorporate flexible generators and loads, along with energy services that span the entire economy, promoting efficient and reliable power system operation [9]. Integrated energy systems offer a solution to combine non-electric products, resulting in stable power supply, reduced carbon emissions, increased use of renewable energy, and economic benefits for dispatchable producers such as nuclear power [10].

At present, the primary sources of energy used to meet power demands consist of fossil fuels, nuclear energy, and renewable sources. Shifting towards a more adaptable energy system has the potential to create new avenues for value generation across all energy sources, both for electrical and non-electrical purposes. As with fossil fuel, solar thermal, and geothermal power generators, nuclear power plants primarily produce thermal energy (heat) and require power conversion devices to generate electricity. While current reactor and power plant designs do not utilize various operating fluids, such as steam, it is anticipated that next-generation reactor systems will incorporate them. Consequently, many of the supporting applications that provide flexibility in traditional thermal systems can also be applied to nuclear energy generation systems [11]. This paper explains how nuclear energy may operate in tandem with other technologies to drive to a decarbonized global economy. Its research contribution includes the following:

- Outlines important prospects and difficulties for nuclear energy in its twin function of enabling a decarbonized, safe power supply while also increasing climate benefits by serving non-electric sectors.
- Provides the most recent scientific discoveries on the environmental effect of nuclear power and emphasizes how regulations may shape markets by assisting in the allocation and distribution of economic risk associated with nuclear projects.

- Examines the importance of cutting-edge nuclear-powered IES to energy system modernisation.
- Describes the most assertive software tools used by academics and scientists to simulate and analyze IES from a technical and economic standpoint.
- Concludes by highlighting the gaps and prospects for additional research initiatives, as well as the obstacles that must be addressed in order to properly incorporate IES in current energy systems.

The rest of the paper is organized as follows: Section 2 discusses the evolving role of nuclear energy and its potential contribution to the development of dependable and cost-effective energy systems. Section 3 subsequently conveys a complete explanation of the most recent IES structures as well as the methods used for their design and comprehensive examination. Section 4 discusses the challenges faced by IES and recommends avenues for novel research, while Section 5 concludes the research.

2. Global Energy and Nuclear

The developing role of nuclear energy and its potential contribution to the creation of reliable and cost-effective energy systems is examined in this section. Furthermore, the prospects for potential investments in nuclear projects that will result in the cost-effective operation of contemporary power systems are outlined.

2.1. The Critical Role of Nuclear Power in Energy System Modernization and Urgent Decarbonization

Recent changes in the global energy grid jeopardize the need for immediate action to solve the climate emergency. The state of emergency in Ukraine has exacerbated an already unpredictable global energy balance caused by rising demand for fossil fuels and growing percentages of variable renewable supply. These accumulating factors have resulted in an important choice regarding the future of energy sector investment: either more fossil-fired power plants in the name of stopgap measures and supply security, or a renewed push toward laying the groundwork required to meet low-carbon energy targets [12]. More than ever, nuclear has the capacity to connect these paths on a global scale, providing energy security via solid low-carbon energy as well as the flexibility to dispatch that energy flexibly, ultimately permitting an integrated pairing with the expanding proportions of variable renewable energy.

The idea that natural gas may serve as a "bridge fuel" that signals the beginning in a sustainable future is being called into doubt by rising natural gas costs, which are challenging a fundamental assumption of the contemporary energy system. Short-term concerns about energy security, especially in the European Union (EU), will alter the whole world's energy picture. Given the unpredictability of fossil fuel pricing, new nations and regions may establish themselves as trustworthy trading partners, refocusing trade on areas with a wealth of low-carbon energy resources, such nuclear power. Plans by the European Commission to lessen reliance on fossil fuels imported from the Russian Federation include a significant role for nuclear power and the deployment of clean hydrogen as a natural gas alternative [13].

Building an energy system that is sufficiently plentiful, secure, varied, and decarbonized is crucial as the world's energy demand rises. It is necessary to completely stop using fossil fuels in order to reach net zero emissions by the middle of this century. For the last two centuries, these fuels have been the driving force behind economic expansion. According to the International Energy Agency (IEA), they still account for more than 60% of global power generation and approximately 80% of the world's energy supply [14]. Abandoning the use of fossil fuels is unquestionably a tremendous and unprecedented challenge for all nations and governments, requiring a radical transformation of how energy services are produced, delivered, and consumed globally, as well as a complete restructuring of the transportation, industrial, and building sectors. Today, there is a renewed emphasis on technologies that can produce large amounts of decarbonized energy while enhancing energy security, accommodating flexibility needs, and enhancing system resilience [15]. One such technology is nuclear, which has extra benefits for the climate in terms of pollution and biodiversity, as well as the ability to address issues of the environment and society.

The repercussions of integrating significant amounts of renewable energy into a power system are both technical and financial, and they constitute a significant technological challenge. This is mostly because wind and solar PV power generation are yet not reliable, predictable, or dispatchable sources of electricity. The output of renewable energy fluctuates with the amount of wind and sunshine present, which is challenging to forecast in advance and might not always be accessible when needed. Climate change is projected to have a growing impact on the generation of electricity from renewable sources in the future, which might exacerbate the unpredictability of renewable energy. Although not immune, nuclear has thus far shown to be less prone to such changes.

2.2. Nuclear Energy's Evolving Role in Achieving a Net Zero Emission System

Modern net zero gas emission systems place a strong emphasis on decarbonizing power generation, by reducing direct emissions in the electric sector, and by utilizing low-carbon-emission types of energy. Notably, their ultimate goal is the full replacement of fossil fuels by enhancing the direct electrification and transitioning to electricity-derived fuels. In comparison to current power systems, net zero emission systems are projected to show increased integration and interconnection [16]. Additionally, nuclear energy is expected to offer a wider range of services and goods, and it will progressively integrate its planning and operations with those of alternate sources of energy [17]. The direct sale of heat for industrial purposes, the sale of hydrogen, synthetic liquid fuels, direct air capture, and potable water produced from high-temperature heat are just a few examples of how non-electric value streams could become more significant under economy-wide deep decarbonization driven by nuclear energy [18].

As it contributes to the system's general stability and other operations, nuclear energy will be more important in a future low-carbon system. To maintain or even exceed renewable energy, nuclear power plants would have to modify their output, which would reduce the facility's capacity factor. The economic value of the nuclear plant may be impacted by this lower capacity factor depending on how highly the energy market views nuclear as a dispatchable source. One approach to solving this issue would be to combine nuclear energy with techniques for thermal energy storage. The cost-effective production of derivative products of other sources of energy, which are largely created via a steam turbine generator, using nuclear energy is another crucial tactic for solving this issue. By taking advantage of extremely unstable energy prices, the intertwined production of electricity and a nonelectric product would optimize nuclear revenues while enabling steady operations at full power. Hence, reducing the cycling requirements and costs while increasing the load factor will enable the integration and use of other processes in a low-carbon system in a more effective way as compared to the nuclear power plant sole operation as an electricity generator. Examples of this mode include the production of hydrogen [19], pure water, chilled water [20], and heat [21], as shown in Figure 1.

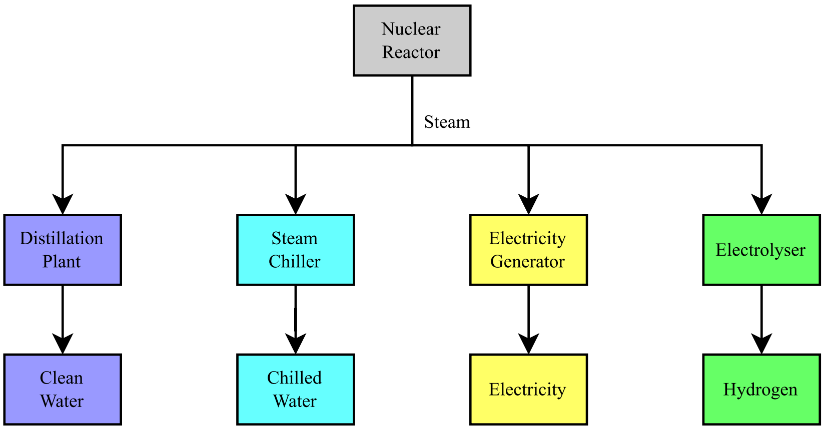

Figure 1. Exploring potential products generated by nuclear energy.

2.2.1. District Heating

Industrial, commercial, and agricultural users of district heating systems acquire heat through a network of distribution pipes. The industrial sector is served by over 40% of the world's district heating networks, while, in China, more than 50% of the nation's district heat is used by industry [14]. Most industrial activities, as well as those in the construction and transportation industries, rely on high-emitting fossil fuels to generate heat. For instance, the production from nuclear plants is shown to be almost immune to volatility in commodity prices, while the cost of producing heat from natural gas plants is quadrupled in contrast to the recent past [14]. Notably, the primary non-electric use of nuclear power reactors that are currently in operation is district heating.

Nuclear-driven district heating systems are an appealing option for both densely populated cities and rural places since they can be economically provided for up to 160 km away at a competitive cost and with minimum heat loss [22,23]. Profoundly, it is possible to enhance efforts to combat climate change by substituting nuclear district heating for fossil fuel heating in buildings [24]. According to the International Energy Association's Net Zero Emissions by 2050 Scenario, renewable and low-carbon sources will provide 91% of building heat in 2050. In addition to providing heat, nuclear district heating systems may also generate low-carbon energy that multiplies the benefits of the technology outside of the power industry [25,26]. Therefore, utilizing the current district energy network, it would be plausible to transition district heating from fossil fuels to low-carbon sources such as nuclear power.

2.2.2. Desalination

Clean water for consumption, agriculture, and industrial applications is produced through the desalination process, a process that is essential in locations with a shortage of water. The need for clean water will only increase as the effects of climate change become more apparent, thus requiring large steps to be taken given the fact that, currently, the desalinated water industry is one of the least developed in the world. It should be noted that the current status of the desalination processes heavily relies on utilization of fossil fuels, which inadvertently makes it costly and a significant source of polluted emissions [27].

Reverse osmosis [28], multistage flash distillation [29], and multi-effect distillation [30] are the three primary desalination methods now in use despite the fact that several more exist. Nuclear energy is a perfect match since desalination techniques such as multistage flash distillation or multi-effect distillation require heat as well as electricity [31]. Utilizing an on-site nuclear reactor to produce fresh water is known as nuclear desalination [32]. One of the many variables that can have a substantial impact on the energy requirement in any desalination process is the plant capacity and water quality. Desalination can be powered by thermal or electrical energy but also by renewable sources, including geothermal and solar energy, but coupling occurs via facilities of smaller scale [33].

2.2.3. Hydrogen Production

While today's main application for hydrogen is as a chemical feedstock, there are still prospects for its usage in the electricity [34], transportation [35], and industrial [36] sectors. Utilizing hydrogen has several advantages, including helping to decarbonize the whole economy and ensuring supply security. To function as an energy storage mechanism, hydrogen may help to diversify energy and fuel mixtures and increase reserve capacity [37]. When heat and electricity are combined to generate hydrogen, several existing systems employ low-temperature electrolysis or high-temperature electrolysis [38].

For the effective synthesis of hydrogen using various techniques, nuclear power may offer relentless availability of both energy and heat. Nuclear energy may be used to produce hydrogen, which can be combined with renewable energy production to build a decarbonized, flexible, and affordable energy system [39,40]. Using nuclear energy to generate hydrogen can be a powerful incentive for running nuclear power stations as a means to prevent curtailment. The feasibility of producing hydrogen using nuclear power and process heat is now being investigated in a number of nations [41]. Any additional electricity or heat generated may be utilized to generate hydrogen, which may then be stored for future electrical consumption or transport fuel, or used for energizing industrial processes, such as steel or ammonia manufacturing [42].

2.3. Assessing the Financial Investment Potential of Nuclear Energy for Establishing a Dynamic and Cost-Efficient Power Grid

A coordinated combination of legislative, regulatory, infrastructural, and other measures is required to mobilize the energy investment needed to address the urgency of climate action while also maximizing synergies with respect to more prevailing development opportunities and mending energy security. The IEA predicts that worldwide energy sector investment would need to be increased by double the current predefined rates in order to reach net zero emissions by 2050 [14]. Simultaneously, an investing strategy should be implemented, which will comprise a comparable rise in investment in renewable energy and smart grid infrastructures, along with a nearly 2.5-fold increase in yearly nuclear energy spending. Such an increase in investment will make it possible to build a sizable low-carbon electrical infrastructure over the ensuing decades, which will assist to minimize future investment risks and demands.

Providing extra information to investors on whether activities are compatible with long-term climate and sustainability goals is a critical component of the framework of policies and initiatives required to foster the low-carbon energy transition. Both governments and the business sector are establishing investment plans in order to fulfill the requisite Environmental, Social, and Governance (ESG) frameworks [43]. ESG refers to the increasingly important non-financial variables that financiers employ when assessing prospective investments to encourage more sustainable and mindful practices [44,45]. Environmental factors may include aspects such as carbon emissions and their effects on the physical health and well-being of individuals. Social considerations may encompass topics such as employment opportunities or initiatives for diversity and inclusion, while governance screening may analyze the procedures utilized by a company or industry to uphold safety and efficiency standards.

Nuclear energy is one of the cleanest and most efficient forms—i.e., high energy density—of energy, and it has the potential to enrich in a sustainable and worthwhile investment alternative by meeting rising global energy demands while also meeting the following critical ESG criteria:

- Since nuclear power plants continuously provide carbon-free electricity while creating relatively little hazardous waste, in contrast to renewable energy sources whose ability to produce electricity depends entirely on weather conditions, nuclear power seems to outperform many other low-carbon energy sources.

- The environmental burden of nuclear power plants is reduced over their life cycle since they exploit much less land and fewer resources than other low-carbon energy sources.
- The nuclear power sector is one of the most strictly supervised in the world, with consideration given to the effects on local communities and worker safety at all stages of a nuclear power plant's life cycle.

The short-term marginal production costs, or the total of the variable operating, maintenance, and fuel costs of the most expensive generator requisite to meet demand at any given time, are the primary drivers of today's wholesale electricity spot prices [46]. Although this method of electricity distribution is very effective, it has led to unstable pricing and obstacles for producers in recovering all of their costs. These difficulties are expected to worsen as the world transitions to a low-carbon economy. Therefore, power market architecture and regulations need to be altered in order to achieve net zero and provide a reliable and secure energy supply [47,48]. In order to align market design with long-term investment requirements and climate goals, a number of initiatives, such as the development of a new, competitive market for long-term contracts, may be helpful [49]. As a result, the cost of funding new investments in low-carbon technologies as well as the overall cost of the energy transition may be reduced, and customers may have longer-term confidence in the price and availability of power.

3. Integrated Energy Systems

This section offers a comprehensive definition of IES and analyzes their essential aspects in depth. Simultaneously, a detailed literature overview of the most recent studies that explore the contribution of nuclear-driven energy systems is offered, as are current software tools that can model and evaluate the IES from a technical and economic standpoint.

3.1. Defining the Structural Morphologies of Integrated Energy Systems

Electricity prices can be driven to very low or even negative levels when renewable generation is high—possibly even exceeding demand. As a result, facilities are forced to reduce output or sell power at a loss under the existing system. These elements reduce the significance of conventional baseload nuclear production. In order to mitigate the financial impact of extremely low or negative market prices on the plant, several nuclear facilities have operated flexibly by cutting power output in response to the rising unpredictability in net demand. The advanced economic dispatch method retains nuclear energy's contribution to grid stability and reduces economic losses brought on by negatively priced power sales, but it leaves plant running expenses untouched. This energy might also be diverted to alternative off-grid energy consumers or integrated into thermal or electrical energy storage devices.

With an emphasis on low-emission technologies such as nuclear and renewable generators, IES under consideration might encompass a variety of energy-producing resources and energy usage approaches. To supply responsive generation to the power grid, IES are cooperatively operated systems that dynamically distribute thermal and/or electrical energy. They are made up of a number of interconnected subsystems, some of which may or may not be physically close to one another, such as a nuclear power plant for producing thermal energy, a turbine for converting thermal energy into electricity, additional sources of electricity production, such as renewable energy sources, and one or more industrial processes that use heat and/or electricity generated by the energy sources to create a commodity-scale output [50]. Technical performance and economic feasibility within diverse deployment markets are taken into account during IES design and optimization [51]. While assessing obstacles to the commercial-scale implementation of IES, various subsystem designs, integration possibilities, and deployment scenarios are taken into account. Figure 2 depicts the desired future morphology of nuclear-driven energy systems.

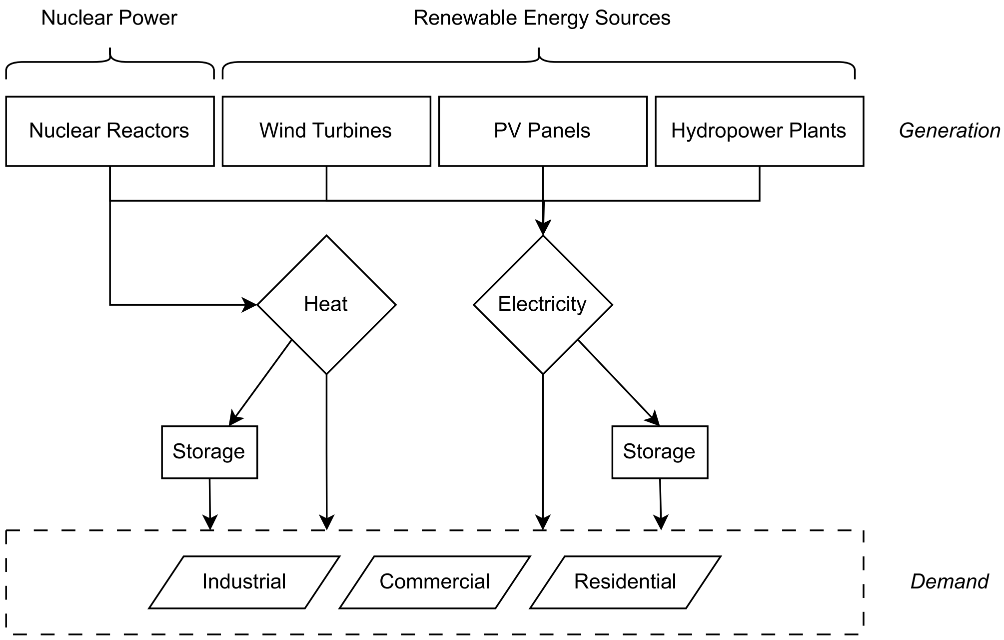

Figure 2. Critical role of nuclear power alongside RES as the backbone of nuclear-driven IES.

The connections between subsystems and the ways in which they communicate with one another and the grid are used to classify proposed IES models. Based on the specified goals of the system design, operational dispatch needs and limits, and economic variables, additional energy output can be dynamically allocated to the production of another commodity or several commodities. These integrated systems' flexibility may be exploited to increase system profitability overall, guaranteeing that the system will remain competitive in the larger energy market while still supplying the grid with non-emitting electricity. To more effectively manage energy inside the system boundaries and with the grid, additional subsystems that enable small-scale thermal, electrical, and chemical storage may be included in the system design. The following lists three broad categories that were taken into account for IES configurations, according to [52]:

- Tightly Coupled IES. As illustrated in Figure 3, several generating sources, energy storage, and industrial processes are co-controlled and directly thermally and electrically integrated behind the grid so that there is only one point of connection to the grid and one financial organization in charge of operating the IES. As a result, rather than optimizing the economic performance of each component separately, the IES is designed for an integrated system.
- Thermally Coupled IES. Subsystems may not be co-located and may have many connections to the same grid balancing region, but the generating subsystems are co-controlled to supply the grid with power and auxiliary services. The location of the industrial process will depend on the required heat quality, heat losses to the environment along the heat delivery system, and the required exclusion zone around the nuclear plant. This category, illustrated in Figure 4, includes thermally and electrically interconnected subsystems that are tightly coupled with the heat power supply. These systems are controlled by a single financial organization, although having many grid connections.
- Loosely Coupled IES. Because there is no direct thermal coupling between subsystems, this arrangement is regulated similarly to the thermally connected system, but generators would only be electrically tied to industrial energy users, as indicated in Figure 5. Prior to connecting to the grid, this scenario enables management of the system's electricity production. However, it should be noted that the system may also contain equipment for converting electrical energy to thermal energy, which would then be used to supply thermal energy input to industrial processes. With such a

choice, current generating facilities might potentially be retrofitted or repurposed with fewer regulatory obstacles. These systems may have several grid connections, but only one financial organization is in charge of their management.

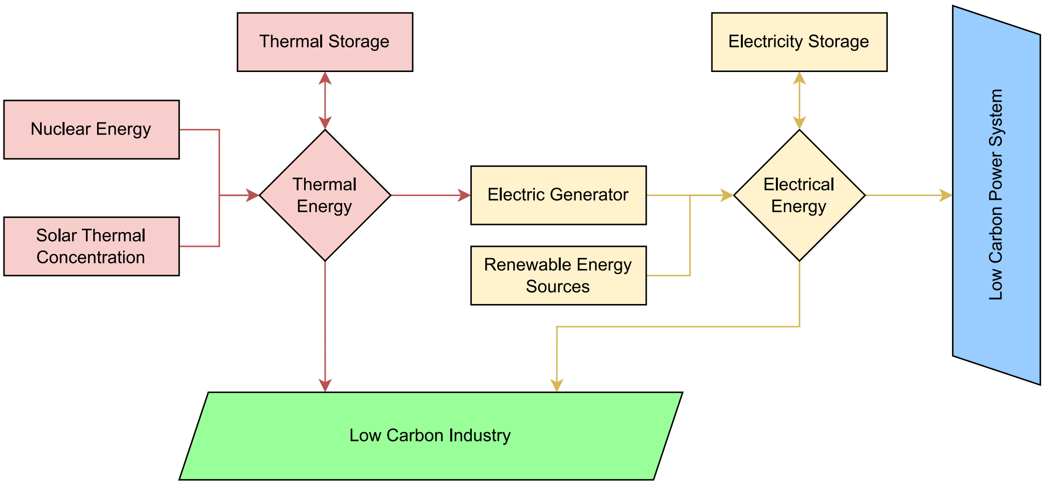

Figure 3. Tightly coupled IES.

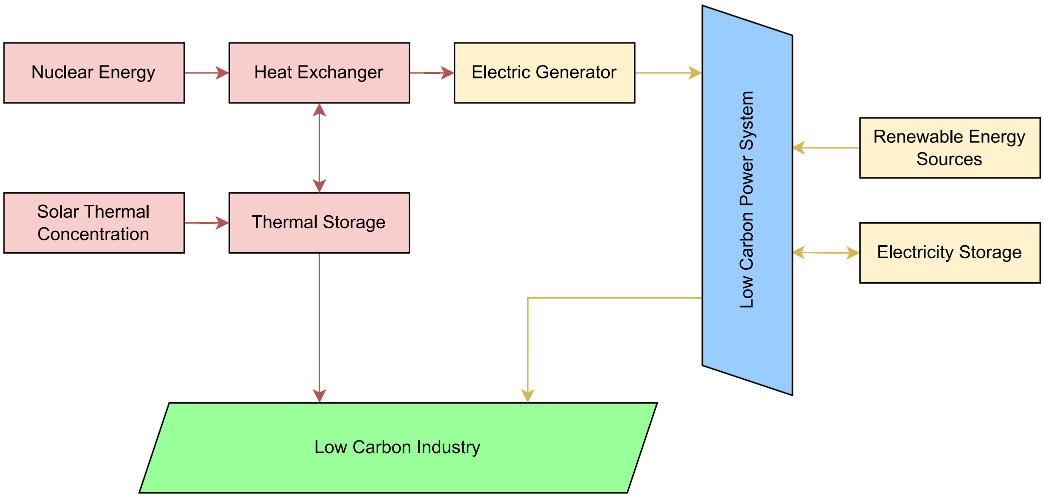

Figure 4. Thermally coupled IES.

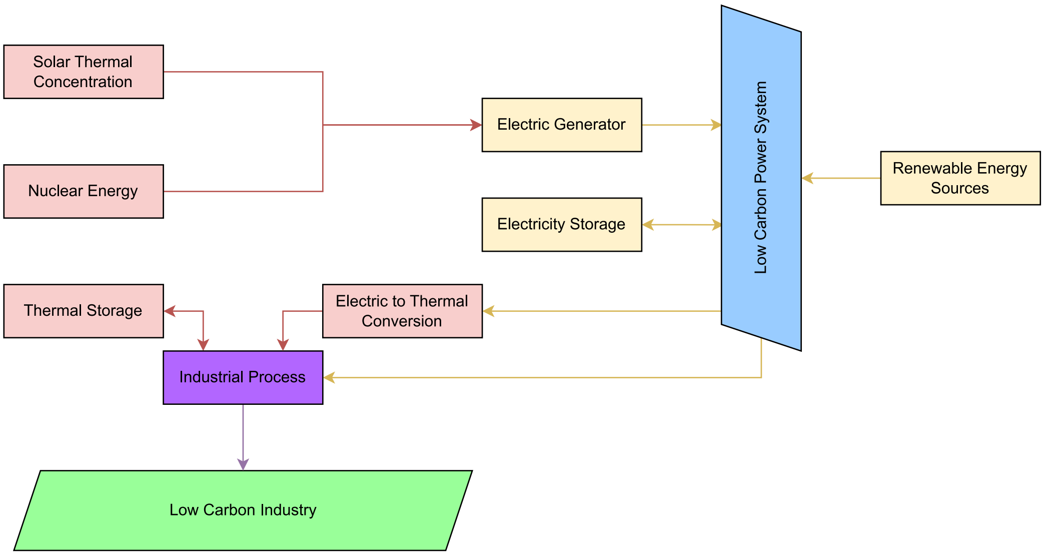

Figure 5. Loosely coupled IES.

3.2. Exploring Existing and Future Nuclear Plant Technologies for Feasible Implementation of IES

Nowadays, the majority of generators that feed electricity into the grid operate autonomously, generating just one kind of energy (electricity) and interacting with other generators that are linked to the system through a grid balancing authority. This is unquestionably the case for nuclear power reactors in the United States that do not now fulfill industrial thermal energy requirements. The hourly selling price of energy is frequently less than the marginal cost of production in regions where wind and solar power generating are being used. Nuclear power facilities cannot continue to operate only in energy markets with such price systems. To remain profitable, expansion into new energy markets is necessary [53]. In order to effectively execute the suggested IES applications, the technologies and nuclear reactors that are now in use in commercial settings as well as those that need to be carefully investigated and developed are described in this section.

3.2.1. Light Water Reactors (LWRs) and Boiling Water Reactors (BWRs)

Nuclear power plants harness the energy of uranium fuel through nuclear fission, which in turn heats water to generate steam for driving turbines and producing electricity. Various reactor types are employed globally in nuclear power plants to generate this form of energy. Among these, BWRs and LWRs stand out as both cost-effective and widely utilized options [50]. These reactors utilize ordinary water as a coolant and heat transfer medium for the nuclear fuel, enabling the efficient conversion of nuclear energy into electricity [54,55].

The importance of LWR plants' participation in the generation of other energy products as well as their flexible operation have been adequately demonstrated by recent modeling and simulation studies. For the anticipated lifespan of a significant capital investment project such as a hybrid plant, the fleet of nuclear reactors already in operation can dependably supply reasonably priced and relatively high-pressure steam. The price of natural gas might increase at any time when the current excess is no longer accessible, according to recent geopolitical developments in Europe. Contrarily, it is anticipated that the price of nuclear fuel will stay stable for many years to come, with little to no price fluctuation up to 40 to 60 years of additional LWR operations. According to several assessments, given particular operating circumstances and clean energy permits, an LWR hybrid plant can also outperform traditional natural gas steam reforming [56,57].

BWRs utilizing water as both a coolant and moderator belong to the same category as LWRs. While they share the commonality of water-based cooling, there are notable discrepancies between the two systems. Regular water, sometimes referred to as light water, acts as the moderator and coolant in LWRs. This water absorbs heat in the reactor core, which is then transported to a steam generator to produce steam, which in turn generates electricity [58]. However, with BWRs, when light water is also used as a coolant, the water inside the reactor core instantly reaches a boiling point, producing steam right there in the plant. The generated steam is then sent via turbines to produce energy. The water in BWRs serves as a moderator and a coolant simultaneously. Regarding steam generation, LWRs rely on a separate secondary loop. In these reactors, a heat exchanger uses the heat that the water coolant removes from the primary loop to produce steam that powers a turbine. BWRs, on the other hand, produce steam right inside the reactor core. After being removed from the water, the steam is used to produce energy [59].

3.2.2. Small Modular Reactors (SMRs)

Nevertheless, with the advent of microreactors (1–10 MWe) and SMR technology (less than 300 MWe), the range of reactor possibilities is about to shift. Microreactors are a distinct type of SMRs that were first created for specialized applications when MW-scale energy generation is either unavailable or too expensive. These reactor designs are made to be readily manufactured in a factory, transportable, and neutronically simple enough that they can operate partially or entirely autonomously [60,61]. Regarding SMRs, it may be expected that a single SMR module would be installed to support both the production of alternative goods and power. The interface exists between the SMR module and thermal energy consumers via appropriately designed heat exchangers, including the potential need for a tertiary loop to maintain system isolation, the control system design for dynamic allocation of energy generated by the SMR module, the sensors required to carry out the desired control functions, and the multi-module operation, wherein modules operated from a single control room may simultaneously be producing electricity and directing their thermal energy consumers. As a result, the US Nuclear Regulatory Commission has not certified any SMR designs.

3.2.3. Advanced Reactors (ARs)

The private sector is actively developing a variety of non-water-cooled AR ideas, frequently with the assistance of federal research institutions. These ideas emphasize intrinsic safety, waste reduction, the production of electrical power at an affordable price, and nonproliferation. Nevertheless, the quality most pertinent to IES is the capability to extract heat at a higher temperature to power industrial operations [62]. The six cutting-edge reactor systems that have undergone various levels of national and international study or deployment include molten salt reactors, fast spectrum sodium reactors, fast lead reactors, supercritical water reactors, fast gas reactors, fast gas reactors, and fast lead reactors. With ARs, it may be possible to reach significantly higher temperatures (500 to 750 °C and more), which opens up opportunities with different industrial users to satisfy their thermal and electrical needs while upholding ecological sustainability. These technologies will need to be developed further, however, because of serious material issues [63]. Further uses of these ideas for non-electric applications inside an IES may be taken into consideration as technical gaps for the commercial implementation of these reactor principles are addressed.

3.3. State-of-the-Art Technologies Utilized by IES for the Manufacture of Energy Products

IES function under the presumption that energy for industrial purposes must be split between producing heat and electricity. Nuclear energy is a good solution since it emits fewer pollutants than other baseload sources such as fossil fuels. Using LWRs and temperature augmentation techniques, industrial steam and heat demands may be satisfied. This may be completed with the least amount of greenhouse gas emissions by superheating steam using fossil fuels, chemical heat pumps, or other techniques. SMRs and ARs can provide heat and energy for industrial operations, but high-temperature reactors with designs that use molten salt or gas cooling might do away with the requirement for steam heating. These concepts, however, need more time to mature and are now cost-uncertain. This study examines several instances of nuclear reactors being successfully used in IES for the production of various energy products.

3.3.1. Hydrogen Production

A research paper highlighting the successful application of IES for hydrogen production is that of [53]. In this study, it is suggested that an IES be developed with exceedingly high penetration of renewable energy sources, taking into account methods for producing and storing hydrogen. The investigated IES is made up of a power-to-heat and hydrogen model that incorporates the thermoelectric procedures as well as operation restrictions for the electrolysis device in order to accomplish the flexible outputs of hydrogen and heat energy, a hybrid energy storage model with two operating modes, and a natural gas network to meet the base load's energy needs. Additionally, Dong X. et al. [64] suggest a demand-side involvement of wind and PV parks in a hydrogen-based integrated energy system (HIES). In order to manage the energy imbalance between supply and demand, increase energy efficiency, and fully use renewable supply, the suggested system is implemented together with the combination of hydrogen and water storage. The study's numerical findings demonstrate that the system's capacity to respond to changes in energy prices may be greatly improved, and the usage efficiency of renewable supply could be maximized. A hydrogen combined gas–electricity integrated energy system with strong coupling properties between the electricity system and the natural gas network, taking into account multiple RES, is also studied in [65]. In this system, the excess renewable energy is used to produce hydrogen, which is then intertwined into the natural gas network.

A typical framework for manufacturing hydrogen utilizing IES is introduced in the majority of studies published in the recent literature [66–72]. This building's distinctive features include considerable use of solar and wind energy, techniques for storing electricity, the storage of heat and hydrogen, and a natural gas system. It is apparent that these suggested IES frameworks are not as cutting-edge as the most recent techniques since nuclear power is not present, notwithstanding their effectiveness in terms of economic feasibility and efficient power system operation. Nevertheless, the Idaho National Laboratory has recently published some research papers concerning the production of hydrogen from nuclear-driven IES.

The technical and economic feasibility of LWR hybrid system operations is assessed in [73]. The paper delves into these systems' potential to respond to diverse industrial and commercial applications for hydrogen production as well as their ability to boost profitability for LWR power generation plants. The assessment is based on actual market circumstances in the Midwest region of the United States, close to an industrial hub that profits from the direct use of nuclear energy. The study suggests that, based on financial criteria for a publicly bonded capital project, H_2 may be generated for around \$1.50/kg, which is less expensive than the standard natural gas steam approach. Technically speaking, hybrid LWR plants may be utilized for seasonal and daily energy storage, which is crucial for preserving system resilience and dependability as renewable energy is introduced [74]. These hybrid plants may manage frequency and potential reactive power at the grid's transmission level by balancing generation and demand on a minute-by-minute basis.

As a variable load resource to be combined with an LWR in nuclear–renewable hybrid energy systems, a high-temperature steam electrolysis facility is suggested in [75]. This IES can allocate electrical and thermal energy in a dynamic manner on an industrial scale to satisfy grid demand as well as the high-temperature steam electrolysis plant's energy requirements without emitting greenhouse gases. The Primary Heat Generation (PHG) system is planned to use a tiny modular reactor based on an LWR. The Thermal-to-Electrical Conversion (TEC) system, which is the main source of power, uses the steam produced there to create hydrogen and oxygen at a High-Temperature Steam Electrolysis (HTSE) facility. With the contribution from renewable sources, which in this case include solar PV and wind, the TEC system generates the extra power needed to fulfill the requirements of both the electric grid and the HTSE plant. By the use of an energy storage system, which reduces or completely eliminates the high unpredictability of renewable energy sources, the output of renewable energy sources is introduced to the electricity distribution system. All of the subsystems are directly integrated "behind" the power grid and co-controlled by a single financial entity since the entire system is coupled to the power grid through a point of common coupling. The suggested IES can respond swiftly with fast-ramping capacity, settle appropriately fast, and sustain the needed change for a suitable period in response to rapid and substantial load changes, according to numerical findings from the application of the proposed system in three case studies. With such dynamic properties, the HTSE plant would be able to enable large-scale carbon-free hydrogen production while managing the fluctuation and uncertainty brought on by high penetration of renewable energy sources.

3.3.2. Water Purification

The demineralization of feedwater and cooling water is one of the various uses for water purification, as is the generation of process or potable water. Commercial applications include a variety of water filtration and desalination techniques. Reverse osmosis (RO), the most widely used commercially available water desalination technique, runs a pump that forces salty water across a membrane exclusively on energy. The semipermeable membrane divides the saline feed water from the fresh water by allowing salts to flow through but not water. For the near future of IES deployment, water purification via RO can be performed by loosely linking an existing nuclear power plant or other baseload facility.

The profile of the net demand is changing as variable renewable energy (VRE) becomes more prevalent [76]. Adding stabilizing (responsive) loads to the grid is one potential method of controlling net demand volatility. Another contemporary issue, which varies by area, is that population increase, along with drought conditions, puts pressure on the scarce natural surface and groundwater supplies, driving up the cost of water resources. Both problems might potentially be solved by water filtration. The most popular method of water purification, reverse osmosis, may be carried out by linking an existing nuclear power station or other baseload plant in a loosely connected electricity-only architecture for the installation of IES in the near future. An example of how this process is used is in the case study of the integration of nuclear power with renewable water in Arizona [77]. The Arizona Public Service made the decision to pump brackish water from the local ground water and treat it via an on-site RO desalination plant directly integrated with a hybrid energy system in order to reduce the associated demand volatility and to acquire less expensive cooling water.

Two cutting-edge nuclear hybrid energy technologies are examined in [78] to generate both clean electricity and water. Both systems generate enough electricity to fulfill demand using SMRs and wind turbines. Using input data for Salt Lake City, Utah on a hot summer day, both systems are emulated. Ice-based freeze desalination (FD) is the desalination technology used in the primary hybrid system. The extra electricity used to produce clean water by freezing is stored as "cold" energy and used to augment power during times of high energy demand. The second nuclear hybrid energy system (NHES) uses RO technology to create clean water. Even though it cannot store energy, RO is more energy-efficient at creating clean water. The study's numerical findings demonstrate that the FD system was able to create enough clean water and increase energy output by up to 12% during periods of high demand. Contrarily, the RO system could produce nearly six times as much clean water as the FD system could, but it would need many more wind turbines to adequately supply the energy need. Overall, these findings highlight the value of thermal energy storage for nuclear systems in increasing output to satisfy varying power requirements.

The research paper of [79] describes yet another attempt to create an IES that is similar to the RO method for water purification without the need of nuclear reactors. In order to deal with the unpredictable properties of renewable energy, this study suggests an IES composed of wind turbines and solar systems to build a microgrid to supply power and diesel generators together with battery storage devices. An IES's ideal energy management is described as an optimum control problem with a number of optimization goals, including running costs, storage costs, and pollution. By calculating the weight factor, the information entropy theory is used to build a trade-off between several aims.

3.3.3. Chemical Manufacturing

For nuclear reactors to be commercially viable, they must be operated close to their nominal design capacity, which justifies high plant construction costs and lowers maintenance and operations expenses. A hybrid energy system that combines nuclear and renewable energy sources might meet the grid's electricity needs while also maximizing the usage of the capital assets by incorporating extra operations that can effectively use excess thermal energy. Several industrial manufacturing operations, such as the chemical sector, might beneficially utilise extra reactor thermal energy and electrical energy that would be accessible in periods of low grid electricity demand or high renewable-generated electricity. The chemical manufacturing sector develops goods by processing organic and inorganic raw materials into fungible fuels, paper, wood products, polymers and resins, metals, refractory materials, glass, semiconductors, fertilizers, medicines [80], etc.

A first study of the successful application of IES in the generation of electricity and methanol is presented in [81]. In addition to generating electricity, this research evaluates the techno-economic feasibility of integrating the manufacture of methanol by the steam methane reforming of natural gas. This process yields carbon monoxide and hydrogen, which are then catalytically mixed to create methanol. Syngas is created by first reforming natural gas with steam in the traditional methanol process. A primary reformer receives a feed of steam and natural gas to partially convert the methane to syngas. At three progressively decreasing pressure levels, steam is produced in the hot secondary reformer. Throughout the facility, the steam is utilised and distributed at various pressure levels. Overabundance steam from the methanol process is typically collected and heated in a special heat recovery and steam generation unit to supply steam turbines that generate electricity to power the plant's auxiliary loads. This process also produces steam from an advanced fast reactor (AFR), which is cooled by sodium. The findings of this paper show that integrating an AFR with methanol synthesis in the direction simulated in this report results in a significant reduction in CO_2 emissions compared to standard methanol production methods while increasing the internal rate of return (IRR) when "must-take" wind-generated electricity is introduced to the energy system as revenue and is available from the methanol plant at all times due to the additional feed from natural-gas-fired heaters to maintain the plant.

Furthermore, [82] reports on a dynamic analysis of two realistic IES with a nuclear reactor as the primary baseload heat source to examine the local and system advantages attainable by their implementation in situations with multiple commodities production and strong renewable penetration. The first arrangement is for a West Texas NHES with a variable thermal load. This design generates energy from a nuclear reactor and a network of wind turbines while converting carbon resources to gasoline utilizing extra thermal capacity. This IES is comprised of an SMR and a steam generator that delivers steam for both electricity generation and gasoline production, a renewable power generation source comprised of a series of wind turbines, an electrical storage system used for power smoothing of the renewable source's electricity, auxiliary heat generation plants, a heat distribution system, a chemical plant complex capable of converting natural gas and water into gasoline, and an electric power generation system. The second arrangement is for a northern Arizona NHES with a variable electrical load. This arrangement uses a nuclear power plant and solar PV stations for energy generation, producing enough electricity to fulfill grid demand while also producing fresh water. This IES has the same primary components as the previous case study, but the chemical plant complex has been replaced with a fresh water production facility that can use energy to transform saline or brackish water into fresh water and brine. These well-defined, compact systems are operated in such a way that the electricity generated by the power cycle and renewable sources is managed by a supervisory controller and distributed to the electric grid in accordance with its needs or to an optimal electric generation strategy determined by an operations optimizer based on multiple factors, such as market price of each product. More details on NHES optimization are provided in [83]. The numerical findings show that the suggested IES designs can manage high levels of penetration, unpredictability, and uncertainty in variable energy supplies, which are difficult to accept using typical energy systems that solely produce electricity. They may also raise or decrease their electricity output over a wide range while maintaining power system stability since they can greatly lower gas emissions by using a nuclear baseload unit and renewables to satisfy grid demand on a continuous basis.

3.4. Prominent Simulation Tools for Analyzing and Implementing Nuclear-Oriented IES

Department Of Energy (DOE) national laboratories, led by Idaho National Laboratory, have been assessing IES for several years via the Department Of Energy Office of Nuclear Energy (DOE-NE) Integrated Energy Systems Program. The DOE-NE Crosscutting Technology Development IES initiative focuses on the research and development of tools and technologies that will lead to the implementation of IES with a clear commercialization route. Researchers are working on a framework for modeling IES that takes into account different reactor types, renewable technologies, and energy users. The Framework for Optimization of ResourCes and Economics (FORCE) ecosystem provides an interface to numerous software repositories, each of which addresses a piece of the problem. Table 1 outlines the issues addressed by each of the simulation tools mentioned above, with references to current research.

Table 1. Software tools for technical and economic analysis of the state-of-the-art IES.

Simulation Tool	Implementation Purpose	References
RAVEN	Multi-purpose uncertainty quantification Parametric and probabilistic analysis Regression analysis Data analysis Model optimization	[75,79,84–86,86–94]
FARM	Supervisory control	-
HERON	Acceleration of stochastic technoeconomic assessment Study of economic viability	[84–89]
TEAL	Thorough economic analysis Computation of NPV, IRR, and PI	-
HYBRID	Physical dynamics of IES Assemble nuclear configurations and control systems	[75,79,86,90–94]

3.4.1. RAVEN

The RAVEN (Risk Analysis Virtual ENvironment) framework is a versatile and adaptable tool for quantifying uncertainty, performing regression analysis, conducting probabilistic risk assessments, analyzing data, and optimizing models [95]. It is specifically designed to analyze complex system codes and provide both parametric and probabilistic analysis. The RAVEN framework can be applied to a wide range of applications, including uncertainty quantification, sensitivity and regression analysis, probabilistic risk and reliability analysis (PRA), data mining analysis, and model optimization. The development of RAVEN was initiated as part of the Risk Informed Safety Margin Characterization (RISMC) pathway, with the goal of providing a comprehensive set of capabilities ranging from data generation and processing to data visualization. RAVEN can investigate both the system response and the input space using Monte Carlo, Grid, or Latin Hyper Cube sampling schemes, but its main strength is in discovering system features, such as limit surfaces, which separate regions of the input space that lead to system breakdown, using dynamic supervised learning techniques.

3.4.2. FARM

The Feasible Actuator Range Modifier (FARM) is a plugin for RAVEN that aims to address the supervisory control challenge in IES projects [96]. Using a linear state-space model representation, FARM predicts the system's future state and output in subsequent time steps. Additionally, it adjusts the actuation variable to prevent any violation of implicit thermal mechanical constraints for the individual subsystems and components.

3.4.3. HERON

HERON, which stands for Holistic Energy Resource Optimization Network, is a toolset and plugin for RAVEN that speeds up the process of stochastic technoeconomic assessment for determining the economic feasibility of grid-energy system configurations [97]. With HERON, users can generate workflows for portfolio optimization of grid-energy systems. This is completed by using stochastically generated time-series and dispatch optimization tools. To create the stochastic histories, HERON utilizes RAVEN's built-in models, which are based on historical market behaviors in specific geographic regions.

3.4.4. TEAL

TEAL (Tool for Economic AnaLysis) is a RAVEN plugin that stores and distributes economic analysis for RAVEN processes [98]. It employs the RAVEN framework for uncertainty quantification, probabilistic risk assessment, parameter optimization, and data analysis to deploy complicated economic studies. Using RAVEN, TEAL allows you to compute the NPV (net present value), IRR, and PI (profitability index). The plugin provides for a general specification of cash flows, with RAVEN providing the drivers. TEAL also features various choices for dealing with taxes, inflation, and discounting, as well as the ability to compute a combined cash flow for components with varied component lifetimes.

3.4.5. HYBRID

HYBRID is a set of transient workflow written in Modelica that may reflect the physical dynamics of different integrated energy systems and processes [99]. The models are designed to be modular, allowing users to easily construct and test various configurations and control systems. The systems under consideration are modular and comprised of a collection of components. A hybrid nuclear reactor, a gas turbine, a battery, and some renewables, for example, might be included in a system. This system corresponds to the size of a balancing area; however, any size system is theoretically possible.

4. Challenges and Opportunities for Effective Design and Integration of IES

To reach the full potential of IES, appropriate design and integration methods, as well as supportive laws and regulations, are required to handle the constraints and capitalize on the benefits. Continuous research and development are also required to constantly enhance the performance and cost-effectiveness of IES components and systems. This section covers the issues and opportunities that must be addressed in order to implement IES in modern energy systems in a comprehensive and resilient manner. Table 2 highlights the potential difficulties discussed further below.

Table 2. Addressing research needs for feasible implementation of IES: a concise table of challenges.

Aspect	Challenges and Opportunities
SMR	Premature form Limited capacity due to technical restrictions Challenging electrochemical synthesis implementation
Modeling and Optimization	Detailed technical descriptions High complexity Large computational time
Power Systems	Reliability analysis Stability assessment Highly efficient and cost-effective power electronics
Electricity Market	Cooperation of partial energy markets Continuous monitoring of the energy markets Establishment of international regulations

4.1. Challenges of Cutting-Edge SMR Technology

SMRs appear to be the primary kind of nuclear reactors that IES will use in the near future. Despite the profusion of beneficial qualities that emerge, several problems must be addressed owing mostly to their early form [100]. Many supporters have stated that SMRs can modify a plant's power output to adapt to changes in electricity demand. Several of these authors discuss the capacity to modify output across quite extended time periods, such as between night and day. Although nuclear power plants can operate in a load-following mode and have done so in some nations, nuclear reactors have technological restrictions that limit their capacity to operate in a load-following mode [101,102]. Technically, shutting down, restarting, or adjusting output power are all more difficult for nuclear power facilities, particularly water-cooled reactors, than for other energy sources. Such modifications can lower operational life and raise maintenance expenses. Due to these regulatory issues, authorities mandate that the power fluctuation rate be kept below certain limits. The current range of allowable power fluctuation rates in nuclear technology is between 1 and 5% of the rated power per minute. This restricted ability of nuclear reactors to modify outputs may not be fast enough to compensate for potentially rapid variations in outputs from wind and solar power facilities.

It is critical to deploy SMRs in order to centralize the production of other energy products. Electrically heated and electrochemical synthesis techniques were previously limited due to the high cost of power as compared to thermally driven reactions using fired heaters [81]. Yet, given the clean and economical energy that SMRs or microreactors may deliver, it is time to reexamine industrial electrochemical processes and build new thermo-electrochemical production processes. Electricity and steam are straightforward to create with any nuclear reactor; the only considerations are the efficiency of power output and the amount of steam superheating and delivery. There is little need for technological improvement in this sector, and the processes of power generation and steam distribution are fully understood.

4.2. Modeling and Optimization Challenges

For many years, energy systems modeling has relied on large bottom-up optimization models that provide detailed technical descriptions of the energy system components. However, there is a challenge associated with these models, namely finding a balance between model resolution, data availability, and computational feasibility. The variability in renewable energy sources over time and the increased management of energy demand in future energy systems present additional challenges. The economic potential and generation costs of renewables are largely dependent on their location, making spatial detail crucial for their optimal use. The intermittency of renewables can be reduced by distributing them spatially, which can also influence the amount of storage required and become a major factor in system costs.

As energy systems become more decentralized, depending on more diversified energy sources and increasingly networked across borders, they become more complicated and interrelated. The concern, therefore, becomes whether energy system models are too compact, in other words, whether they may omit certain crucial characteristics of the systems they describe by making resolution trade-offs or employing simplified assumptions. In some significant ways, the issue of complexity is connected to the question of size. A model is often developed to either study the long-term evolution of an energy system with coarse resolution or to examine the planning or operation of a system over a shorter time with fine resolution. High-resolution phenomena, such as demand variations, may, nonetheless, be relevant for long-term system design. Due to the inherent processing needs, integrating information across these diverse scales with their proper resolution remains a difficulty. Rather than defining complex interactions among many parts of a system and simulating the entire system as an integrated whole, the complexity science paradigm specifies individual parts (agents) in as simple a formulation as possible, then specifies the rules they follow and their interactions with the environment. This method makes it easier to decouple processes that occur at multiple sizes by describing agents at different scales and allowing them to communicate.

4.3. Reliability and Stability Challenges in Power Systems

A collection of models that deal with one specific facet of energy, electricity, are even more separated from broad energy system models. Power systems models have traditionally been used by utilities and other organizations in the power sector to make choices ranging from investment planning to operational tactics, such as generator dispatch [103]. This set of applications can be loosely associated with normative-optimization and predictive-simulation modeling methodologies once more. In general, power system models are distinguished by more depth and attention to temporal fluctuation as a steady balance of supply and demand is a critical component of a functional power system [104].

The literature on the stability of nuclear-powered IES is extremely limited. The most recent research efforts have focused on the stability performance of hybrid renewable energy power systems employing constant voltage stabilizers [105], super-capacitors [106], or optimizing approaches [107] to achieve IES stability. However, there are certain study gaps in the current literature, such as studies on the dependability of power systems interconnected with nuclear-powered IES, as well as studies on the stability of power systems in the event of severe disruptions. Regarding the previous example, upcoming research papers will likely need to address inquiries related to the potential of renewable energy sources to remain connected during instances of electrical faults, as well as the performance of nuclear reactors. Another area of interest is the role they can play in facilitating the restoration of power networks in a seamless manner via storage systems.

4.4. Opportunities for Electricity Market Redesign and Reestablishment

Models studying the power market have also delved into the territory previously controlled by massive energy systems models. One explanation is that the fluctuation in renewables influences pricing, resulting in different incentives to develop alternative types of power plants [108,109]. A detailed and comprehensive investigation of the effective integration of nuclear-powered energy systems necessitates the construction of a dynamic process model that accounts for transitory activities that follow market demand functions, such as electricity trading prices that vary over time. International collaboration initiatives, including both nuclear and heat stakeholders, should also be promoted further. As a result, there is a need to establish a new regulatory board or improve the rudimentary form of the current ones to formulate new rules and guidelines and grant license for operation. Several regulatory authorities may be required to be involved for each subsystem and their interaction. Electrical and other energy institutions may require new rules, re-regulation, or deregulation.

5. Conclusions

In conclusion, this report completed a detailed assessment of recent literature on the subject of IES and highlighted research issues and opportunities that will establish them in highly efficient energy systems. Initially, we were able to emphasize the significance of nuclear energy in the evolution of power systems, as well as the fact that IES represent a viable strategy for modernizing and decarbonizing energy systems by enabling the seamless integration of renewable energy sources, energy storage systems, and smart grids, resulting in a more efficient, dependable, and sustainable energy system. Furthermore, this study attempts to underline the considerable potential provided by nuclear-powered energy systems to increase energy efficiency, reduce greenhouse gas emissions, and improve the overall resilience and flexibility of the energy system. However, as specifically stated in this research, IES deployment confronts various problems, including legislative and economic impediments, interoperability, and effective design and integration techniques. The development of advanced energy management and control algorithms that can intelligently improve the reliability and stability of IES should also be taken into consideration as another research objective. This further aims to address the resilience and security challenges associated with IES. The performance and cost-effectiveness of IES components and systems must be continually improved in order to meet these difficulties. Hence, supportive laws and regulations must also be enacted in order to encourage the widespread adoption and profitability of IES.

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