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2024

El-Emam, R. S., Constantin, A., Bhattacharyya, R., Ishaq, H., & Ricotti, M. E. (2024). Nuclear and renewables in multipurpose integrated energy systems: A critical review. *Renewable and Sustainable Energy Reviews*, *192*, 114157. https://doi.org/10.1016/j.rser.2023.114157

Nuclear and Renewables in Multipurpose Integrated Energy Systems: A critical review

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Abstract:

Hybrid energy systems for multi-purpose applications are an evolving technology concept which is garnering increased interest in the international nuclear energy community, energy system designers and planners and national decision makers in the context of deep decarbonization and net zero targets for climate change mitigation. They are expected to reduce costs and increase flexibility in operation of nuclear reactors when coupled with intermittent renewable energy sources, while also producing various commodities such as hydrogen or potable water. A considerable amount of R&D is still needed, and adaptive solutions must be considered for each geographical area and based on the involved components, available infrastructure, and policy in place. This paper provides an in-depth look at the strengths, weaknesses, opportunities, and threats of such systems, while addressing some of the aspects related to the creation of the business case for such systems, such as decentralization and digitalization of future energy systems. The regulatory aspects are the ones that impose challenges on the emerging hybrid energy systems and this paper highlights some of the considerations that are needed for the couplings involved, in terms of licensing procedures and safety analysis. The potential contribution of such integrated energy systems towards achieving the United Nations Sustainable Development Goals (UN SDGs) as developed by the United Nations Development Programme are also discussed. Concerning the stakeholders, special attention should be paid to building social acceptance and trust as this lays the foundation for successful implementation of such projects. By focusing on areas such as research and development, integration of technologies, policy support, market development, grid integration, energy storage, efficiency improvement, system modelling and simulations, significant advances in hybrid energy systems deployment can be achieved.

Keywords: Integrated energy systems; Nuclear; Renewable; Sustainable Development Goals (SDGs); Licensing; Internet of Things (IoT); Business models

1. Introduction

Climate change is possibly the greatest threat which mankind is facing today. The Paris Agreement was signed at the COP 21 meeting in 2015 and it set the goals to achieve net-zero emissions of greenhouse gases (GHGs) by 2050, with the target of restricting global temperature rise under 2°C above pre-industrial levels [1]. In this context, the Intergovernmental Panel on Climate Change (IPCC) published a special report [2] that emphasized the rapid and deep decarbonization requirements in all sectors of the economy along with carbon dioxide removal (CDR) from the atmosphere. All pathways that restrict the warming to 1.5°C require CDR alongside economy wide and drastic reduction in the use of fossil fuels. Additionally, in the context of climate change conferences such as COP27, supranational organizations such as the International Atomic Energy Agency (IAEA) have highlighted the contributions nuclear energy and additional nuclear power applications can make to tackle climate change and adapt to the consequences that are already being felt worldwide [3]. Along with the emissions reduction efforts, several negative emission technologies (NETs) are also likely to be required, including both engineered (e.g., carbon dioxide capture, mineralization, etc) and natural solutions (reforestation, regenerative agriculture, etc).

After the Paris Agreement, there has been growing global interest in finding viable, economical, and integrated solutions to achieve low carbon, affordable, resilient energy generation to decarbonize various sectors such as electric power, process heat supply for industrial purposes, transportation fuels and industries using fossil fuels as feedstock or raw materials. Nuclear and renewable energy are the two leading low-carbon energy supply options and achieving net zero energy systems will require harnessing both forms of energy in suitable proportions and their application in producing new low-carbon energy vectors such as clean hydrogen for the heavy emitting and hard to abate sectors such as chemicals synthesis, metallurgy, etc. In fact, econometric data analysed by different researchers for different nuclear equipped country clusters (e.g., Brazil, Russia, India, China, and South Africa (BRICS) and Organisation for Economic Co-operation and Development (OECD)) indicate that the deployment of nuclear and renewables in the national energy mix has clearly contributed to the decrease in CO_2 emissions intensity of their economic activity [4, 5]. This therefore provides insights into designing future energy mixes centred on nuclear-renewable combinations, considering regional or national demand and supply situations.

Nuclear-renewable integrated energy systems are hybrid facilities consisting of renewable energy generation systems, nuclear reactors, energy storage and co-located or coupled industrial processes making use of heat, electricity and other material feedstocks generated by this configuration. These arrangements can address the requirement for grid flexibility and reliable supply, integration of higher shares of renewables, optimal utilization of investment capital, minimization of power modulation and curtailment of generation and GHG emissions reduction. Nuclear power carries substantial potential to play a vital role in GHG emissions reduction and nuclear power has already contributed to avoiding a substantial quantity of CO_2 emissions over the decades. Numerous countries have such energy sources available in their countrywide energy mix and are in principle, already operating a nationally integrated nuclear-renewable energy system. However, a few have also observed or considered the conceivable synergies between them, particularly when it comes to stand-alone configurations of such systems meeting a more localized energy demand (e.g., within a limited region or an industrial complex). A system integrating both nuclear and renewables can drastically reduce GHG emissions compared to continued dependence on conventional fossil fuels without abatement. Such integration can also support cogeneration for multigeneration purposes such as hydrogen production, seawater desalination, district heating and cooling, synthetic fuel production and other industrial applications. Further R&D in the individual technologies, their integration along with the suitable policies and market incentives are imperative to be considered as the next steps towards deployment of these systems. Synergies in the nuclear and renewable integration have been discussed on international platforms such as the IAEA meetings as the possible options to decarbonize the energy production and multigeneration [4]. While historically nuclear reactors have operated in base load mode, with new age reactors, nuclear power too offers flexible operation depending on the energy demand, whereas renewables for instance solar and wind are naturally intermittent. Through such flexible operation, carrying out balancing act that is also identified as load following, nuclear power integration with renewable energy can improve the renewable energy efficiency and overall energy system resilience, reliability, and affordability.

The current study is motivated by the need to address various technical, commercial, and regulatory issues in order to truly harness the potential of nuclear-renewable hybrid multipurpose integrated energy systems on the transition to a deeply decarbonized world. These issues are critical in achieving policy support for system deployment and managing multiple levels of stakeholder expectations.

This paper provides an in-depth look at the strengths, weaknesses, opportunities, and threats of nuclear-renewable integrated energy systems (NR IES) or hybrid energy systems (NR HES), while addressing some of the aspects related to the creation of the business case, such as decarbonization, decentralization and digitalization. Regulatory aspects, the need of social acceptance and building trust in stakeholders, as well as some national attitudes towards deployment of hybrid energy systems are highlighted in the following sections.

2. Integrated Nuclear-Renewable Multipurpose Energy Systems: Previous studies

The benefits and challenges in developing, deploying, and managing integrated energy systems have been studied by several agencies. The Joint Institute for Strategic Energy Analysis (JISEA) has been working closely on the nuclear-renewable hybrid energy systems (HES) and their economic potential in the United States of America. In August 2016, a report on the economic potential of two nuclear-renewable hybrid energy systems was published [5]. It presents cost-benefit assessments of a system of nuclear-fossil-renewable (solar PV or wind) generators coupled with industrial processes such as synthetic gasoline production and sea water desalination. It is determined that the net present value-to-cost ratios for the configurations is greater than one for the range of conditions considered in the study, thus proving its profitability. Another report on the economic potential of three nuclear-renewable hybrid energy systems producing thermal energy for industrial users was published in December 2016 [6]. Such configurations allow for sale of low value electricity as heat when demand for power is low and also permit direct supply of nuclear heat and even thermal energy storage. It was determined that nuclear heat supply would be more profitable that supplying it via natural gas combustion, particularly when avoided CO_2 emissions and a suitable social cost of carbon are considered in the analysis. An additional report was published on the economic potential of nuclear-renewable hybrid energy systems producing hydrogen as an industrial commodity in April 2017 [7]. Hydrogen production using either low temperature water electrolysis or high temperature steam electrolysis was found to be profitable only under certain conditions, depending on relative market values of electricity and hydrogen, particularly under high volatility of electricity prices due to supply or transmission side constraints. Idaho National Laboratory recently published a paper on the reimagining of future energy systems: a detailed summary of the US driver for energy utilization maximization through integrated nuclear-renewable energy systems, describing the motivation for developing integrated energy systems to meet electrical demand and other industrial services (heat/hydrogen/water), the software tools to simulate and evaluate the integrated system performance and prototype or demonstration cases studied so far [8]. MIT Energy Institute (MITEI) published a detailed report [9] on how nuclear flexible operation can assist in adding more solar and wind to the grid. The assessments were done through power systems modelling and showed the need for flexible reactor operations to reduce dependence on fossil fuel plants for grid balancing services and for reduction of power curtailment, in the face of rising share of grid integrated variable renewables. Similar research was also conducted at Argonne National Laboratory (ANL) [10] describing the advantages provided by nuclear flexibility in energy system operations and integration with renewable energy. The actual realized advantages of these systems have been seen to depend on regional factors such as geographical and meteorological conditions and electricity market design. There are also numerous studies in the literature focusing on nuclear cogeneration [11, 12], describing hydrogen production [13-16], and sea water or brackish water desalination [17, 18] using nuclear heat and/or electricity, tackling the technical and economic aspects of such projects when based on a range of technological options [19-22]. In nuclear-renewables integrated energy systems, these processes can make use of input energy from any of the supply options. Figure 1 exhibits a generic illustration of nuclear-renewable HES being proposed for multigeneration purpose including electricity, hydrogen, chemical, heating and cooling to serve grid interconnection, industrial processes, and residential applications.

A detailed review on nuclear-renewable hybrid integrated systems was published recently focusing on the current status, configuration, operation, benefits, prospects and feasibility of the hybrid integrated systems [23]. Numerous probable integration techniques together with their operation were discussed, considering six interconnection aspects of electrical, chemical, thermal, mechanical, information and hydrogen along with current approaches to modelling system performance and licensing these systems for deployment. Renewable energy and nuclear power integration in North Africa was analysed with focus on regional energy requirements and energy imports and exports to meet the massive growth in demand [24]. For the specific case of Algeria, the authors conclude that renewables are the more feasible option for energy system design An economic case study about a coupled nuclear-renewable system comprising of a gas cooled high temperature small modular reactor and solar PV and wind generators and a steam electrolyser based hydrogen plant was published as well to establish the financial feasibility considerations associated with system deployment [25]. Costs and environmental concerns related to fossil fuels are encouraging researchers and organizations to seek alternative energy sources to help satisfy the globally intensifying energy demand in a sustainable and environment-friendly manner. The collaboration among the three applied energy laboratories of the U.S. Department of Energy, namely Idaho National Laboratory, National Renewable Energy Laboratory (NREL) and National Energy Technology Laboratory, led to a recent study on the novel multi-input and -output hybrid energy systems that synergistically integrate diverse sources of energy, including nuclear, renewable and fossil with carbon capture, to offer sustainable, reliable and cost-effective power, mobility, heat and other commodities [26].

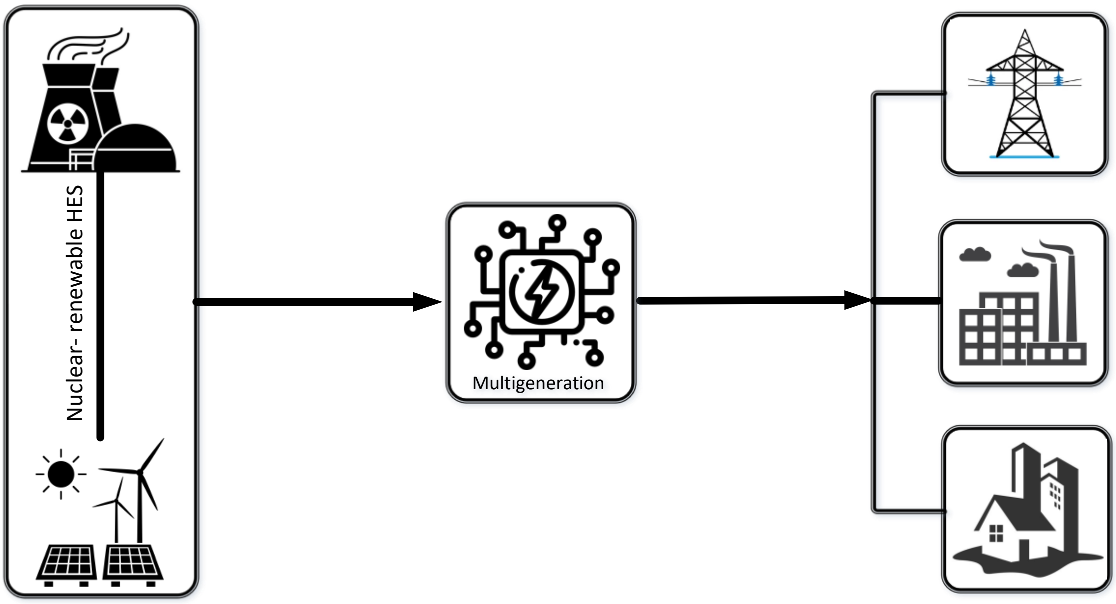

Fig. 1: Illustration of nuclear-renewable hybrid multipurpose integrated energy system

The International Atomic Energy Agency recently published, a series of country specific case studies to describe relevant market conditions and trends, and considerations for implementation, as well as gaps that require additional technology and regulatory developments [27]. The Idaho National Laboratory produced numerous reports to support the Integrated Energy Systems (IES) Program under the Department of Energy, that investigate various configurations for system integration and nuclear power plant integration [27], as well as flexible plant operation and generation [28]. A study on tightly coupled novel hybrid energy systems, including renewable, nuclear, and fossil with carbon capture, presents a framework for modelling and optimization of energy generation, transmission, services, processes and products, and market interactions [29]. A recently published research article conducted the analysis of nuclear and renewable energy integrated systems for marine ships [30]. In this article, four dissimilar hybrid energy systems with different stand-alone and integrated configurations of renewables and nuclear energy systems were analysed and compared. The renewable-nuclear hybrid system was found to be the best for integration with the marine industry, not only to improve economic performance but also to reduce GHG emissions. Another research study investigated different coupling methods for nuclear and renewable integrated energy systems [31]. In this study, three different coupling methods of single and multiple resources and multiple products-based coupling and direct coupling were examined for the optimal planning of nuclear and renewable integrated energy systems. Dynamic analysis of the nuclear and renewable integrated energy system coupled with high-temperature steam electrolysis (HTSE) system was conducted by Idaho National Laboratory [32]. It proposed an HTSE plant to be operated as a flexible load resource for the integrated energy system. The designed system was found to be proficient in dynamically distributing thermal and electrical energy on an industrial scale, to meet both HTSE plant energy requirements and grid demand without generating GHG emissions. A comprehensive review article was published recently on nuclear-renewable hybrid energy systems, summarizing various aspects related to system design, development and deployment [33]. To overcome the intermittency and geographical location dependence of renewable energy sources as well as government policies and public apprehensions of nuclear energy, this study proposed the integration of renewable and nuclear generation and addressed the apprehensions concerning grid flexibility, energy security, climate change, optimal return on investment and settling public concerns.

A report was published by International Energy Agency focusing on the renewed interest in the role of nuclear power generation in clean energy systems, both in developed and developing nations [34]. The report emphasises that nuclear and hydropower are the pillars of low-carbon generation of electricity and together, they deliver three-quarters of total low-carbon generation; it recommends continuing the existing fleet in the light of dispatchability requirements of future energy systems which have to phase down fossil-based generation. It clearly states that sole dependence on renewables will make for a much more expensive energy transition, thereby suggesting the need for integrated energy systems. Some efforts were made by a paper published recently [35], focused on the nuclear-renewable hybrid energy system, grid-connection and feasibility analysis using HOMER as the software tool. It finds that out of only nuclear, only renewables and nuclear-renewable hybrid option of power supply to meet a specified demand, the hybrid system is established to be the most economically feasible alternative. Another research study [36] reviewed the nuclear-renewable hybrid energy system' potential for sustainable power production in the specific case of Malaysia. It suggests that a hybrid system consisting of a small, modular reactor integrated with renewables is likely to be the most suitable approach towards decarbonization and energy supply security, in its approach to reducing the carbon emissions intensity of its economy. A report was published by the Idaho National Laboratory on the nuclear-renewable hybrid multigeneration systems targeting the market potential with the industrial energy users such as chemical synthesis plants, who need electricity and additional services such as clean feedstocks [37]. In the near term, sectors like industrial gases, polymers, elastomers, machinery and metallurgy were found to be the biggest potential beneficiaries of hybrid energy systems in achieving decarbonization in an economical manner.

Clean energy availability and affordability have a very strong correlation with the state of welfare of a nation and are crucial components of achieving the 17 interlinked global goals described as the Sustainable Development Goals (SDGs). Theses SDGs and their underlying targets were adopted in 2015 by the UN General Assembly and are proposed to be accomplished by 2030. Nuclear-renewables integration for multigeneration can help achieve the SDGs, more specifically SDG 7 (affordable and clean energy), SDG 11 (sustainable cities and communities) and SDG 13 (climate change mitigation).

3. SWOT analysis of integrated energy systems

The deployment of integrated energy systems requires careful consideration of multiple conflicting factors, right from the initial planning phase. This section highlights many of these factors crucial for deliberations by energy planners.

3.1. Strengths

The major strength of hybrid nuclear and renewable in multi-purpose integrated energy systems lies in the contribution of such projects towards the reduction of greenhouse gas emissions and mitigation of climate change, consistent with national climate change commitments and targets. These energy systems leverage i) the high-capacity factor and long-experienced supply of reliable base-load and relatively cheap electricity, provided by the nuclear power industry for several decades and ii) successful and reliable operation of renewable energy systems in several countries. With respect to supply security, there are reasonable reserves of uranium ore worldwide, as well as more equitably distributed solar and wind energy harvesting capability across nations. The issue of intermittency can also be overcome in the integrated systems discussed here. The following are some other elements of strengths of such projects:

- The available knowledge base created through the significantly long design, operating and maintenance experience with the current fleet nuclear reactors
- Experience in multipurpose use of nuclear energy –for example, in desalination, via different technologies, and for district heating along with electricity production, with no major technical problems;
- The low life cycle carbon footprint of nuclear power plants, which reduces further when waste heat of the plant is recovered, potentially upgraded, and utilized for low temperature applications;
- The high availability and capacity factor and reliability associated with price stability (due to much lower influence of fuel prices on nuclear heat/electricity prices), in nuclear projects for electric power production, brings strength to the concept of demonstrating nuclear in hybridization with renewables and for multi-purpose applications;
- The nuclear heat economics, providing also security of supply;
- The excellent research and mature manufacturing capabilities and capacities in industry of solar (especially PV technologies) and wind turbine technologies along with steep price reduction due to technology learning curve effects;
- More effective utilization of the renewable energy resources available to a nation while ensuring domestic energy security not affected by geopolitical issues;
- The contribution to cover the increasing energy and water demands;
- The long-term price certainty of products and services from integrated systems which are favorable conditions for industrial users;
- The reliance, to a great extent, on the use of standardized, off-the-shelf technologies (especially in projects for desalination, conventional electrolysis for hydrogen production, and district heating) with no requirement for a lengthy research and development phase;
- The high overall operating efficiency of multi-purpose plants compared to single purpose power plants;
- The potential to cater to high-temperature applications markets in specific industries such as metallurgy, targeted by concentrated solar thermal and High Temperature Reactors (HTR) designs: the use of their heat and/or recovered heat for low temperature applications can provide additional versatility and bring better public acceptance compared to other technologies;

3.2. *Weaknesses*

The inherently variable characteristics of renewable energy systems is one of the main concerns in the deployment of these systems However, in N-R IESs, this concern is largely eliminated with integration of baseload energy sources (i.e., nuclear and renewables), along with availability of energy storage and other forms of flexible loads/demand centers. Additional concerns come from the geographical concentration of nuclear fuel materials. The fact that over 70% of the world's uranium comes from three countries (Kazakhstan, Canada, and Australia), although politically stable, still possess suppliers risk issues to the scene. In addition, even though disposal in deep geological repositories is currently under consideration is several countries, the high-level waste disposal when once-through nuclear fuel cycle is used can still be perceived as another issue. The following points are some of the other weaknesses related to N-R IES projects:

- Knowledge and experience in implementing such projects bases may not be considered enough by stakeholders and decision makers, to pursue a demonstration plants;
- Issues associated with thermal coupling of nuclear island with industrial applications require more investigation to establish necessary regulations to facilitate the licensing of the plant;
- Competition with the well-established technologies of conventional combined heat and power, and the cheaper and more flexible industrial steam production plants;
- Limited recognition and understanding of sustainability aspects of nuclear energy;
- Private sector favoring short-term investment rather than taking the risk of investing in large industrial and energy projects that require long lead time with delayed return on investment;
- Inadequate awareness of the benefits of nuclear cogeneration projects among stakeholders and decision makers, leading to concerns about their public acceptance (e.g., desalinated water from a nuclear facility may be considered unacceptable for consumption);
- Possible long periods of low prices of fossil fuel, as well as non-fully liberalized energy market;
- Excluding hydropower, renewable energy still has a low contribution (~12%) in the global electricity generation compared to fossil-produced electricity at over 60%;
- Lack of investment policies to enable and facilitate investors to take long term risk by involvement in such projects;

- Greater need for critical minerals for the renewable segment of the NR HES, which are geographically concentrated in few regions and can possibly create new or additional supply chain issues and energy security concerns.

3.3. Opportunities

Opportunities of integrated energy system projects involving nuclear and renewable sources are growing rapidly now with the rising interest in Small Modular Reactors (SMRs), which adopt advanced and inherent safety features in their designs with integrated passive cooling systems. The smaller Emergency Planning Zones (EPZ) for SMR designs can allow for siting SMR based cogeneration plants closer to the customers of the plant’s products. In addition, incorporating alternative nuclear fuel cycles (e.g., the use of closed fuel cycle), partial fuel recycling (e.g., use of mixed-oxide (MOX) fuels), and thorium fuel cycles would enhance the nuclear opportunities on both short and long terms. Additional opportunities are as follows:

- Partnerships opportunities between public and private sectors in large industrial nuclear cogeneration projects;
- Potential for such systems to replace the retiring large industrial plants within the coming 30 years;
- Serving the expanding heat market and plug-in market, industrial, and agriculture sectors, as well as serving markets overseas through exports of energy products;
- New generations of nuclear plants are being designed for load following and variation in power output, which can be enhanced with the integration of energy storage systems (including lower cost thermal energy storage, redox flow batteries etc.) and flexible loads such as water electrolysers;
- Potential for innovation in the economy of the country increasing the attractiveness for investors;
- Creation of new diversified job market and benefits from the economic multiplier effects of developing clean energy systems;
- The growing concerns associated with the climate crisis, driving the move towards renewable and nuclear energy systems;
- Possibility to take advantage of strong public and governmental support to utilization of solar and wind energy systems, in order to launch national and international projects for R&D and deployment of hybrid systems demonstration;

- The fast development of solar energy technologies and the continuous progress in increasing PV lifetime and operational efficiency;
- Development of new advanced nuclear fuels that can enable flexible operation of traditional nuclear reactors which have historically operated in base load manner. Experience from the flexible operation of the French nuclear fleet can also provide useful lessons and best practices for the current fleet of reactors that have not yet operated with regular power modulation.

3.4. Threats

Threats to the deployment of integrated systems are mainly centered on the potential nuclear accidents and the concerns surrounding long-term nuclear waste storage, together with the associated health, environmental, societal and physiological perceptions on ionizing radiation along with national nuclear policy changes. Other elements of externalities which act as threats mainly for nuclear cogeneration projects include:

- Occurrence of national economic crisis, or worldwide financial crisis leading to a similar recession of 2008 that might lead nations to abandon nuclear power projects midway or not consider them at all. Political instability, including wars, national and international conflicts, and natural disasters may also create similar adverse conditions for project deployment Weak regulations to abate CO2 generated from fossil fired power plants and continued support to fossil fuel exploration and fossil-based energy programs;
- Risk of carbon leakage, with industries escaping to less restricted markets aiming to avoid the associated high cost of CO2 tax instead of investing in low carbon technologies at the domestic level;
- Bureaucracy and the burden of high regulatory aspects of nuclear power and cogeneration plants;
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- Lack of sufficiently qualified human resources for specialized energy systems management;
- Occurrence of a nuclear incident or accident in another country that may affect public and political acceptance for delving further in the nuclear program;
- Delay in the permitting and construction process and the associated cost increase;
- Lack of governments’ financial and political support to renewable and/or nuclear energies;

- Instability of national policy, regulations and procedures towards renewable energy systems;
- Development of clean coal technologies and carbon capture, sequestration, utilization, and/or storage especially in coal-rich countries which leads to continuation of fossil energy programs;

4. Improved drilling technologies can bring shale gas at competing prices in some parts of the world, thus perpetuating natural gas based heating and power generation in those regions.**Technical Challenges**

The recent years have brought rapid technological developments of individual elements of hybrid energy systems enabling significant cost reductions, and this takes into account the increased need for specialized equipment, system complexity, and multi-dimensional risk. For such precommercial or emerging systems, a key challenge lies in the balance between the three dimensions - cost, complexity, and risk, meaning the benefits of hybridization needs to prove a significant return on investment over the added risk in order for investors to support such projects. Hybridization itself brings additional challenges as the power generating utilities needs a change in paradigm, from operation of single technology type to ensure flexibility and operation while minimizing costs and maintaining reliability in operation with integration of a variety of energy sources available. This comes with challenges in terms of regulations for electricity markets, for utilities providers and for energy policy implementation.

Ensuring a full market participation by developing of advanced design and control of generation that enable the transition from centrally operated systems to hierarchical, distributed controls will require additional effort in the upcoming years in order to ensure optimal operations. Coupling with non-electric applications involving the use of heat and production of commodities, such as hydrogen or potable water, would require further developments and adaptation for existing technologies, which relies on considerable testing and validation, modelling and simulation and establishing of appropriate codes and standards. Another challenge associated with the complexity of such systems comes from the wide variety of subcomponents and interconnections needed to be managed in real time, and in an efficient manner, as well as deep understanding of the system architecture that will have case specific features and characteristics. Moreover, the hybrid energy systems are going to use more communications, controls, data and information (e.g., smart grids) that can pose interoperability and cybersecurity issues. They will include also distributive technologies like EVs, bi-directional energy storage and dispatch, grid-efficient buildings, distributed storage and the interdependencies between all of these components linked together through the electricity grid makes the system complex to operate, in order to balance generation and demand.

Future systems trend more and more towards a significant share of renewables, and systems need to be able to inherently deal with period of generation scarcity due to weather-driven events, such as stormy weather, or calm weather when the renewable energy fluctuates, and also to exhibit the resilience to weather extremes. Technologies needs to work together to ensure the stability of the grid in high renewables penetration scenarios.

Although there is considerable dedicated R&D and pilot activities for the emerging hybrid energy systems, there is a need to address the risks associated with first-of-a-kind systems at the commercial scale. Moreover, some of the technologies with high potential to be integrated in such systems, like small modular reactors with the ability to meet energy needs for a variety of users and suitable for non-electric applications, such as heating, hydrogen production or water desalination, are still not commercially deployed. The existent analysis tools and computational capabilities to assess the profitability of hybrid energy systems, as well as additional hardware developments – such as sensors, metering equipment, various controls, communication equipment – are needed to ensure optimized performance and forecasting capabilities.

5. Decarbonization, decentralization and digitalization-based business models

The commercial feasibility of nuclear-renewables integrated energy systems based on mature technologies can be ensured by development of innovative business models for them, centred on the 3D objectives of energy system planning - decarbonization, decentralization and digitalization (as shown in Fig. 2).

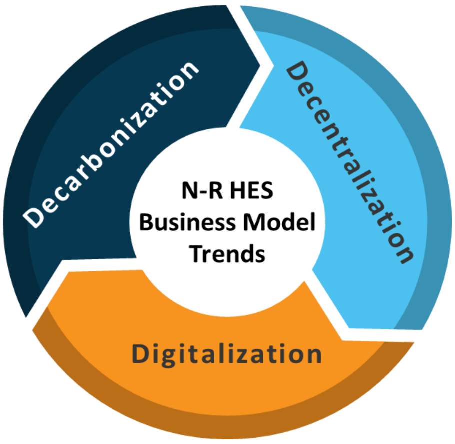

Fig. 2: 3Ds-based business model for N-R HES

5.1. *Decarbonization*

McDonough [38] placed working carbon (i.e. carbon put to human use) in three different categories: durable carbon, fugitive, and living carbon. In addition, he discussed three different management strategies on carbon, these are: carbon negative (i.e., actions causing pollution), carbon positive (i.e., actions that converts or recycle carbon into soil nutrition or durable form), and carbon neutral (i.e., actions that maintain or transform carbon). Integrated energy systems are designed and deployed with the aim of decarbonizing as many sectors as possible and not only the electricity supply system in a region. Thus, one of their important objectives is to reduce and finally eliminate emissions of carbon dioxide and methane, as part of the overall transition to a sustainable energy system and environment. In this way they can provide decarbonization solutions to help several users/consumers with their energy transition and climate action plans via creation of energy and utility communities. Heat (at several temperature levels)/electricity/water/cooling services/hydrogen/oxygen can all be supplied more economically and reliably as a service from the integrated energy system to nearby commercial consumers or industrial hubs or clusters, who do not have to own and maintain their own standalone utility system assets for these products or services. As part of future development, pilot projects which demonstrate technical feasibility of these systems can also be used to develop and test new business models and replicate the successful outcomes in future projects.

5.2. *Digitalization*

Digital transformation and its role in the decarbonized economy is increasingly being endorsed by stakeholders and decision makers in energy sector, who are embracing advanced technologies involving hybrid cloud, Internet of Things (IoT), and Artificial Intelligence (AI). AI was introduced to the nuclear power sector more 30 years ago by several organizations including the electric utility, equipment vendors, and involved universities and research institutes [39]. Increased digitalization of the energy systems is foreseen with the continuous improvement and cost reduction of computing power and data storage capacities. However, introducing such innovative technologies in systems with a nuclear component requires corresponding changes in regulations of safety, control, operation and security of the plant against new or emerging threats.

Incorporating IoT in energy systems allows for real time data collection and creation of data flows via connected smart meters and sensors to track multiple energy vectors in the system, as shown in Fig. 3 where uni- or bi-directional flow of energy, materials and information are all possible in the integrated systems. The use of machine learning (ML) capabilities of AI allows for analyzing the collected data, deriving decision-useful insights from them and facilitating continuous adaptation and improvement of energy system operation. This results in better understanding and optimizing the system performance, reliable monitoring and control of the system.

In nuclear-renewable hybrid energy systems, the use of digital innovative technologies such as AI and ML allows for flexible remote communication and analysis of collected data for process control [40], predictive and preventive maintenance as well as fault detection and diagnosis and warnings for abnormal conditions, accidents and potential failures arising in the grid, nuclear or renewable plant, and storage and distribution systems [41]. This helps in optimizing decision making process in operation, maintenance, refurbishment, and decommissioning and can avoid costly downtime and the resultant economic losses due to avoidable errors. But enhanced digitalization also brings increased cyber security concerns and the need to be equipped with robust and credible techniques and security control frameworks to monitor and deal with threats and risks to protect information, assets and data privacy of the energy systems. The impact of such concerns is amplified when dealing with energy systems involving a nuclear component. Further assessment of the digital technologies considering safety, security, reliability and technology readiness levels are necessary to facilitate smooth and safe digital transition.

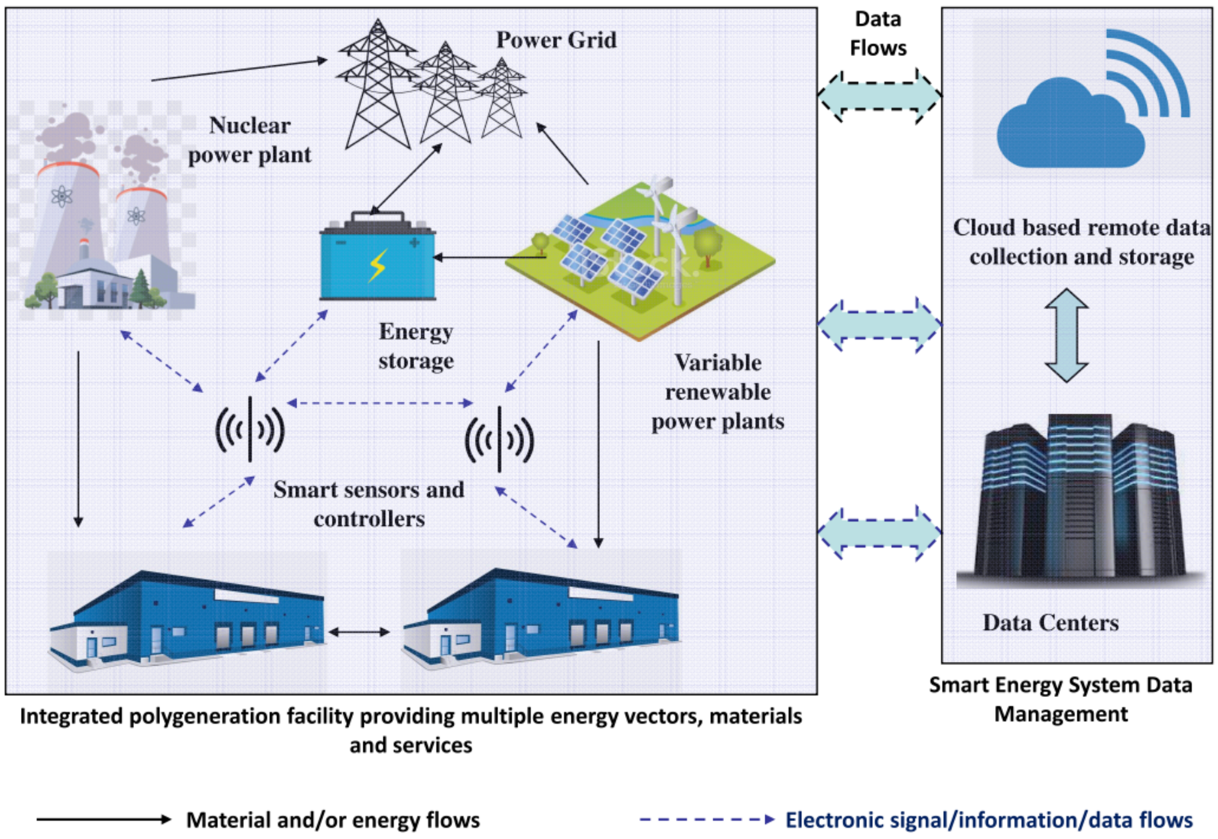

Fig. 3: Nuclear-renewables hybrid energy system for polygeneration integrated with advanced digital technology for data management

Application of digital tools and technologies such as Virtual Reality (VR) and Augmented Reality (AR) platforms for training and human resource development in process and energy industries is also gaining importance. Software for realistic plant-wide 3-D visualization and simulation of and employee walk-through with haptic control functionality in an industrial facility are common examples of cost and time effective training tools [42]. While industry has always depended on computer console-based simulation platforms for operator training, the capabilities of these systems have increased enormously with advances in digital technologies. More realistic immersive experience during training has been found to be more effective for employees engaged in industrial system operation and maintenance [43].

Since the last decade, the nuclear industry has also made use of these technologies for personnel training, as discussed by Johnsen and Mark [44] through various examples. As part of system deployment, personnel working in complex integrated energy systems for flexible polygeneration applications will also benefit from similar training mechanisms with reduced duration, costs and risks, as in conventional or stand-alone power generation industry today [45]. Such training for more complex systems can be expected to take longer than that in other industries, hence even before the system is physically set up, operators can begin to develop a sense of the facility through virtual reality.

Information batteries function very much like any other type of energy storage device, which can facilitate baseload operation of energy generation assets like nuclear reactors. When a system generates more energy than it needs, the extra energy is employed to tackle resource-intensive computational issues like brute-force algorithm decryption. The information received as a consequence of this issue can then be sold since the energy required to collect it has already been expended when there is no longer any spare energy. Cryptocurrencies are the most well-known and prevalent examples of information batteries. In [46], in order to quickly respond to the load-following requirements, the research conducted examines the possibility of coupling nuclear power reactors with a crypto-asset mining facility to execute the demand regulating role. When the electrical grid is fully supplied with renewable energy, the nuclear plant, when running at full capacity, will divert some of its energy to the mining operation. An integral economic assessment of the coupled system is performed by the authors. This is an example of a rapidly evolving and energy intensive industry both benefiting from a new energy paradigm and itself contributing to its optimal and economic operation.

5.3. ***Decentralization***

Blockchain technology refers to a very secure, reliable, decentralized, sharable electronic database consisting of records of digital transactions which can be viewed by any member of the network but which cannot be edited or modified [47]. It is often referred to as a digital ledger. This technology has found many applications in stand-alone distributed energy networks (both on the supply and the demand sides) such as mini or micro-grids based on renewables and energy storage and smart metering mechanisms [48] and is expected to become even more important as the world adopts more such energy forms instead of large centralized fossil fuel plants. The possible applications include peer-to-peer energy transactions, trading and billing, storing and managing data collected by IoT sensor devices, carbon/emissions trading and so on [49, 50].

In case of nuclear-renewable hybrid energy systems, the nuclear segment and many of its components represent the most safety critical parts in the overall scheme. Any early detection and mitigation of any off-normal conditions originating here is crucial to overall safety and system operability and integrity. Diaz et al. [51] describe integration of blockchain technology with in-service inspection records of critical components such as the nuclear steam generator.

Chang [52] describes development of secure integrated nuclear power plant management systems based on real time operational (and abnormal events) data collection and storage through blockchain. Advanced security systems for the entire nuclear fuel cycle (including materials, nuclear or radiological facilities, transportation systems) against various threats (physical, electronic) can be implemented via applications of blockchain technology, as recently described by Umayam and Vestergaard [53]. The safe, reliable and resilient operation of nuclear integrated systems in remote areas (especially when not connected to a central grid system managed by qualified personnel deployed full time at the site) can benefit greatly from application of this technology, since under normal operation, they can possibly be run through minimal human intervention. Block chain technologies are also expected to help in applications such as real time tracking of the output from a mix of generators and hence help in determination of the carbon emissions intensity of the overall system. This can help the energy consumer provide an accurate record of the emissions associated with the products and show compliance with low carbon certification schemes.

6. Regulatory aspects

Adoption of nuclear-renewable integrated energy systems for polygeneration applications also requires the development of economic, regulatory and commercial frameworks specific to these systems and the markets and users they can potentially cater to. The integration of disparate primary and secondary energy sources and users in hybrid systems represents a departure from the current energy systems with separate energy value chains for different applications. Given that there are still no such commercial scale systems deployed anywhere (even though individually these are mature technology options), there is naturally a great deal of uncertainty surrounding their characteristics, performances and potential failures (both technological and financial). Additionally, many kinds of configurations are possible for these systems (starting with the type of reactor and the nature of its secondary cycle, the type of renewables, the kinds of polygeneration applications to be coupled to them, the nature of coupling and so on), thus there would be unique regulatory concerns for each kind of system. These make the development of a uniform regulatory process for these systems quite challenging.

Regulation in the integrated systems refers to two major aspects – financial and technical. The first form of regulation is related to the market(s) for the products of such systems and the associated economic and financial aspects (e.g. business models and markets, product dispatch mechanisms, pricing of the different products/services of polygeneration, the need for renewables forecasting and pricing to account for their variability as against the stable heat/electricity prices from nuclear reactors, different levels of taxation policies for different energy forms) and whether it will be decided by the system owner(s), the government or the market itself or a combination of them [54]. The stakeholders involved are the power plant owners, the energy consumers and the distribution agencies and service providers connecting the two [55]. The need for a separate regulated or a liberalized market for integrated energy systems (along with methods to unbundle the different services originating from the hybrid system) can be dealt with by the current legal framework of the country governing existing generation systems [56] and new business models developed for these systems. The legal framework generally covers distinct public utilities including the existing electricity market, heat market, water distribution infrastructure, fuel markets and so on, including setting the tariffs for energy, trading mechanisms of energy etc, with some potential amendments and additional clauses. Most countries have national electricity laws, many of which have been or are being modified to accommodate the rising share of distributed energy sources and energy storage systems feeding into regional or national grids, such as renewables in a predominantly base load, fossil fueled energy mix [57]. . These can be extended to cover nuclear-renewable energy systems as well.

The second regulatory aspect is technical and is related to the safety, security and stability of these energy systems. This is ensured based on the codes, standards, licensing and permits systems and the best practices guiding their operational characteristics [58]. This section analyses some of these issues.

6.1. *Technical considerations in integrated energy system regulation*

I. Variety of designs and coupling schemes:

In integrated energy systems, some features create more challenges in arriving at a harmonized regulatory regime for integrated systems, when comparing with single energy source and output form (e.g. only nuclear with electric power exported to grid) [33]. Among the most critical challenges: i) the presence of multiple energy forms and their individual generation patterns (some base load and dispatchable, some diurnally and seasonally variable, short and long duration energy storage), ii) the presence of different end users (heat/electricity/water/hydrogen), iii) the possibility of varying demands of the various products and services, iv) diverse interconnections and interactions among the sub-systems (e.g. thermal, electrical, chemical or any combinations of these linkages) and v) the specific natures of additional safety considerations in the coupled systems. In principle, integrated energy systems aim to achieve flexibility in energy production and utilization. However, the inherent natures of the generation and consumption systems and their inter-connectedness may not always allow to advantageously use the degrees of freedom theoretically present in them.

II. Relative sizes of the components:

The overall scale of the integrated system (particularly with reference to the national or regional grid capacity) and the relative capacities and outputs of the sub-systems (e.g. comparatively large nuclear share and smaller contribution from renewables or vice versa, major output in the form of heat or electricity of product of co/poly-generation, degree of flexibility of operation of the nuclear reactor, etc) will govern the nature and extent of interactions between them [59] and will have an impact on the regulatory process.

III. State of grid connection:

The possible configurations of the integrated system will have a role in shaping the regulation framework for these systems. Among the different possibilities: i) whether all power generators are grid connected or only nuclear reactor is grid interactive, whereas the renewables are present as off-grid systems and supporting specific poly-generation activities alongside nuclear heat and electricity; ii) whether cogeneration/poly-generation will be carried out only with renewables or it will be switched over to nuclear cogeneration partly or entirely, when renewable generation is low due to normal or extreme weather events or seasonal factors; iii) the physical location of the systems and components relative to one another, e.g. in the nuclear island or conventional island or even beyond the nuclear exclusion zone.

There is improved understanding of the challenges of integrating base load and variable renewable energy systems into the same power transmission grid. A lot of attention has been devoted to developing control strategies for these systems to ensure reliable grid operation [60]. Many nuclear equipped nations who are simultaneously growing their share of renewable energy and energy storage infrastructure have already begun to address these issues, based on the technical and financial assessments performed till now and are in the process of upgrading and modernizing their national grid infrastructure [61]. Nuclear-renewable hybrid energy systems may face lesser problems in being deployed in such regions, owing to the experience already gathered and the level of preparedness attained. The exact control philosophy would depend on the relative generation capacities of the nuclear and renewables sections and the nature and extent of the energy consumers or loads present in the integrated system.

IV. National outlook:

The complexity of regulation of integrated systems would also depend on the specific situation and state of preparedness of the nation considering these systems, as indicated by the scenarios in Table 1. Even though many nuclear equipped nations are also possibly using renewable electricity as part of their national energy systems, the converse is not necessarily true everywhere. Developing integrated energy systems based on new designs of nuclear reactors such as SMRs, micro reactors or fission batteries present novel technology risk which finally translates into financial and regulatory risks as well [62].

Table 1: National energy scenario and impact on regulation of integrated systems

National situation	Implications on regulation
1 *Retrofitting other energy forms and end users with existing nuclear power plants* – Operating nuclear power reactor is available and adding renewables and poly-generation systems coupled to it is being considered for the first time	- Regulatory framework for nuclear reactor licensing is already present along with framework for electricity (and other products/services) production, transmission and distribution, so the regulatory risk for the nuclear segment of the process can be. - Insights may be drawn from the already existing distinct or system specific mechanisms for nuclear and renewables licensing to design a regulatory process for integrated systems, so multiple agencies may ultimately be involved in the regulation of these systems. - Additional assessments related to safety and stability of these systems and the potential feedback loops and interactions between them would be needed as part of regulatory licensing. - Standalone micro grids/smart energy system experience or expertise will help evaluate the additional effects likely to arise in or out of the integrated energy systems. - Product standards (e.g., for freshwater, hydrogen, synthetic fuels, batteries for energy storage, hydrogen storage) will have to be defined in compliance with existing industry standards (national or international).
2 *Considering nuclear new build* – Nuclear power reactor and poly-generation are being considered for the first time alongside other energy forms including renewables already in use	- Developing the regulatory framework for nuclear reactor might tend to dominate the licensing process for the integrated system as it would be more complex, time consuming and resource intensive activity than the licensing or permits for renewables (which will already be in place). - Additional complications in licensing can arise if the first nuclear reactor is being imported or developed with assistance of a foreign supplier, where a different regulatory regime might exist. - The nation may consider whether to operate the integrated system after connecting it to the national grid or in an island mode, with interconnections only to the users of the energy and poly-generation services (as is envisaged for nuclear micro-reactors or fission batteries to be deployed as independent power packs in remote, off-grid areas).

6.2. Impact of coupling schemes and interconnections

Depending on the specific coupling configurations present in the nuclear-renewables integrated energy system, certain conditions can arise which might present additional safety and reliability implications of regulatory concern. These must therefore be considered for further analysis as part of regulatory licensing procedures, as described in recent literature [63]. While it is commonly believed that the nuclear segment will present the greatest safety issues and implications, even with or without renewables and poly-generation systems integrated with it, there is greater diversity of systems and components in integrated energy and poly-generation systems, leading to far more diverse and unique kinds of hazards to deal with, qualitatively and quantitatively. A single metric such as the numerical value of core damage frequency cannot quantify the safety implications arising out of the integrated energy systems for poly-generation, as is common practice in the probabilistic safety analysis of standalone nuclear power reactors. These additional design basis events or accident scenarios can include, for example,

- the potential pathways of radioactivity carry over in some products of cogeneration (e.g., contamination of product freshwater or hydrogen with radio-isotopes in case of a thermal desalination unit or a high temperature hydrogen production plant respectively) which may be prevented through suitable engineered barriers (e.g., intermediate heat transport loops) and material selection (e.g., special coatings on materials of construction used for the process equipment),
- fire, explosion hazards from coupled hydrogen plants with potential impact on integrity of the nuclear system,
- leakage and dispersion of toxic/flammable chemicals from cogeneration units (e.g. water treatment chemicals in desalination, chemical species in water splitting processes,
- failure or rupture of pipelines, engineered barriers or other mechanical components connecting the sub-systems via material streams and/or thermal energy streams,
- potential for a damaged wind turbine blade in an extreme weather event such as hurricane to externally impact the nuclear structures and containment as a low trajectory turbine missile [64],
- situations leading to sudden loss of electrical or thermal loads in the integrated systems (for short or extended durations).

Many other events can be identified for analysis of design basis accidents in these systems, depending on the specific nature of the overall facility.

Apart from safety and reliability considerations of these systems, there is also increasing emphasis on the assessment of the vulnerability and resilience of these integrated systems. Vulnerability indicates how susceptible the system and its integrity and functioning are to external factors and resilience indicates how swiftly the system can be restored to its last operational or functional state after it is affected by an external event or disruption. These features are affected by the nature of the individual components and the type of integration and interaction among the systems. This is an important assessment for any energy infrastructure, particularly when it includes long lifetime assets such as nuclear power systems. Lin and Bie [65] describe several external events such as extreme weather, earthquakes and sabotage that can severely strain integrated energy systems, though in their study they do not explicitly address nuclear-renewables integrated plants. They also describe methods to quantify system resilience and strategies to ensure that resilience is built into the system right from the design stage. Sharifi and Yamagata [66] address resilience issues in urban energy networks and define elements of a resilience assessment toolkit, elements of which are well applicable to nuclear-renewables-poly-generation systems also.

7. Social Acceptance and Trust in Stakeholders

The public is part of the stakeholder group in national energy projects. They can be defined as the external stakeholders being affected by the outcomes of the deciding stakeholders. The main two elements of concern in hybrid energy systems involving nuclear and renewable energy sources for multigeneration are i) the nuclear element and ii) its relation to the commodities produced from the system. The involvement of the general public in the process when adopting projects involving nuclear energy is essential to achieving the desired objectives of the project. This applies to any nuclear power projects in general, yet, it is more crucial when considering nuclear for co- or multi-generation. The public would demand more honest and open information through dialogues of communication with the proponents of the nuclear and renewables and other stakeholders beyond electricity production.

In hybridization of nuclear-renewable projects for poly-generation integrated energy systems, the issues related to the coupled application would be added to the concerns of the public. This includes public concerns with regards to environmental impact, radioactive contamination, and health-risk of using the co-generated commodity. Stakeholders should get involved in increasing public awareness on the misconceptions related to these issues. The role of deciding stakeholders is to maintain socio-political involvement when starting the consideration of nuclear program (i.e., starting from readiness to make a knowledge commitment to a nuclear program, through bidding process for a nuclear plant, and to commissioning and operation). This can be achieved by pursuit of communication with the public on the governmental interest in, and societal and economic benefits of implementing the proposed nuclear program. It is also their role to sustain honest responsive approach to raised concerns and enquires from the public.

The influence of the general public on future of energy policies and towards deciding on nuclear energy adoption can be very crucial. For instance, Germany and Switzerland phasing out nuclear and conversely, USA and UK deciding on building new plants are cases where the public directly affected the national energy policy. In Sweden, a referendum brought the government to opt out nuclear power in 1980, and 30 years later, the parliament voted to revoke this decision. In some other cases, energy policies are developed based on economic and political aspects only which may result in social conflicts with the public. Several studies in the literature have discussed the question of applying referendums and political deliberation towards understanding the potential of integrating nuclear in national-level energy policy [67-69].

Transparent communication between concerned stakeholders and with the general public manner is essential when pursuing a nuclear program to ensure that all concerned citizens participate in the dialogue. Public figures, distinguished climatologists and environmentalists, and societal opinion leaders have influential role in shedding more light on the role of nuclear energy in climate change mitigation. Such public support brings wider and effective awareness among the public. IAEA publication No. NG-G-3.1. “Milestones in the Development of a National Infrastructure for Nuclear Power” [70] highlights stakeholders’ involvement and role to ensure effective communication towards enhancing public acceptance when a country is pursuing a nuclear program. IAEA publication No. NG-G-5.1 “Stakeholder Engagement in Nuclear Programmes” [71] provides theoretical and practical guidance on the development and implementation of stakeholder engagement programmes and activities. In addition, information on the public acceptance issues in nuclear-driven desalination projects can be found at IAEA TECDOC 1642 “Environmental Impact Assessment of Nuclear Energy” [72]. In [73], Idaho National Laboratory examines the stakeholder interactions for the nuclear-renewable hybrid energy systems program, highlighting both past and present interactions. The program brings together industry users of nuclear energy and nuclear technology developers to create a new paradigm for the production and use of nuclear energy for industrial applications.

8. National attitudes towards deployment of hybrid energy systems

The decision towards deployment of stand-alone or centralized hybrid energy systems for poly-generation with nuclear and renewable electricity generators will necessarily be taken in the context of the broader goals of deep decarbonization, long term sustainability and energy security of an individual nation. With the demand for electrification rising as many fossil fuel dependent sectors such as transport shift towards electrification, the need to re-shape the entire electricity system exists naturally for most nations. Alongside electrification, there is also the need for low carbon energy vectors and feed stocks as commodities towards industrial decarbonization (such as hydrogen and its derivatives), the production of many of which depends on clean electricity and heat availability.

Over the next one to two decades, the growth in electricity demand is expected to be much larger in the developing economies and emerging markets, compared to the developed and industrialized nations. This is because of the well-established correlation between per capita energy consumption and the state of welfare and quality of life of the citizens [68]. Thus, leveraging all kinds of low carbon generators in a hybrid configuration to meet such demand may be expected to be a priority area in the developing world. In fact, some of the highest rates of deployment of renewable energy resources and construction of new nuclear reactors are observed in the developing nations such as China. Interest in adopting nuclear power is also on the rise in several African nations, who are looking to have their first operating nuclear power plants by mid 2030s. As many of these nations have substantially lower per capita energy consumption, their energy infrastructure is not as extensive as that in the developed nations. Consequently, the developing nations that are not yet locked into fossil fuel dependent growth trajectories appear to be the best candidates to adopt nuclear and renewable generation in optimal configurations to support their growth.

For nations such as India which are still heavily dependent on coal based thermal generation, the need to phase out coal gradually to meet the declared net zero carbon emissions targets exists with the requirement to supplement the electricity system with reliable, base-load low or zero carbon electricity generators, which includes nuclear power. While current efforts are directed towards accelerated deployment of renewables in many of these countries, stable and least cost supply of power would require a mix of variable renewables and baseload power plants such as nuclear reactors on the supply side and energy storage and demand management technologies on the consumption side [69]. It is in this context that the deployment of advanced nuclear reactor technologies such as small modular reactors at existing sites of coal fired power plants is being actively considered [70]. These arrangements are the defining traits of a hybrid energy system, and nations considering such projects may be said to be adopting hybrid energy systems into their future energy mixes. However, for most of these nations, indigenous efforts and use of domestic resources would need to be supplemented by technological co-operation and financial support from developed nations (e.g., through technology licensing, imports of materials and components, training, and human resource development, etc.). Yet another example could be that of a land area constrained nation which cannot deploy adequate renewable energy systems to meet its electricity demand, and therefore adopts energy dense and resource efficient options such as nuclear power (including developing advanced nuclear technologies and small modular reactors) to meet its electricity needs. This highlights the complementary roles of nuclear and hydrogen, rather than a competitive approach which prioritizes one at the expense of the other.

The situation may be contrasted to that in several developed nations, particularly in the European Union, which have been pursuing a nuclear phase out policy for their electric power sector due to safety and security considerations. Under the current geo-political scenario and energy resource diversity and adequacy considerations however, many of them are reconsidering and even reversing these decisions in the wake of energy security considerations as well. The European Union’s acceptance of advanced nuclear technologies into their sustainable finance taxonomy may be cited as an example of treating nuclear technologies at par with the more recognized and accepted renewable energy generators for meeting environmental objectives and energy needs on a long-term sustainable basis [71]. Thus, this attitudinal shift is another way in which nuclear-renewable hybrid energy systems are gaining political support in advanced economies.

9. Conclusions and Policy Implication

The hybrid or integrated energy systems, considering integration of nuclear reactors and renewable energy sources, are a viable solution to power generation and production of additional commodities (such as hydrogen and potable water) while also ensuring storage of heat, electricity and other energy vectors and using it in a more effective and opportune way. They can bring a substantial contribution to minimisation of GHG emissions and ensuring flexibility in operation of electricity generation systems. Advances in research and recent technology development bring with them the potential for optimal and cost effective integrated system operation. Such nuclear-renewable integrated energy system can not only help in decarbonization, decentralization and digitalization owing to the challenges but can also offer significant contribution towards achieving SDGs especially SDG 7 (affordable and clean energy), SDG 11 (sustainable cities and communities) and SDG 13 (climate change). Overall, hybrid energy systems offer the potential to substantially transform electricity markets by optimizing energy generation, storage and consumption, while simultaneously addressing the challenges of intermittency, grid stability, and sustainability. National energy policy in nations considering the deployment and operation of integrated systems involving nuclear and renewable energy systems requires defining medium and long-term roadmaps with identified goals with regards to the potential share of the different energy systems in their energy mix to meet the future demand. The commitments of these countries towards a net zero energy future and decarbonization of the electricity and energy sectors requires policies and pathways to enable the integration of such systems into the country energy mix. This should also include pathways for the issues related to establishing energy market regulations to facilitate the deployment of such systems.

There are still challenges associated with technical aspects, economics, licensability as well as stakeholders' engagement but the system level strengths and opportunities presented by the hybrid energy systems (discussed in detail in this paper) make them a very promising technology that is expected to play a significant role in fundamentally transforming the energy and electricity markets of the future.

Continuous research and development are needed to improve the efficiency, durability and cost-effectiveness of different energy systems, as well as the integration of different technologies. This can involve the development of advanced control systems and software that can optimize the use of different energy source based on availability, demand, and cost. Government policies can play a critical role in promoting the development and adoption of hybrid energy systems. This can include policies to provide financial incentives for the development and installation of these systems, to de-risk investments in them by positioning them as fit-for-future and low carbon energy infrastructure as well as regulations to ensure that they are used in a sustainable manner. Energy storage is a crucial component of many hybrid energy systems, especially those that involve intermittent renewables. Advancements in energy storage technologies can greatly enhance the effectiveness of hybrid systems. By focusing on these areas, significant progress can be achieved in advancing hybrid energy systems and making them more prevalent in the energy mix. It is also evident that most of the current research and development efforts in integrated energy systems have primarily been led by advanced and developed economies in North America and Europe, focusing on their specific energy transition plans. Developing economies are expected to be greater beneficiaries of such programs, particularly nations which have just begun to consider the nuclear option as part of their low carbon energy mix. As these nations still have to build the necessary infrastructure for sustaining higher level of human development and sustainable growth, it is imperative for them to focus on long term factors and choose low carbon and the most cost-effective pathways to an inclusive and sustainable future. Thus, country specific research focusing on identifying the best use cases for hybrid energy systems should be a major priority for future work in this domain.

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