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Safety Assessment of Non-Electric uses of nuclear energy

Overview of Nuclear-Renewable Hybrid Energy Systems

Input to D1.1 “Report on potential non-electric uses of nuclear”

30.06.2025

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List of abbreviations

BWR	Boiling Water Reactors
CRP	Coordinated Research Project
CSP	Concentrated Solar Power
DETAIL	Dynamic Energy Transport and Integration Laboratory
DSA	Deterministic Safety Analysis
GHG	Greenhouse Gas
HES	Hybrid Energy Systems
HTGR	High-Temperature Gas-Cooled Reactor
HTR	High Temperature Reactor
I&C	Instrumentation and Control
IAEA	Atomic Energy Agency
IE	Initiating Event
INL	Idaho National Laboratory

JISEA	Joint Institute for Strategic Energy Analysis
LOOP	Loss of Off-Site Power
LWR	Light-Water Reactor
MED	Multi-Effect Distillation
NPP	Nuclear Power Plant
N-R HES	Nuclear-Renewable Hybrid Energy Systems
NREL	National Renewable Energy Laboratory
OECD / NEA	Organisation for Economic Co-Operation and Development / Nuclear Energy Agency
ORNL	Oak Ridge National Laboratory
PEM	Polymer Electrolyte Membrane
PSA	Probabilistic Safety Assessment
PV	Photovoltaics
PWR	Pressurized Water Reactors
R&D	Research and Development
RO	Reverse Osmosis
SCADA	Supervisory Control and Data Acquisition
SMR	Small Modular Reactor
TRL	Technology Redness Level
US DOE	U.S. Department of Energy
US NRC	U.S. Nuclear Regulatory Commission

1 Introduction

This report is an outcome of Task 1.2 "Nuclear–Renewable Hybrid Energy Systems" under Work Package 1 "Potential Non-Electric Uses of Nuclear Energy" and contributes to Deliverable D1.1.

It provides a literature-based overview of the concept and key features of Nuclear–Renewable Hybrid Energy Systems (N-R HES). These systems are gaining attention as promising solutions for decarbonized energy supply and cross-sector integration, especially given the increasing share of renewable energy and advances in nuclear technologies, such as Small Modular Reactors (SMRs).

To ensure comprehensive coverage of relevant research beyond technical reports, a systematic literature search was conducted using the Scopus database. The search strategy combined both general and specific terms to capture the interdisciplinary scope of the topic. The query used was: ("hybrid" OR "integrated") AND ("nuclear renewable") AND ("energy system").

The keyword co-occurrence map generated using VOSviewer [1] is shown in Figure 1-1 based on the extracted publication data. It visualizes the relationships and thematic clusters among frequently occurring terms, highlighting key areas of focus and emerging trends for N-R HES.

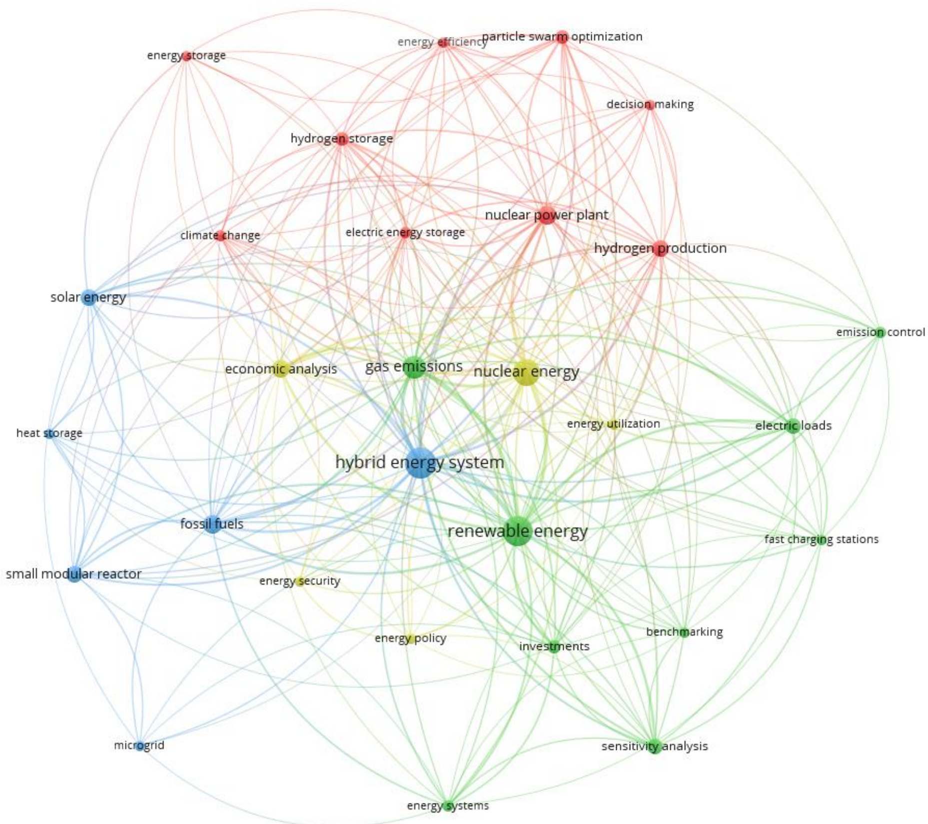

Figure 1-1 N-R HES Keyword Co-occurrence Map

The publication trend shows an increase in research on N-R HES from 2014 to 2025, with a particularly sharp rise between 2018 and 2024. This reflects growing scientific interest driven by concerns over climate change and the need for sustainable and reliable energy sources.

The global distribution of publications underscores the widespread attention this topic is receiving. The research highlights the importance of N-R HES in addressing climate and energy challenges with key areas of focus including hydrogen production, load balancing and non-electrical use. The integration of nuclear and renewable sources is seen as a promising strategy to reduce dependence on fossil fuels and enhance energy system resilience.

The bibliographical analysis performed served as the basis for drafting this report.

2 Concept of Nuclear Renewable Hybrid Energy Systems

2.1 Origins and Evolution

The concept of integrating nuclear energy with renewable sources in a hybrid system began to receive increased attention within the energy research community in the early 2010s in the United States [2]. This interest emerged in response to the growing challenges in increasingly complex energy systems, as the expansion of intermittent renewables (e.g., wind and solar) on electric grids introduced variability that placed economic and operational pressure on baseload nuclear plants. Instead of viewing nuclear and renewables as competitors, the cooperative integration of these resources was proposed.

In July 2014, Idaho National Laboratory (INL), National Renewable Energy Laboratory (NREL) and Massachusetts Institute of Technology (MIT) convened a foundational workshop "Integrated Nuclear-Renewable Energy Systems" to explore hybrid configurations combining nuclear power with renewable generation and industrial applications [3]. The same year, Ruth et al. published a seminal analysis characterizing these systems as a novel paradigm designed to meet grid flexibility requirements, address renewable intermittency and improve the economic utilization of nuclear reactors by reallocating output to alternative products during periods of low electricity demand [4]. The concept received further endorsement through U.S. Department of Energy (US DOE) initiatives, including the Quadrennial Technology Review and programs run by the Joint Institute for Strategic Energy Analysis (JISEA), as well as by INL and NREL, resulting in the formulation of a structured technical development roadmap [5], [6].

In response to increased interests in Member States, the International Atomic Energy Agency (IAEA) organized the Technical Meeting on Nuclear–Renewable Hybrid Energy Systems for Decarbonized Energy Production and Cogeneration in Vienna, 2018, "to review and discuss concepts and innovative solutions pertaining to nuclear–renewable hybrid energy systems for decarbonized energy production and cogeneration". Proceedings from this 2018 Technical Meeting (published as IAEA-TECDOC-1885 in 2019 [7]) highlight that while many countries focused on either nuclear or renewables, few had explored the synergies between them. The IAEA noted that viable, integrated low-carbon solutions are needed to meet climate goals, and that coupling nuclear and renewables could provide resilient production of electricity, heat, fuels and chemicals for deep decarbonization.

By the 2020s, the N-R HES concept had evolved from a theoretical idea to a topic of active research, with demonstration proposals and case studies emerging. In 2022, the IAEA published a technical report (Nuclear Energy Series No. NR-T-1.24 [8]) dedicated to Nuclear–Renewable Hybrid Energy Systems, underlining the maturity of the concept.

In 2021, IAEA launched the Coordinated Research Project (CRP) on N-R HES (I32012) [9]. It focuses on reviewing available tools and data, identifying gaps in current methodologies, and developing case studies that assess the integration of renewables with both existing and advanced nuclear reactors. The project also seeks to define best practices and provide technical guidance for the analysis and optimization of these hybrid systems.

Several projects assessing low-carbon energy generation solutions, such as heat, electricity, and hydrogen production from nuclear reactors in the context of nuclear cogeneration and potentially relevant to N-R HES, have been funded under the Euratom Research and Training Programme (2021 to 2025) within the Horizon Europe framework [10]:

- NPHyCo (Nuclear Powered Hydrogen Cogeneration): the project aims to assess the implementation feasibility of coupling between Generation 2 reactors (especially VVER) with a hydrogen production plant. The status and technical plant described in [11].

- GEMINI 4.0: the project aims to consolidate the design of a High Temperature Reactor (HTR) to demonstrate that the GEMINI+ system can, in addition to low-carbon process heat, provide a global solution for the competitive and safe decarbonisation of industrial activities, and confirm that this new form of cogeneration of various energy products does not negatively affect the safety of the combined plant [12].

- TANDEM (Small Modular Reactor for a European sAfe aNd Decarbonised Energy Mix): the project studies the integration of SMRs into hybrid energy system (HES), by providing tools and methodologies to assess such systems and implementing them on demonstrative cases to show the role that SMRs have to play for the energy transition. The project examines how SMRs can operate in coordination with renewables and energy storage to deliver electricity, district heating, and hydrogen, while ensuring safety and operational flexibility. A main outcome is the development of an open-source simulation platform based on Modelica, combining SMR safety modelling tools (such as CATHARE) with energy system analysis. TANDEM explores two reference scenarios: an urban SMR-supported energy system and a multi-vector industrial energy hub. The results are intended to inform technical, regulatory, and system-level strategies for SMR deployment across Europe [13].

2.2 Definition and Components

As the concept is still emerging, there is currently no universally accepted definition of N-R HES and interpretations vary depending on the context:

- IAEA Definition: *"Nuclear–renewable hybrid energy systems are integrated facilities comprising nuclear reactors, renewable energy generation and industrial processes that can simultaneously address the need for grid flexibility, greenhouse gas (GHG) emission reductions and optimal use of investment capital"* [8].

- NREL Definition: *"N-R HESs are defined as systems that are managed by a single entity and link a nuclear reactor that generates heat, a thermal power cycle for heat-to-electricity conversion, at least one renewable energy source, and an industrial process that uses thermal and/or electrical energy"* [14].

Despite differences in terminology, both the IAEA and NREL emphasize the importance of integration: N-R HES are not simply nuclear and renewable units operating in parallel, but a coupled system with coordinated control and shared operational functions.

The term 'hybrid' in N-R HES refer to integration and multi-modality - nuclear and renewable components are intended to operate in a coordinated and complementary manner, rather than functioning independently.

Figure 2-1 illustrates the basic structure of N-R HES.

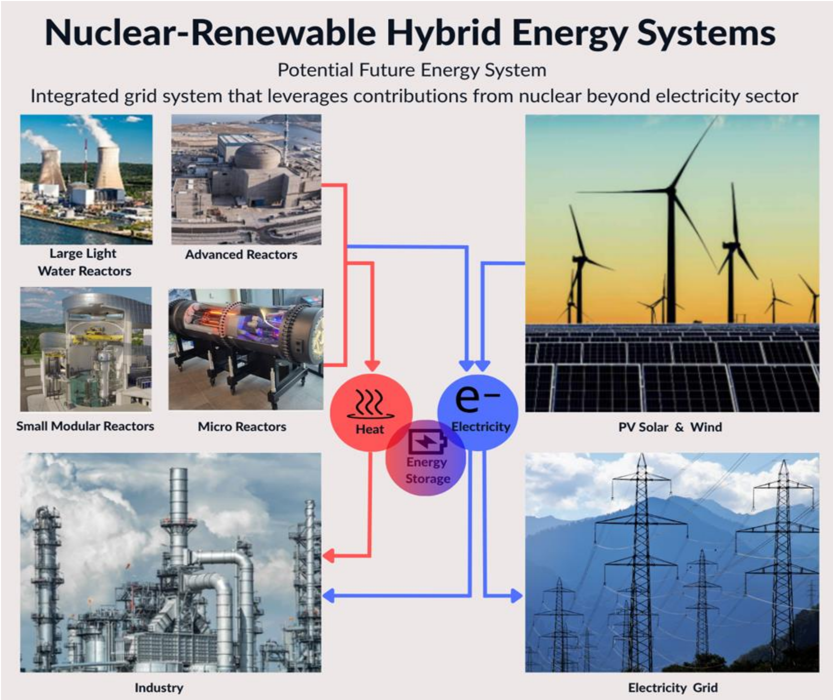

Figure 2-1 Generic Representation of N-R HES

In a typical N-R HES architecture, it may include the following subsystems [15]:

- *Nuclear reactor(s).* The nuclear reactor provides baseload heat and electricity (via the power conversion subsystem) without emission of GHGs. The nuclear subsystem should operate at a high capacity factor to cover operating and capital costs and have a profitable internal rate of return. The reactor(s) will also perform more efficiently and maintenance costs will be minimized if operated at or near steady-state design conditions. Nuclear-generated heat will be apportioned to the industrial process and storage based on net load.

- *Power generation.* The steam turbine in the power generation subsystem converts thermal energy generated by the nuclear reactor into electrical power. The amount of power generated can be ramped up or down depending on the amount of steam dispatched to it.

- *Renewable energy generator(s).* Depending on location, renewable source(s) can provide comparatively low-cost electricity and heat. Solar PV, wind and hydropower are considered low-carbon/low GHG energy sources. However, electricity generation by variable renewable technologies (i.e., solar PV and wind) is not dispatchable, meaning that it cannot provide power to follow grid load. Stand-alone renewable energy supply requires sizing the capacity and energy storage systems to meet diurnal, weekly, and seasonal energy demand throughout the year. It would also require a significant build-up of transmission lines to balance area demands and vast new power electronics to deal with power quality conditions.

- *Industrial process.* When coupled within an N-R HES, the industrial process receives heat and/or electricity from the nuclear reactor(s) and the renewable energy source as needed, or as heat/power is available. The process uses that energy and additional feedstocks to produce highly valued commodity products that provide another income stream to the N-R HES. When heat from the nuclear reactor is diverted to electricity production, the heat delivered to the industrial process can be reduced, or the heat necessary to operate the process must be derived from another source (e.g., natural gas, or stored hydrogen if the aim is to reduce carbon emissions). A second option resembles a traditional combined heat/power system in which the nuclear reactor would be owned by a given industry or complex of industries with the nuclear reactor(s) providing a dedicated source of heat and power to the industrial processes but occasionally directing electricity to the grid under a contract to provide reserve capacity when needed.

- *Storage (electrical, thermal and/or chemical)*. Energy storage buffers may be used to attenuate the dynamics of subsystems or to defer energy delivery to a later time. Electrical storage options primarily focus on batteries. Thermal storage options include both liquid (e.g., molten salt) and solid (e.g., firebrick) forms. Heat removed from storage can be used either directly in the industrial process or to generate steam that will be fed to the steam turbine. Electrical energy may also be stored in the form of heat for conversion back to electricity when needed for use in thermally driven processes. Chemical energy storage may include production of hydrogen, which can later be combusted or used for the production of electricity. Note that the specific need for and potential benefits of energy storage may differ for each N-R HES architecture. Energy storage systems (ESS) are needed of an appropriate size that can allow the integrated systems to perfectly meet the grid demand while keeping the subsystems of N-R HES within its operational limits [16].

Figure 2-2 provides a schematic representation of N-R HES, highlighting that non-electric use of nuclear are an integral part of the system. These non-electrical use are treated separately from heat and electricity. The list of applications corresponds to Task 1.3 and follows the same numbering (letters in brackets correspond to the numbering in Task 1.3 Work Package 1).

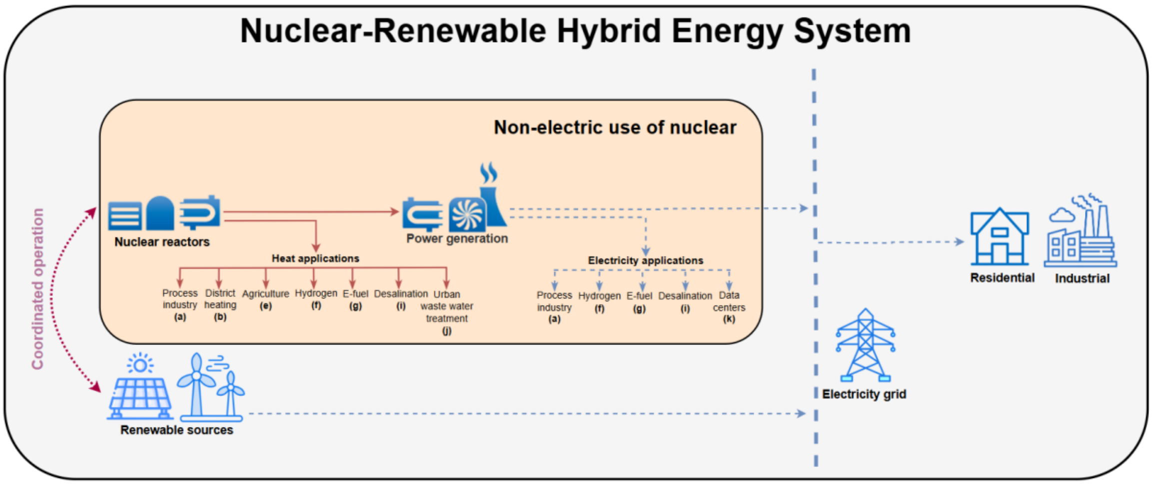

Figure 2-2 N-R HES and Non-electric Use of Nuclear

2.3 N-R HES vs. Conventional (Non-Hybrid) Energy Systems

N-R HES are distinct from conventional configurations in which nuclear and renewable plants operate independently within the same grid. In such arrangements, each source functions separately: nuclear plants typically provide baseload power, while renewables contribute variable output. Grid operators manage overall system balancing externally, relying on dispatch strategies, market mechanisms, or auxiliary generation. In contrast, N-R HES involve physical coupling and coordinated operation, enabling integrated energy management across both electric and non-electric applications.

The implications of this distinction are as follows:

- *Integration vs. Independence*. N-R HES may share infrastructure and be managed by a unified control system. In contrast, conventional nuclear and renewable plants are separately sited and controlled. Hybrid integration enables dynamic coordination, such as shifting nuclear output in response to renewable fluctuations. Standalone plants cannot redirect excess energy internally (e.g. for hydrogen production), often leading to wasted generation or economic losses.

- *Energy Flow Paths.* In a hybrid, energy can be routed not just to the grid but between subsystems (e.g., nuclear heat to industry, renewables to electrolysis). Conventional plants each have one primary output path and any coordination is external and slower. Internal routing allows hybrids to function more efficiently and adaptively.

- *Coordinated Control vs. Market Dispatch.* Hybrid systems optimize their internal operation in real time based on cost, carbon or demand. Conventional plants rely on market signals, which may result in inefficient dispatch (e.g., limiting wind output while nearby industry uses fossil heat). N-R HES allows for closed-loop, system-wide optimization.

- *Flexibility and Load Following.* Traditional nuclear plants are quite inflexible and renewables are non-dispatchable. Hybrid systems provide load-following by internally shifting energy between outputs. This allows nuclear units to behave more flexibly – responding to grid needs without reducing output unnecessarily or requiring external backup.

- *Product Diversity.* While conventional nuclear or renewable plants usually produce only electricity, hybrids can co-produce other industrial products. This reduces the need for separate, redundant infrastructure and allows more efficient energy use.

- *Economic Resilience.* When electricity prices are low, a hybrid can divert energy to other profitable outputs (e.g., hydrogen). Separate plants lack this flexibility, leaving them exposed to market fluctuations. Hybrid systems provide strategic flexibility across multiple energy markets.

- *Implementation Simplicity.* Conventional systems are simpler to build and operate with well-established practices and clear separation of responsibilities. Hybrids introduce complexity and require novel integration strategies, controls and regulatory approaches - highlighting the need for demonstration projects and further R&D.

2.4 Modern Energy System Attributes in N-R HES

The comprehensive set of attributes defining modern energy systems, as outlined in [17], was assessed for its applicability to N-R HES and expanded to include nuclear-specific safety considerations. These attributes, along with a structured overview of the key strengths and limitations of N-R HES, are summarized in Table 2-1.

Table 2-1 Key Attributes of Modern Energy Systems and Their Application to N-R HES

Attribute	Definition	N-R HES Strengths	N-R HES Limitations
Resilience	Ability to withstand and adapt to faults, natural disasters or resource variability	Able to redirect energy (e.g., from nuclear or renewables) to storage or industrial loads during grid or generation outages, improving capacity to recover from disturbances	Increased system complexity introduces more potential failure points
Reliability	Capability to continuously provide energy to consumers	Baseload nuclear ensures stable operation while renewables reduce intermittency, making overall	Tight integration raises dependency: failure in one subsystem (e.g., control logic) could impact the entire

Attribute	Definition	N-R HES Strengths	N-R HES Limitations
		system more reliable than standalone systems	system if not adequately considered
Safety (nuclear component)	Protection of people and the environment from harmful effects of ionizing radiation	Safety is a core attribute for N-R HES and must be equivalent to or exceed the level of safety provided by current standalone nuclear power plants	Hybrid integration increases interaction scenarios
Security (nuclear component)	Protection of persons, property, society, and the environment from harmful consequences of a nuclear security event	Shared perimeter improves physical security; nuclear-grade cybersecurity extends to all connected systems	More interfaces and subsystems increase cyber-attack surface and require rigorous, multilayered security measures
Economics	Potential to produce positive long-term returns via diverse revenue streams	Multi-product output (electricity, heat) allows optimized dispatch and earnings under varying market conditions	Higher complexity; cost effectiveness depends on stable markets, carbon pricing, and regulatory support
Affordability	Delivery of low-cost energy to support widespread socio-economic access	Extended product suite and higher capacity utilization lower the levelized cost of energy per unit	Economic viability can be constrained by financing costs, regulatory barriers, and upfront infrastructure expenses
Flexibility	Ability to adapt operation to changing resource availability, market signals, and demand profiles	Energy management systems can shift output between electricity, process heat, or hydrogen, enabling high adaptability	Requires complex control systems, transient simulation, and component designs that withstand frequent operational changes
Sustainability	Capacity to deliver low-carbon energy while minimizing environmental impact across whole lifecycle	Clean electricity and thermal outputs help decarbonize multiple sectors and reduce emissions from fossil alternatives	Lifecycle impacts (e.g., mining, materials, end-of-life) require ongoing monitoring to ensure sustainable implementation

2.5 Opportunities and Benefits

The opportunities and benefits of N-R HES, as identified through the literature review, are presented in Figure 2-1.

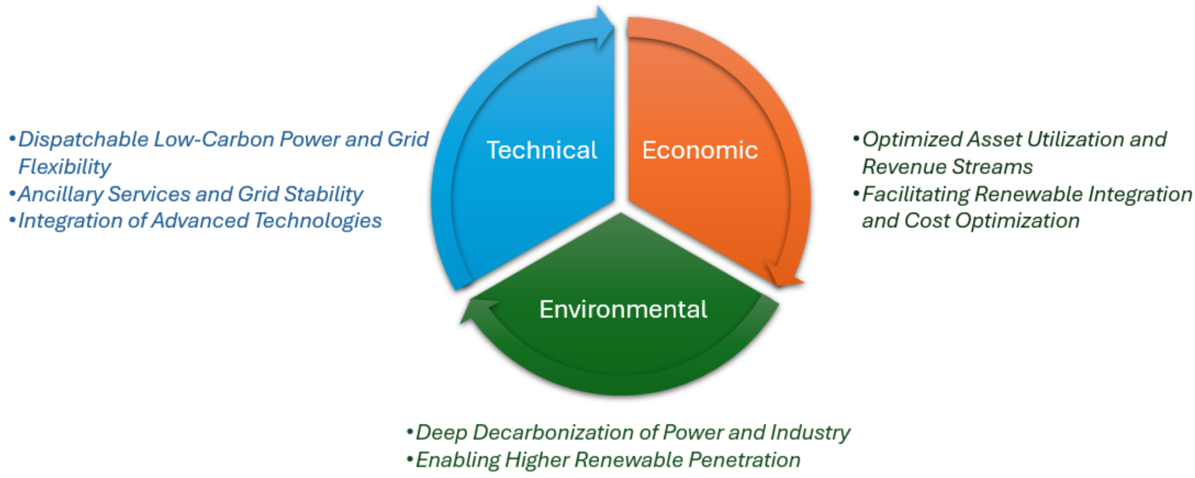

Figure 2-3 Opportunities and Benefits of N-R HES

Technical

- *Dispatchable Low-Carbon Power and Grid Flexibility***.** N-R HES offers low-emission firm and dispatchable energy outputs by integrating nuclear baseload capacity with the operational flexibility of renewable sources. Their capacity to dynamically allocate energy between grid electricity and non-electric applications enables real-time load balancing and ancillary service provision. This operational flexibility directly addresses a primary constraint in high-penetration renewable systems: the need for responsive non-fossil reserve capacity, thereby enhancing grid stability and reducing dependence on carbon-intensive peaking assets.

- *Ancillary Services and Grid Stability***.** Hybrid systems can support grid frequency regulation, voltage control, and inertia services by modulating controllable industrial loads and utilizing nuclear turbines for rotational inertia. This enables fast-acting stabilization mechanisms absent in conventional nuclear or renewable-only configurations.

- *Integration of Advanced Technologies.* SMRs and advanced reactors enhance hybrid system flexibility and efficiency and can support implementation of advanced nuclear technologies.

Economic

- *Optimized Asset Utilization and Revenue Streams.* N-R HES enhances asset efficiency by ensuring nuclear plants operate continuously while redirecting energy outputs as market conditions change. This minimizes economic losses during low electricity price periods by generating alternative products like hydrogen or ammonia.

- *Facilitating Renewable Integration and Cost Optimization.* N-R HES reduces the need for standalone balancing assets by stabilizing grid operations. They also minimize the curtailment of renewable energy and improve market efficiency by absorbing excess generation during low demand. Co-location of systems reduces infrastructure duplication, yielding potential capital savings.

Environmental

- *Deep Decarbonization of Power and Industry***.** N-R HES reduces emissions by replacing fossil-based energy in power and industrial sectors. Nuclear-renewable combinations can supply electricity and/or heat with minimal greenhouse gas output, enabling significant progress toward net-zero goals.

- *Enabling Higher Renewable Penetration***.** N-R HES helps integrate more wind and solar power into the grid by managing variability and reducing the need for curtailment. By redirecting excess electricity to other productive uses, these systems support more efficient resource utilization and enhance renewable capacity value.

3 Coupling of Nuclear and Renewables

N-R HES coupling describes how nuclear and renewable energy systems can be integrated into a hybrid configuration. This integration is defined by two key characteristics: level of subsystem integration and type of energy flow between the subsystems, as described in the following sections (see Figure 3-1).

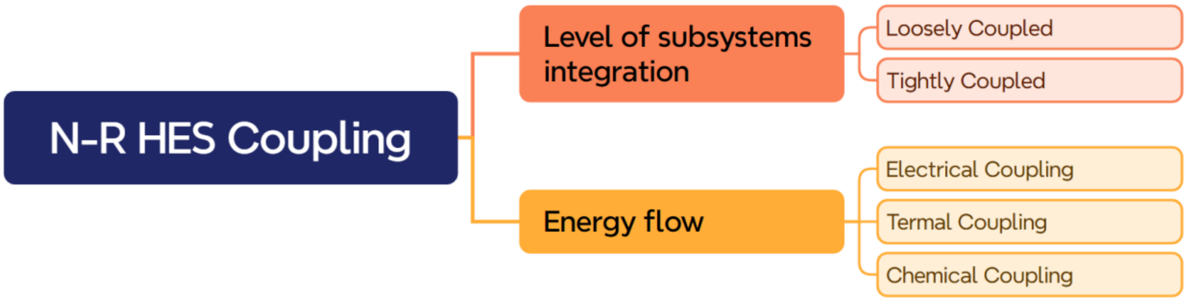

Figure 3-1 N-R HES Coupling

3.1 Level of Subsystems Integration

This characteristic describes how closely the nuclear and renewable components are integrated:

- *Loosely coupled systems* involve nuclear and renewable components that are physically separate but coordinated through market or grid-level interactions. Each energy source typically supplies electricity to the grid independently, while a shared industrial process (e.g., hydrogen production, desalination) draws electricity or heat from one or both sources depending on availability. Energy flows are optimized through operational scheduling or price, but without shared physical infrastructure or real-time control coordination.

- *Tightly coupled systems* are characterized by direct physical and operational integration of the nuclear and renewable components within a single facility. Energy generated by either or both sources can be dynamically routed between grid export and internal processes, such as electrolysers or thermal loads. A unified control system manages the hybrid system as an integrated entity, enabling real-time energy switching, load balancing, and buffering. These configurations often include shared components such as thermal circuits, turbines, or energy storage and may operate in islanded or semi-autonomous modes, offering enhanced flexibility and resilience.

Tightly coupled systems offer higher efficiency and control but require co-location, compatible thermal/electric parameters, and more complex design and permitting. Loosely coupled systems are more flexible to deploy and scale, especially in regions where co-siting nuclear and renewables is constrained by geography or regulation.

Definition and distinctive characteristics of key coupling configurations of N-R HES are summarized in Table 3-1.

Table 3-1 Definition and Distinctive Characteristics of Key Coupling Configurations of N-R HES

Configurations	Definition and Distinctive Characteristics
Loosely Coupled	• geographically distinct sources that interact through electrical grid to meet energy demands • coordination typically occurs via market mechanisms

Configurations	Definition and Distinctive Characteristics
Tightly Coupled	• direct thermal and/or electrical integration of multiple energy-generation technologies, behind the grid, to meet multiple energy demands • systems may include multi-input, multi-output; single-input, multioutput or multi-input, single output options

3.2 Energy Flow

This characteristic specifies the form of energy exchange between the nuclear and renewable subsystems.

Energy flows in hybrid systems are usually classified as electrical, thermal and chemical coupling (also referred to as process coupling), and are often used in combination. Each coupling method has distinct technical characteristics and advantages, and hybrid systems may integrate multiple forms of coupling to maximize overall efficiency and operational flexibility. The following information describe these energy flow methods in more detail and explain the respective roles and differences between thermal and chemical coupling.

Electrical coupling

Electrical coupling is the most straightforward form of integration, wherein the nuclear and renewable units are linked via electrical networks (a common bus or the broader grid) and coordinate their power output. In an electrically coupled hybrid, both the nuclear plant and the renewable generators feed electricity to shared loads or the grid, adjusting their generation to meet demand.

Because all interactions occur via electricity, physical proximity of the plants is not required in electrical coupling. The nuclear and renewable facilities could be located far apart, as long as they share the same grid or market. Electricity can be transmitted long distances with minimal losses, unlike heat which can only be moved short distances without significant loss [4]. The flexibility of electrical coupling also allows integration of demand-side management and energy storage: for instance, during times of excess renewable power, controllable loads (like water heaters, chillers, or electrolysers) can be turned on to absorb the surplus, whereas during deficits the nuclear plant or storage can quickly increase output. Electrically coupled hybrids can also provide valuable grid services, such as spinning reserve and frequency regulation [4].

Thermal coupling

Thermal coupling integrates the hybrid's components via heat transfer. Nuclear reactors produce a large amount of thermal energy, which is normally converted to electricity or dumped as waste heat. In a thermally coupled N-R HES, a portion of this reactor heat is directly utilized by other processes or shared with other energy sources. A common example is cogeneration: using nuclear heat for a secondary purpose such as industrial steam supply, district heating, or desalination, in addition to electricity generation [18].

Another form of thermal coupling is the integration of nuclear and renewable thermal energy sources. A nuclear reactor can be paired with a CSP system that collects solar heat. During sunny periods, solar collectors provide high-temperature heat to drive a shared steam cycle or charge a thermal energy storage tank. When solar input wanes, the nuclear reactor's heat steps in to maintain steady output [19]. Nuclear heat can also be used to charge thermal storage when grid demand is low, allowing the stored energy to be released later when needed.

The feasibility of thermal coupling depends significantly on the temperature and quality of the heat needed. Light-water reactors are limited to moderate temperatures, while advanced reactors such as high-temperature gas-cooled reactors, molten salt reactors, or fast reactors can provide much higher outlet temperatures suitable for demanding industrial processes [36].

Thermal coupling requires co-location due to the challenges of transporting heat efficiently over long distances. This necessity can affect siting decisions [4]. Safety considerations, including intermediate heat exchangers, could have influence on N-R HES implementation [20]. Despite these challenges, thermal coupling enhances system efficiency by utilizing reactor heat for both power and non-electric applications.

Chemical coupling

Chemical coupling links nuclear and renewable systems through energy-intensive chemical processes that produce storable fuels such as hydrogen, ammonia, or synthetic hydrocarbons. These chemical products embody the energy from the hybrid system and can be stored, transported, and used in other sectors.

Hydrogen production is the most widely discussed form of chemical coupling. It can be achieved through several pathways:

- low-temperature electrolysis using electricity;
- high-temperature electrolysis (HTE), which uses a combination of heat and electricity for improved efficiency;
- thermochemical cycles, such as the sulfur-iodine or copper-chlorine cycles, that use high-temperature heat to split water [21].

HTE and thermochemical cycles require reactor outlet temperatures above 500 ^{o}C, which can only be achieved with advanced reactor technologies [22]. In many hybrid concepts, nuclear energy provides the consistent heat input, while variable renewable electricity supplements the system, particularly during periods of surplus generation.

Chemical plants can act as flexible loads in the hybrid system, helping to balance variable power supply. However, they also introduce complexity, particularly in terms of dynamic operation, safety, and system integration. Most chemical processes are designed for steady-state operation, and adapting them to variable energy input requires advanced control systems, storage buffers, or modular designs [22], [23]. Co-locating chemical facilities with nuclear plants requires additional safety considerations due to the presence of flammable or toxic substances like hydrogen [24].

Despite these challenges, chemical coupling provides significant advantages: it enables long-duration energy storage, helps integrate high shares of renewables, and allows nuclear-renewable hybrids to supply fuels and feedstocks to other sectors, enhancing overall system flexibility and decarbonization potential.

Comparison: thermal vs. chemical coupling

Thermal and chemical coupling serve different, though complementary, functions in N-R HES.

- *Energy form:* Thermal coupling uses reactor heat directly for immediate applications, while chemical coupling transforms energy into chemical bonds for later use.
- *Storage:* Thermal energy can be stored short-term (e.g., in molten salt), but chemical energy can be stored and transported over long durations and distances.
- *Efficiency:* Thermal coupling is more efficient as it avoids conversion losses. Chemical coupling sacrifices some efficiency for greater flexibility and storage capability.

Combining thermal and chemical coupling can maximize the utilization of a reactor's output, enabling immediate heat use while storing excess energy for future use. For example, a nuclear-renewable hybrid could supply steam to an industrial process while producing hydrogen during periods of low electricity demand. This dual approach enhances energy system resilience, efficiency, and sustainability

In Table 2-1 are summarised a key features and functions of coupling mode of N-R HES.

Table 3-2 Key Features and Functions of Coupling Mode of N-R HES

Coupling Mode	Key Features and Functions
Electrical Coupling	• Nuclear and renewable subsystems connected via grid or common bus (most straightforward form of integration) • Allows coordinated power supply and load following • No physical proximity needed – interaction via electricity • Supports grid services
Thermal Coupling	• Reactor heat used for electricity and industrial processes (cogeneration) • Could include nuclear-CSP integration or charging thermal storage (e.g. molten salt) • High efficiency via direct use of reactor heat • Requires co-location due to heat transport constraints • Advanced reactors (e.g. HTGRs) needed for high-temperature applications (e.g., hydrogen, steelmaking)
Chemical Coupling	• Uses to drive chemical processes (e.g. electrolysis, ammonia synthesis) • Converts electricity/heat into storable chemical energy (e.g. hydrogen) • Acts as dynamic load and storage buffer • Enables sector coupling and flexible operation based on grid signals • Requires safety measures if co-located near reactors (e.g. hydrogen hazards)

3.3 Coupling Categories (according to IAEA)

According to the IAEA Nuclear Energy Series No. NR-T-1.24 [8], N-R HES configurations can be categorized based on the number of energy inputs and outputs, as well as the degree of integration or coupling between components. In this context, coupling refers to the physical and operational interconnection of energy conversion and delivery pathways.

N-R HES configurations are classified into four categories:

- loosely coupled systems;
- tightly coupled systems with a single input and multiple outputs;
- tightly coupled systems with multiple inputs and a single output; and
- tightly coupled systems with both multiple inputs and multiple outputs.

Each configuration type reflects a distinct system architecture and degree of functional integration.

Loosely coupled N-R HES

Loosely coupled hybrid systems are characterized by the independent operation of nuclear and renewable energy components, with interaction occurring only via the electrical grid or market mechanisms. These systems are not physically integrated, and energy exchange is limited to electrical signals. For example, a nuclear power plant might reduce its output in response to high levels of solar generation, thereby avoiding curtailment of variable renewable energy. Such coordination is typically enabled by grid operators or automated dispatch systems. The primary focus of this configuration is to maintain a reliable supply of electricity, continuously meeting grid demand.

While loosely coupled systems are comparatively simple to implement requiring no redesign of existing assets or co-location of infrastructure, their ability to realize deeper operational synergies is limited. They do not leverage shared thermal or chemical processes, and as such, represent a transitional step toward more integrated hybrid architectures.

Tightly coupled N-R HES: single input, multiple outputs

Tightly coupled systems with a single energy input and multiple outputs are often realized through cogeneration architectures. In this configuration, a nuclear energy source is used to simultaneously produce electricity and one or more non-electric energy products, such as district heat, desalinated water, or hydrogen. These systems are physically integrated, often within a shared infrastructure footprint, and require centralized control to allocate energy among various outputs based on demand, market conditions, or operational constraints.

This category commonly employs both thermal and chemical coupling mechanisms. For example, nuclear thermal energy can be directly transferred to a district heating network, while surplus electricity may be diverted to an electrolyser for hydrogen production. Such multi-output designs can significantly improve overall energy utilization and create diversified revenue streams for nuclear operators.

Tightly coupled N-R HES: multiple inputs, single output

This configuration introduces multiple energy inputs, typically nuclear and one or more renewable sources, combined to produce a single energy output such as electricity. The components are physically integrated and jointly managed through centralized control systems. Unlike loosely coupled systems, these configurations facilitate real-time operational synergy between firm (nuclear) and variable (renewable) resources.

These systems are designed to exploit the complementary generation profiles of nuclear and renewables, enhancing reliability and optimizing asset utilization.

While such integration improves flexibility and resource complementarity, it also presents significant engineering challenges. The differing temporal dynamics of nuclear and renewable sources must be reconciled, and control systems must be capable of maintaining stable operation under fluctuating inputs. The added value lies in the system's ability to co-optimize diverse inputs for a targeted energy service, often reducing reliance on fossil-based backup systems.

Tightly coupled N-R HES: multiple inputs and multiple outputs

The most advanced configuration is the tightly coupled hybrid system with multiple inputs and multiple outputs. These systems function as integrated energy hubs, simultaneously processing various energy sources into a range of energy products including electricity, thermal energy, hydrogen, synthetic fuels, and clean water. They are fully integrated across physical and operational layers and are supported by advanced energy management systems.

In these systems, all three coupling mechanisms: electrical, thermal and chemical are typically present. For example, a nuclear reactor may provide constant baseload electricity and heat, a solar PV installation may contribute variable electrical input, and the combined energy may be directed toward grid support, hydrogen production, or district heating, depending on system conditions and market demand. Energy storage is often included to buffer short-term mismatches and facilitate load shifting.

While these systems offer the highest degree of energy system decarbonization and resilience, they are also the most capital-intensive and complex to design, regulate, and operate. They require cross-sector collaboration, integrated planning, and new regulatory and market frameworks to become commercially viable at scale.

The comparison of the N-R HES categories is presented in Table 3-3.

Table 3-3 N-R HES Coupling Categories and Their Key Characteristics

Category	Primary Configuration	Main Applications	Advantages	Challenges
Loosely Coupled	Independent operation of nuclear and renewable systems supplying a shared grid	Grid support, load balancing, ancillary services	Simple implementation, utilizes existing infrastructure, minimal coordination	Limited system integration, potential inefficiencies, no heat or process synergy
Tightly Coupled: Single Input, Multiple Outputs	Integrated system producing electricity, heat, and additional outputs from a single energy input (typically nuclear)	Hydrogen production, cogeneration, district heating	Efficient resource use, co-product flexibility, reduced carbon intensity	Complex thermal management, high capital cost, regulatory interface for non-electric applications
Tightly Coupled: Multiple Inputs, Single Output	Tightly coupled nuclear and renewable energy sources feeding a single output pathway	Hybrid energy parks, shared hydrogen production infrastructure	Optimized resource complementarity, improved flexibility and reliability	Integration of variable and firm sources, high control complexity, thermal/electrical compatibility
Tightly Coupled: Multiple Inputs and Outputs	Fully integrated system combining various energy inputs and producing multiple outputs	Multi-sector energy hubs: electricity, fuels, heat, water	Maximum system efficiency, sector coupling, grid and market flexibility	High system complexity, multi-vector control, challenging licensing and cost structure

4 N-R HES Applications and Their Technology Readiness Level

4.1 Applications

N-R HES can serve a wide variety of applications depending on the specific needs. In general, the range of N-R HES applications are determined by the following factors:

- subsystem characteristics (nuclear and renewables);
- level of subsystem integration (loosely coupled, tightly coupled);
- energy exchange (thermal, electrical or chemical);
- operating mode (baseload, peak load, load-following).

Thermal characteristics of the nuclear reactor play a critical role in determining its potential for non-electric applications in N-R HES. Reactors with higher operating temperatures are better suited for direct thermal integration with industrial processes, opening up new opportunities for advanced reactor designs.

Traditional Light Water Reactors (LWRs) produce steam at temperatures of approximately 280–300 °C and are primarily optimized for steady-state baseload electricity generation [25]. Although LWRs can be integrated into hybrid systems, their moderate outlet temperatures limit their use to mid-temperature applications, such as district heating (e.g. in Ukraine and the Czech Republic [26]).

In contrast, advanced reactor technologies (e.g. High-Temperature Gas Reactors (HTGRs) and sodium or molten salt-cooled reactors) can deliver thermal energy at significantly higher temperatures (ranging from 500°C to over 1000 °C). These elevated temperatures enable efficient integration with a variety of high-temperature industrial processes, including chemical synthesis, synthetic fuel production and high-efficiency hydrogen generation.

Figure 4-1 presents parameters of the reactor designs and possible non-electric applications [27].

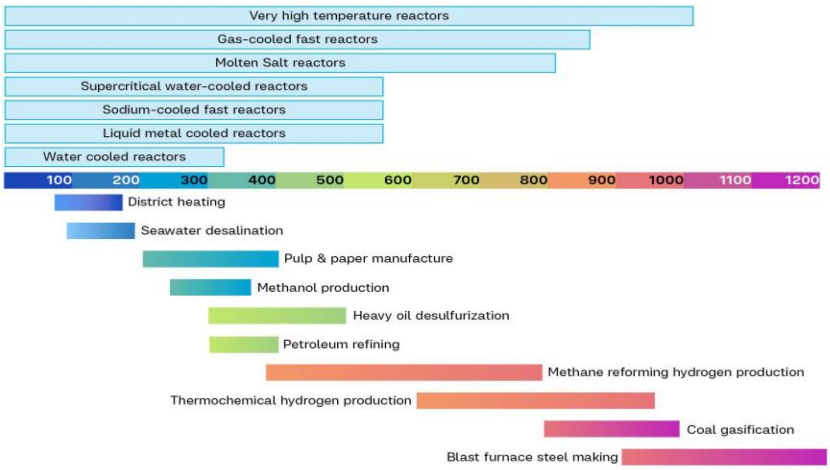

Figure 4-1 Reactors Parameters and Possible Applications

SMRs and microreactors are often seen as favorable for hybrid systems due to their scalability and potentially greater operational flexibility. According to the OECD/NEA [23], SMRs offer a wide range of thermal power output: from 30 MWth to1300 MWth and outlet temperatures between 100°C and 1200°C. Their output aligns well with typical industrial thermal demands making them suitable for co-location with industrial processes in N-R HES.

Figure 4-2 depicts the range of SMR designs categorized by power output and temperature capabilities for various heat applications [28].

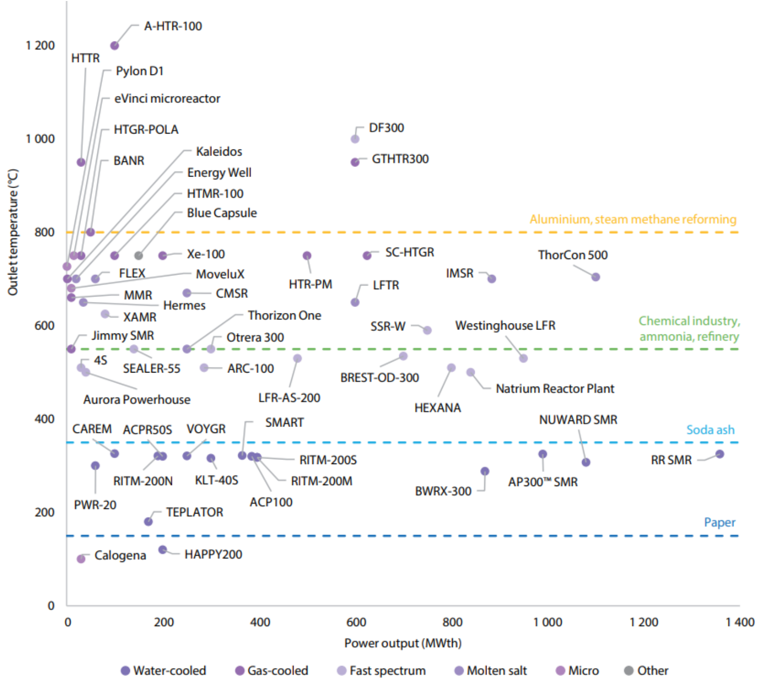

Figure 4-2 SMR Range of Sizes Thermal Power and Temperatures Output

Within N-R HES heat is not solely produced by nuclear reactors - concentrated solar power (CSP) plants can also generate high-temperature heat suitable for integration with a nuclear plant's steam cycle or thermal energy storage systems [15]. Geothermal and biomass are additional renewable options capable of providing stable heat or power outputs [29], making them viable for hybrid configurations that supplement or complement nuclear reactor output.

Key N-R HES application include:

- *district heating:* nuclear heat can be used to provide hot water or steam for residential and commercial heating networks, improving energy efficiency and reducing fossil fuel use in urban areas, especially during cold seasons [26];

- *desalination:* nuclear reactors can supply the thermal energy and electricity required for desalination technologies such as multi-effect distillation (MED), multi-stage flash (MSF), or reverse osmosis (RO), enabling large-scale freshwater production in water-scarce regions [30], [31];

- *ammonia production:* ammonia is produced using hydrogen and nitrogen. Nuclear-assisted hydrogen production supports low-carbon ammonia synthesis, important for fertilizers, chemicals and as a potential fuel or hydrogen carrier [4]. A notable example is a US–Ukraine project to demonstrate hydrogen and ammonia production using SMRs with innovative high-temperature electrolysis [32];

- *synthetic fuels:* nuclear energy can provide the input energy for the production of synthetic hydrocarbons (e.g., via Fischer-Tropsch synthesis), methanol, or other value-added chemicals using CO_2 and hydrogen, contributing to a circular carbon economy [33];

- *paper production:* paper and pulp industries require large amounts of steam and electricity. N-R HES can offer stable steam supply (from nuclear) with renewable integration for auxiliary or peak power. This hybrid approach decarbonizes a key process industry [4];

- *data centers:* data centers demand high-capacity uninterrupted power and cooling. Nuclear ensures 24/7 power availability, while renewables help offset grid demand. N-R HES with thermal storage can support resilient and green data center infrastructure [34], [35];

- *urban wastewater treatment:* nuclear power can supply continuous electricity and thermal energy to support energy-intensive wastewater treatment processes, including aeration, membrane filtration, and sludge drying [36];

- *fast charging stations:* require high, variable electricity loads. N-R HES can provide reliable power by combining nuclear baseload with renewable energy and storage, reducing grid stress and enabling low-carbon, scalable EV charging infrastructure [37], [38];

- *steel production:* nuclear energy can contribute to low-carbon steelmaking by supplying electricity and/or hydrogen [18]. High-temperature reactors can also provide process heat for ore preheating or novel reduction technologies. Renewable energy sources can also provide clean electricity for arc furnace steelmaking;

- *agriculture heating:* Nuclear energy can provide low- to medium-temperature heat (e.g., under 150°C) for agricultural applications such as greenhouse heating, soil warming, and aquaculture systems [39]. This heat can be delivered via steam or hot water for year-round food production in cold climates. Renewable energy sources (e.g., solar thermal or biomass) can complement this supply by providing heat during daytime or in transitional seasons;

- *industrial process:* heat high-temperature reactors can directly supply thermal energy to industrial applications, such as chemical manufacturing, petroleum refining, or food processing, displacing fossil-based heat sources and reducing emissions [4];

- *hydrogen production:* nuclear energy can supply high-temperature heat and/or electricity for hydrogen production via electrolysis (e.g., PEM or high-temperature electrolysis) or thermochemical cycles (e.g., sulfur–iodine) [40]. Electricity generated by renewable energy sources (e.g. solar PV and wind turbines) can also be used for PEM. Hydrogen is a versatile energy carrier used in industry, transport, and power systems.

Applications of nuclear non-electric use are already being implemented in areas such as desalination and district heating [26], [30]. In parallel, hydrogen production is emerging as a key frontier for integration with nuclear energy systems.

The advantages of using nuclear energy for hydrogen production have gained significant relevance in recent years [41]. Research is focused not only on the direct use of nuclear-generated electricity and heat for hydrogen production, but also on positioning hydrogen as a core product within N-R HES architectures [40]. Nuclear systems can deliver a stable thermal or electrical baseline, while variable renewable sources address fluctuations in demand or support secondary processes.

Given the important role of clean hydrogen in decarbonizing energy-intensive and emissions-heavy industries, current research is intensively focused on modeling its integration within hybrid energy systems [42]. These efforts aim to:

- optimize system performance across dynamic energy demand profiles;
- evaluate coupling strategies such as high-temperature steam electrolysis and low-temperature PEM electrolysis;
- assess the economic viability of hybrid hydrogen production systems.

Complementing these modeling efforts, full-scale demonstrations are now underway. The US DOE is supporting several Nuclear-Powered Hydrogen Demonstration Projects [43], highlighting the strategic push to integrate hydrogen production into both current and advanced nuclear platforms.

An example is the Nine Mile Point nuclear station in the United States. In 2022, it deployed a 1.25 MW PEM electrolyser capable of dynamic dispatch - modulating hydrogen output in real time to absorb surplus electricity and enhance grid flexibility. This initiative marks the first instance of a nuclear facility in the U.S. producing hydrogen in direct response to grid conditions, establishing a model for multi-product operation at nuclear sites [44].

Figure 4-3 Constellation's Nine Mile Point Hydrogen Pilot Demonstration Project's Electrolyser

Figure 4-4 illustrates the Dynamic Energy Transport and Integration Laboratory (DETAIL) at INL, a testbed designed for validating N-R HES configurations. DETAIL enables real-time simulation and hardware-in-the-loop (HIL) testing to assess dynamic interactions among nuclear, renewable, storage and industrial subsystems.

The facility supports the development of advanced control strategies for coordinating energy flows and enabling flexible, multi-product operation (e.g., electricity, heat, hydrogen). It allows evaluation of system integration approaches under variable demand and supply conditions, providing a platform to test load-following, dispatch optimization and coupling strategies for process heat and electrolysis technologies [45].

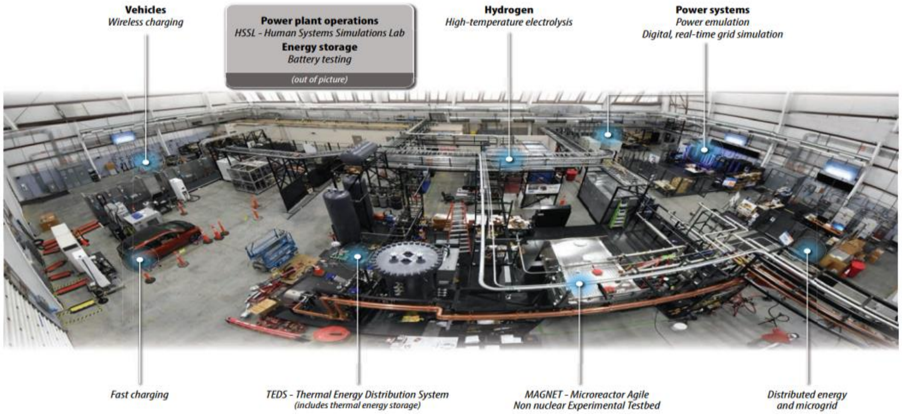

Figure 4-4 Dynamic Energy Transport and Integration Laboratory in INL

4.2 Technology Readiness Levels

The Technology Readiness Level (TRL) scale offers a standardized approach for assessing the maturity of a given technology, ranging from early-stage basic research (TRL 1) to full-scale commercial deployment (TRL 9) [28], as illustrated in Figure 4-5. It gives valuable insights into the level of technological advancement, the current status of the technology and the estimated time and investment required for further development within the technology sector.

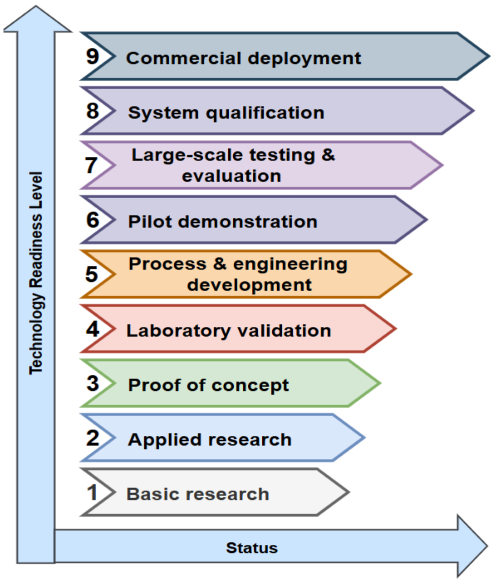

Figure 4-5 TRLs Scale

Table 4-1 outlines the definitions and description for different TRLs for N-R HES, based on [8], [28].

Table 4-1 Technology Readiness Levels for N-R HES

TRL	Status	Definition	Description
1	Basic research	Observation and reporting of fundamental principles	This is the lowest level of technology readiness. Scientific research begins to transition into applied R&D. At this stage, technical synergies between nuclear and variable renewable energy sources (heat/power) are identified through literature reviews

TRL	Status	Definition	Description
2	Applied research	Concept formulation	The concept of a nuclear-renewable hybrid energy system is defined
3	Proof of concept	Analytical and experimental evidence of critical functions	Active R&D is initiated. This includes analytical studies and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology (e.g. thermal or power loops of hybrid system).
4	Laboratory validation	Components or breadboard systems validated in controlled lab environment	The basic technological components are integrated to establish that the pieces will work together. Prototype subcomponents (e.g. interaction of a high-temperature heat exchanger with possible applications, hybrid dispatch control software) tested under representative conditions.
5	Process & engineering development	Laboratory-scale validation and prototype demonstration in a relevant environment	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. A small integrated hybrid unit (reactor-simulator + photovoltaic system + consumer + electrolyser) operated in a test cycle to verify dynamic load monitoring.
6	Pilot demonstration	Engineering-scale prototype demonstrated in relevant (field) environment	This level represents a major step up in a technology's demonstrated readiness. The operating environment for the testing should closely represent the actual operating environment. Pilot hybrid plant using a research reactor or nuclear-simulator heat source co-located with renewables, connected to a micro-grid or industrial user.
7	Large-scale testing & evaluation	Full-scale demonstration in operational environment	The demonstration of an actual system technology in operation environment. Testing full-scale N-R HES subsystems prototypes in a relevant environment with a range of simulants.
8	System qualification	Actual system complete and qualified through extended testing and demonstration	The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. N-R HES fleet-ready: regulatory approvals finalized, long-term reliability & economics confirmed, supply-chain and O&M procedures mature.
9	Commercial deployment	Actual system proven in routine commercial service	The technology is in its final form and operated under the full range of operating mission conditions. N-R HES operating in accordance with design, licensing basis.

Achieving high TRLs for individual subsystems, such as nuclear reactors and renewable energy sources does not guarantee the readiness of the integrated system. Even if each individual subsystem reaches TRL 9, the overall N-R HES may still remain at a lower TRL due to the inherent complexity of system integration. Coupling these technologies creates unique technical, operational and regulatory challenges that do not exist in their standalone applications. These include the qualification of shared heat-transfer loops and power-electronic interfaces, the development of robust and responsive control architectures that can manage real-time interactions among subsystems and the need to verify system-wide safety and performance under dynamically coupled operating conditions. Integration also raises additional licensing and regulatory considerations, especially when thermal and electrical interconnections blur the boundaries between traditionally distinct systems. Table 4-2 provides the TRLs of subsystems that may comprise an N-R HES, based on [8], [46].

Table 4-2 TRLs for Some Key Subsystems in N-R HES

Subsystem	Technology	TRL
ENERGY SOURCES (Electricity & Heat)		
Gen-II/III LWR	PWR/BWR units now operating worldwide	9
Integral-PWR SMRs	NuScale VOYGR-6, GE BWRX-300, Holtec SMR-160	6-7
High-temperature reactors	HTGR (X-Energy Xe-100), HTR-PM	7
Fast & molten-salt reactors	TerraPower (natrium reactor plant), Kairos KP-FHR	4–5
Renewable electricity sources	Utility-scale solar PV, on/offshore wind, run-of-river hydro	9
Renewable heat sources	CSP towers (Noor III), geothermal flash	8–9

Subsystem	Technology	TRL
APPLICATIONS		
Desalination plants	MED, RO	8–9
Hydrogen production	Alkaline / PEM electrolysers (≤90 °C); HT-PEM / SOEC (700-850 °C)	5-8

Fully integrated, tightly coupled N-R HES have not yet been commercially deployed. While current subsystem TRLs indicate progress toward market readiness, several key challenges remain. These include advancing interface technologies, demonstrating pilot-scale integration, streamlining licensing processes and establishing market structures that recognize the flexibility and decarbonization value of hybrid system.

5 Specific Considerations for N-R HES Deployment

5.1 Technical Constraints

Technical constraints in N-R HES are shaped by both the chosen coupling mechanism and the degree of subsystem integration. Based on the literature review, the following technical constraints have been identified and are discussed below.

System integration complexity

Integrating nuclear reactors with renewables (and industrial processes) raises system complexity. Nuclear and renewable plants have different design codes, safety regulations and operational modes. For example, nuclear power plants are built to very stringent pressure-boundary and safety standards (e.g. seismic events), whereas wind/solar plants follow less stringent requirements. The IAEA report [8] notes that “existing nuclear and renewable energy systems adhere to significantly different design standards and requirements, leading to challenges in deploying integrated N–R HESs”. To resolve this, designers should standardize interfaces so each subsystem can function safely. This means nuclear standards prevail for any interface connected to the reactor side, while renewables/industry can follow their usual codes on the other side.

Integration usually involves a shared medium or coupling component. For thermal coupling, this might be a common heat exchanger or manifold that links reactor output to a turbine or process. For electrical coupling, it is the point of common coupling to the grid or power electronics. The IAEA observes that coupling via electricity avoids many cross-contamination issues, but co-location can still create system vulnerabilities (e.g. an industrial accident affecting the NPP site). In tightly coupled systems, designers often introduce a tertiary isolation loop (for heat or chemical streams) specifically to “ensure isolation of radiation under postulated accident scenarios”. This requirement is a direct result of integration complexity: any direct path between reactor coolant and external processes has to be evaluated for leaks or failures, and mitigated by extra loops, valves and sensors.

The control system for an N-R HES is also far more complex than for standalone plants. A single HES control must monitor reactor status, renewable forecasts, grid demand and coupled-process loads in real time. The IAEA recommends autonomous or smart control algorithms, with “fewer humans in the loop” because of the large data streams and rapid decisions required. Integrating disparate time scales (e.g. fast wind fluctuations vs. slow nuclear transients) further complicates coordination.

Overall, the integration complexity of N-R HES is a major constraint. Even if each component is mature on its own, the coupled system has a much lower TRL. As the IAEA report [8] notes, subsystems at TRL 9 independently may combine into a system at TRL 3–6 when tightly integrated. In practice, almost all proposed N-R HES designs are at best “proof-of-concept” stage. This means that N-R HES commercialization could be time-consuming and expensive.

Load-following and control

Traditional NPP are designed to run as baseload units with minimal output variation. By contrast, renewables like wind and solar are intermittent and non-dispatchable. Coupling them in an HES therefore imposes new load-following and control requirements on the nuclear side. In many regions with high renewables penetration, nuclear plants are being asked to back down or ramp output to balance the grid. However, existing large reactors have inherent limits: typical pressurized water reactors can only ramp at a few percent per minute (often around 3–5%/min). This may be insufficient for high renewable shares. The IAEA report notes that most current NPPs were “not designed for large window power manoeuvring, such as daily 100–50–100% cycles”. Achieving rapid load changes without violating thermal margins requires advanced fuel, core design or control strategies (e.g. burnable poisons, soluble boron removal) [8].

Empirical studies confirm the trade-offs: if an NPP performs routine daily load-following, its total energy output falls and capacity factor drops. Fuel cycles are less efficient, and operating costs rise, since higher-power daytime production is exchanged for low-power nighttime operation. For example, the IAEA report cites studies showing that load-following raises generation cost and reduces revenue, all else equal. On the other hand, participating in load-following can increase the unit's revenue if spot prices are high during scarce hours. The same report suggests that "the electricity price of the more resilient NPPs can be made higher by actively contributing to the load variations and stabilization of the electricity grid". In other words, a hybrid plant may recoup the cost of flexibility by selling power or process heat when it is most valuable. Combining cogeneration (selling heat or hydrogen) and storage helps: energy diverted to an industrial process during low demand avoids curtailment and provides an alternate revenue stream, mitigating the loss in electricity output [8].

Nuclear-renewable hybrids can also use energy storage or bypass systems to aid load-following. For instance, integrating batteries or thermal storage allows the reactor to run at a smoother profile, with excess renewable energy dumped into storage. Simple measures like a steam bypass or dump valve can absorb short spikes in output. More advanced controls (model predictive, AI-driven) can further optimize trade-offs.

Finally, modern reactor designs (e.g. SMRs or advanced designs) are being developed with more flexible control in mind. Some SMRs can vary power rapidly or even automatically adjust output to match grid frequency. HTR can also throttle thermal output by varying coolant flow. Nevertheless, retrofitting flexibility into the nuclear side remains a constraint: it may require regulatory approvals and hardware upgrades.

Thermal management and inertia

Thermal management in N-R HES refers to how heat flows are balanced between nuclear and other units. A fundamental constraint is thermal inertia. A nuclear reactor has massive thermal inertia (huge heat capacity) and typically slow transients; in contrast, renewable generators (e.g. PV panels) have essentially zero thermal inertia (their power output can change almost instantaneously with sunlight). When these are coupled (especially thermally), the system must reconcile these different time scales. Rapid changes in demand or renewable input cannot be accommodated by instantly changing reactor core temperatures – instead, the HES must redirect or store energy. Inertia is not solely a disadvantage: it gives system stability. The large rotating masses and thermal capacity of nuclear turbines provide inertia to the grid, helping to dampen short disturbances. But integrating renewables reduces overall inertia unless additional measures are added. Balancing these factors – thermal storage vs. dynamic response vs. efficiency – represents a key thermal management challenge in N-R HES design.

Another challenge is temperature/pressure matching. Nuclear systems (e.g. PWRs) may deliver steam at 300°C and 15 MPa, whereas a solar thermal or chemical process might operate at quite different conditions. Directly coupling them can be infeasible. This is why intermediate heat exchangers or multiple loops are used, but each adds inefficiency and potential failure points. For example, the IAEA document observes that thermally coupled HES often require an extra loop to isolate the reactor "preventing any potential contamination of coupled subsystems under off-nominal conditions". Such tertiary loops inherently reduce net efficiency (every heat transfer has losses), which constrains economic viability.

Component compatibility (pressure, temperature, flow)

Component compatibility presents a persistent constraint in the design of N-R HES. Direct coupling is rarely practical due to mismatched operating conditions, prompting the use of intermediate loops, heat exchangers, or isolation barriers. Molten salts in solar thermal storage, for example, can be corrosive at elevated temperatures and may challenge the integrity of nuclear-grade materials. Steam conditions suitable for high-temperature electrolysis often exceed typical reactor capabilities, requiring advanced heat transfer systems. Pressure differences between subsystems call for control devices to ensure safe and stable operation. Variability in flow rates and thermal demands could lead to transient stresses or mechanical instability. These issues complicate integration, reduce efficiency, increase design complexity and demand careful engineering of system interfaces.

Infrastructure co-location and siting

Hybrid systems with thermal or chemical coupling require physical proximity between NPP and auxiliary systems to minimize energy losses. Thermal transport over long distances leads to degradation of temperature gradients and increased parasitic loads which reduces overall system efficiency. High-temperature piping and heat exchangers should be engineered for minimal loss and mechanical integrity.

Siting constraints arise from nuclear safety requirements and can limit co-location options with renewable infrastructure, particularly when optimal solar or wind sites are topographically or environmentally distinct.

Shared infrastructure such as electrical switchyards, cooling systems and water intake structures must be designed to handle the combined load of both nuclear and renewable components. Transmission systems may require reinforcement to accommodate peak hybrid output.

High-temperature thermal coupling, such as from nuclear heat to industrial hydrogen production or desalination units, imposes strict material and layout requirements. Pipe materials must tolerate thermal gradients, pressure variation and potential corrosion from working fluids (e.g. steam, molten salts). Expansion joints, insulation and monitoring systems should be engineered to maintain safety and performance across the thermal interface.

Component layout should consider radiation shielding, access for maintenance and system isolation in the event of faults. The physical arrangement of hybrid elements should allow for independent shutdowns and inspections without disrupting the entire system. Infrastructure siting therefore requires integrated planning across thermal, electrical, structural and safety domains.

Material degradation and different lifetime

N-R HES configurations involve components with fundamentally different design lifespans and degradation mechanisms. Nuclear systems are engineered for multi-decade operation with limited downtime, whereas renewable technologies such as photovoltaic arrays and electrolyser stacks exhibit shorter operational life and require periodic replacement. Synchronizing maintenance schedules across these systems is a significant operational challenge.

Hybridization introduces new thermal, mechanical and chemical stresses on materials. Frequent load cycling causes thermal fatigue in reactor pressure boundaries, heat exchangers, and balance-of-plant piping. Flexible operation outside original steady-state conditions can lead to accelerated creep, fatigue and embrittlement of reactor materials.

Interfaces involving hydrogen production or desalination introduce aggressive operating environments. High-temperature steam electrolysis subjects components to elevated thermal gradients and potential chemical attack. Electrolyte-based systems may degrade seals, welds and piping due to corrosive species and operating pressure differentials.

The potential for contamination across system boundaries adds further complexity. If intermediate loops become activated or contaminated by radioactive species, maintenance becomes subject to radiological protection measures. This affects equipment replacement, inspection intervals, and component disposal, all of which must be included in the safety case.

System reliability and redundancy

N-R HES shared components such as turbines, heat exchangers or electrical switchgear represent potential single points of failure. A malfunction in these systems can affect multiple outputs simultaneously, reducing overall system availability.

System-level fault isolation is critical. Each subsystem must be capable of safe shutdown or independent operation during a failure in another subsystem. This requires redundant control logic, decoupled thermal and electrical loops, and priority management strategies during contingency conditions.

In the event of partial system outages, control systems must be configured to prioritize critical loads. For example, continued operation of desalination or hydrogen production may be required even if the NPP unit is offline, necessitating auxiliary power supplies or grid backup. Conversely, during nuclear maintenance or refuelling, renewable or stored energy resources could partly compensate for the loss of baseload supply.

Designing for high reliability in a nuclear–renewable hybrid context requires detailed analysis of failure modes, component interactions and coordinated maintenance. Physical and functional redundancy, modular replacement strategies and adaptive control logic are essential to ensure sustained performance under both normal and faulted conditions.

5.2 Modelling Tools and Methods

Modelling plays a critical role in the development and deployment of N-R HES by enabling comprehensive analysis of system behaviour under various operational and market scenarios. It is essential for evaluating system performance, optimizing design and operation, assessing safety, informing policy and investment decisions. Due to the complex nature of N-R HES (integrating electrical, thermal and chemical subsystems) advanced modelling tools are required that can capture multi-domain interactions, dynamic control strategies and hybrid-specific safety considerations. Modelling serves multiple purposes, including: evaluate performance and safety; optimize system design and operation; support policy and investment decisions.

Key modelling needs in N-R HES:

- multiphysics dynamics (thermal-hydraulics, electrochemistry);
- multi-timescale operations (real-time control to long-term planning);
- economic performance under market variability;
- safety analysis (normal and transient conditions);
- multi-product energy flow interactions.

Multiphysics dynamics

Dynamic coupling of nuclear and renewable systems involves multi-physics modelling (neutronic, thermal hydraulics, electric grid dynamics, etc.). Equation-based languages like Modelica are well-suited to such integrated simulation. For example, TANDEM is constructing a Modelica component library that can couple nuclear reactor models with balance-of-plant and renewable subsystem models to simulate the full hybrid system [47]. Oak Ridge National Laboratory (ORNL) has similarly developed Modelica frameworks (e.g. the TRANSFORM library [48]) and uses the RAVEN toolkit to simulate hybrid system dynamics and perform probabilistic analysis [49]. These tools allow one to build detailed dynamic models of modular reactors (neutronic, thermal-hydraulic core models, turbine cycles, control systems) connected to other processes (heat exchangers, electrolysers, storage tanks). Steady-state tools (powerflow, energy-balance solvers) can be used first to size components, followed by full transient simulation to capture response to changes in load or resource (e.g. variable wind/solar). The TANDEM workshop agenda also highlights the use of coupled codes (e.g. CATHARE or ATHLET with Modelica) for simulating safety-relevant transients in co-generation scenarios. In summary, dynamic multi-physics modeling of HES leverages modular libraries (Modelica, MATLAB/Simulink, or custom frameworks) that integrate reactor system models with renewable and industrial process models for time-domain analysis [13].

Multi-timescale operation

Hybrid systems must be optimized over multiple time scales: from fast control loops to hourly/daily dispatch to long-term planning. A common approach is hierarchical: first perform steady-state or capacity analyses to set component sizes and baseload flows, then apply dynamic simulation and optimization for time-dependent operation. For example, IAEA guidance recommends using steady-state modeling to establish energy balances, then detailed dynamic models to simulate hourly or sub-hourly operation under realistic dispatch scenarios [8]. NREL's REopt optimization tool embodies this: it uses one year of hourly renewable generation and load data to determine optimal subsystem sizes and dispatch schedules that minimize life-cycle cost [50]. REopt's mixed-integer linear program formulates constraints (e.g. turbine ramp rates, storage charging limits) and an objective (e.g. maximize net present value or minimize levelized cost) Opportunities for Research and Development. Likewise, IAEA is developing the FRAMES framework which couples short-term unit-commitment (hourly dispatch) with long-term capacity expansion to quantify nuclear's role in integrated systems. In practice, multi-timescale operation modeling often involves linking fast dynamic models (seconds–minutes) for control and stability with slower economic dispatch models (hours–years) to ensure overall system feasibility and performance [51].

Economic performance under market variability

Evaluating HES economics requires modelling electricity and product markets alongside system operation. Optimization tools incorporate time-varying prices, incentives, and constraints to assess profitability. For instance, NREL used the REopt model to optimize HES designs and schedules for various applications (e.g. synthetic fuel, desalination, hydrogen production) under realistic electricity and heat price trajectories [24]. REopt maximizes net present value (NPV) by choosing subsystem sizes and dispatch strategies given hourly renewable output and production-cost model PLEXOS-generated electricity price curves [50]. The optimization includes multiple revenue streams (capacity payments, energy markets, ancillary services, policy credits) and minimizes capital and operating costs. Similarly, IAEA notes that techno-economic optimization aims at maximum profitability or minimum levelized cost, subject to technical limits (ramp rates, subsystems constraints). Sensitivity and uncertainty analyses (e.g. Monte Carlo via RAVEN) are also used to assess impacts of fuel price, demand, and technology cost uncertainties on HES economics. In long-term planning, tools like FRAMES evaluate carbon targets and investment decisions, determining optimal capacity mixes and dispatch to meet emission or cost goals [51].

Safety analysis under normal and transient conditions

Safety modelling of HES must ensure nuclear safety margins while accommodating hybrid operation. This involves simulating normal and off-normal transients in coupled systems. Traditional reactor safety codes (e.g. RELAP5, TRACE, CATHARE, ATHLET) are used to model core and coolant transients, but HES applications require extending these to include interactions with industrial processes. For example, loss-of-load or reactor trip scenarios may now involve heat dump into storage, hydrogen plant tripping, or other non-reactor processes.

TANDEM specifically addresses such safety issues, identifying new initiating events due to coupling and studying their mitigation [12]. IAEA guidance emphasizes that any hazard in the non-nuclear subsystem must not compromise nuclear safety. For instance, a hydrogen system explosion must be prevented from impacting the reactor; this imposes design constraints (e.g. physical separation, barriers) [8]. Safety assessment thus requires integrated modeling of accident propagation: subsystem models (storage tanks, heat exchangers, electrical components) are coupled with reactor models, and overall plant safety is evaluated using conservative bounding scenarios. Advanced simulation frameworks may co-simulate reactor thermo-hydraulics with process dynamics, allowing evaluation of fast transients (pump trips, valve closures) and slower sequences (cooldown, loss of grid). In all cases, the required safety level is at least that of a standalone nuclear plant, which may involve enhanced instrumented interlocks and simplified configurations (e.g. passive cooling) [8].

Interactions between energy products

Hybrid systems commonly co-produce electricity and secondary products (heat, hydrogen, water, fuels). Models must capture these energy-product interactions. IAEA highlights applications such as seawater desalination, hydrogen generation, district heating, synthetic fuel or petrochemical production in HES contexts [8]. In modelling, each product chain is represented by modules with specific energy inputs and outputs. For example, a hydrogen module would draw high-temperature heat and electricity to run an electrolyser or thermochemical cycle. Optimization tools then dispatch output between markets: if electricity demand is low, power may be diverted to hydrogen production or to charging thermal storage, and vice versa. NREL studies illustrate this flexibility: one hybrid scenario produced synthetic gasoline, another powered a desalination plant, several supplied industrial heat, and others generated hydrogen, all within a combined dispatch framework. The models track the flows of each product and include their values in the economic objective. Multi-product constraints are handled by extending energy balance equations: for example, thermal energy from the reactor may flow partly to an electrolyser and partly to district heating, with shared flow limits. In summary, interaction modelling treats the hybrid as a multi-output system: simulation tools include each product's demand profile and conversion efficiency, ensuring that the dispatch optimizes the mix of electricity, heat and additional fuels or feedstocks [24].

Gaps and further research

Despite the availability of specialized modelling tools, notable gaps and challenges persist in accurately capturing the N-R HES complexity and integrated behaviour. Table 5-1 summarizes the key limitations in current tools/methodologies and outlines potential directions for future advancement.

Table 5-1 Modelling/Tools Limitations and Future Advancements

Limitation	Future advancement
• Limited interoperability between sector-specific tools	• Develop standardized interfaces and co-simulation protocols
• Inadequate support for uncertainty propagation and stochastic modeling	• Integrate AI/ML for dynamic control and optimization
• Weak coupling between economic and technical simulations	• Expand shared component libraries (e.g., TANDEM initiative)
• Lack of integrated safety modeling at system level	• Couple high-fidelity physics models with market and control frameworks
• Scarcity of open-source, validated hybrid component libraries	• Enhance multi-product modeling and hybrid economic dispatch

5.3 Safety and Security Concerns

Integration of the nuclear reactors with renewables and industrial processes rises specific safety and security concerns.

Safety concerns

Hybridization introduces a range of safety issues not typical of standalone nuclear facilities. The most pressing involve subsystem interactions, dynamic operations and expanded list of initiating events:

- radiological interface risks: direct coupling of nuclear heat or electricity to external industrial systems (e.g. hydrogen electrolysis, desalination) creates potential pathways for radionuclide transport. Interface failures could potentially result in the transfer of contaminated fluids to non-nuclear components, thereby breaching localization principle [8], [52];

- dynamic load-following stress: unlike baseload nuclear operation, N-R HES may require reactors to respond flexibly to variable renewable inputs and industrial loads. Rapid power ramps, thermal cycling and mode transitions could potentially challenge fuel integrity, pressure boundary conditions, introducing fatigue and increasing risk of transient-induced faults [53], [6];

- expanded list of initiating events: hybrid configurations generate new initiating events (IEs) not considered in traditional design-basis accident analysis:

  - sudden disconnection or failure of industrial loads (e.g., hydrogen electrolyser trip);

  - load-induced transient instability caused by variable solar or wind input;

  - cross-system control failure (e.g., failure in a shared control system misrouting power or heat);

  - process-side failures (e.g., pressure vessel explosion in chemical subsystem) impacting the nuclear island.

- thermal-hydraulic instabilities: thermal coupling with high-demand processes (e.g., steam methane reforming) can introduce complex heat sink dynamics. If industrial demand fluctuates rapidly, this may lead to pressure transients, two-phase flow instabilities or thermal shock within reactor systems [8], [54];

- interface control and instrumentation complexity: integrated control logic coordinating nuclear and non-nuclear subsystems may lead to unclear delineation of control responsibilities, especially under faulted conditions. Incorrect prioritization or failure to isolate could initiate unintended shutdowns, trips or unsafe operating conditions [6];

- containment boundary compromise via shared Infrastructure: shared site infrastructure (e.g. cooling towers, steam lines) could act as pathways for containment bypass if not properly isolated. For example, chemical explosions or fires in an industrial module could compromise shared ventilation or conduit systems [53];

- site hazards and common-cause external events: co-location of renewable generation and industrial loads with the reactor can elevate the risk of common-cause failures from natural hazards (e.g., flooding, seismic events). These may simultaneously disable both reactor safety systems and critical process loads [5];

- human factors cross multi-domain interfaces: operators managing hybrid systems should monitor a broader set of parameters and coordinate between nuclear, electrical, and process subcomponents. Increased cognitive load and unclear procedural boundaries could result in delayed or incorrect responses to off-normal events [8];
- emergency response complexity: with multiple co-located domains, must account for chemical hazards, electrical fire scenarios, and radiological releases. Overlapping hazards may delay first responder access or cause evacuation procedure conflicts [8].

Security concerns (physical and cyber)

Security concerns include:

- expanded physical footprint and threat surface: co-located industrial plants extend site perimeter with less protected assets (e.g. integration of solar fields, wind farms, or hydrogen plants extends the site boundary, increasing potential points of unauthorized access or sabotage) [52];
- interlinked infrastructure vulnerabilities: physical or cyberattack on shared utilities may affect NPP safety systems [53];
- cybersecurity exposure: SCADA and I&C links across systems raise intrusion risk via weaker industrial control points; could induce unsafe setpoint changes (e.g. reactor setpoints, sensor spoofing, or denial-of-service scenarios that affect safety-critical controls) [6]. A 2021 DOE hybrid systems workshop noted that while hybridization may not introduce entirely new categories of cyber threats (the threats are those common to each technology), it does increase the number of access points and integration of third-party components, thereby elevating the cybersecurity risk profile [60]. Interoperability issues between legacy nuclear systems and newer renewable controllers could also create security gaps if not properly managed. The potential consequences of a cyber attack on a hybrid system include false sensor signals, unauthorized control commands, or denial-of-service on control networks – any of which, in a worst-case scenario, could initiate unsafe conditions (e.g. misleading the reactor control system about power demand or cooling status).

Initiating events specific to N-R HES

The coupling of nuclear plants with renewable or industrial subsystems (e.g. hydrogen electrolysis, desalination, thermal storage) could introduce new IEs not present in standalone reactors or increase frequency of the previously considered IEs. These are driven by thermal, electrical, chemical or control linkages between the reactor and the hybrid subsystem. Key hybrid-specific IEs include loss of coupled load or heat sink, steam-extraction breaks and chemical/electrical accidents. The following section outlines the key IEs, including their causes, coupling context and safety implications.

Loss of coupled load (thermal/electrical)

In hybrid configurations, reactor heat or power is often directed to industrial processes such as hydrogen production, desalination, or district heating. A sudden shutdown of these downstream processes induces a rapid loss of thermal and/or electrical load. This abrupt off-take reduction initiates a transient characterized by steam pressure buildup and potential turbine overspeed, necessitating prompt response from control system. NPPs are designed to accommodate sudden load loss but the integrated hybrid context introduces new scenarios (e.g. simultaneous loss of a thermal and electrical load). A sudden trip of a HTE hydrogen plant removes both electrical and thermal loads from the reactor, resulting in a coupled transient that impacts the reactor's thermal-hydraulic and power generation balance. The IAEA notes that in hybrid couplings (thermal or electrical) the design must address the "sudden cessation of demand" for heat or power [24]. Such load-loss events propagate immediately to reactor protection (turbine trip, reactor trip) and must be covered by safety systems.

Steam-extraction line break (thermal coupling)

When a reactor's steam or heat loop is directly coupled to an industrial user (e.g. steam to a hydrogen plant or desalination unit), a rupture in that coupling piping is a critical IE. A large steam line break in the hybrid heat extraction loop will instantaneously depressurize the steam branch, causing a rapid loss of steam inventory and heat removal path. In light-water reactors this acts much like a main steam line break – rapidly removing heat from the core and inserting positive reactivity unless mitigated. Analyses identify such breaks as the "major risk" added by an HES connection [22]. The IAEA specifically notes that "partial or complete breakage in the steam extraction piping" is postulated in steam-coupled hybrids, and it would produce a transient comparable to a design-basis steam line break accident [24]. Smaller leakage events in the extraction circuit (e.g. cracked pipes or failed valves) also create transients and are treated as initiators in fault trees. In all cases, reactor protection (scram on pressure drop, closure of main steam isolation valves) and decay-heat removal systems must operate. Loss of the extraction heat sink may also force the core to dump power into the normal condenser or auxiliary systems. Thus, a hybrid steam-line break can directly lead to reactor trip and potential core damage if safety systems fail to isolate the break and remove decay heat.

Hydrogen release and switchyard explosion (chemical/electrical coupling)

On-site hydrogen production introduces chemical hazards that may exceed those considered in traditional NPP safety analysis. Hydrogen leak and subsequent explosion in or near the electrical switchyard is a key hybrid-specific IE. In this scenario, leaked H_2 accumulates and ignites, creating an overpressure that can destroy switchyard transformers or breakers. Vedros et al. report that even modest hydrogen detonations (e.g. igniting ~13 kg H_2) can produce blast pressures (~0.39 psi at 1 km) sufficient to disable off-site power lines [22]. Such a blast-induced switchyard failure typically causes a loss of off-site power (LOOP). The reactor then must rely on emergency diesel generators and trip on loss of grid. Both PWR and BWR studies confirmed this: a hydrogen detonation near the plant may directly cause LOOP, which then drives reactor shutdown and emergency cooling actions [22].

Electrical faults from hybrid loads (electrical coupling)

The addition of large electrical loads or converters (e.g. electrolysers, electrolysers, or battery systems) creates new electrical faults. For instance, a sudden overcurrent or short-circuit at the hybrid interface (transformer/inverter feeding the reactor or grid) can occur if the hydrogen plant or storage fails. Vedros et al. model scenarios where an H_2 plant transformer or load faults, causing protective relays or breakers to trip [22]. These faults can induce reactor trips if they trigger generator or bus trips. Similarly, abrupt disconnect of the hybrid load (e.g. pump or compressor failure) causes voltage/frequency transients. The FMEA in [22] identifies "electrical power load loss from the HTEF" and overpressure events as hazard categories. Though classical IEs (e.g. grid fault, turbine trip) exist, hybrid operation can alter their frequency or severity, so they must be reanalysed in context of the integrated system.

Heat-transfer fluid or steam leaks (thermal/chemical coupling)

Hybrid systems often circulate special fluids between the reactor and process (e.g. secondary steam loops, molten salt loops). A leak or rupture of the heat-transfer medium (steam, hot oil, molten salt, etc.) in the hybrid interface can initiate accidents. For example, a rupture in a secondary loop carrying reactor steam to a heat exchanger or electrolyser would dump radioactive steam or coolant. According to FMEA analyses, "heating medium (steam or HTF) leakage at the HTEF" is a potential external event [22]. Such a leak can produce overpressure or fire (if fluid is flammable) and can also cause partial loss of flow to the reactor. The safety impact depends on the circuit: for a secondary steam loop it resembles a small steamline break (thermal transient), while for a closed-circuit fluid it may lead to chemical hazards or pressure excursions. In all cases, leak IEs propagate by flooding or fire potential and by suddenly altering reactor cooling. Relief systems and leak detectors in the hybrid loop are needed to prevent escalation to a core damage scenario.

5.4 Licensing Considerations

Licensing of N-R HES presents specific challenges that should be addressed to support their broader deployment.

Fragmented regulatory regimes

N-R HES involve multiple subsystems-nuclear, renewable and industrial that fall under distinct regulatory authorities. Nuclear safety is typically overseen by an independent nuclear regulatory body while renewable and industrial operations may be under energy, environmental or occupational safety regulators. This fragmented jurisdiction complicates licensing.

Shared infrastructure (e.g. heat exchangers, thermal loops, digital controls) raises questions about oversight responsibility. Without early coordination, regulatory gaps or overlaps may occur. The NRC, in ML25055A251, acknowledges this and emphasizes defining regulatory boundaries early in project development [55].

N-R HES developers should proactively engage with relevant regulatory bodies across all domains to identify safety interfaces and clarify jurisdictional responsibilities from the outset [56], [57].

Lack of hybrid-specific guidance

Current IAEA standards such as SSR-2/1 [20], SSR-2/2 [58] and GSR Part 4 [56] provide basis for nuclear safety but do not address hybrid system specifics. For example, SSR-2/1 Requirement 35 states that cogeneration units must prevent radionuclide transfer but does not address other safety aspects relevant to hybrid systems [20].

Technical report IAEA NR-T-1.24 [8] highlights these gaps and proposes some key concepts: defining system boundaries, categorizing shared structures, systems and components but these are not incorporated into IAEA Safety Standards (Safety Requirements or Safety Guides).

The U.S. NRC, as noted in [55], indicated that existing licensing frameworks may be applicable to hybrid projects, provided that hybrid-specific risks are fully addressed.

Expanded safety analysis requirements

N-R HES could introduce operational modes and initiating events not traditionally considered in NPP safety analyses.

GSR Part 4 and SSR-2/1 require comprehensive safety analysis for all credible initiating events. Applying this to hybrid systems necessitates deterministic and probabilistic safety assessment covering coupled operational modes specific initiating events from renewable and industrial systems.

Defense-in-depth and functional independence must be preserved. Components affecting nuclear safety regardless of whether they originate in industrial or renewable subsystems must be safety classified and qualified accordingly [20], [57], [59].

Safety cases should also address common-cause failures across shared systems, cybersecurity risks in joint instrumentation and control.

Multi-hazard emergency planning

Traditional nuclear emergency preparedness frameworks are primarily designed to address radiological risks, with predefined Emergency Planning Zones, dose-based protective actions and site-specific emergency response strategies. Integration of nuclear power with industrial processes and renewable systems in N-R HES introduces new complexity to emergency planning.

In hybrid configurations, additional hazards such as toxic chemical releases, high-pressure process failures, may arise from co-located non-nuclear systems. These hazards can occur independently of, or in combination with, nuclear events. For example, a process upset in a hydrogen production facility may pose an immediate threat to site personnel or compromise access routes during a simultaneous radiological release. Likewise, shared infrastructure or control systems may create common-cause failure pathways, increasing the probability of cascading events.

Emergency planning for N-R HES must therefore evolve to reflect these multi-hazard conditions. Protective measures must address both radiological and non-radiological consequences, considering different hazard propagation speeds, exposure types and population vulnerability profiles. Public alert systems must be capable of distinguishing between hazard types while providing clear, actionable guidance. Coordination protocols between on-site emergency teams, local responders and off-site authorities must integrate chemical, fire, and radiation response capabilities [56], [57]. Tabletop exercises and integrated emergency response drills should reflect realistic hybrid scenarios.

License structure

Licensing of N-R HES introduces specific considerations related to how hybrid configurations are addressed within the NPP license. This includes assessing whether the existing license should be amended or if a new licensing framework is required.

If the hybrid system is loosely coupled, where renewable or industrial components operate independently and do not impact NPP safety, modifications may be addressed through a license amendment. This would involve updating the plant license to reflect changes in output routing, auxiliary loads or system boundaries without altering the underlying nuclear safety case.

In contrast, tightly coupled configurations, where thermal or electrical connections to industrial processes such as hydrogen production are integral to the plant's operation, may not be adequately covered by a simple amendment. These arrangements could introduce new initiating events, involve safety important components or depend on shared infrastructure that extends beyond the originally defined license boundary. In such cases, a more extensive license revision may be required, potentially involving an expansion of the license scope or the development of a new licensing framework. Interface control documentation, updated safety analyses, and coordinated evaluations across all subsystems should then be incorporated into the licensing basis.

Regulatory competence

The N-R HES deployment introduces regulatory aspects that require strengthened institutional competence. Effective oversight of N-R HES demands regulatory expertise across diverse technical domains and a clear understanding of the interactions between nuclear and non nuclear components.

Regulatory authorities must be capable of evaluating configurations that involve thermal and electrical coupling and integrated infrastructure. This includes the ability to assess how these interactions may affect NPP safety, especially in scenarios where non nuclear subsystems introduce new initiating events, fault pathways or operational dependencies.

To meet these demands, regulatory bodies should expand internal capabilities. This includes building cross disciplinary expertise in nuclear technology, renewable energy integration, chemical processing and modern instrumentation and control systems. Personnel should understand how hybrid configurations influence safety classifications, reactor performance and transient behavior. Regulators should be equipped to review integrated safety cases that cover multiple subsystems and involve coupled scenarios.

Inspection procedures should be tailored to reflect the specific characteristics and operational complexities of N-R HES

Participation in international initiatives and technical exchanges can support competence development. By engaging with other regulators, research institutions, and standard setting bodies, national authorities can stay aligned with evolving practices and benefit from shared experience in hybrid energy system assessment. Without this competence, the licensing and oversight of integrated systems may face delays, gaps, or inconsistencies that undermine public trust.

Where in-house expertise is limited, regulators may also draw on the capabilities of technical support organizations to provide independent analysis, modelling and technical review aligned with regulatory needs.

6 Conclusions

This report presents an overview of Nuclear-Renewable Hybrid Energy Systems (N-R HES) based on a literature review. It outlines the concept, benefits and opportunities of N-R HES, as well as their potential applications and key considerations for future deployment. These considerations include technical challenges, safety and security aspects, modeling approaches and licensing framework.

Rather than viewing nuclear and renewable energy as competing technologies, the N-R HES concept emphasizes their coordinated integration within a hybrid system. This synergy leverages the complementary characteristics of both energy sources to enhance overall system efficiency.

To fully realize this potential, further research, pilot-scale demonstration projects and international collaboration are essential. These efforts will support the exploration of N-R HES architectures, validation of integrated performance under real conditions and development of suitable regulatory and market frameworks. In parallel, advancements in modelling tools and safety analysis methodologies will be necessary to facilitate the transition from conceptual designs to deployable solutions.

The transition toward decarbonization, diversification of energy carriers and increased system resilience positions N-R HES as a strategic integrative solution. They offer significant potential for cross-sector coupling, enhanced energy security and innovation in the non-electric applications of nuclear energy.

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