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The Integration of Hybrid Nuclear Renewable Energy Systems

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ABSTRACT

Two principal options for low carbon energy generation are nuclear energy and renewable energy. The renewables in the energy systems are increasing. As the decarbonization of energy generation is one of the main goals of the sustainable development, many activities are being carried out in the field of synergy operation of the low carbon energy generation sources.

Hybrid nuclear and renewable energy systems are defined as integrated systems consisted of nuclear reactors, renewable energy generation sources and industrial processes that can simultaneously achieve grid flexibility, greenhouse gas emission reductions and optimal use of investment capital. Those systems can take advantage of coupling nuclear and renewable energy generation sources to increase the benefits of each technology to provide reliable, sustainable electricity to the grid and to provide low carbon energy to other industrial energy sectors as well.

In the recent years there are many research activities in this field. Integration of these systems is currently in development phase. There are some loosely coupled hybrid nuclear and renewable energy systems in operation with primary focus of supporting electricity demand. As these systems present the potential for sustainable energy generation, a higher development is expected in the future.

The paper presents the basic concept of hybrid nuclear and renewable energy systems, an overview of current research activities and the case study of GEN group.

1 INTRODUCTION

The main goal of world’s energy transition is to decarbonize energy production. Energy transition refers to global shift from fossil-based to low-carbon energy generation technologies. Two options for low-carbon energy generation are nuclear energy and renewable energy sources. A share of renewable energy sources is increasing in world energy production with the aim of reducing CO_2 emissions. As the renewable energy sources are variable and dependent on weather and natural conditions; and on the other hand, nuclear power plants are able to provide continual energy generation; a coupling of both systems present an opportunity to increase benefits of each technology. A synergy between nuclear power plants and renewable energy sources presents potential and opportunity for sustainable development. To avoid grid instability and supply issues due to physical limitations of the renewable energy sources the integration of hybrid nuclear and renewable energy systems presents a potential solution.

A basic concept, main components and structure of hybrid nuclear renewable energy systems are for example described by A. Arefin et al. [1] and M. F. Ruth et al. [2]. Various possible integration techniques along with their operation are discussed in detail. Moreover, different aspects of interconnections are identified. A. Arefin et al. [1] also discusses about the reactor licensing, permitting procedures along the different benefits of hybrid nuclear renewable energy systems. IAEA-TECDOC-1885 [3] shows different national approaches to deployment of nuclear and renewable energy sources, as well as the research & development (R&D) efforts for the deployment of hybrid energy systems.

In this paper a definition, structure and integration of hybrid nuclear renewable energy systems is presented, and the current R&D status is reviewed. In the last section, an example of GEN group hybrid nuclear renewable energy system is described.

2 HYBRID NUCLEAR RENEWABLE ENERGY SYSTEMS

Hybrid nuclear renewable energy systems (N-R HES) are cooperatively controlled systems that dynamically apportion thermal and/or electrical energy to provide responsive generation to the power grid. N-R HES include multiple subsystems, which may or may not be co-located. The main components of N-R HES are: nuclear heat generation source (nuclear island), turbine island, at least one renewable energy source, an industrial process that utilizes heat and/or electrical power form energy sources to produce a commodity-scale product [2].

2.1 Classification of N-R HES

In general, there are three types of N-R HES architectures. In dependence of electrical and thermal connection N-R HES are classified to loosely coupled HES, thermally coupled HES and tightly coupled HES. The basic concepts of all mentioned types of N-R HES are depicted in Figures 1 - 3. These concepts are simplified and not all components are necessarily part of system configurations.

Loosley coupled N-R HES: These systems contain generators which are only electrically coupled to industrial energy users. The basic scheme of a loosely coupled N-R HES is represented in Figure 1.

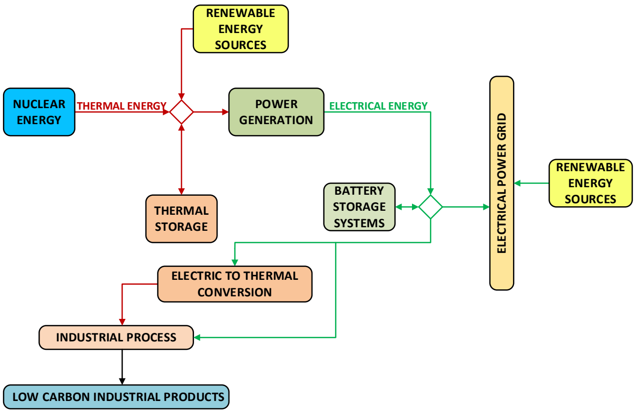

Figure 1: Loosely coupled N-R HES

There is no direct thermal coupling of subsystems (except thermal to power conversion equipment and electrical to thermal energy equipment to provide thermal energy input to the industrial processes). This scenario allows management of electricity within the system [4] and retrofit of existing generation with regulatory changes. These systems have more than one connection point to the electrical grid. They are managed by one entity [4].

Thermally coupled N-R HES: These systems contain thermally integrated subsystems, that are tightly coupled with heat generation source. The systems have more than one connection to power grids but are managed by a single entity. The nuclear and renewable systems are co-controlled to provide energy and ancillary services to the grid. The location of the industrial process facility depends on heat quality, heat losses along the heat delivery system and the limited zone around the nuclear power plant [4]. The basic scheme of the thermally coupled N-R HES is represented in Figure 2.

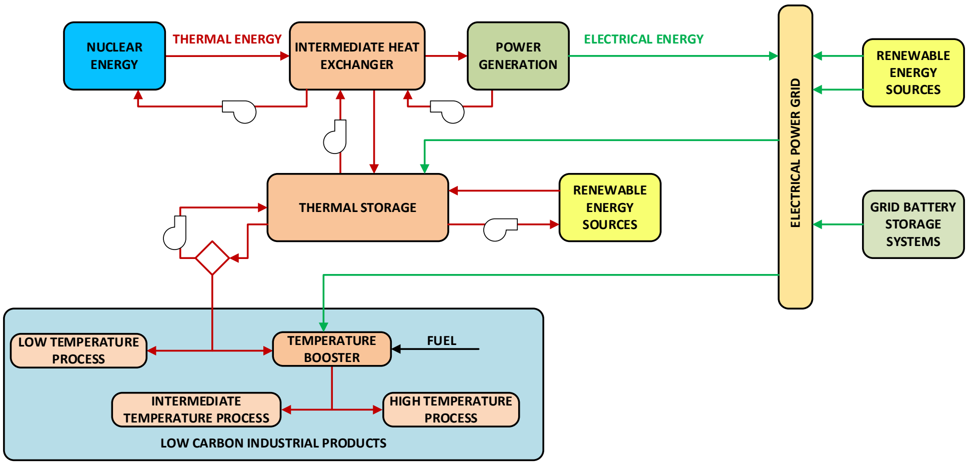

Figure 2: Thermally coupled N-R HES

Tightly coupled N-R HES: Nuclear and renewable energy sources are directly integrated with the industrial processes behind the grid. There is only one connection point to the grid. All integrated systems are co-controlled and only one entity manages the whole system. The system is optimized for the whole (integrated) system rather than for each individual subsystem [4]. The basic scheme of a thermally coupled N-R HES is represented in Figure 3.

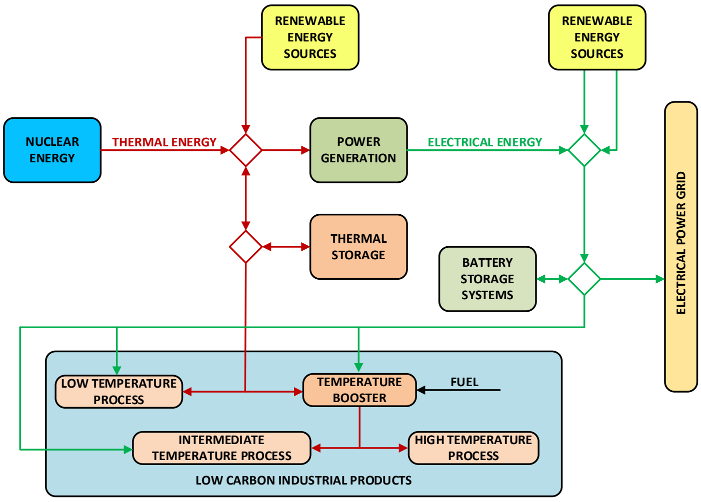

Figure 3: Tightly coupled N-R HES

3 CURRENT STATUS OF N-R HES SYSTEMS

The concept of N-R HES is still in the R&D phase. Technical and economic analyses have been carried out for some concepts of N-R HES systems. Currently, there are in operation some systems, where individual units operate independently, but the operator can manually adjust the operation of each of the individual subsystems with the aim of more efficient operation of whole system. In this section, some technical solutions of N-R HES operation are presented.

3.1 Hybrid system with CSP

In recent years many ideas have been developed in order to maximize the power generation from the integrated systems consist of nuclear power plants (NPP) and renewable energy sources (RES). The integration of concentrated solar power (CSP) in NPP is used to heat steam before expansion in high pressure (HP) or low pressure (LP) turbine. As the steam reach higher enthalpy value (steam from CSP has higher temperature than steam from NPP), the thermal efficiency increases [3], [5]. The schematic diagram of NPP-CSP hybrid system is presented in Figure 4.

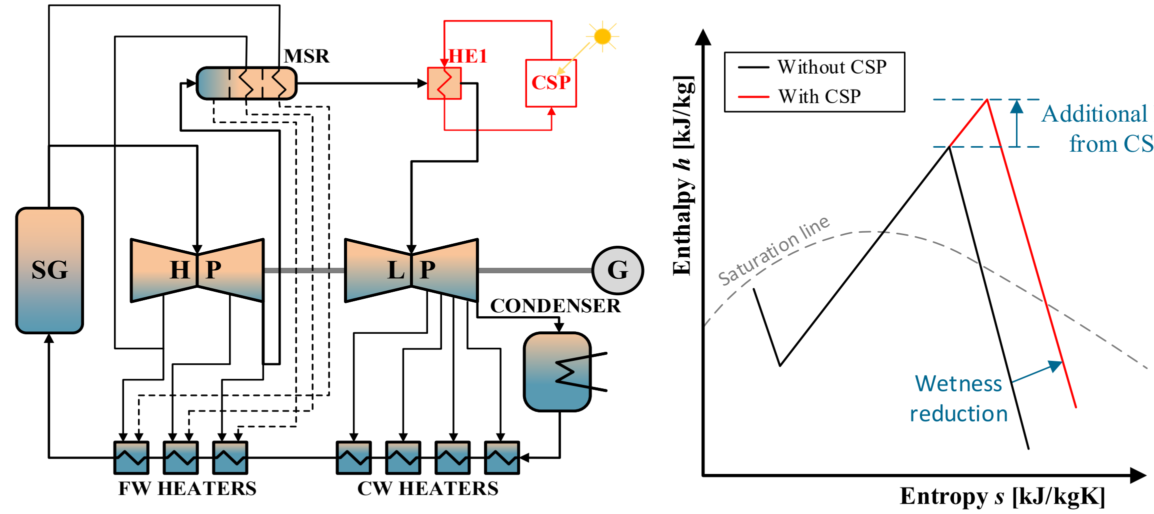

Figure 4: NPP–CSP hybrid system

When CSP is out of service, there are some pressure losses in heat exchanger (HE1). To avoid plant performance decrease, bypass pipe around the heat exchanger can be installed. Another solution could be the CSP plant with installed thermal storage. IAEA-TECDOC-1885 [3] describes more research activities on N-R HES with CSP, including CSP with heliostats and CSP with solar tower.

3.2 Micro grid with SMR and RES

H. Gaber [6] presents the Canadian research project of smart grid infrastructure associated with low-carbon energy supply. The smart grid energy system includes distributed generation of thermal and electric energy as well as gas network, energy storage systems and control management systems. In order to ensure sufficient reliability, this network consists of interconnected micro grids, which provides integration of thermal, gas, electricity, water and transportation networks to meet target loads with suitable conversions, co-generation, and storage strategies [6].

The integration of Small Modular Reactor (SMR) and Renewable Energy Sources (RES) within micro grid architecture can provide resilient energy solution to meet different load profiles with different capacities [7]. Micro grid with SMR can also provide balanced heat and power supply and can be designed, configured, and controlled to meet target demand. Figure 5 presents a concept of micro grid with SMR and RES. The system includes photovoltaic system, wind turbine, SMR reactor, fuel cells and energy storage system. All subsystems are controlled by SCADA system.

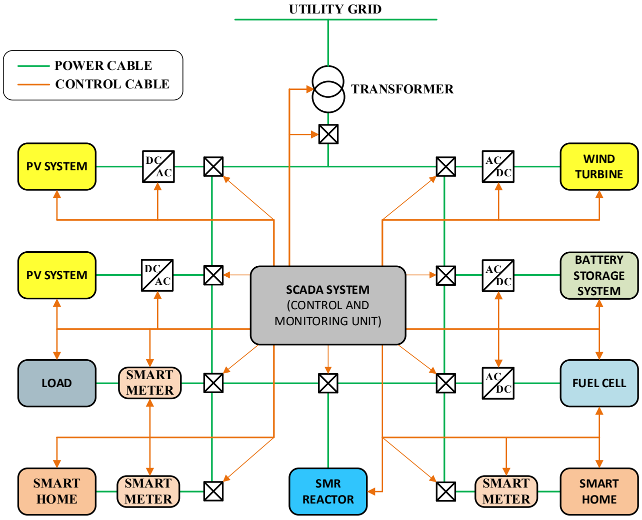

Figure 5: Micro Grid with SMR and RES

3.3 N-R HES with different industrial products

Idaho National Laboratory [4] analysed four different configurations of tightly coupled N-R HES. System configurations were made for different industrial products in four different states in USA. Each industrial process is supplied from two or more energy sources. Figure 6 presents the basic scheme of four different N-R HES configurations, i.e. liquid fuels, desalination, thermal energy in an industrial park and hydrogen production.

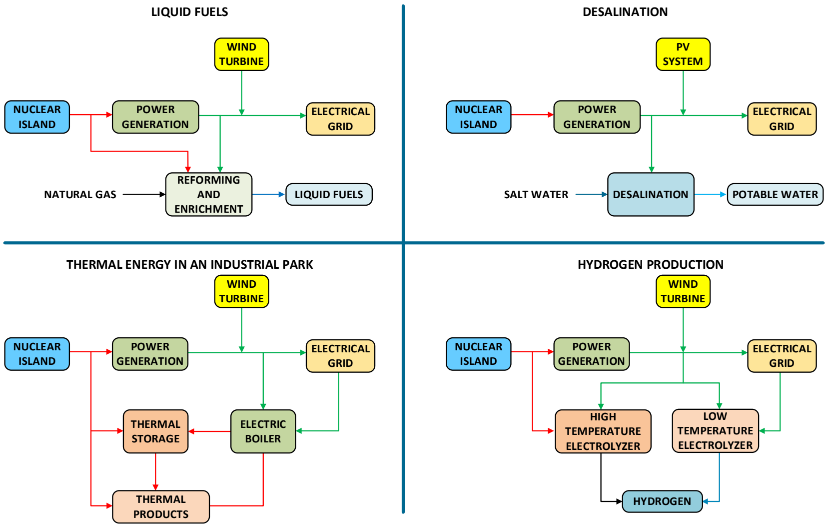

Figure 6: Scheme of four different configurations of N-R HES

The liquid fuels N–R HES includes a subsystem that converts natural gas to the liquid fuel. The desalination N–R HES case includes a reverse osmosis (RO) desalination unit which requires only electricity as the industrial process. The thermal energy N–R HES generates a thermal product (either steam or heat transfer fluid) that can be provided to one or more customers. To produce the thermal product at a constant rate, two variants are considered: thermal storage and an electric boiler. The hydrogen N–R HES case involves two variations for the industrial process subsystem. In the first, the industrial process is a high temperature electrolyser (HTE) that utilizes both heat and electricity to generate hydrogen. In the second, the industrial process is a low temperature electrolyser (LTE) that requires only electrical coupling but has a lower efficiency [3].

4 GEN GROUP HYBRID NUCLEAR-RENEWABLE SYSTEM

The GEN Group Control Centre ensures optimal production across the Group's power plants (presented in Figure 7) and optimizes operating costs for the entire Group. GEN Control Centre is the central hub for steering the operation of power generation facilities under normal as well as emergency operating conditions. GEN Control Centre's main tasks are to ensure maximum utilization of all available production units, coordinate and synchronize the operation of production units and to minimize the impacts of unforeseen events.

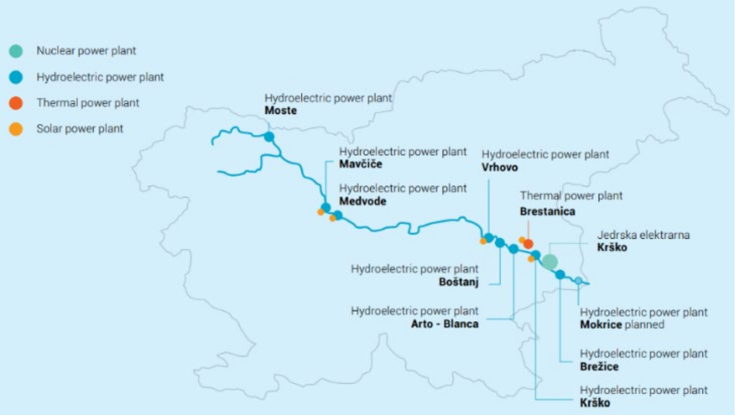

Figure 7: GEN group power generation units

GEN Control Centre has direct remote control of the hydroelectric power plants on the lower Sava river –with exception of HPP Brežice. GEN Control Centre also supervises the production process at Savske elektrarne Ljubljana hydroelectric power plants (Moste HPP, Mavčiče HPP, Medvode HPP, Vrhovo HPP), Brestanica Thermal Power Plant, and Krško Nuclear Power Plant. To interact and collaborate in the electricity market, the production units are brought together under the GEN balancing subgroup. Optimized operating plans are designed (day-ahead, intra-day) for this balancing subgroup. Production is constantly being monitored for deviations from the plans, and if any deviation is observed, appropriate measures are taken. This allows us to fully utilize all the synergies arising from the individual production units across the entire GEN Group. GEN Group also steer the production units operation during emergencies and unforeseen events. Also, GEN group play a key role in providing ancillary services as a tertiary backup source within the national electric power grid.

4.1 Optimization of the use of cooling towers in the Nuclear power plant Krško

Nuclear power plant Krško (NPP Krško) is pressurized water reactor (PWR) with thermal power of 2000 MWth and net electrical power of 700 Mwe. NPP Krško is cooled with once through cooling system with Sava River and additionally with cooling towers. The cooling towers (CT) are in operation when the flow of Sava River is too low because the river should not be heated over 3 °C due to the NPP Krško cooling. The NPP Krško has 3 sets of cooling towers (2 with 6 cells and one with 4 cells). The water is circulated with two cooling tower pumps, each can provide 7,5 m^3/s of flow.

The operation of cooling towers consumes up to 4 % of produced electrical energy. Also the water that is cooled with cooling towers is not as cold as the Sava River, which consequently means that the efficiency of the NPP Krško is lower. In order to avoid or at least postpone the running of cooling towers, GEN group Control centre tries to partially manage the river flow passing NPP Krško by means of regulation of the level in the upstream accumulation lakes . The hydro plants that can be used for control and optimization are located upstream from NPP Krško (HPP Vrhovo, HPP Boštanj, HPP Arto–Blanca and HPP Krško). Energy savings are not negligible. Generally, savings of around 2–3 MW over a few days span (up to a week) are recorded or in a shorter timescale up to 26 MW. The accumulation of hydro power plants on lower Sava River is small, with total of 5 million m^3, which represents an energy reserve that can be converted into electricity within a day when operating on full power (at average flow of the Sava River). Nevertheless, it is enough to additionally feed the river flow before the Krško NPP and postpone the start of cooling towers. A scheme of circulating water (CW) cooling system and its operation modes are presented in Figure 8.

When the water flow falls under 107 m^3/s and cooling towers have to be turned on, GEN Group Control Centre accumulates and discharges water from the lakes in such a way that only one cooling tower pump is actuated for as long as possible. If the water flow falls under 87 m^3/s, the second cooling tower pump turns on. If the water flow falls under 57 m^3/s all of the cooling discharge is returned to the intake. If the water flow is between 57 and 87 m^3/s (or between 87 and 107 m^3/s) accumulation lakes can be filled again with the surplus of flow as it is reported in GEN Group technical report [8].

An important factor for good optimization is monitoring of meteorology. If, for instance, rain is foreseen after a period of drought, accumulation lakes can be totally emptied. Another important factor is the price of electricity on the market. When the price of electricity is low (for instance on weekends), cooling towers on NPP Krško operate and accumulation lakes are being filled; when the prices are high, cooling towers are turned off and accumulation from lakes is used.

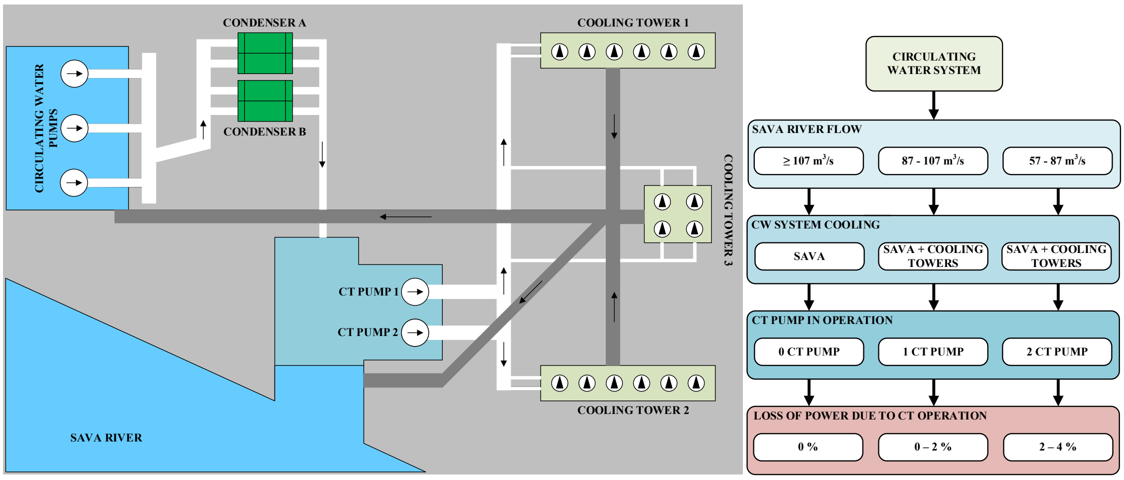

Figure 8: Scheme and operation mode of CW cooling system

5 CONCLUSION

In this paper hybrid nuclear renewable energy systems are investigated. The share of variable renewable energy sources in electrical grid system is increasing. To avoid uncertainty and instability, electrical grid requires the construction of balancing capacities to have the ability to ensure the security of the system. Nuclear energy presents a stable energy source in low-carbon energy generation and allows sustainable development of energy sector. In order to compensate the variability of renewable energy sources, hybrid nuclear renewable energy systems can be introduced.

The concept of hybrid nuclear renewable energy systems is in the R&D phase. There are some independent systems of nuclear power plants and renewable energy sources where the operator can adjust the operation of the individual subsystem with the aim of more efficient operation of whole system. There are several studies how to introduce hybrid nuclear renewable energy systems, such as nuclear power plants with concentrated solar power, wind turbines and organic Rankin cycle, as well as the systems with nuclear power plants, renewable energy sources and different industrial products.

GEN group through its Control Centre developed “quazi” hybrid system, which control the production of hydro power plants on Sava River with the aim to optimize the usage of cooling towers at NPP Krško. In order to avoid or at least postpone the running of cooling towers on NPP Krško, GEN group can partially manage the river flow passing NPP Krško by means of regulation of the level in the upstream accumulation lakes. Generally, savings of a few MW over a few days span (up to a week) are recorded. By such optimization of production, economical as well environmental benefits are noticed.

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