SOME CONSIDERATIONS ON THE LOAD-FOLLOWING CAPABILITIES OF THE NUCLEAR POWER BY DEVELOPING SMALL MODULAR REACTORS

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Abstract

The paper discusses the role of nuclear power in the future energy markets. The basic assumption is a high need for flexibility of the energy production due to the increasing of the share of intermittent energies, stimulated by the climate policies. An analysis of the performances for load following of the current nuclear systems is performed. The development of nuclear plant based on Small Modular Reactors is discussed together with their opportunities to increase the flexibility performances. The manoeuvrability, the variation of electricity production by cogeneration, and the heat storage are analyzed from the SMR perspective.

Keywords: *Energy market, Nuclear power, Flexibility, Manoeuvrability, SMR, Co-generation*

Introduction

Beyond the horizon of 2050, a neutral carbon energy mix in Romania is expected. Such a scenario implementation is supported by: (1) the current national and European Union (EU) energy policies; (2) the opportunities offered by the aging of the fleet based on the fossil-fuels; (3) tendencies of the prices for variable renewable (vRES) technologies (solar photovoltaic and wind); (4) the existing potential of the country for renewable sources; (5) possibilities to develop nuclear power (existing nuclear programme, infrastructure, experience, involvement in the development of innovative nuclear systems).

Looking to the potential role of the nuclear development in the perspective of the future energy market, some important challenges should be discussed: (1) flexibility; (2) integration with vRES; (3) economics; (4) adaptability to non-electric applications; (5) reduction of the water consumption; (6) resistance to extreme weather conditions.

The strategic documents underline the importance of the innovative nuclear systems to face these challenges. Some of the actions of the national Energy and Climate Plan [1] are oriented ″to capitalize the high level of specialization achieved in nuclear research through the development of technologies for advanced IV generation reactors, as well as the development of related infrastructure for lead-cooled fast reactors, through European and international partnerships″.

Looking to the nuclear power option, clearly it is offering some key advantages such as the security of supply, the stability in production, large amount of energy at affordable prices, zero carbon emissions, dispatchability. More flexibility is expected to be developed by the innovative systems such as the on-going Generation IV systems and SMRs.

The paper discusses the potential of Small Modular Reactors (SMR) in the context of future energy market of Romania. A small modular reactor is defined as having the power less than 300 MWe and respecting the feature of modularity (with consequence in factory fabrication and transportability).

The main assumptions are connected with the strategic development of the country, the influence of the regional context, the influence of the European policies, and the impact of the globalization.

Romanian energy market

The current energy market in Romania is moving firmly towards a fully free market. During the last decade, Romania maintains its position of net exporter in the region, although the difference between the exported and the imported quantities gradually decreases from year to year, and due to structural changes, it is possible a change into a net importer of energy.

The existing interconnection capacity is around 10% of the net production. Romania aims, by 2030, to reach an interconnection capacity of 15.4% [1].

The production of electricity has a daily and seasonal variability generated, mainly, by the evolution of the total consumption. The balance between electricity demand and production is established on a commercial basis, in real time, on the Balancing Market (BM). The availability of a sufficient amount of energy is based on the approach of contracting for periods of one year maximum. The BM is a mandatory market, which means that participants operating dispatchable units have an obligation to supply all available electricity on this market. Balancing energy corresponding to the secondary regulation, the fast tertiary regulation and the slow tertiary regulation is traded on BM.

Balancing energy is ensured by: (1) increasing power (increasing the production of a dispatchable unit or by reducing the consumption of a dispatchable consumer); (2) reducing power (reducing the production of a dispatchable unit or increasing the consumption of a dispatchable consumer).

In the current power systems, the flexibility is achieved via three mechanisms [2]: (1) fast ramping energy generation sources (physical or virtual); (2) flexible loads (for example, demand response or energy storage); (3) interconnectivity allowing energy imports and exports.

From a temporal point of view, the flexibility includes three categories of changes of power generated/consumed: (1) at the level of daily programming of sources with low speed of change (slow ramp), over a period of 12 to 24 hours, depending on the weather forecast and consumption planning for the day before; (2) at the level of a few minutes to hours, a situation which is called load tracking; (3) very rapid variations, in the range of seconds to a few minutes, situation which is subject to existing procedures and regulations.

In the last decade, in addition to consumption-induced variability, energy production from renewable resources has introduced a new complexity.

To illustrate the variability of production and consumption in Romania, three representative days were selected, as follows:
(1) 10 August 2020, as a summer day characterized by high temperature and insolation, evolution shown in Fig. 1;
(2) 16 August 2020, as a summer day characterized by lower insolation (predominantly cloudy sky), evolution presented in Fig. 2;
(3) 8 January 2019, as a winter day with low temperatures and high energy consumption, evolution shown in Fig. 3.

These different patterns of the consumption and the intermittent production, wind (W) and solar photovoltaic (PV) production, may be approached by the flexibility of hydro power plants (plants on the interior rivers, with the constraint of existing water reserve), interconnection exchanges, flexibility of coal-fired plants, and flexibility of gas-fired plants.

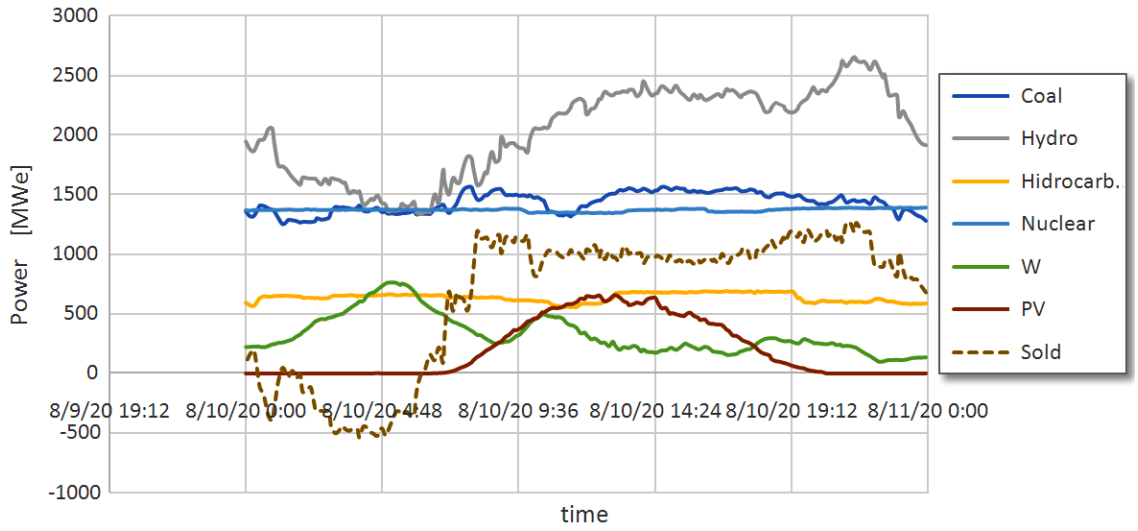


Fig.1 Variation of the production and the sold, on 10 August 2020 (summer, sunny day)

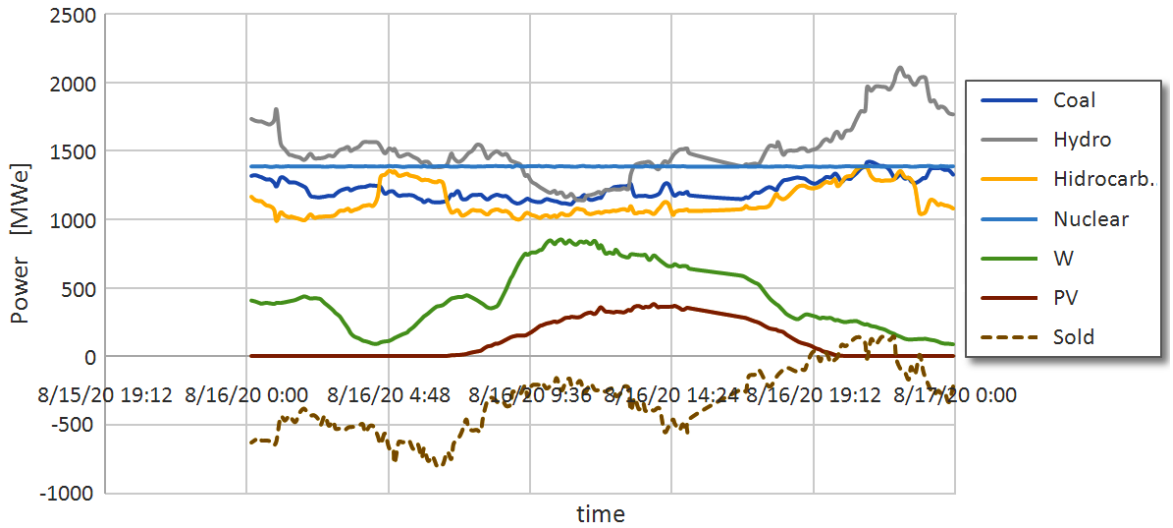


Fig.2 Variation of the production and the sold, on 16 August 2020 (summer, cloudy day)

For the first example (Fig. 1), it can be seen that, after 8 o'clock in the morning, there was a significant increase in consumption and a drastic decrease in wind energy production. Balancing through the variation of hydro production was not enough. For market reasons (availability of interconnection, prices, emissions), the import of energy was preferred instead of the solution to increase production based on fossil fuels.

Unlike the day with great sunshine (Fig.1), in Fig. 2 the profile of production for a summer cloudy day shows a negative sold (the electricity production was higher than consumption) for most of the day, except for a short period after 19 o'clock, therefore the excess was exported. An important effect was determined by the placement of the maximum wind production during the day, i.e. in the usual area of increasing consumption.

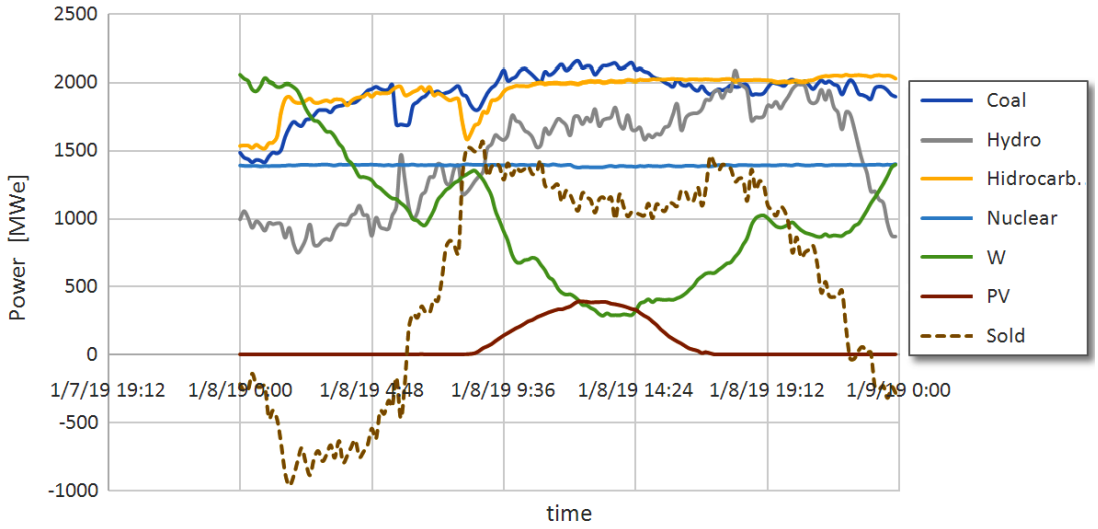


Fig.3 Variation of the production and the sold, on 8 January 2019 (winter, cold day)

For the difficult winter day (profile presented in Fig. 3), a significant increase in total electricity consumption occurred, compared to the summer days presented above. Also, the wind electricity production showed a minimum during the period of high consumption. At the same time, hydro availability was low. Production based on fossil fuels was increased, but the reserves were insufficient, therefore the choice was a significant import of electricity, even if the conditions on the market were not the most favourable.

From the presented production, profiles and typical load of the national grid, it may be concluded that the increasing of the share of intermittent energies may drastically impact the load-following approach. In the absence of the energy storage capacities, difficulties will dramatically increase.

In terms of the variability prediction, the PV production is quite well predictable according with the forecasting modern methods. In contrast, the W production is very low predictable. Therefore, W capacity increasing will impact more on the needs of flexibility.

The role of the nuclear power plant in the energy market

Under the past and current conditions of Romanian market, the nuclear plant operates at rated power (100%) without participating in balancing. The nuclear units are operated in load base mode and high-capacity factors were obtained (globally, greater than 90%) based on CANDU daily refuelling feature. The reasons are both economic in nature, but also in terms of technical requirements (low reserve reactivity of CANDU type reactor correlated with the Xe effect and by the material behaviour in transients).

In the last decade, the accelerated development of large wind farms (e.g. Fantanele plant, 1400 MWe capacity) has introduced a stringent need for more flexibility. Until now, the balancing was achieved by hydro and fossil-fuel plants. In the perspective of doubling the nuclear power by the continuation of the works at Cenavoda Units 3 and 4, the envisaged solution to the low flexibility of the NPP is to compensate by storage. An investment in hydro-pumping plant was proposed and approved by the Government (2014), but the project was not yet implemented.

Generally, the nuclear plants have a capacity for load-following. It is limited and it will be explained in this section. In the large reactors (LR), the variation of the power (the ramping) is based on control rod movement (or dedicated grey rods) or on the modification of the Boron concentrations in the core. A valuable experience for the manoeuvrability of the LRs is available in the nuclear sector of France. Considering the economics, the ramping is generally uncompensated [2], the reactor generating less energy, but with the same operating costs.

The variation of LR power is conditioned by three limiting factors: (1) reactivity effects, including reactivity reserve, (2) Xe^{135} poisoning and induced local oscillations, (3) thermal cycling of materials in the active area.

There are applicable European Utilities requirements [3], defined for LWR systems (see Table 1).

Table 1. Requirements for the nuclear load-following in the EU

	Requirement	Values
1	Range of continuous power level to be reached	50% to 100% of nominal power
2	Low power level (to be use in case of urgent interventions)	20% of nominal power
3	Rate of change	3% / min of rated power
4	Maximum no of variations	2 per day, 5 per week, 200 per year
5	Special raps (for major variations, emergencies)	up to 20% / minute

Experience of France shows the following peculiarities: (1) daily variations in nuclear power generated between 5% and 10%; (2) for certain periods, the variation may exceed 20%; (3) usual power levels used: 50%, 100%; (4) usual ramps 1%-5% /min.; (6) some special units in operation (6 hours at low power). France's experience is extremely suggestive for the ability of a system with high nuclear penetration to respond to consumption variability.

Since 2010, France has annually added about 1.8 GW of vRES capacity, a challenge being to ensure the flexibility by nuclear energy production [4]. Studies carried out by Éléctricité de France (EdF) predicted an evolution of the flexibility requirement expressed by the need for a 20 GW reduction in the power provided by nuclear power plants [5]. In March 2019, there was practically a decrease of 19.5 GW (from a nuclear maximum power of 52.3 GW to a minimum of 32.8 GW) [5], without changes to existing capacities. During the pandemic, the decrease was even more drastic reaching the minimum of 19.9 GW on 5 July 2020 [5], manoeuvres successfully performed based on existing capabilities.

The manoeuvrability of the new power plants has been slightly improved. For example, in the case of the EPR reactor, the usual power variation range for LF is between 25% and 100% of the rated power [6], but the power variation speed remains limited to 5% / min.

In the case of PWR units, the manoeuvrability is achieved through the control rods, while for the BWR the change of the circulation flow in the primary is mainly used, followed by the manoeuvring of the control rods. Both methods lead to a decrease in reactivity and, correspondingly, to a smaller number of fissions, thus to a lower thermal power.

Unlike gas-fired power plants, in the case of nuclear units, a reduction in electricity production does not result in a reduction in costs because: (1) capital costs are not affected; (2) O&M costs are fixed costs and independent of the power rate; (3) nuclear fuel represents only about 10% -15% of production costs and there is a non-linear relationship between power produced and fuel consumption. Thus, the economic consequences of load following are to reduce revenues without a reduction in operating costs, which has an effect of increasing capital costs on unit power. Therefore, in many energy markets, nuclear operators are not economically motivated to participate in the balancing process. France is one of the exceptions, as the nuclear fleet is operated by a centralized authority.

Another mechanism to reduce the production of electricity from a NPP is to evacuate the steam before it reaches the turbine, in order to quickly reduce power generation. Although it is possible and, occasionally, used in emergency scenarios, this method can be unprofitable and can lead to a decrease in the service life of the turbine system, therefore it is not widely practiced.

Integrated power systems try to reduce this disadvantage by redirecting excess steam, heat and/or electricity to coupled applications. When the electricity demand of the network is reduced, nuclear power plants can redirect energy from the turbine assembly to coupled processes (e.g. desalination, hydrogen production, process heat), thus the use of the flexibility given by cogeneration.

Some of these processes may also require an electrical input, which could be provided directly by the nuclear power plant. Preliminary analyzes indicate that this technology is economically viable in a number of scenarios, and offers an alternative to heat dissipation achieved by limiting electricity generation [7]. Similar to the case of reducing the steam flow in the turbine (by bypass), when defining the maximum flow variations, the impact on the turbine system must be taken into account, together with the restriction of not making additional changes in the secondary. Research is currently underway to identify synergistic approaches to coupling nuclear power generation with thermal applications [8].

Demand flexibility is a rather managerial alternative, at the level of the consumer system, being achieved through financial incentives, for example through attractive prices. Systems in which the legislative framework allows for significant fluctuations in seasonal and daytime electricity prices create both challenges and opportunities.

Finally, flexibility can be solved by storing energy either in the form of electricity (for example in batteries) or in the form of heat.

Flexibility of SMR systems

In this section, the capability of the nuclear power for flexibility according with the grid's demand is discussed. In Fig. 4 a schematic view of the methods to obtain the flexibility is presented.

A NPP with several SMR modules, instead of a single LR, has the possibility to operate at maximum capacity of all modules and the transfer of the entire thermal power, of some of them, for the generation of adequate by-products. Therefore, the load-following strategy is realized at the site level, by the transfer of energy in the form of electricity or heat, in various proportions. The overall efficiency of the SMR plant will be maximized by design for the dominant pattern (100% electricity, cogeneration with a certain fraction of heat or 100% thermal energy).

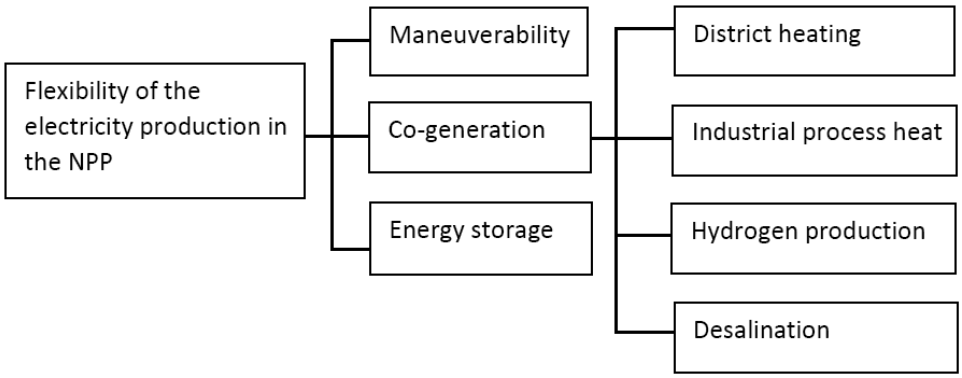


Fig.4. Flexibility of nuclear energy production

Flexibility by manoeuvrability

From the point of view of the manoeuvrability, the SMR systems do not improve essentially the flexibility characteristics. It remains limited due to the material stress and poison induced oscillations.

However, some important features in the support of the load-following are created by the development of a plant in the modularity concept and by the lower power per module: (1) the number of the modules offers an increase possibility of the variation of the total power of the plant by operating some modules at full power, some of them at reduced power, the others being in shut down; (2) the electrical power produced by a module may be more easily controlled through the variation of the steam reaching the turbines; (3) SMR systems have a better flexibility than the LRs one by using storage, and by the co-generation approaches.

In case of the NuScale SMRs-based plant, the load-following strategy is developed at a level allowing the operation in tandem with the wind generation [9]. For long periods when the electricity demand is low, such as weeks, the solution is to take one or more modules offline. For intermediate periods (days), the manoeuvring of the power (using of the control rods) for one or more modules is planned. For short transients in the demand (generally very unpredictable), the solution is the steam bypassing the turbine and discharging directly into the condenser. For some very short transients, the steam discharging into the environment by using the safety valve is also possible.

The impacts of the last two solutions on the environment are considerably lower than in the case of LR, due to the size of the module, smaller turbine, and also due to some simplifications at the level of the systems. On the other hand, some improvements to reduce the impact of the power cycling are reported, by using appropriate materials for the components and equipment [9]. Also, the system is designed to allow a decrease of the power down to a level of 40% of the nominal power, by using only the control rod movement without Boron adjustments [9].

Flexibility by co-generation

The co-generation is the use of the energy as electricity and/or heat, concomitantly, in diverse proportions. The use of heat in a variable amount introduces the idea of flexibility by cogeneration (LFC) [10]. In such a manner it is possible to meet the electricity demand concomitant with a drastic reduction of economic penalties due to a lower electricity production.

This is done by operating the nuclear unit at its rated power, all the time, without intervention in the active area or the primary circuit. For example, during the day when there is a high consumption (and, correspondingly, a high price of electricity), the nuclear energy is transformed into electricity injected into the network, while during the hours of low consumption (a low price, correspondingly) the excess power can be directed to an external system (e.g. a desalination plant, an electrolysis plant) that produces valuable by-products (water and hydrogen, respectively).

The coupling is efficient for those systems that require large amounts of energy (heat or electricity) and whose production cost is dominated by the cost of energy. The cogeneration based on heat supply is preferable because the heat-to-electricity conversion introduces inherent losses, SMR systems being ideal for this type of application [11].

LFC can be performed in a pre-programmed approach or dynamically. In the case of pre-programmed LFC, based on historical data and predictions at the level of a national dispatcher, the utilities know the amount of electricity they have to produce every hour.

In dynamic LFC mode, a regulation of the electric power injected in the network is needed in accordance with the variations induced by renewable energy sources, as well as the variations of consumption. Clearly, the dynamic mode is much more difficult than the pre-programmed one.

The SMR systems flexibility is better than the LR one because many of the industrial and district heating applications allow the use of a limited amount of thermal energy. The existence of a number of modules offers several degrees of freedom in terms of operation planning, task tracking intervention, and use of heat for cogeneration. Additionally, due to the improved safety expressed in a significant reduction in the emergency preparedness zone, a SMR may be sited closely to urban agglomeration, therefore close to the consumers of heat and steam.

One of the approaches in support of the flexibility by cogeneration is using of the excess energy to desalinate water. In [11] it is demonstrated that a desalination plant is flexible enough to be coupled with an SMR system operating in load-following mode. The study uses the NuScale system (45 MWe) based on the reverse osmosis method. The coupling of NuScale SMR with different desalination technologies is analyzed in [12], the analysis showing how easy and effective the coupling is.

The coupling of six SMR systems (SMART, Korea) with desalination plants is discussed in [13], analysis showing a rate of return of 11% and a repayment period of about 14.7 years. Moreover, the study advances a combination of an offshore wind farm and an SMR that functions as a virtual power plant. A key result is that the combination of a wind farm and SMR in demand tracking mode could improve synchronization with demand by up to 60% - 70% compared to the wind-only system.

Another example is the use of electricity, heat, or electricity & heat for hydrogen production. The flexibility of the production transferred to the electricity network by production of hydrogen is analyzed in [14]. Both technical and economic feasibility are evaluated for three possible technologies: alkaline electrolysis (electrolysis at normal temperatures, NTE), high temperature electrolysis (HTE) and thermochemical electrolysis with sulphur iodine (ISE).

Conceptually, the hydrogen produced by nuclear units can be used to store energy for subsequent electricity production or as a raw material to produce a variety of products, from fertilizers and steel to new synthetic fuels. In addition, by operating alongside chemical plants and renewable energy sources, current and future nuclear power systems can be used to generate a range of alternative revenue streams and help to reduce the emissions of carbon dioxide, sulphur dioxide, nitrogen oxide, mercury and smog particles throughout the energy, transport and industrial sectors [2].

It should be noted that water electrolysis is not competitive with natural gas production. However, if we consider the periods of low electricity prices (night, as well as in the peak production periods) even electrolysis at normal temperatures could become competitive. An important window of opportunity is opened by the new context of systems with high penetration of vRES (especially dominated by wind and photovoltaic) where fluctuations have introduced significant impact in electricity prices on the intraday market [15] reaching, in some cases, even negative prices [16].

In the case of coupling with a High Temperature Reactor (HTR), the thermochemical electrolysis with sulphur iodine is one of the most attractive options. Hydrogen is produced by chemical reactions based on sulphuric acid heated to about 9000 °C [17], with an overall yield of about 45%. Due to the reaction materials corrosivity, the selection of structural materials is an important and still open issue. The technical aspects of coupling a sulpho-chem iodine thermochemical electrolysis plant with a HTR (GTHTR 300 °C) are presented in [18], resulting in a thermal efficiency of 45% - 50%, and a production of up to 1.4 million Nm^3/day. In this case, heat is transferred via an intermediate loop to the hydrogen production system. To reduce losses, the system is located near the reactor building.

The use of the heat for district heating and/or industrial processes may be a solution for the load following. The SMR systems flexibility is better than the LR one because many of the industrial and district heating applications allow the use of a limited amount of thermal energy.

A study of the use of thermal energy resulting from NuScale SMR for oil recovery and refining processes is presented in [19]. The results show that, based on operating costs, the use of NuScale is competitive compared to the use of natural gas (with a low price of 5 USD/Mbtu) even in the conditions where there are no taxes on CO_2 emissions. The capital investment for NuScale SMR can be recovered in 25 years, if the cost of natural gas exceeds 9.5 USD/MBtu without emission taxes, or at 7.5 USD/MBtu at a tax level of 40 USD/MT CO_2. To conclude, the option is technically viable, but the economic feasibility is not clear and it is largely determined by the cost of emissions.

The use of thermal energy from a NuScale SMR system for shale gas extraction, through hydraulic fracturing technology, is proposed in [20]. For this, the nuclear system would provide heat for the preheating of the oil shale to 210 °C - 250 °C (using closed steam heating pipes), and then an additional heating would be done, to 370 °C, with electric heaters. Based on the characteristics of the typical rock of shale gas extraction cases, it is expected that heating is sufficient only during periods when electricity consumption is low. The study stated that a reactor would be enough to supply steam for a lifespan of 60 years within a radius of 2 km. However, such an application would require some relocation, which raises serious questions about licensing.

The use nuclear heat for a bio-refinery is proposed in [9]. It uses algae as a raw material, and their cultivation is done in a fermenter as an alternative to technologies using large cultivation areas (thousands of hectares). Due to biomass perishability, continuous heating is required. Consequently, the bio-refinery is not suitable for LFC, but can be retained as a cogeneration possibility.

Flexibility by energy storage

The only type of large-scale available storage is that of hydro-pumped power plants. This option is valid only in relief and climate favourable conditions. It is used with great success in Norway, due to the hydropower high share (over 95% of total electricity generated [21]). In such conditions, the strategy of exporting energy is limited to the periods when the price market is very profitable, otherwise the storage is used.

On the other hand, the most important hopes for the energy storage are linked to the development of systems with Lithium-ion batteries. These are used in a limited, subsidized and small-scale approach (Australia and USA, 130 MWh - 900 MWh). This technology is considered to be: (i) costly now and, also, in the future, (ii) with a major impact on the availability of mineral resources.

Batteries are becoming more and more commercially available, the cost price showing a clear downward trend in the last decade. Flywheels, supercapacitors and superconducting magnets, are sometimes used instead of batteries due to their extremely fast response. However, storage systems with very fast access to the energy are limited in terms of their total capacity. These systems can provide services such as frequency regulation and voltage stabilization, rather than storing significant amounts of energy.

Thermal energy storage can be achieved through very different technologies. Depending on the technology, the storage and use of excess heat can be for hours, days or months. Storage media include water or ice reservoirs, earth masses or bedrock accessed through heat exchangers, deep aquifers contained between impermeable layers through boreholes, as well as eutectic alloys and phase change materials. Thermal energy storage, both seasonal and short-term, is considered an important means of balancing the variable production of renewable energy.

A nuclear thermal energy storage and recovery system designed for the Korean APR1400 system is presented and analyzed in [22]. The system is tertiary and it is designed to reliably and efficiently storage of the thermal energy aimed for a flexible energy generation. The analysis is oriented to an optimal configuration in terms of efficiency, minimal impact on existing facilities, system control. Under these conditions, an efficiency of over 80% was estimated. With regard to normal operating conditions, transients and accidents, no significant impacts on the system are expected.

The thermal energy storage system for the Korean power plant APR1400 uses synthetic oil as a heat transport fluid (tertiary system) due to the possibilities of working at high temperature [23]. A system of broken rock layers placed in carbon steel vessels is used. During the design of the system, the storage objective of 20% of the thermal power of the reactor was set as a target. Correspondingly, an energy recovery of about 11% of the thermal power of the nuclear unit will result. The paper emphasizes that a simple economical scaling of the system can be done, if a higher storage capacity is desired, due to the marginal cost of carbon steel vessels filled with rock. On the other hand, any nuclear installation with access to water could use thermal energy storage in a system placed on a large, turnkey barge, with a simultaneous reduction of installation costs and risks.

Using a cheap and highly available material, such as crushed stone, contributes to lower investment costs. For large storage capacities, in the case of the rock bed, a cost of 10 USD/kWth is expected [24]. By comparison, the cost for a battery-based system (Hornsdale power reserve, Australia) is estimated at 66 USD/kWth. Also, the estimated life of the storage system with broken stone bed is over 60 years, while for batteries it is estimated at 15-20 years.

The literature offers different thermal energy storage media (pressurized water, steam, cryogenic air systems, concrete blocks, crushed stone layers, geological layers, molten salts, silicon or alumina bricks, metal hydrides - for reactors with high temperatures, etc.).

In order to meet the energy systems requirements, thermal storage media must meet the following criteria [23]:
(1) high storage density;
(2) chemical and mechanical stability (ability to store and release energy for a large number of cycles without degradation of the material);
(3) efficient heat transfer between the transfer fluid and the storage medium (related to thermal conductivity, thermal capacity and sizing);
(4) the process must be reversible (storage/release with return to initial state);
(5) profitability.

The option of storing thermal energy, from existing PWR nuclear units, in steam storage systems is presented in [25]. The advantage of this approach resides in the possibilities of adapting the installations. The heat from the reactor is stored directly in the form of steam. Another turbine is provided separately for conversion to electricity. Thus, the whole system is similar to a cogeneration plant, with heat storage and equipped with a second generator.

Being in development, SMR systems can be designed as systems with built-in thermal energy storage, in order to obtain a high flexibility, without using excessively the heat evacuation in the external environment. The great advantage is a more efficient and simple handling of the amount of excess energy to be stored.

Conclusions

In the context of future energy market, due to the climate policies implementation, technological improvements, and prices evolution a significant increase of the intermittent energies is expected. Consequently, storage capacities and load following capabilities are compulsory needed to obtain the balance between consumption and production.

The current nuclear plants have limited capabilities for load following due to economic penalties and technical constrains. However, some countries experienced the nuclear load following with a considerable performance.

The innovative systems, including SMRs, are developing an improved flexibility based on a better manoeuvrability, by implementing cogeneration applications, and also by the use of the thermal storage of the energy. Such systems may be used in complementarity with wind and photovoltaic farms to reach the needs of the variable consumption in the grid.

Even the load-following capabilities of SMR systems are considerably better than of those of the large reactors, the functionality of a grid with variable renewable and nuclear impose the need of peak units or large capacities of energy storage. It is expected that a combination of heat storage and hydrogen production can meet large-scale storage requirements, from seasonal to hourly.

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