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HYBRIDIZATION OF A SMALL MODULAR REACTOR WITH A SOLAR POWER PLANT USING A SUPERCRITICAL CARBON DIOXIDE BRAYTON CYCLE

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ABSTRACT

Co-existence of nuclear-renewable energies in a single hybrid power plant is considered as a possibly efficient and flexible option to significantly reduce environmental impacts due to combination of two climate-friendly decarbonized energy sources. The concept refers to an innovative system, which locally balances the fluctuating renewable energy source such as solar, by the steady base load nuclear output, thereby smoothening the energy production. This hybrid system also features a thermal energy storage (TES) and the whole combination allows accommodating the daily and seasonally varying electrical grid demand (which specification is likely to sharpen with the increased penetration of renewables energies). In the literature, many works address hybridization of solar and fossil thermal sources or solar and other renewable sources, such as geothermal or biomass. Several concepts of hybridization of nuclear and fossil thermal sources have been also investigated. On the other hand, few works have been reported on hybridization of a solar power plant with a small modular nuclear reactor (SMR). In such a system, the proven pressurized water reactor technology is usually considered and a steam Rankine cycle is used as the power conversion system, the operating pressure being lowered compared to conventional PWRs.

Inline, the current preliminary work investigates integration of a SMR with a concentrated solar power plant (CSP) equipped with a TES. However, a supercritical CO2 Brayton cycle is originally applied for power generation. The nuclear energy loop transfers heat to the thermodynamic cycle and the solar heat allows upgrading the turbine inlet temperature. Implementation of the TES enables continuous scO2 heating and thereby non-stop plant operation. The proposed high temperature hybrid configuration is aimed at benefiting from the technological advances as regards key components such as heat exchangers and gas turbines so that high performances are considered along the plant thermal efficiency optimization process. An alternative option based on hybridization of a SMR, a low temperature solar power plant, an absorption chiller and a cold energy storage, is also investigated.

1. INTRODUCTION

Solar energy has become a trending topic when talking about renewables. However large-scale integration of solar energy into the electric grid presents some major technical challenges. As an intermittent energy source, solar energy requires either energy storage or fuel-based backup power so that it can provide dispatchable and reliable power. Concentrated solar power (CSP) offers specific benefits as a renewable energy source due to the ability to readily incorporate energy storage. CSP concentrates sunlight by a number of mirrors and uses the heat collected from sun’s radiation to heat up a working fluid (oil, molten salt …). The heated fluid can then be used with conventional power generation equipment (i.e., turbines, generators, etc.) to produce electricity. Current CSP power plants consist in three parts including the solar field, the thermal energy storage (TES) subsystem and the power block. TES is considered as the key part of the CSP because such subsystem provides not only dispatchable electricity but also stability to the electricity network in case of high fraction of renewable production or intermittency due to weather conditions. In other words, TES allows CSP achieving higher capacity factor. Besides, CSP is also advantageous because of its amenability to hybridization with other energy sources in order to reduce capital costs by sharing equipment as well as to enhance the energy dispatchability and reliability. Moreover, co-generation of solar energy and another energy source in a hybrid power plant might bring opportunity for more flexible operation by alternating between energy sources, which can lead to improved overall efficiency through synergy of the different energy sources.

Hybridization of solar energy with other energy source has been studied intensively in the literature. A review on the studies and published papers concerning conventional and non-conventional hybrid solar–thermal power plants since 1970s was carried out by (Ref. 1). Moreover, the technical and economic advantages as well as the issues of the technology was also described and analyzed by (Ref. 2). The work of Jamel et al. pointed out that hybridization of existing fossil fuel power

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plants (i.e. steam-cycle power plants, combined-cycle power plants and gas-turbine power plants) with solar energy is one potential option to overcome the rapid depletion of fossil fuel reserves and their environmental effects while generating stable and reliable electricity. More interestingly, co-generation of CSP with other fossil and renewable power generation also allows reducing solar plant capital costs due to joint use of common equipment by hybridization (Ref. 1, 3, 4). Up to now, several integrated CSP-coal or CSP-natural gas hybrid power plants are under construction or already in operation.

In addition to fossil fuel like gas and coal, hybridization of CSP with other energy source like biofuels, geothermal, photovoltaics and wind, has been also of interest. Recently, Powel and Rashid published a review article in which they summarized the findings from the previous works conducted in the last ten years in which various energy sources were hybridized with CSP (Ref. 5). The article also provides an overview of the possible hybrid configurations, with advantages and disadvantages discussed.

Some publications could be found in the literature concerning a hybrid concept of a nuclear power plant with a thermal energy storage. The aims were to increase the nuclear power plant flexibility by employing the thermal storage system in an energy grid containing high contribution of renewable energy sources such as solar and wind (Ref. 6, 7, 8, 9). It is known that the existing nuclear power plants generate constant base load power and are most economic when operated at constant power levels. In other words, it is needed to run the nuclear power plants as many hours annually as possible to maintain a high capacity factor.

While many combinations of solar with another source of energy have been proposed and put into practice, integration of solar energy with nuclear energy has not been yet investigated widely. Ruth et al. introduced a potential concept of nuclear-renewable hybrid energy systems (Ref. 10). According to the authors, integrating nuclear and renewable energies in a single hybrid energy system allows balancing the fluctuating solar/wind-generated electricity by a portion of nuclear-generated electricity to response the power demand. If the demand is low, the excess nuclear heat is stored in the thermal energy storage for later use. Furthermore, such a hybrid system could not only provide secure and reliable power corresponding to the greatly increasing variability of the electric demand but also provide affordable and low carbon energy.

A conceptual design of solar-nuclear hybrid power plant including a nuclear energy loop, a solar energy loop and electrical generation loop was demonstrated by Sakadjlan et al. in their pattern published in 2015 (Ref. 11). Recently in 2016 and 2017, Popov et Borissova proposed innovative configurations of hybrid nuclear-solar power plant systems (Ref. 12, 13, 14). They are described and commented in next section. Due to the shortage of strong solar-nuclear hybrid power plant concept in the literature, the above introduced work will be taken as the reference case.

Moreover, the current work also suggests an integration of a small modular reactor and a concentrated solar power plant equipped with a thermal energy storage in which supercritical CO_2 Brayton cycle is adopted for power generation. Evaluation of plant's performance between a coupled nuclear-solar power plant and an ordinary nuclear power plant is reported and advantages/disadvantages of utilization of SCO_2 Brayton cycle instead of classical steam Rankine cycle in such innovative hybrid system is also discussed. An alternative option based on hybridization of a SMR, a low temperature solar power plant, an absorption chiller and a cold energy storage, is finally investigated.

2. NUCLEAR-SOLAR HYBRIDIZATION USING RANKINE CYCLE

The nuclear power generation at large scale has been commercialized since several decades. Up to now, of all the traditional energy sources, nuclear appears to be the only candidate which can offer abundant and cheap power without emission of greenhouse gas. Despite of the amazingly increasing development and penetration of renewable energies, typically solar and wind, nuclear still takes an important role in generating clean electricity in the power industry. However, since the initial investment to construct a large nuclear power plant is costly, the licensing procedure and erection time are long, most developing countries which do not have experience of building nuclear power plants or countries with small grid size cannot easily afford. Such conditions initialized new projects on small and medium nuclear reactors. Since the years of 2000s, there has been a growing interest for the development and deployment of small and medium size nuclear power plants to meet the expanding need for clean and sustainable power in a broader range of energy markets. A small modular reactor (SMR) is characterized by its small power capacity (less than 300 MWe) and involves small and modularized components. SMR is substantially factory manufactured and installed in the the plant rather than stick-built on the site. Such small size also allows a significant reduction of construction period. Because of its small and modular characteristics, the SMRs are expected to be more flexible and adaptable for integration with other energy sources (like solar or wind) in a hybrid power plant.

Nowadays, more and more attention is given to SMR research and development in all nuclear nations around the world. Various technologies have been selected for the designs of SMR. The majority of operating, under-construction or design conceptual SMRs are based on classical PWR nuclear power plant technologies using water coolant; whereas, some other SMRs take the advanced technologies of 4th generation of fast neutron reactors employing metal, molten salt or gas as coolant. Moreover, there exist also SMRs designed based on nuclear propulsion technology such as submarine, aircraft carrier, icebreaker and barge (Ref. 15). In the studies taken as references (Ref. 12, 13, 14), SMR design values were derived from Nuscale project and are summarized in Table 1.

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Table 1: Design parameters of SMR plant (from Ref 13, 16)

Reactor core thermal power	159933 kWt
Turbine inlet temperature	255 °C
Turbine inlet pressure	31 bar
Steam flow	71.3 kg/s
Feedwater temperature	149 °C
Condenser pressure	0.085 bar
Net electric power	~ 43911 kWe
Thermal efficiency	27.45%

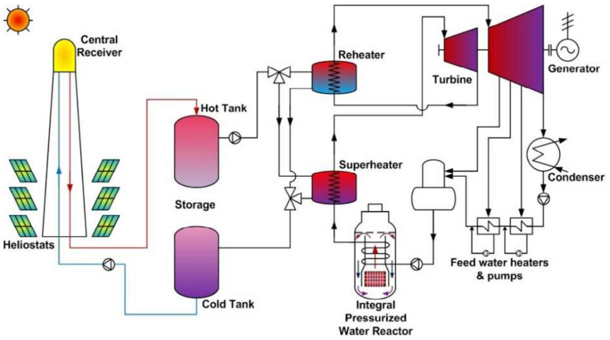

Figure 1: configuration of SMR - Solar tower hybrid power plant (extract from Ref. 13)

Three different solar power plant technologies including the solar photovoltaics (PV), solar tower and parabolic troughs have been selected for coupling with a small modular nuclear reactor (SMR) and a thermal energy storage (TES). For clarity reasons only solar tower case is described in detail hereafter. Similarly to the solar-nuclear hybridization presented by (Ref. 11), the wide spread Pressurized Water Reactor type has also been taken as the reference nuclear power plant and Rankine cycle is also coupled in the power block. Heat from solar field is also used for superheating and reheating the steam at the inlet of turbine stages which results in significant improvement of plant thermal efficiency. The most promising configuration is shown in Figure 1. The introduced hybrid power plant consists of four main parts, which are solar field, thermal storage, SMR and power block. Two-tanks molten salt thermal energy storage is equipped to the solar field and SMR acts as a steam generator. The nuclear steam is superheated by the exchanged heat with the hot molten salt circulating in the solar field before it enters high pressure turbine. Reheat is also carried out prior to steam expansion in the low turbine stages.

Calculations with Thermoflex were carried out by Popov and Borisova to evaluate the performance of hybrid plant and to compare to that of the SMR plant alone. In our study, we use another simulation tool, named as Engineering Equation Solver (Ref. 17), to assess the hybrid plant performance. Calculation results provided by EES are given in Table 2 and they are in good agreement with Thermoflex results. As clearly seen, hybridization of SMR to solar power plant enhances significantly the plant efficiency in comparison to that of the nuclear power plant. Enhancement of 10 points has been obtained for the hybrid plant.

Table 2: Performance comparison of hybrid power plant to nuclear alone power plant

Plant parameters	**SMR alone**	**SMR + CSP + TES**
Turbine inlet temperature [°C]	255	555
Turbine inlet pressure [bar]	31	30.4
Net electric power [MWe]	44	92
Net electric efficiency [%]	27.45	37.47

3. NUCLEAR-SOLAR HYBRIDIZATION AT HIGH TEMPERATURE USING SCO2 CYCLE

The steam-Rankine cycle was the most suitable power conversion system for a conventional water cooled nuclear reactor for more than 60 years. It has demonstrated a good efficiency and system reliability when the reactor operating temperature is below 350°C. To improve the economy and safety of nuclear reactor systems, two distinct research trends in the nuclear technology are considered. One trend focuses on the small modular reactor (SMR) development as previously mentioned. The other trend concerns the design and development of advanced nuclear reactor concepts for next nuclear reactor generation (Gen IV nuclear reactor). Since the early 2000s, more and more attentions on Gen-IV reactor systems are recorded. The working temperature of the advanced nuclear reactor goes far beyond that of existing water cooled reactor. The aim of increasing the operating temperature over 500°C is to achieve higher efficiency than in the past. Various concepts of Gen-IV reactor systems have been proposed and studied using different coolants such as helium, sodium, lead, molten salt and gas. In such situation, the supercritical carbon dioxide (SCO2) Brayton cycle has been widely considered as a favorable candidate for being employed in the next generation nuclear reactor power conversion systems. Previous analyses of SCO2 Brayton power cycle have demonstrated that the cycle shows better efficiency and has many advantages compared to the traditional Rankine cycle (Ref. 18, 19, 20, 21, 22).

In our project, the possibility to employ SCO2 Brayton cycle for a nuclear-solar hybrid power plant will be investigated. Various Brayton cycle layouts will be applied for the power block of a nuclear-solar power plant (NSPP) coupling a small modular nuclear reactor (SMR) with a concentrated solar power plant (CSP). Similarly to the cited NSPP configuration proposed by Popov et Borisova, the CSP with thermal energy storage (TES) is located at the outlet of the SMR. The heat from CSP serves for heating up the SCO2 temperature before it enters the turbine. The percentage of solar heat contribution is increasing from 0 to 100% and the corresponding hybrid plant efficiency is calculated respectively using EES.

Following conditions and component parameters:

- The maximum pressure in the SCO2 loop is P_{max} = 20MPa (other values of P_{max} were considered but not presented in this paper)
- The minimum temperature is the temperature at the outlet of precooler T_{min} = 27°C (condensing mode)
- Turbine efficiency: $E_{turbine}$ = 93 %
- Compressor efficiency: $E_{compressor}$ = 89 %
- Effectiveness of recuperators: $E_{recuperator}$ = 95 %

These are taken from (Ref. 23) in which the author investigated different cycle layouts for coupling of SCO2 Brayton cycle with a SMR or a sodium-cooled fast reactor within a wide range of turbine inlet temperature, from 250°C to 850°C. Parametric calculations were carried out aiming at optimizing the working conditions at a given inlet turbine condition (temperature and pressure) including the outlet pressure of the turbine, the split ratio (for recompression layout), the outlet temperature of the condenser. In our study, we firstly applied the model from Ref. 23 and carried out the calculations of SCO2 Brayton cycle for a SMR with our tool EES. A good agreement has been obtained between the two calculation tools.

Then, the model is used for calculations with the currently considered NSPP to evaluate the performance of the hybrid plant with SCO2 cycle and compare it to the previously case when Rankine cycle is employed for NSPP as shown in (Ref. 13). The heat output from the SMR and the CSP are taken as those from the reference case (i.e. Q_{SMR} = 160 MWt and Q_{CSP} = 86 MWt). Additionally, following criteria from the NSPP given by (Ref. 13) are taken:

- The inlet and outlet temperatures of the SCO2 loop passing through the steam-SCO2 heat exchanger cannot greater than those of the steam cycle , i.e. $T_{OHX} \leq T_{out,SMR}$= 255°C, $T_{IHX} \leq T_{in,SMR}$ = 149°C
- Maximum temperature in the SCO2 loop cannot greater than the maximum temperature provided by the solar loop T_{max} <= 555°C

Recompression SCO2 Brayton cycle is examined, as illustrated in Figure 2, using a similar methodology. However the efficiency of hybrid power plant is much less than that of the nuclear power plant. In fact, in the reference hybridization of SMR-CSP-TES with a steam Rankine cycle presented by (Ref. 13), the maximum temperature in the steam can achieve 555°C which is 300°C greater than the temperature at the outlet of SMR (255°C) and is ~ 400°C greater than the inlet temperature of SMR (149°C). Such large temperature difference is essential to bring significant efficiency enhancement for the hybrid plant. Unfortunately, with a SCO2 recompression cycle, the temperature difference between the hot and the cold sides (hot side refers to the outlet of the heat exchanger and cold side refers to the inlet of the heat exchanger) is more limited. The following Table 3 provides the optimal temperature difference obtained by a recompression cycle at 20MPa when hot temperature is varied from 240 to 555°C. It is seen that the recompression SCO2 Brayton cycle is only efficient in a limited range of temperature.

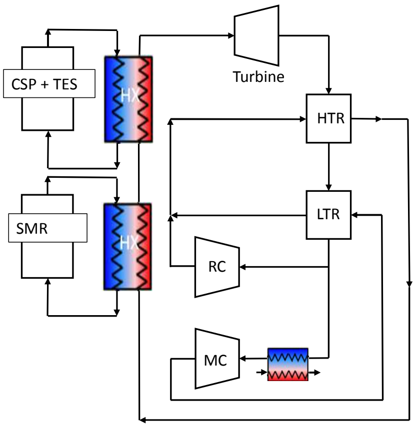

Figure 2: Recompression layout of SCO2 Brayton cycle for NSPP.

It can be noticed that temperatures appearing in the second line of Table 3, correspond actually to the coupling case of the SCO2 recompression cycle to the currently considered SMR. Considering additionally that the temperature getting out from the lower heat exchanger of Figure 2, i.e. 255°C, is also the temperature entering the upper heat exchanger (with solar cycle), according to the fourth line in Table 3, the corresponding outlet temperature of the upper heat exchanger should be 399°C in the optimal case. However, with the provided solar heat from CSP, the SCO2 temperature only increases up to 320°C max which is far away from the optimal value. Therefore, a low plant efficiency is observed for this hybrid using recompression SCO2 cycle.

Table 3: Optimal calculation for recompression SCO2 cycle at 20MPa with varying temperature range

P_{min} MPa	Split ratio	T_{OHX} °C	T_{IHX} °C	ΔT °C	Efficiency (%)
8.235	0.684	**240**	**139**	101	27.96
8.2338	0.684	**255**	**149**	106	29.46
7.779	0.624	**380**	**240**	120	39.4
7.779	0.625	**399**	**255**	144	40.56
7.791	0.624	**405**	**260**	155	40.92
7	0.589	**555**	**380**	175	49.08

Other layouts SCO2 Brayton cycle have been also considered but none of them provides interesting findings on the advantage of employing SCO2 Brayton cycle for improvement of NSPP plant's performance.

In the following paragraph, a cascaded configuration employing three recompression SCO2 Brayton cycle at different temperature ranges is introduced (Figure 3). As above explained, the direct employment of recompression SCO2 Brayton cycle could not help improving the hybrid plant due to the limitation of temperature difference between the inlet and outlet of heat exchanger. In the below configuration, SCO2 is heated up gradually in three steps. The temperature ranges in each stage are optimized to obtain maximum overall hybrid power plant.

The overall efficiency for the currently considered hybrid NSPP with the proposed cascaded configuration containing three recompression SCO2 Brayton cycles is 38.81%. About 11 points increase of plant efficiency is achieved in comparison to when the NPP is alone and simple layout SCO2 Brayton cycle is used. For the case when the recompression layout is utilized for an alone NPP, more than 9 points of plant efficiency enhancement is obtained due to hybridization with the CSP.

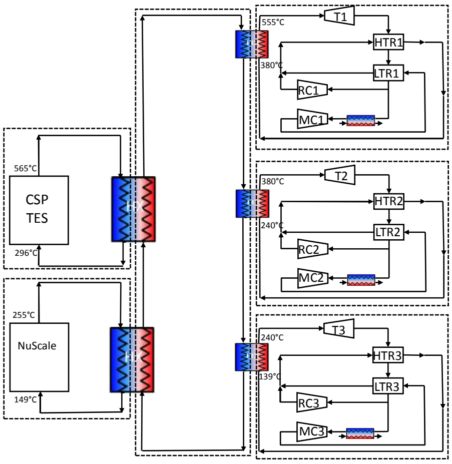

Figure 3: Cascaded layout of three recompression SCO2 Brayton cycle for NSPP.

It is seen that for a nuclear power plant, SCO2 Brayton cycle shows better plant efficiency than the Rankine cycle. About 2 points of increase in SMR plant efficiency could be obtained by replacing the Rankine cycle by recompression SCO2 Brayton cycle (29.46% vs 27.45%). Moreover, when being integrated with the solar tower power plant (NSPP case), the application of SCO2 recompression cycle with cascaded configuration shows competitive plant efficiency to Rankine cycle (38.81% for SCO2 cycle and 37.47% for Rankine cycle). This result is obtained by using certain hypothesis concerning the efficiencies of the cycle components (turbine, compressor, recuperators) as well as other assumptions for maximum pressure temperature and minimum temperature of the cycles. A sensibility study on those parameters would be of interest to investigate the effects of them on the plant efficiency. Additionally, it should be highlighted that beside the advantage in cycle efficiency, other factors should be considered including the size and cost of components (especially the turbomachinery).

Table 4: Efficiency of three cascaded recompression SCO2 Brayton cycles for NSPP

Loop	Imposed parameters	Optimised parameters	Loop efficiency
Upper	Pmax = 20MPa Tmin = 27°C T_{OHX}= 555°C	Pmin =7 MPa T_{IHX}=380°C Split ratio = 0.5891	49.08 %
Middle	Pmax = 20MPa Tmin = 27°C T_{OHX}= 380°C	Pmin=7.78MPa T_{IHX} = 240°C Split ratio= 0.6264	39.4%
Bottom	Pmax = 20MPa Tmin = 27°C T_{OHX}= 240°C	Pmin=7.78MPa T_{IHX} = 138.7°C Split ratio = 0.6838	27.96%

These aspects are not covered in the framework of our paper but have been shown in the literature are much more favorable for SCO2 Brayton cycles than for Rankine cycle. Therefore, it is convincing that the application of SCO2 Brayton cycle for the nuclear-solar hybrid power plant instead of using the classical Rankine cycle has high potential and further research should be considered in the future to make the concept feasible.

4. NUCLEAR-SOLAR HYBRIDIZATION AT LOW TEMPERATURE USING SCO2 CYCLE

As mentioned previously, two nuclear-solar hybrid power plant configurations are proposed in the current work. The above section presents the so-called high temperature hybrid plant configuration. As discussed, at operating temperature up to 600°C and utilization of sCO2 Brayton loop for the power conversion, the high temperature nuclear-solar hybridization provides interesting benefits, including an attractive thermal efficiency in comparison to the system employing Rankine steam cycle. Moreover, it has several other advantages over water cycles (i.e. more compact, lower water consumption …). However, the solar power plant as well as the thermal energy system operating at high temperature can be expensive (Ref. 13). Also, the use of such high temperature systems (i.e. molten salt) can have some constraints for our application (220°C freezing point; proximity of nuclear reactor). Therefore, we are investigating an alternative nuclear-solar hybrid power plant which does not employ high temperature solar power technology or high temperature heat storage. In this section, the second hybrid configuration will be introduced, called low temperature nuclear-solar hybridization, representing an electrical production system based on a nuclear-solar coupled heat source at lower range of operating temperature, i.e. less than 300°C. More precisely, the low temperature hybridization idea is based on the use of low temperature technologies of the solar thermal collectors (Ref. 24) and thermal energy storage (Ref. 25) allowing operation at a wide but lower range of temperature, in between 100°C to 300°C instead of 600°C. Moreover the constraint to keep a low temperature under 27°C for the heat sink can be a real challenge and this issue is coped with the low temperature concept.

The heart of the architecture lies in the position of the solar heat source in the hybrid system. In the high temperature case, the solar source locates downstream of the nuclear heat source, serving for superheating the SCO2 flow out going from the nuclear-SCO2 heat exchanger so that the SCO2 enters the turbine at higher temperature, resulting in significant enhancement of the thermal efficiency of the hybrid power plant. In the current low temperature hybridization, the heat from the solar field will be used to preheat the SCO2 in the power conversion cycle before it enters the nuclear-SCO2 heat exchanger then the turbine. This aims also at improving the overall efficiency of the hybrid power system. In addition, the proposed configuration makes the hybrid system flexible. Indeed, one part of the solar heat serves for direct generation of electricity through a SCO2 Brayton loop as described. The other part of the solar heat could be used to feed an absorption chiller which in turn will produce cold water for cooling down the SCO2 at the inlet of the compressor. This allows the power block operating in a condensing mode for which the inlet temperature to the compressor could be lowered compare to ambient temperature. Such cooling process helps reducing the work required by the compressor, hence, increasing the total net work done by the system as well as its thermal efficiency. The working principle of the low temperature solar-hybrid power plant is described hereafter.

The hybrid system is composed of a molten salt cycle (solar heat source), a nuclear heat source and a SCO2 cycle (Figure 4). The SCO2 first receives one part of the available solar heat and is preheated (state 10) before entering the second heat exchanger in which it is heated again by the heat from the nuclear steam cycle (state 11). Then, the heated SCO2 arrives at the turbine inlet (state 1). SCO2 flow is expanded in a turbine connected to an electricity generator (state 2). Then, in order to increase the efficiency of the cycle, SCO2 exchanges heat to the high temperature recuperator (HTR, state 3), then to the low temperature recuperator (LTR, state 4). In case of the SCO2 Brayton recompression layout as shown in Figure 4, at state 4, the SCO2 flow is split by a factor X named split ratio. One part of the SCO2 flow passes successively through two stages of cooling (state 4 up to state 5). The flow is first cooled down to ambient temperature due to connection to an external cooling source. Then, it passes through another precooler in which the heat from SCO2 is exchanged to a cold liquid source. Hence, SCO2 becomes cooler. Such cold liquid source is produced by an absorption chiller which is fed by a part of the available solar heat. The sCO2 is then compressed in a compressor (MC) to the state 6. The compressed fluid is heated by the recuperated heat from the LTR (state 8). The other part of SCO2 flows extracted from the main flow does not pass through the recuperator but directly enters the recompression compressor in which it is compressed and gets out at state 7. This outgoing flow reintegrates to the main flow at state 9 before entering to the high temperature recuperator in which the SCO2 is heated up again before returning to the solar-SCO2 heat exchanger (state 10) and the cycle continues.

It is noted that according to the currently presented hybrid configuration, depending on the electric demand, the partition of the solar heat serving for SCO2 cycle for generating electricity and for feeding the absorption machine can be adjusted. Also, the cold liquid produced by the absorption machine can be used directly for SCO2 cooling or in case of excess, it will be stored in the cold storage for other applications.

Figure 4 provides the schematic diagram of the proposed low temperature nuclear-solar hybrid plant with details of the components existing in the solar field (solar thermal collectors and the two molten-salt tanks of the thermal energy storage system) as well as the absorption chiller (composed of a generator, an absorber, an evaporator and a condenser) with the cold liquid storage (with two storage tanks). Absorption chiller technology can be either H2O-LiBr type or NH3-H2O type (as in Figure 4). In the current study, NH3-H2O is preferred as lower temperatures can be obtained.

As done for the high temperature hybrid plant, static calculations with EES have been performed to evaluate the thermodynamic performance of the low temperature hybrid plant. Similar SMR is employed with nuclear thermal heat output of 160 MWt. The solar field with heliostats are now replaced by the solar thermal collectors operating at low temperature (less than 150°C). An adaptive thermal energy storage will be equipped (ex. steam, oil …). However, the thermal capacity of the solar field is assumed to be the one given by (Ref.13) (Q_{solar} = 86 MWt). Pressure drop is neglected. Assumptions for efficiencies of the components in the SCO2 cycle (turbine, recuperators, and compressors) are the same as in the section 3.1 while the coefficient of performance (COP) of the chiller is supposed to be 0.6.

The temperatures at the cold and hot legs of the nuclear-SCO2 heat exchanger are maintained at the inlet and outlet temperature of the reference SMR (i.e. T_{IHX} = 149°C at state 11, T_{OHX} = 255°C at state 1). The inlet turbine pressure (also called as the maximum pressure) is imposed at 20 MPa. The SCO2 flow is supposed to be cooled down to 5°C before entering the main compressor (i.e. the temperature of the cold liquid produced by the absorption chiller is assumed as 5°C, as an example). The inlet temperature to the solar-SCO2 heat exchanger (state 10) varies corresponding to varying participation of solar heat for SCO2 preheating. The parameters to be calculated include the inlet compressor pressure, the split ratio, the repartition between the solar heat serving for SCO2 preheating and the one consumed by the chiller to produce cold liquid at 5°C, the optimized output power as well as the overall thermal efficiency of the hybrid power system.

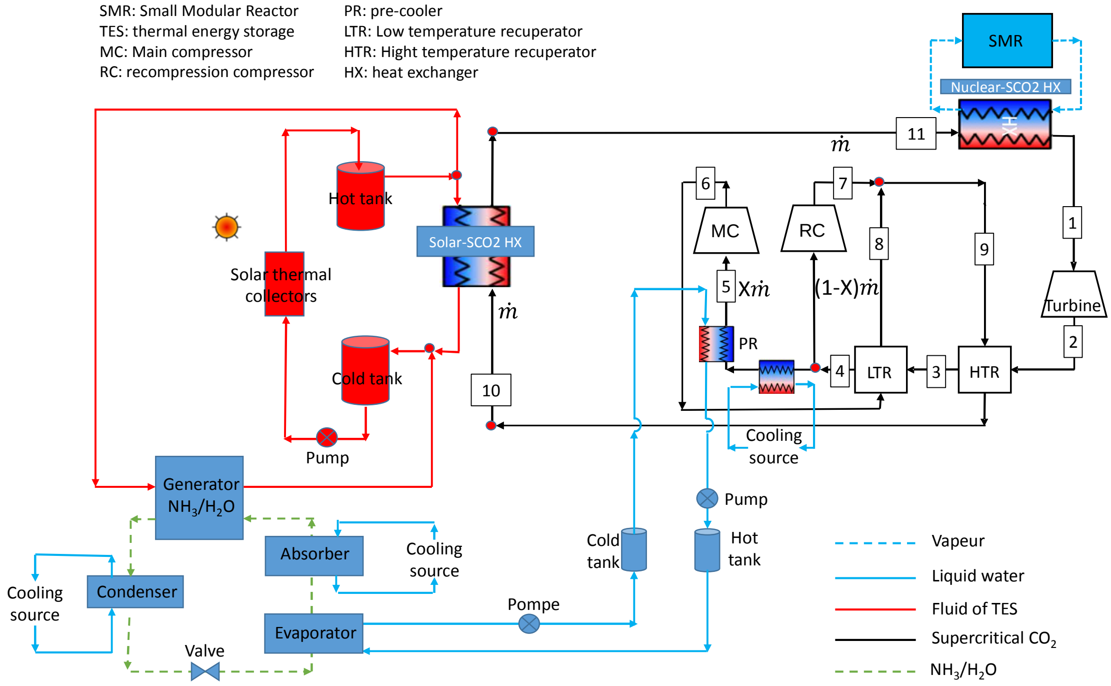

Figure 4: Schematic diagram with detailed components of solar field with thermal energy storage and absorption chiller with cold liquid storage.

In the following, Figure 5 and Figure 6 exhibit the net output power obtained for the currently studied nuclear-solar hybrid power plant as a function of the percentage solar heat serving directly for SCO2 preheating, respectively. It is seen that the participation of solar heat for preheating SCO2 before entering the nuclear-SCO2 heat exchanger reveals better performance in comparison to the non-preheating case. Indeed, up to 18% of power enhancement could be produced at the output of the generator, corresponding to about 2 points improvement of the plant efficiency.

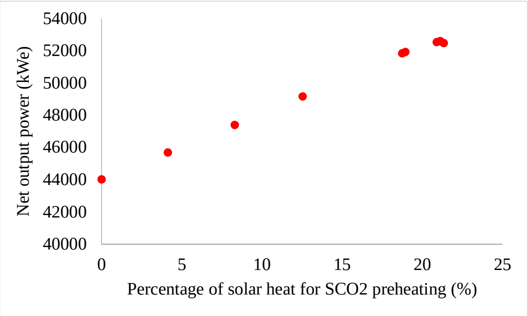

Figure 5: Net power output obtained by the low-temperature hybrid plant

It is noted that the ambient temperature is quite high compared to low temperature of the cycle (27°C vs 5°C), leading to a high demand of cold liquid for the SCO2 cooling process (from 27°C to the inlet compressor temperature of 5°C). Therefore, the main part of the available solar heat is consumed by the absorption chiller for cold liquid production. Only about 20% of the solar heat will serve for preheating in the SCO2 cycle. By contrast, if reference temperature was lower or cold liquid temperature higher, the cold liquid requirement for SCO2 cooling would be much less and as a result a higher part of the solar heat could be used for SCO2 preheating.

It is observed that in terms of thermal efficiency, the low-temperature hybrid plant is not as attractive as the high-temperature one. However, with such configuration, low temperature technologies for solar power plant could be employed, making the idea potentially competitive thanks to cost reduction trends for low-temperature heat generation CAPEX (Ref. 24). Furthermore use of low-temperature heat storage can be interesting due to low energy capacity cost (Ref. 25).

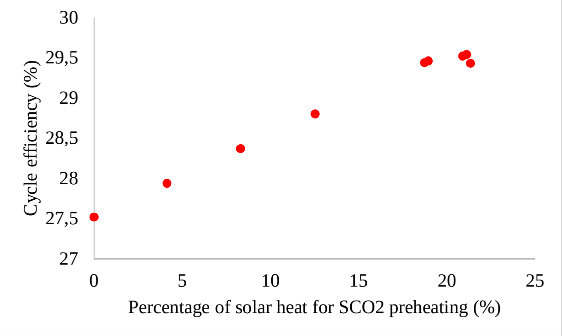

Figure 6: Thermal efficiency obtained by the low-temperature hybrid plant

CONCLUSIONS

Both nuclear and solar can provide significant contribution to provide clean and sustainable electricity to the power industry. Nuclear power plants generally provide constant base load power while solar energy is intermittent. Balancing fluctuating solar with nuclear energy is considered as the solution for the current and future energy systems, in order to improve the viability of the nuclear power plant in an electricity grid containing a significant fraction of renewable (solar and wind) energy sources. A literature survey has been carried out and showed that there exist only few works on the design and development of nuclear-solar hybrid power plants. The paper reviews and provides a detailed analysis of hybrid small nuclear reactor – solar tower power plant equipped by a TES, recently available in the literature.

The paper investigates the potential application of the SCO2 Brayton cycle instead of a Rankine cycle in the power block of the hybrid plant; nuclear and solar heat were chosen to be identical with the reference concept plant, without any attempt of optimization. Two conceptual architectures for the nuclear-solar hybrid power plant employing SCO2 Brayton cycle have been proposed for different conditions of operating temperatures. The high temperature hybrid power plant takes benefit from the solar heat to heat up the SCO2 at the outlet of the SMR, allowing an important increase of inlet turbine temperature, leading to improvement of the cycle's thermal efficiency. Such high temperature hybrid configuration involves three SCO2 loops according to recompression layouts, allowing a gradual increase of SCO2 temperature from about 150°C up to 555°C. This hybrid power plant reveals a better thermodynamic performance in comparison to the case when the SMR is alone. An increase of up to 11 points can be obtained due to hybridization. Moreover, the idea of SCO2 Brayton cycle seems to be really competitive to the classical Rankine one thanks to its advantageous characteristics such as the compactness and the friendliness to the environment.

Despite many advantages of the high temperature hybrid power plant configuration, it can be interesting to propose a low temperature alternative. This configuration will be based on low-temperature solar heat generation technology currently developed for industrial processes and district heating and low-temperature heat storage. The low temperature hybrid power concept consists in a plant in which the solar heat is consumed for two purposes, first to preheat the SCO2 before it returns to the nuclear-SCO2 heat exchanger and second to feed an absorption chiller in order to produce cold liquid which serves for precooling the SCO2 at the inlet of the main compressor. In terms of thermodynamic performance, due to hybridization, 2 points of efficiency enhancement could be obtained by such hybrid system. More interestingly, the architecture allows utilization of low temperature technologies for solar field as well as for the TES system.

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