Load shifting of nuclear power plants using cryogenic energy storage technology

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Abstract
To balance the demand and supply at off-peak hours, nuclear power plants often have to be down-regulated particularly when the installations exceed the base load requirements. Part-load operations not only increase the electricity cost but also impose a detrimental effect on the safety and life-time of the nuclear power plants. We propose a novel solution by integrating nuclear power generation with cryogenic energy storage (CES) technology to achieve an effective time shift of the electrical power output. CES stores excess electricity in the form of cryogen (liquid air/nitrogen) through an air liquefaction process at off-peak hours and recover the stored power by expanding the cryogen at peak hours. The combination of nuclear power generation and the CES technologies provides an efficient way to use thermal energy of nuclear power plants in the power extraction process, delivering around three times the rated electrical power of the nuclear power plant at peak hours, thus effectively shaving the peak. Simulations are carried out on the proposed process, which show that the round trip efficiency of the CES is higher than 70% due to the elevated topping temperature in the superheating process and thermal efficiency is also substantially increased.

1. Introduction
Recent years have seen a renewed interest in increasing nuclear power generation in both developed and developing countries due to energy security and environmental considerations. The latter is also very much associated with reducing the carbon footprint because of the highest percentage of carbon emission from the power generation sector and very limited contribution from renewable energy to total power supply [1–4]. Nuclear power plants (NPPs) feature high capital costs and low operating costs. The costs of energy from such a capital-intensive technology can be low if the facilities are operated at full capacity, and therefore NPPs have been mainly used as a base-load source of electricity production. However with increasing installations, the capacity of nuclear power may exceed the baseload of power grids. For example, in France the nuclear power contributes about 53% of the country’s total installation capacity and generates about 79% of the overall electricity [5,6]. In these circumstances the excessive electricity at off-peak times has to be either exported to other countries or stored for later use. If the above measures fail to balance the generation and demand the NPPs have to be down-regulated regularly. When the NPPs operate at a part capacity, the cost of electricity production becomes very high. Furthermore frequent changes in the load affect strongly on the aging of the equipments and the performance of the fuel, and hence causing problems in both the economic and safety aspects [7].

A considerable effort has been made to deal with load-shift of NPPs and the conventional method is pumped-hydro. More recent decades have seen the development of new approaches to the use of excess electricity for maintaining the NPPs at nearly the full load. These include steam accumulator storage [8], large scale hydrogen production and storage [9–12] and geothermal heat storage [13]. Here we propose the use of cryogenic energy storage...
The thermal efficiency of nuclear heat utilization at peak hours [34]. The integration of NPPs and CES technology could increase which is much lower than that of fossil fuel fired power plants [31]. Nuclear fuel in the reactor vessel is engaged in a fission chain reaction, heating primary coolant (water) in the primary coolant loop. The heated primary coolant is pumped by Pump 1 into the high pressure side of Heat exchanger 1 to transfer heat to the secondary coolant (water) in the low pressure side of the heat exchanger, leading to vaporization of the secondary coolant to give high pressure steam. The high pressure steam then expands in a steam turbine, which drives Generator 1 to produce electrical power. After the expansion in the turbine, the working fluid becomes water–steam mixture, which, upon cooling down, condenses in the Cooling tower to give liquid phase water. The water is then pumped back into Heat exchanger 1 by Pump 2, completing the cycle.

Down-regulation of the load of pressurized water NPPs in the cases of low demands includes the control assemblies being inserted into the reactor vessel and associated changes of the coolants [37]. Apart from the safety issue and lifetime reduction, such operation modes also suffer two challenges in load following. First is the limited power changing gradient which normally takes a few hours to achieve about half load. Second is that the down-regulation of NPPs only balances the generation and demand at trough hours while other plants such as gas-fired power stations have to be employed to meet the peak demands.

2. The proposed system

2.1. The pressurized water NPPs and load regulation

Pressurized water NPPs account for a large portion of the world’s nuclear power plants [35,36]. Fig. 2 shows the schematic diagram of a typical pressurized water NPP. Nuclear fuel in the reactor vessel is engaged in a fission chain reaction, heating primary coolant (water) in the primary coolant loop. The heated primary coolant is pumped by Pump 1 into the high pressure side of Heat exchanger 1 to transfer heat to the secondary coolant (water) in the low pressure side of the heat exchanger, leading to vaporization of the secondary coolant to give high pressure steam. The high pressure steam then expands in a steam turbine, which drives Generator 1 to produce electrical power. After the expansion in the turbine, the working fluid becomes water–steam mixture, which, upon cooling down, condenses in the Cooling tower to give liquid phase water. The water is then pumped back into Heat exchanger 1 by Pump 2, completing the cycle.

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2.2. The proposed NPP–CES system

An integrated NPP and CES system is proposed in the present paper, which has the potential to resolve the issues associated with the load regulation of NPPs. Fig. 3 shows the principle of the integrated system, which consists of a NPP sub-system and the CES sub-system. The NPP sub-system in the integrated system is similar to the conventional pressurized water NPP as shown in Fig. 2. The only difference lies in that there are two three-way valves in the secondary loop, which enables the working fluid to feed into either the steam turbine to produce electricity or Heat exchanger 4 to super-heat high pressure air in CES sub-system (see Fig. 3). The CES sub-system consists of an air liquefaction unit in the left part and a cryogenic energy extraction unit in the right-bottom part of Fig. 3. The integrated system has three operational modes depending on the end-users’ demands:

1. Energy storage mode: At trough hours when the demand is much lower than the rated power of the NPP, the NPP operates in a traditional way to drive the steam turbine to produce electricity and the excessive power is used to drive the air liquefaction unit to produce liquid air (energy is stored in liquid air). In this process, dry air stream (2) and return gas stream (10) are mixed and compressed to an elevated pressure (5) by a two-stage compressor (Compressor 1 and Compressor 2) with inter-cooling (3–4) in Heat exchanger (5). After rejecting heat via Heat exchanger 6 in the main cold box (Process 5–6), the high pressure air is cooled to the lowest temperature level, followed by a near-isentropic expansion process in the so-called Cryoturbine to give liquid air. A fraction of the product is vaporized in the cryogenic...
tank and introduced back to the main cold box through Heat exchanger 6 and the inter-cooler Heat exchanger 5 to supply part of the cold energy. The remaining cold requirement of the main cold box is met by the cold stored in Thermal fluid tanks (see more details in later discussion).

(2) Energy release mode: At peak hours when the demand is higher than NPP's rated power, the cryogenic energy extraction unit is turned onto produce additional power. In this process, liquid air in Liquid air tank is pressurized first by the Cryogenic pump. The high pressure air transfers its cold energy to the cold storage media in Process 16–17 via Heat exchanger 2 followed by a pre-heating process in Heat exchanger 3 by the exhaust gas stream (Process 26–27). In the meantime, the secondary coolant in NPP is introduced into Heat exchanger 4 by switching on the three-way valves. This leads to further increase in the temperature and pressure of the air, which, upon expansion in a four-stage air turbine with inter-heating in Heat exchanger 4, drives Generator 2 to produce electricity. The exhaust air is used first to preheat the high pressure air in Heat exchanger 3 and then to regenerate the desiccant in Dryer.

(3) Conventional mode: At non-rough and non-peak hours, both the air liquefaction unit and cryogenic energy extraction unit are switched off so that the NPP operates in a conventional way to drive the steam turbine to produce electricity. With thermal insulation technologies, cold dissipation from liquid air tank and thermal fluid tanks is expected to be low.

One can see that the air liquefaction sub-system works in a similar way as the simplest Linde–Hampson liquefier except for taking advantages of the external cold energy in Heat exchanger 6. It should be noted that in the air liquefaction unit, cryoturbine is used to generate liquid product instead of the use of a throttling device in a conventional setup. The working fluid expands in a near-isentropic manner in the cryoturbine with both temperature and enthalpy decreasing and hence generating more liquid product while producing additional shaft power [38]. Cryoturbines have been used extensively in the production of liquid natural gas. Recent improvements on the cryoturbine design have led to an isentropic efficiency as high as 88% on a test stand and a very efficient shaft power recovery [39,40].

Cold storage and recovery acts as a bridge between the air liquefaction unit and the cryogenic energy extraction unit. It aims to recover the cold energy released during liquid air preheating process. In this process air is under the supercritical state, and as a result the cold is produced in the form of sensible thermal energy. Fig. 4 shows the isobaric heat capacity of air as a function of temperature at different pressures. One can see that the isobaric heat capacity of air changes only slightly in the heating process, particularly at very high pressures. Similar to the use of liquids to store sensible heat, cold energy can also be stored in thermal fluids (see below) and such fluids can give good temperature gradient match during heat exchange and hence an efficient cold recovery. In this process the thermal fluids are used not only as a working fluid but also as a cold storage medium.

From the above discussion, selection of correct thermal fluids is important. Fig. 5 shows the isobaric heat capacities of some commonly used refrigerants. Clearly, no single fluid can fully cover the working temperature region of liquid air pre-heating process. The combination of propane and methanol works as both the cold storage liquids and the working fluids for heat transfer, which cover the required temperature range and have a high heat...
capacity. For each of the two fluids, a two-tank configuration is proposed for cold recovery and storage; see Fig. 3. The two thermal fluids are pumped from the hot tanks to the cold tanks during the cold storage process (the energy releases mode), and flow back during cold release process (the energy storage mode). The use of thermal fluids for both transferring and storing thermal energy can greatly simplify the design of the system in that no additional heat exchangers will be needed. Moreover, the operating strategy can be much more straightforward – the amount of cold energy and the objective temperature can be easily adjusted by controlling the flow rate of the fluids. This is extremely difficult to achieve using the conventional way of storing cold in a packed pebble bed.

The cryogenic energy extraction unit is coupled with the NPP through the thermal energy utilization process via Heat exchanger 4. One can see that hardly any thermal energy is wasted in the cooling process and hence the power output is expected to increase significantly. By integrating with CES technology the reactor core and the primary loop of NPPs operate steadily at full load at all times while the net output power is adjusted only by the CES unit. As the energy extraction process in the CES sub-system is similar to power generation using a gas turbine, a much faster rate of power change could be achieved in comparison with the conventional down-regulation of NPPs.

3. The performance of the integrated system

The integrated system is evaluated by model simulations using an in-house developed package named Thermal System Optimal Designer (TSDO) under the Matlab environment. For simplification and quickly illustrating the concept, the integrated system is assumed to run at a steady state in each operating modes with negligible pressure drop and heat loss during the heat transfer process. In the TSDO thermal properties are calculated using the commercial software REFPROP 8.0 developed by National Institute of Standards and Technology (NIST). Models for components are developed based on energy and mass balances in the TSDO, whereas the pinch constrains in multi-flow heat exchangers are also respected, which represents the second law of thermodynamics. As a systematic simulator the TSDO enables parametric optimization to obtain the best operational conditions for a high performance.

One of the most important performance indicators of an energy storage technology is its round trip efficiency. Such a parameter represents the conversion efficiency during energy storage and energy recovery cycle. As the integrated NPP–CES system is a hybrid of power generation and energy storage, the round trip efficiency is defined as the ratio of the increased power output in the energy release mode to the energy consumed for cryogen production in the energy storage mode:

\[
\eta_{RT} = \frac{W_{ER} - W_C}{W_{ES} \cdot t_{ES}}
\]

Here \(W_{ER}\) and \(W_C\) are respectively the power output in the energy release mode and conventional mode, \(W_{ES}\) is the power consumption for liquid air production in energy storage mode, and \(t_{ES}\) and \(t_{ER}\) correspond to the energy release and energy storage durations. In the following the round trip efficiency is selected as an objective function in the parametric optimization. Table 1 summarizes the assumptions for the calculations. It should be noted that, for clarity and simplification without losing the most important features of the system, power consumption for pumping the thermal fluids and driving the air dryer have been neglected as they are much lower compared with other components.

Taking a NPP at a rated power of 250 MW as an example, parametric optimization gives the flowrate, temperature and pressure data as listed in Table 2. It is seen that the air liquefaction capacity for such an integrated system is 150 kg/s (equals to 540 tons/h). This scale of liquefaction operation has been used commercially in natural gas liquefaction process for both the base load plants and the peak shaving plants [41]. Compared with large scale LNG production, air liquefaction in the proposed system is simpler as most of the cold energy is supplied by the cold storage unit instead of external cold production in LNG production using cascade, mixed-refrigerant or \(N_2\) expander cycle methods. Furthermore, cold storage and recovery using thermal fluids enables very efficient heat transfer process and as a result significantly decrease the power consumption in the air liquefaction process. Fig. 6 shows the composite curves (temperature against heat load diagram) in cold storage (Heat exchanger 2) and cold recovery (Heat exchanger 6) processes. One can see that the temperature gradients of the hot fluids and cold fluids match well in both the processes so that the minimum driving force constraint (imposed by the pinch point) which causes inefficient heat exchanges is improved. As can be seen from Table 2, the high pressure fed air is cooled to 102 K before the expansion process in cryoturbine to produce liquid air and about 84% of the feed air is liquefied in this process compared with the Linde–Hampson liquefier which is only about 7% at the same topping pressure. The main feed air cooling is found to be a supercritical process at about 13,409 kPa (the critical pressure of air is about 11,385 kPa) while the topping pressure in energy release process is slightly lower at about 11,385 kPa.

Table 2 also reveals that the mass flow-rates of cold storage fluids are more or less the same with liquid air (1.1 times for propane and 0.6 times for methanol). Considering that the densities of pro-

![Fig. 5. Isobaric heat capacity as a function of temperature for some common refrigerators at the ambient pressure.](image-url)
pane and methanol are similar to that of liquid air, the storage volumes of these thermal fluids are then close to the storage volume of liquid air. In comparison, cold storage in solid media such as pebbles or concrete requires a storage volume approximately 10 times that of stored liquid air[^19]. Thus storing cold in thermal fluids makes the integrated system more compact and hence has a great potential to reduce the capital costs.

Both power/heat and exergy analyses are conducted to assess the performance of key components in the system so that pertinent guidance could be provided for system performance improvement. Table 3 shows the results with the exergy loss ratio defined as the percentage of exergy loss to the overall power/exergy changes. It can be clearly seen that the net power consumption in energy storage mode is 76.74 MW while about two thirds of the exergy loss occur in the power transfer processes (air compression). The exergy loss in the main heat transfer process in Heat exchanger 6 contributes less than one third with a low exergy loss ratio of about 8%. Although the exergy loss ratio in Heat exchanger 5 is high, the total exergy loss in this process is only about 0.07 MW as the grade of thermal energy is low (close to the ambient temperature).

In the energy release mode the energy changes occur mainly in heat transfer processes for both the cold recovery in Heat exchanger 2 and superheating of the compressed air in Heat exchanger 4. The exergy loss ratio in Heat exchanger 4 is approximately 20% mainly due phase change process which leads the pinch point constraint and hence lowers the efficiency. The exergy loss in cold recovery process in Heat exchanger 2 is low (~10%) due to the use of thermal fluids. The net power output in the energy release mode is 687.51 MW which corresponds to a round trip efficiency of about 71.26%. Based on such an operation strategy the NPP–CES integrated system generates 173.26 MW electrical power at trough times (8 h per day), 687.51 MW at peak times (1 h per day) and 250 MW at the remaining hours.

It should be noted that the energy release unit in the integrated system can operate without the NPP unit, while being heated by ambient or other heat sources. Such an operation can extend the operation hours by adjusting the mass flow-rate in the energy release mode although the net power output decreases significantly and there is a decrease in the round trip efficiency. However, these results also reveal that the energy release unit can also be used as the back-up unit in the NPPs (instead of currently used expensive and short lifespan battery and diesel gensets based backup units).

![Fig. 6. The composite curves in cold storage and recovery processes: (a) cold storage in Heat exchanger 2 and (b) cold recovery in Heat exchanger 6.](image-url)
4. Further discussion on the operating conditions

In this section, discussion is made on possible ways to enhance the performance of the integrated NPP–CES system. First, the storage pressure effect is investigated. Thermodynamics tells that the higher the pressure, the easier the gas can be liquefied and hence a higher CES round trip efficiency could be achieved [21]. We therefore investigated the influence of the storage pressure on the NPP–CES integrated system. Fig. 7 shows the results. An increase in the storage pressure shows a linear increase in the round trip efficiency and the increase rate is about 0.8% per bar increased. This indicates that the storage pressure affects mainly the liquefaction process as both the net output power and the mass flow-rate of liquid air in the energy release mode changes only slightly with increasing storage pressure. Here the almost constant net output power is because the increased storage pressure reduces only the power consumption of the cryogenic pump.

Second, the effect of the secondary loop topping pressure of the NPP in energy release mode is examined. In the energy release mode of the integrated system, the steam in the secondary loop of the NPP is used to superheat the high pressure air instead of driving the steam turbine. Fig. 8 shows the results. One can see an almost linear increase in the round trip efficiency with increasing secondary loop topping pressure. Different to the influence of the storage pressure, the mass flow-rate of liquid air in the energy release mode decreases with increasing secondary loop topping pressure. This indicates the secondary loop topping pressure affect mainly on the energy release mode. Although the mass flow-rate of liquid air decreases, the net output power is seen to be almost independent of the topping pressure.

It should be noted that the increase in either the energy storage pressure or the NPP secondary loop topping pressure could face technical and economic challenges. For example, currently cryogenic tanks are typically operated at a pressure below 10 bars at a 100 ton scale and generally at the atmospheric pressure for over 100 ton scales. As a consequence the selection of the working pressures should consider the balance between the system performance and the capital, operation and maintenance costs.

Third, the ambient temperature is expected to have some effect and this is investigated and the results are shown in Fig. 9. The round trip efficiency is seen to decrease by about 2% for every 5 °C increase in the ambient temperature. Similar to the storage pressure, the ambient temperature has a much stronger effect on the air liquefaction process than that on the energy release process in terms of the net output power (The mass flow-rate of liquid air in energy release mode changes very slightly with the increase of the ambient temperature). This agrees well with the fact that the power consumption of LNG plants in arctic regions such as Norway is much lower than those in other regions [42,43]. These results also indicate that locations with a low ambient temperature are preferred for the installation of NPP–CES integrated systems.

The above analyses also indicate that the net output power in the energy release mode changes very slightly around about 690 MW. As a result, the integrated system is capable of generating some 2.7 times the power at peak demands compared with a NPP alone system, regardless of the location of the installation and the operating pressures.

5. Concluding remarks

A new system for meeting different loads in electrical grid has been proposed in this work. Such a system integrates the nuclear power plant and the cryogen based energy storage technology. Thermodynamic analyses are carried out on the system under fairly general baseline assumptions and the results show that the round trip efficiency of electrical energy storage is about 71% while the net output power in the energy release mode is about 2.7 times that in a nuclear power plant alone. The round trip efficiency is similar to the pumped hydro storage method while the proposed technology does not rely on any favorable geography (except for the NPP sites). This provides a potential method to change the net power output of NPPs instead of down-regulating the NPPs regularly. Sensitivity analyses are carried out on the operating condi-
tions and the results show that the storage pressure and ambient temperature mainly affect the air liquefaction process while the secondary loop topping pressure of the NPP affects more on the energy release process.

The modeling work has shown competitive performance of the integrated system which enables base-load nuclear power generation to play a flexible role in load shifting. The integration is likely to be practically feasible as modification to current NPP is only on the secondary loop (steam Rankine cycle) and such modification can be achieved with on-shelf technologies. The main obstacle, in our view, to bring such a technology to real-world applications is the lack of revenue mechanism under current market conditions. Further work is therefore needed to study the economic and policy aspects associated with the integrated system in addition to an experimental or demonstration study.

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