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Integration of Heat-only Small Modular Reactor with Thermally Driven Systems

Hussein Abdulkareem Saleh Abushamah[1]
[1]Faculty of Electrical Engineering, University of West Bohemia
301 00, Pilsen, Czech Republic
abushama@fel.zcu.cz
Tomáš Kořínek[2]**, Radek Škoda**[1,2]
[2]CIIRC, Czech Technical University in Prague.
160 00, Prague, Czech Republic
Tomas.Korinek@cvut.cz, Radek.Skoda@cvut.cz

ABSTRACT

The nuclear small modular reactor (SMR) technologies represent potential competitive carbon-free solutions for replacing fossil fuel-based energy generation. In addition to several SMR technologies designed for electricity generation, some others, like Teplator, are under development for district heating applications. As the heating demand fluctuates over time, using the excess heat during the low demand periods could enhance the load following flexibility, capacity factor, and the economics of the integrated system. Depending on the output temperature of the nuclear plant, the excess heat could be used for different secondary applications. This study aims to investigate the options as secondary thermally driven applications to be integrated with heat-only reactors such as the solar chimney concept, thermoelectric tubes, Kalina cycle and organic Rankine cycle technologies for low-temperature electricity generation and other heat-driven systems like water desalination and hydrogen production. The calculations are based on a typical heat-demand profile, where the overall efficiency and secondary products are roughly estimated for different candidate integrations. This study concludes that the hot water temperature generated by SMRs plays an essential role in the performance of the secondary heat-driven outputs. Therefore, further studies seem required to model the tradeoff between costs, SMR's output temperature, and overall system performance in order to achieve an optimized integrated system.

1 INTRODUCTION

According to U.S. Energy Information Association forecast, global energy demand is expected to have a 50% growth by 2050 [1]. Considering the global warming challenge, increasing the share of carbon-neutral energy sources is vital to supply the growing demand. Nuclear power is one of the promising technologies that can effectively contribute to the energy mix. A particular technology of nuclear power plants is categorized as Small Modular Reactors, which are small with an electrical capacity of less than 300 MW and modular, meaning that they could be constructed part by part at factories and then transported to be installed at the site [2]. This type of reactor has the potential to offer a more straightforward, standardized, and safer modular design. It can be factory-built, requiring a smaller initial capital investment and shorter construction times. The SMRs could be compact enough to be transported, used in isolated locations without advanced infrastructure and a power grid, or clustered on a single site to create a multi-module, large-capacity power plant. [3]. Due to these valuable advantages, there is a growing global interest in SMR technologies, where several concepts and designs are proposed and developed for different applications, such as electricity generation, district heating, hydrogen production, and water desalination [4]. However, improving the economic feasibility of SMRs compared to the large conventional nuclear power plants (NPP) is a key matter [5].

In the EU, the heating demand contributes to a considerable share of the total energy consumption, an average of 50% [6]. Furthermore, the heat-only SMRs could be significantly cheaper than the ones for electricity generation since it does not include electrical infrastructures like turbine, power generator, and electrical substation, and this lower investment cost could attract more investors. On the other hand, the low capacity factor due to the daily fluctuations and seasonal changes in heating demand may limit the economics of the heat-only reactors. As the nuclear fuel cost contributes to a relatively small share of the total NPP's lifetime cost (around 10%), increasing the capacity factor of the SMR could effectively improve its economic competitiveness [7]. Therefore, designing and developing SMRs for heating applications integrated with other heat-driven applications could lead to a feasible energy solution. The currently under-development heat-only SMRs are addressed in Table 1 [8]. This study describes the possibilities of integrating heat-only SMRs with low-temperature driven systems for electricity generation and other applications like water desalination. It investigates how the output temperature of SMRs has a critical role in the performance of secondary applications.

Table 1: Heat-only SMRs under development.

Name	**Reactor thermal output (MW_t)**	Core Inlet/Outlet Coolant Temperature (°C)	Status
Teplator	< 150	< 175 / < 192	Conceptual design
NHR200-II	200	232 / 280	Basic design
DHR400	400	68 / 98	Basic design
HAPPY200	200	80 / 120	Detailed design
RUTA-70	70	75 / 102	Conceptual design

2 HEAT DRIVEN APPLICATIONS

2.1 Solar chimney power plant

Solar chimney power plant is a technology that uses sunlight to increase the air temperature at the collector, leading to a pressure difference that causes an updraft air flow driving a turbine for electricity generation [9]. Fig. 1 illustrates a typical drawing of this system. Because sunlight is not always intensively and effectively available in many countries for running this technology, especially during the winter, using excess heat from a heat-only SMR instead of sunlight could be potential. Fig. 2 represents the efficiency of a typical solar chimney as a function of the inlet air temperature and height of the chimney. The drawbacks of this technology are its very low efficiency and its high capital cost.

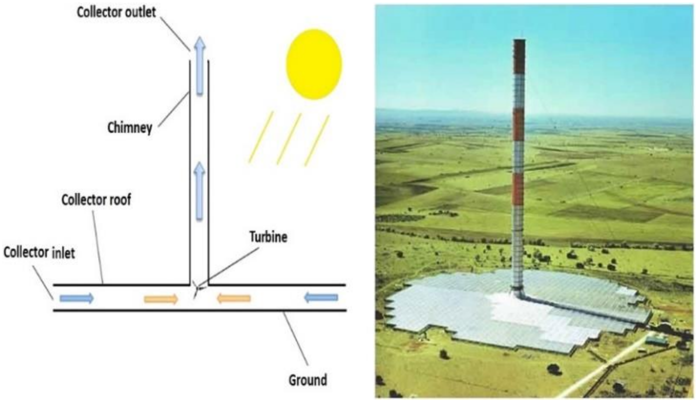

Figure 1: Solar chimney power plant.

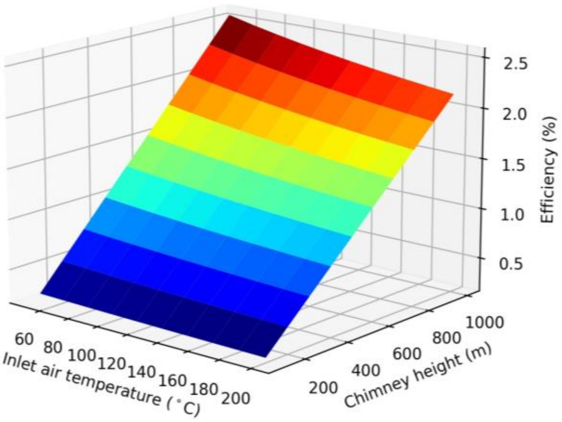

Figure 2: A typical solar chimney efficiency vs. air inlet temperature and tower height.

2.2 Thermoelectric tubes

Thermoelectric technology is an electricity generation system that can directly convert heat flux to electricity, providing the opportunity to recover waste or excess heat from even small temperature differences [10]. The working principles of this technology are based on a phenomenon discovered in 1821 called the Seebeck effect, revealing that a temperature difference at the joint of different metals causes electromotive force and voltage difference [11], as illustrated in Fig. 3. One of the crucial factor affecting the efficiency of this technology is the temperature difference between the heat source and heat sink as simulated and illustrated in Fig. 4 for a typical system [12]. Therefore, in aiming to design an integrated heat-only SMR and thermoelectric electricity generation system, it is vital to evaluate different design temperatures for the heat source.

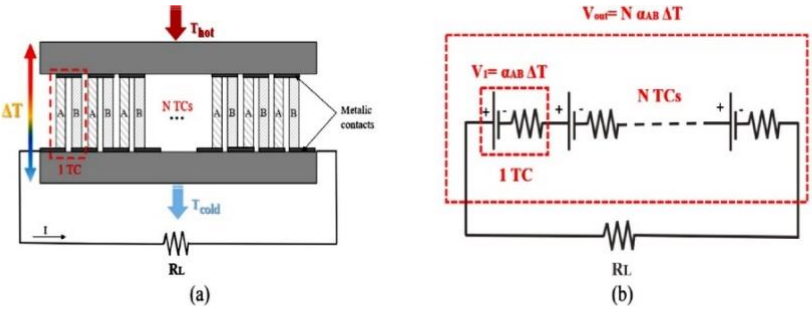

Figure 3: Thermoelectric power generation working principle [13].

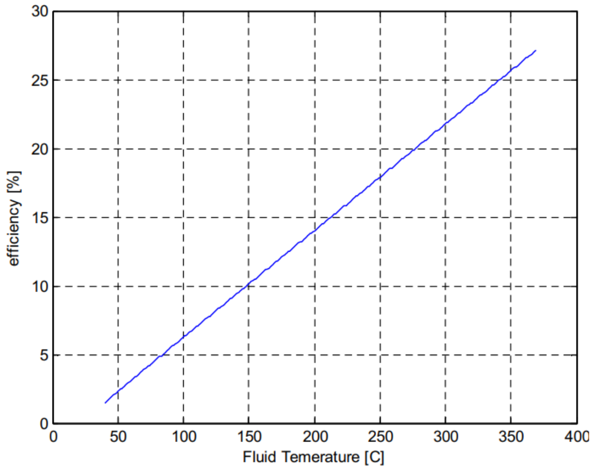

Figure 4: A typical thermoelectric tube’s efficiency vs. heat source temperature (heat sink 20 °C) [12].

2.3 Kalyna cycle and Organic Rankine cycle-based electricity generation

One of the thermodynamic cycles for converting thermal power to mechanical power is called the Kalina cycle, which utilizes a solution of two fluids with different boiling points as working fluid, like a mixture of water and ammonia [14]. Fig. 5 (a) illustrates a typical Kalina cycle electricity generation system. The boiling point of the solution could be adjusted to suit the heat source temperature by selecting an appropriate ratio between the components of the solution. This provides the opportunity to use low-grade heat sources such as low-temperature geothermal heat, thermal solar energy, and waste heat. Consequently, integrating the heat-only SMRs (often designed to supply low-temperature heat for district heating applications) with Kalina cycle-based electricity generation may lead to a competitive system. As the efficiency of the Kalina cycle depends on its working fluid temperature and pressure, as given in Table 2, the efficiency of integration of this cycle with SMR is highly influenced by the temperature of the SMR output. Another thermodynamic cycle is called the organic Rankine cycle, which has a system similar to the conventional steam cycle electricity generation, but instead of water, it uses an organic fluid like hydrocarbons, hydrofluorocarbons, etc., as working fluid [16]. Like the Kalina cycle, this cycle could be operated by low operating temperature, offering effective use of heat recovered from various low-temperature heat sources, which can not be used by conventional steam cycles. Fig. 5(b) illustrates a simulated typical organic Rankine cycle performance using Freon-R12 as an organic working fluid with different working temperatures.

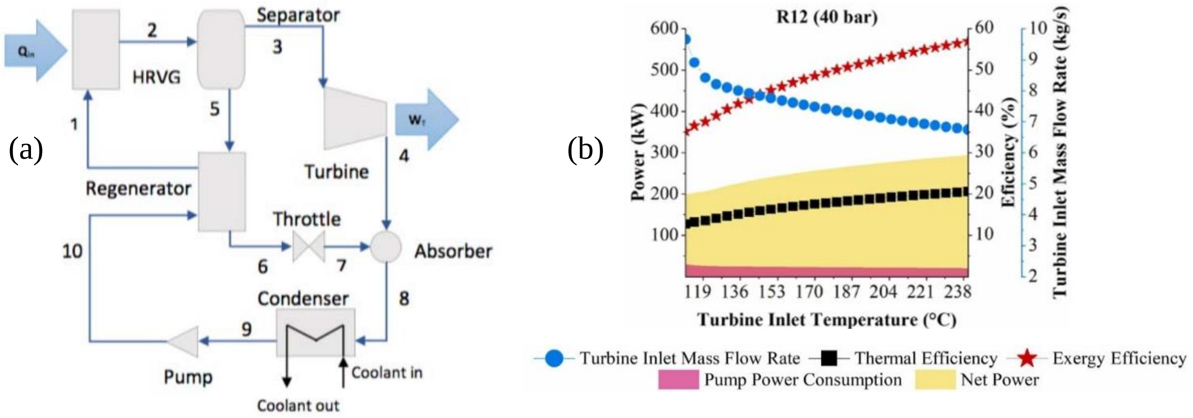

Figure 5: Schematic diagram of the Kalina cycle system (a) and performance of a typical organic Rankine cycle (b) [15] [16].

Table 2: The efficiency of a typical Kalina cycle system for electricity generation [15].

		Temperature (°C)						
		130	**140**	**150**	**160**	**170**	**180**	**190**
Pressure (MPa)	**2**	1.6463	4.88	6.8973	8.9147			
	2.5	1.6721	4.9673	6.9464	8.9255	11.1787		
	3	1.6541	4.786	6.8555	8.9251	11.1233		
	3.5	1.5962	4.876	6.999	9.1221	11.2768	12.9699	
	4	1.6543	4.9851	7.0543	9.1235	11.0691	12.8784	
	4.5	1.5632	4.9321	6.9792	9.0263	11.0448	12.8666	14.9847
	5		4.7876	6.83705	8.8865	11.1	12.8537	14.9839

2.4 Hydrogen production and water desalination

Hydrogen is a promising energy source capable of effectively contributing to carbon emission elimination attempts. Hydrogen can be produced by several technologies categorized into four main groups: electrolysis, photolysis, biolysis, and thermolysis [17]. Most of the effective thermally driven hydrogen production processes require high-temperature sources in a range of 400 – 2200 °C. For example, the single-step thermal dissociation of water, known as water thermolysis, requires a high-temperature heat source above 2200 °C to have a reasonable degree of dissociation, i.e., to separate H2 and O2. Hydrogen production by thermochemical water splitting cycles requires heat with a temperature of 425 – 450 °C (hydrogen iodine decomposition), or 800 – 900 °C for sulfur–iodine cycle-based hydrogen production [18]. Only a few novel methods have been proposed which could utilize low-temperature heat sources for hydrogen production. For example, Raka et al. [19] proposed a process that utilizes a heat source with a temperature of (60 – 140 °C) to run a hydrogen production process called ammonium bicarbonate reverse electrodialysis, as illustrated in Fig. 6. In this system, electricity is produced based on salinity gradient power, at the same time, this electricity drives an electrodialysis process of water to produce hydrogen.

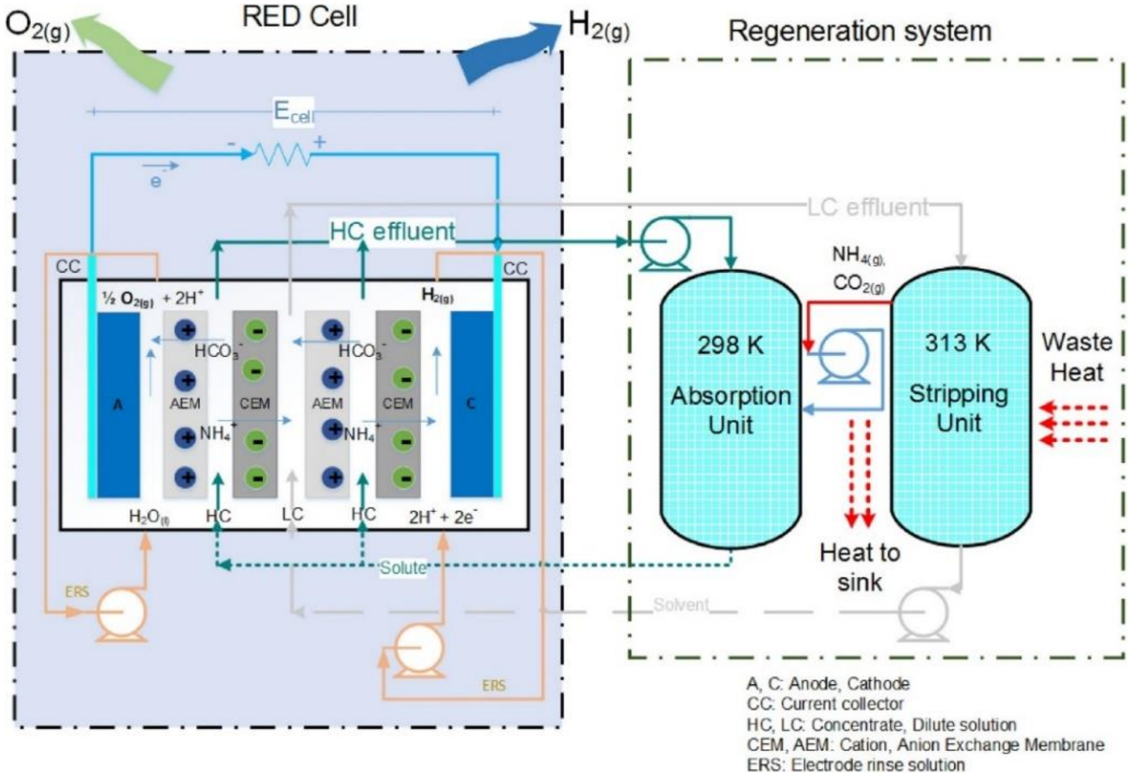

Figure 6: Schematic of Reverse Electro-Dialysis (RED) system based on ammonium bicarbonate salt with regeneration system for hydrogen production.

Thermal water desalination could be performed by humidification-dehumidification (HD) or thermal distillation processes (including multi-effect distillation, multi-stage flash, and vapor compression). Distillation processes require high temperature/pressure steam source like (>70 °C) for driving a multi-effect distillation, while an HD system could be driven by low-temperature heat sources like hot water (50 – 90 °C). Yasmine et al. [20] concluded that upgrading the grade heat sources' temperature using an absorption heat pump to drive a multi-effect distillation process could be considerably more economical than the HD method.

3 CASE STUDY AND RESULTS

A typical average daily district heating demand profile of a small city in the Czech Republic, Otrokovice, is illustrated in Fig 7. The peak point is around 35 MW thermal power demand. One unit Teplator with a thermal capacity of 50 MW is assumed to supply this demand. A two-week period during the low-demand times is considered for refueling and other maintenance actions. Fig. 7 also illustrates the average daily excess heat that will be available over a year. Here, generating electricity by thermoelectric tubes and organic Rankine cycle technology is evaluated and illustrated in Fig. 8 (a, b), using the data given in Fig. 4 and Fig. 5

(b), respectively. As you can see, the temperature of the fluid used to drive the electricity generation process plays an essential role in the efficiency and the potential amount of electricity generation, and higher temperatures lead to higher rates of electricity generation.

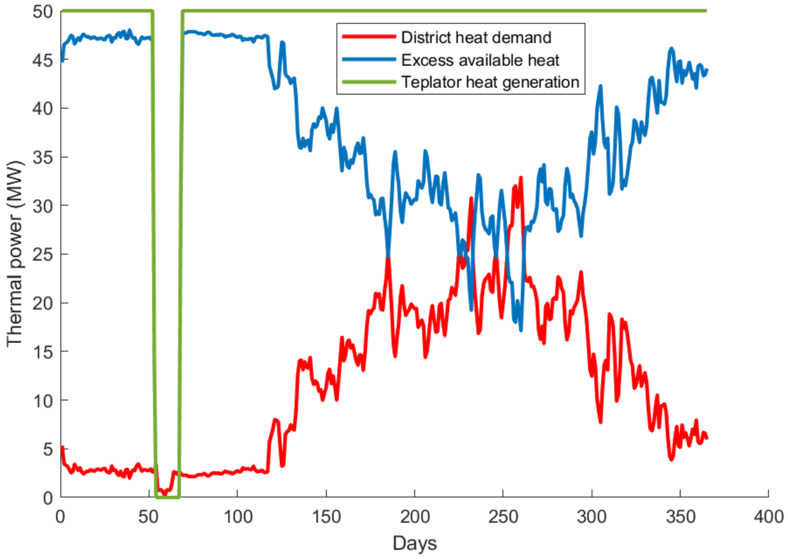

Figure 7: A typical annual day-based heat demand profile, maximum heat generation by Teplator, and the excess heat.

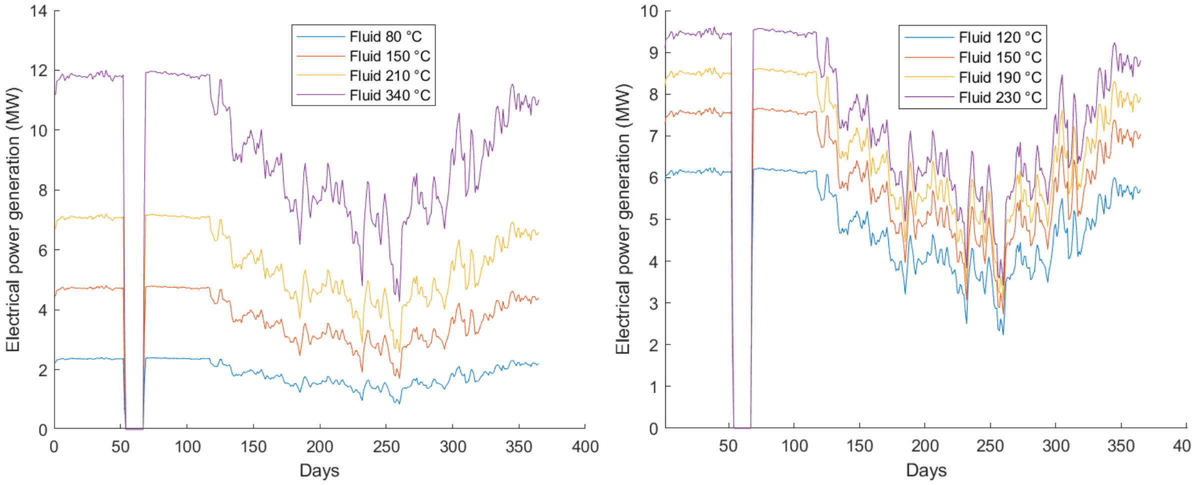

Figure 8: The expected electrical power generation by thermoelectric tubes (left) and organic cycle (right) technologies by Teplator's excess heat associated with the given demand profile.

4 CONCLUSION

In many countries, heating demand contributes a considerable share of the total building energy consumption, which is mainly supplied by fossil fuels, resulting in significant carbon dioxide emissions. In this regard, district heating systems supplied by carbon-free energy sources could effectively provide a techno-economic solution. Therefore, there is a growing interest in small modular heat-only reactors for district heating applications. However, the economic of this approach could be limited in some cases when it is employed only for heating demand, as the seasonal and daily fluctuations of the demand reduce the capacity factor of the nuclear plant, especially when the nuclear heat plant is operated in an island mode, i.e., one heat source for one city or town. To overcome this issue, in addition to the possibility of employing heat storage, using the excess heat for other applications like electricity generation, hydrogen production, and water desalination could improve the economics of the whole system. However, heat-only SMRs, like Teplator, are designed to supply a low-temperature heat appropriate for district heating purposes. Therefore, low-temperature-driven technologies should be considered to be integrated with heat-only SMRs. On the other hand, this study showed that higher temperature heat sources often lead to better performance when it comes to electricity generation by thermoelectric tubes, Kalina cycle, organic Rankine cycle-based electricity production, or hydrogen production and water desalination. Therefore, there is a tradeoff between increasing the heat-source temperature, costs, and the opportunities of higher efficiency secondary applications. Consequently, further studies are required to model this tradeoff in order to find the optimum designs of heat-only SMRs to be integrated with other applications.

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