Small Modular Reactor as a Part of a District Heating System

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INTRODUCTION

We studied the use of a small modular reactor (SMR) as a part of a district heating supply in a representative Finnish city. The recent studies of nuclear combined heat and power (CHP) in Finland have focused on using a large nuclear power plant to supply most of the required heat into the district heating system. In this study, our focus was the suitability of a SMR scale reactor acting as a part of the district heat supply mix for a representative model city. The consumption and reference case production palette was modelled according to a projected development of the city of Espoo by year 2030.

Power and district heating in Finland

Finland is a part of the Nordic electricity network which has large resources of hydropower, nuclear and biomass. In recent years the amount of wind power has also increased strongly and in Finland one nuclear power plant is nearing commercial operation and construction license of a second new reactor is under regulatory review. As it is, the electricity is both relatively cheap and low-carbon. The remaining large energy use of fossil fuels is in heat production.

Large Finnish cities are heated with extensive district heating networks. The heat is supplied by power plants burning coal, gas and biomass as well as large-scale heat pumps. The heat demand can vary ten-fold from the peak consumption during winter to low consumption during the summer mostly consisting of the use of hot water.

Assumed district heat consumption time series is based on earlier work [1] and electricity time series are Nordpool spot prices from 2015 (Figure 1).

District heating options for a model city

The assumed district heating production structure is shown in Table I. There are several CHP plants using both natural gas and biomass, as well as heat only plants using same fuels. In addition, there is a 40 MW heat pump facility. As there are no district heating focused SMRs available currently, a NuScale module by NuScale Power Inc. [2] was used as a representative SMR. The techno-economic data was taken from [3,4]. As we used only one reactor module, the construction costs were assumed to be 30% higher than the referred values. The operation and maintenance costs per energy produced for such a small plant were assumed to be twice the costs of the large nuclear power plant. Two SMR cases were compared to a reference case (heat production without nuclear): using a module for CHP and using a reactor module for heat production only. For the purposes of this study, it was assumed that the SMR could be sited next to an existing district heating network.

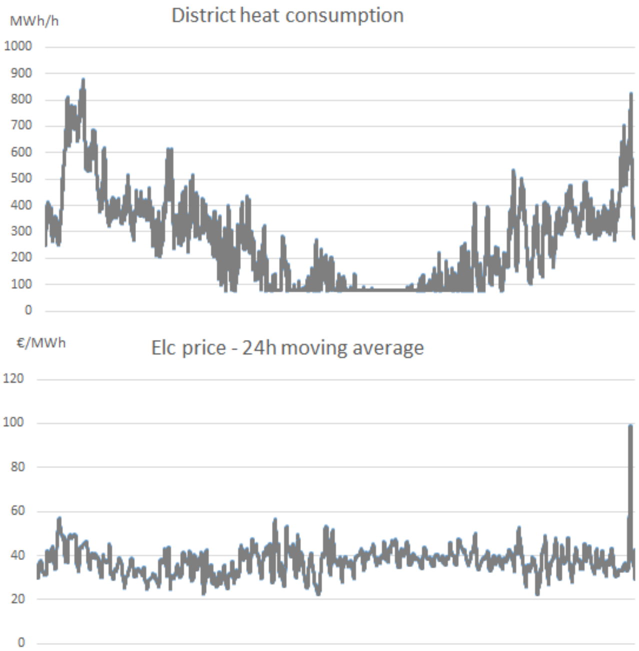

Fig. 1. Assumed district heat consumption for the model city and 24 h moving average of electricity spot prices.

TABLE I. Assumed production plants.
Fuel costs are included in nuclear O&M.

Plant type	P_{th}; P_e (MW)	O&M (€/MWh)
Nuclear heat	152; -	5.6
Nuclear CHP	94; 35	8.9
Natural gas combined cycle CHP	214; 234	0.7
Biomass CHP	156; 74	1.8
Gas turbine + waste heat CHP	76; 42	0.4
Heat pump	40; -	-
Biomass heat plant	80; -	2.1
Natural gas heat plant	580; -	0.8

The economic optimization of the dispatch of the various generating plants to match the heat consumption is performed with modelling assumptions as per Table II. The optimization is performed using GAMS (General algebraic modeling system) based optimisation model for operation of several power plants connected to district heat network. Optimisation model finds annual least cost operation of each production component fulfilling district heat demand. Electricity generated by CHP power plants and consumed by heat pumps is traded by market electricity prices. Model uses mixed integer programming for power plant scheduling taking into account minimum loads and start-up costs. Operation of each production unit is modeled by using public sources.

TABLE II. Other assumptions used.

Emission permit price	20 €/ton
Natural gas price	27 €/MWh
Biomass price	35 €/MWh
Heat tax - CHP (gas)	12.1 €/MWh
Heat tax - boiler (gas)	17.4 €/MWh
Grid cost (HP)	35 €/MWh

RESULTS

In the simulated scenarios, the SMR acted as a baseload plant as seen in the Figure 2. The low need for the heat during summer months effectively limits the usability of the high capital cost nuclear power plant. While the CHP plant can operate at high utilization rate, the heat only plant would need to operate at low power for several months during summer, thus lowering its utilization rate. The inclusion of SMR affected the system behavior in comparison to reference case in several ways as demonstrated by the utilization rates of the fleet as seen in the Figure 3. Role of natural gas fired power plants decreases in SMR cases. Heat pump utilization remains in high level due to high efficiency due to low operation costs and high flexibility. Even with high level base load supply by nuclear reactor a high utilization of biomass fired heat plant is required.

Our results show how SMRs could act in conjunction with other low-carbon sources in producing district heat. Inclusion of the nuclear heat would reduce both the marginal cost of the district heat production as well as its CO_2 emissions. Compared to large nuclear power plants, the potential for the reduced emergency planning zones and appropriate thermal power could make the SMRs a viable alternative. In this study, additional costs for DH infrastructure were not taken into account; these would add to the capital costs and thus increase the payback time of the investment. While the low summer demand limits the feasible nuclear capacity, this limitation could be eased through the expansion of the district heating grids and their interconnections as well as the potential seasonal heat storage.

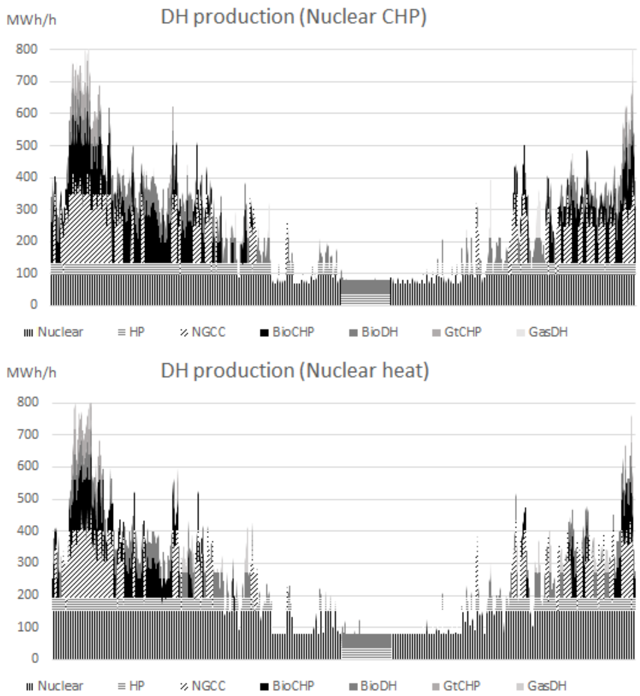

Fig. 2. District heat production for various sources in cases using nuclear reactor for combined heat and power and for heat only.

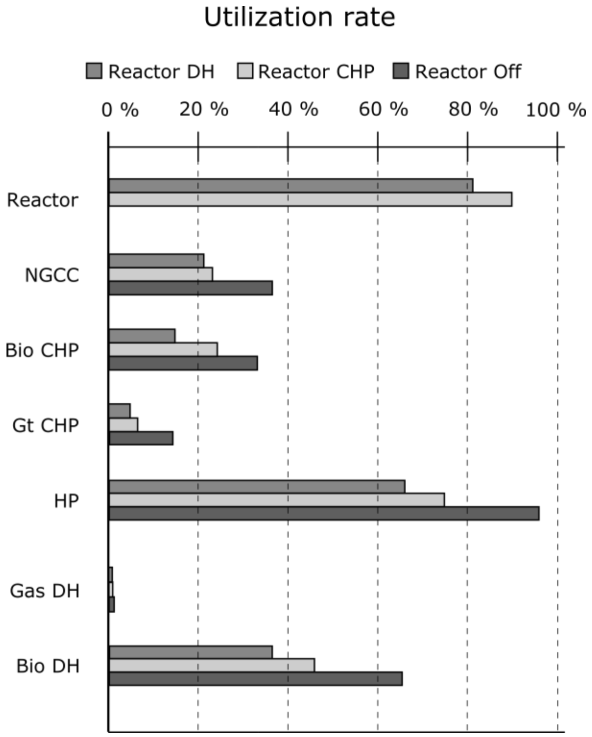

Fig 3. Utilization rate of the production fleet in three simulated scenarios.

The DH production cost in is 38-42% lower in the SMR scenarios compared to the no-nuclear reference case. The heat only case showed lower DH production costs than the CHP case as seen in Figure 4. The inclusion of the nuclear heat plant reduces the marginal cost of the district heat production as seen in the Figure 5.

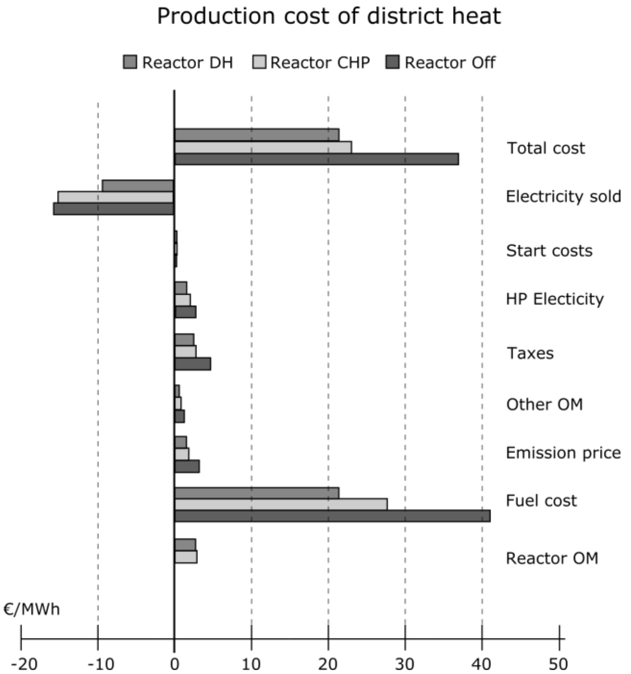

Fig. 4. The total and component production costs of district heat.

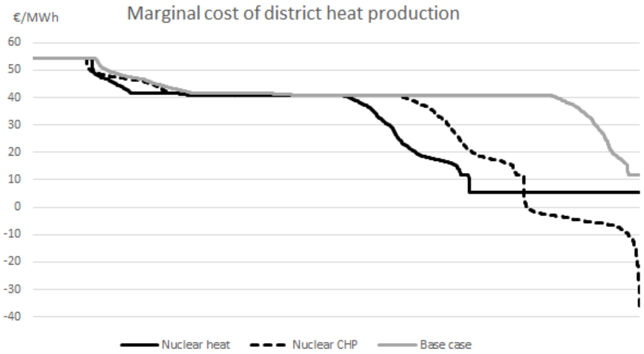

Fig. 5. The marginal cost of hourly district heat production, arranged from the most expensive to least expensive hour. The cost in nuclear CHP case becomes negative for some hours due to the electricity produced.

The payback period for an investment in the nuclear plant was estimated based on the cumulative expenses and incomes in the reference case versus the costs and incomes in the SMR scenarios. The cost and consumption structure was assumed to be same in years 2030-2050 for the purposes of calculating the payback period. This assessment would yield a payback period of a little over 10 years for the nuclear heat reactor and a payback period of approximately 14 years for the CHP reactor, assuming interest rate of 5%. The main reason for the longer payback time for the CHP option is the low assumed cost of the electricity. The sensitivity of payback period to used cost assumptions are shown in Figure 6, illustrating the variation of payback time between 10 - 20 years.

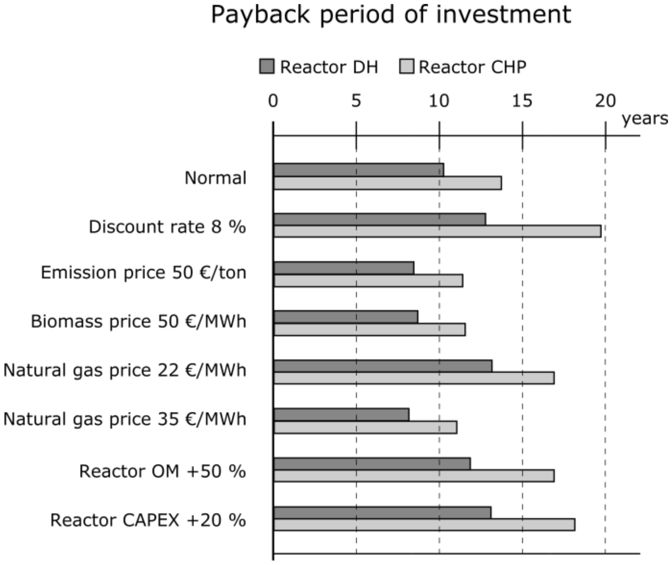

Fig. 6. Sensitivity of the investment payback period to the assumptions made.

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