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Nuclear Power for the Decarbonization of the District Heating Sector in the Czech Republic

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ABSTRACT

The article summarizes and evaluates the progress of research on nuclear power utilization for decarbonizing of the district heating sector. Nuclear power represents the most concentrated carbon-free energy source, which should become an integral part of the heat energy industry of the future. The current primary fuel mix for district heating is based mainly on fossil fuels – coal and gas. This work evaluates the current situation of nuclear-based district heating by conventional large nuclear power plant units and maps the future possibilities of new small modular reactors concepts applications or new-build plants integration. It introduces the district heating sector situation and the current potential of nuclear sources for heat production. The existing heat-only SMR concepts are presented and compared. Heat energy demand in the Czech's largest cities is detailly described and evaluated for nuclear unit utilization. Finally, a summary of all possibilities of nuclear source applications for the Czech Republic district heating sector decarbonization is provided, emphasizing topical issues and challenges.

1 INTRODUCTION

Energy production is currently facing a comprehensive effort of its decarbonization. The primary focus is aimed at the decarbonization of electricity production with renewable (wind and solar-based) electricity sources support. The district and process heat production is currently entirely overshadowed in this effort, despite the importance of this energy sector in many European countries. This work aims to the potential of nuclear sources evaluation for district heating applications in the Czech Republic.

The heat energy sector in the Czech Republic has always been linked with electricity production; cogeneration represents the most efficient way of covering our energy needs. Current outdated coal-based power plants in coal-mining regions will need replacement in the following years. An appropriate small modular reactor concept could be the right solution for covering the local heat demand and clean electricity production.

2 DISTRICT HEATING IN EUROPE AND THE CZECH REPUBLIC

Eurostat data provides total derived heat energy consumption in the European Union of nearly 2 000 PJ (for 2020).[1] The popularity of district heating varies across Europe, with the highest utilization of district heating in the northeastern part of Europe. Fuels used for heating production in the EU and the Czech Republic are shown in Figure 1. Currently, 63% of produced heat energy in the European Union comes from fossil fuels combusting, thus with a significant adverse environmental impact.[2]

In the Czech Republic, 38% of citizens are served by a district heating network, and the total amount of produced heat for district and process heating is 157 PJ. The final district heating consumption of the residential and public sector is 52 PJ; the rest of the total amount represents process heating, industrial sector, and distribution losses. The primary fuel for heat generation in the Czech Republic is coal, with nearly 50% share, followed by gas and biofuels. The fuel mix is linked with the electricity production mix because the largest coal-based power plants usually serve the nearest cities with heat energy, and the small local district heating sources (coal or gas-based) produce electricity and heat energy in cogeneration.[3]

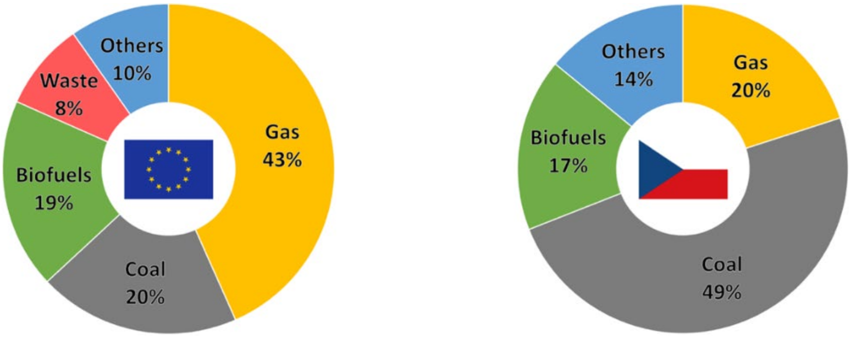

Figure 1: EU and Czech Republic heat generation by primary fuel [2][3]

3 NUCLEAR SOURCES FOR DISTRICT HEATING

3.1 Large conventional NPPs

The utilization of nuclear sources for district heating can already be identified in several European countries. Table 1 shows large nuclear power plants currently serving the nearest cities with heat energy for domestic heating, and additionally, several other units are in operation in Russia.[4]

Table 1: Nuclear power plants for heat production in operation [4][5][6]

Country	Plant name	Reactor type	Electric power
Bulgaria	Kozloduy	2x VVER-1000	2 080 MW
Czech Republic	Temelín	2x VVER-1000	2 164 MW
Hungary	Paks	4x VVER-440	2 027 MW
Romania	Cerna voda	2x CANDU-6	1 411 MW
Slovakia	Bohunice	2x VVER-440	1 000 MW
Switzerland	Beznau	2x WH 2LP PWR	760 MW
Ukraine	Rovno	2x VVER-440 2x VVER-1000	2 835 MW
	South Ukraine	3x VVER-1000	3 000 MW
	Zaporozhye	6x VVER-1000	6 000 MW

In the Czech Republic, only the Temelín NPP is currently serving heat energy to the nearest small city Týn nad Vltavou (8 000 citizens), with 157 TJ of heat in 2020.[3] The new interconnection of the NPP to the town of České Budějovice (nearly 100 000 citizens) is under construction. The pipeline will be 26 km long with a transfer capacity of 100 MW_{th} and will cover 1/3 of the current heat demand with an expected 750 TJ of delivered heat.[7]

The second Czech NPP, Dukovany, currently does not produce heat energy. Still, the nearness of Brno city (380 000 citizens with heat consumption of more than 3 500 TJ per year) evinces potential for future utilization of nuclear-based heat. This idea was firstly proposed 45 years ago. Currently, concerning the proposed new unit's construction, the 41 km long pipeline construction is in the early phase of its design.[8]

Considering the current situation and decarbonization efforts, the number of nuclear-based district heating networks should increase, especially in the case of newly built nuclear units with long proposed operation lifetimes.

3.2 Small modular reactor concepts

The latest IAEA SMR Technology Developments publication lists 70 reactor concepts, and many of them propose utilization for combined heat and power generation. Nearly all of them are currently in the design phase without constructing any pilot plant. Unfortunately, secondary circuits and heat production technologies' detailed specifications are unavailable. However, the conventional steam offtakes to the installed heat exchangers and further hot water/steam distribution are expected. Therefore, there is a proven technological possibility of heat energy supply. Naturally, the delivered heat energy will decrease the electrical power output. On the other hand, only four listed concepts are proposed for heat-only energy production without cogeneration. The first is the discontinued Russian concept RUTA-70, developed in the nineties, two of them are currently under development in China – DHR400 and HAPPY200, and the last one is TEPLATOR, under design in the Czech Republic. Figure 2 shows preliminary visualizations of these reactors.[9]

Figure 2: Visualisations of heat-only reactors DHR400, HAPPY200, and TEPLATOR [9]

DHR400 is a light-water moderated and cooled reactor with a 400 MW_{th} thermal output, operating at atmospheric pressure and a water outlet temperature of 98°C. It will use shortened (2.1 m) PWR fuel assemblies with an enrichment below 5% uranium-235. The same fuel is proposed for the light-water reactor HAPPY200 with an output thermal power of 200 MW_{th}, an outlet water temperature of 120°C, and operating pressure of 0.6-0.8 MPa.[9] Due to the heavy water-based moderation, the last concept, TEPLATOR, is designed to use already irradiated or fresh, slightly enriched VVER-440 fuel assemblies. Several TEPLATOR units are proposed – the first TEPLATOR DEMO will work at atmospheric pressure with an outlet water temperature of 98°C.[12]

The newest concept, not listed in the IAEA SMR publication, is Finnish LDR-50. It proposes operation on low pressure (0.5 MPa) with 50 MW_{th} thermal power output and water outlet temperature up to 120°C. The reactor core will consist of truncated (1-1.5m) PWR or VVER-1000 fuel assemblies with 2-3% enrichment and a light water moderator.[10] Another, historical, Finnish heating reactor concept (SECURE) was already being developed in collaboration with Sweden in the 1970s with two unit types (200-400 MW_{th} power output and 95-160°C outlet temperature).[11]

4 APPLICABILITY POTENTIAL IN THE CZECH REPUBLIC

4.1 Heat energy demand

Figure 2 shows heat energy demand in Czech cities. Since 70% of all the produced heat energy and district heating network of 11 of the 12 largest Czech cities is based on fossil fuels combusting, there exists an actual effort of decarbonization of this sector. The potential of replacing fossil fuel-based technologies with biomass combusting is limited, and solar or geothermal technologies are nearly inapplicable in Czech Republic's geographic conditions. Considering the current geopolitical situation, also the proposed gas-based way of the energy sector "decarbonization" needs to be revised. For these reasons, nuclear sources represent a possible alternative for district heating of the future.

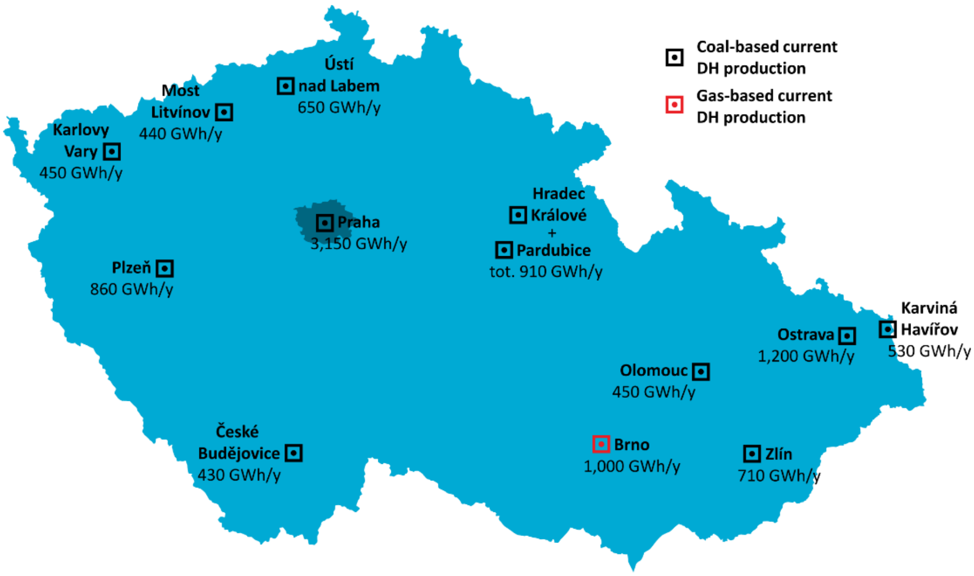

Figure 3: Heat energy demand in the TEPLATOR potential localities [12]

The maximal implementation of existing large nuclear power plants into the current district heating networks could replace outdated coal or gas-based sources without any prolonged licensing or construction processes and contribute to decarbonization targets. Temelín NPP will extend the existing network with České Budějovice interconnection shortly, and Dukovany NPP evinces an excellent potential for possible connection with Brno city. The large thermal power output of current NPPs is very beneficial for the possibility of regulation of delivered energy, which varies during the day and heating season.

Besides České Budějovice and Brno, there are two other localities – northwest (Karlovy Vary, Most, Litvínov and Ústí nad Labem) and northeast (Ostrava, Karviná and Havířov) of the Czech Republic. Both are important coal mining regions with significant energy demand, and the heat and electricity production there is historically based on hard coal or lignite. Considering current decarbonization efforts, green deal, carbon allowances price, etc., these outdated plants need to be replaced soon. Nuclear power – heat only or combined heat and power SMR concepts represent the perfect zero-carbon energy sources for these localities.

The last localities can be found in the middle part of the Czech Republic – cities Prague, Pilsen, Hradec Králové, and Pardubice. They are currently served by local or nearby coal-based heat or power plants. The significant heat demands at all the localities provide an excellent potential for a nuclear source for district heating.

4.2 Potential localities

On the other hand, the construction of new small modular concepts for heating brings several challenging issues. There exist only a few concepts in commercial operation. Thus, the construction of any unit needs to be preceded by a long comprehensive licensing process. The siting process for the final locality will be complicated, too, especially in the coal-mining region, due to inappropriate geological conditions. For these reasons, our work is currently focused on localities with nuclear facilities in operation or historically approved localities with no current installation. Besides two current existing NPP, three different localities exist.

Nuclear Research Centre Řež is located several kilometres from the Prague metropolis. Currently, two research nuclear reactors are there in operation (15 MW_{th} + zero power). This locality is then entirely suitable for nuclear installation, and it is also near the current heat pipeline, which serves Prague from the Mělník coal power plant. Heat demand in the locality (more than 11 PJ/year) represents an excellent potential for the new nuclear unit construction.[7]

Tetov is a historical nuclear source locality with up to two 1 000 MW_{el} units proposed. Since 2006, no nuclear units have been planned there. Still, this locality is approximately 25 kilometres from the current pipeline, which serves agglomeration Hradec Králové + Pardubice with 3.25 PJ of heat per year from a coal-based Opatovice power plant. Additionally, the locality also evinces a potential for serving another nearby city – Kolín.[13]

Also, the last potential locality – Blahutovice was proposed for two 1 000 MW_{el} units. In this locality, the combined heat and power production was expected, with up to 2x 850 MW_{th} of heat energy output. The prospective unit could serve wide surroundings with several important cities – the leading consumer represents heavy-industrial cities Ostrava, Karviná, and Havířov (6.25 PJ per year). Blahutovice locality meets all the crucial requirements for the nuclear facility siting.[14]

4.3 Unit power output, operation, and economics

All the above-listed localities require the construction of appreciable lengths of heat pipelines with significant transfer capacity. Considering the lower investment costs of SMR concepts, especially TEPLATOR, the pipeline cost represents an important part of the final investment and thus affect the final price of produced heat. For instance, the last part of the Temelín – České Budějovice interconnection will cost 70 million EUR for 11 km of pipeline.

For the competitive price of produced heat, the nuclear unit requires the maximal utilization of installed capacity due to the total investment cost. Finding the optimal installed output of the unit to cover the locality needs is challenging for heat production. During the heating season, the required heat production varies severalfold. If installed output fully covers the winter demands, it will be oversized for the rest of the year and operates only with tens of percent of capacity. Additionally, in the summer months, there is only some minimal level of heat generation necessary for hot water production. This approach is unfeasible from an economic point of view. For the fluctuating heat demand during the day, an essential part of nuclear-based district heating is energy storage systems – conventional hot water storage or innovative solutions (molten salts or phase-shifting materials).[15]

Figure 4 shows the dependence of the price of produced heat on the unit's constant heat energy output during the whole heating season for one TEPLATOR 50 MW_{th} unit. This is the lowest proposed installed output for all current heat-only concepts. During the heating season, the produced heat is approximately 1.5 PJ. Thus, the application is possible only in the largest Czech cities with a combination of suitable additional regulable sources – gas or biomass. Then the nuclear unit can be maximally utilized, and additional sources will cover the demand peaks or the summer season consumption. Utilization for lower output levels – 10 MW_{th} or 20 MW_{th} seems fully uncompetitive. The ideal solution for lower heat energy demands represents combined heat and power SMR concepts with a totally different operation economy.

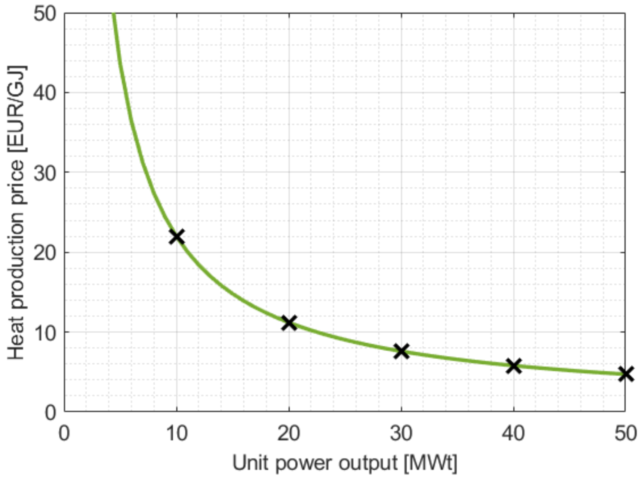

Figure 4: Dependence of produced heat price on the unit power output

5 CONCLUSIONS

Finally, any nuclear heat generation is clean, carbon-free, and reliable and will always lead to CO_2 emissions and air pollutants reduction. The concentration of nuclear energy released during nuclear fission is incomparable with any other carbon-free sources. Nuclear units then represent an excellent alternative to current outdated fossil fuel-based power or heating plants. The popularity of district heating in the Czech Republic is high, and the primary fuel is coal, which needs to be replaced soon.

Nuclear sources aim mainly to the localities with significant heat demand, especially the heat-only concepts – DHR400, HAPPY200, TEPLATOR and LDR-50. The district heating network cannot be based only on one significant (nuclear) source; additional conventional sources will be necessary, together with a thermal energy storage system. The manoeuvrability and final economics are significantly better for the combined heat and power generation.

In the Czech Republic, three current potential localities can be found which are partially prepared for nuclear facility siting (Řež, Tetov, Blahutovice). The surroundings of all the localities evince an appropriate heat demand. The alternative approach represents the maximal utilization of existing conventional NPPs for heating the nearest cities (České Budějovice, Brno).

Several important issues obstruct the wide spread of nuclear for district heating – minimum of SMRs in commercial operation, long licensing and siting process, economics, etc. However, there is no other possible alternative for clean and efficient heat production in the future.

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