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The Potential of the TEPLATOR Application in the Central Europe Region

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ABSTRACT

The innovative emissions-free concept of future district heating source TEPLATOR was introduced in 2020 by a group of researchers from CTU in Prague and UWB in Pilsen in the Czech Republic. TEPLATOR will use already spent nuclear fuel assemblies for a clean and economical heat-only production with an output range between 50 MWt and 170 MWt. This article evaluates the progress of the TEPLATOR applicability potential development, mainly focusing on the TEPLATOR fuelling.

The TEPLATOR facility potential location assumes a significant heat demand exceeding 1.5 PJ per year, and a currently operating district heating network is required. Then the production price of heat generated by TEPLATOR could reach less than 2 EUR per GJ of energy, which indicates an attractive alternative to the outdated coal-based heating plants and new intended gas boilers. The popularity of district heating varies across Europe, and there currently exist many promising locations for the TEPLATOR application.

The fuelling of TEPLATOR will be provided with the spent fuel from NPPs operating VVER, PWR, or BWR. The overview of the reserves of available fuel assemblies in EU countries is presented and assessed for the TEPLATOR use. The possibilities of spent nuclear fuel transportation have been investigated and evaluated. The final economic assessment of spent fuel utilization is provided. An alternative approach for the countries with no light water reactors in operation represents slightly enriched fresh nuclear fuel. The economic study of the TEPLATOR operation with fresh fuel has been performed and compared with the possibility of spent nuclear fuel use.

1 INTRODUCTION

District or process heat production is an integral part of the energy sector. The primary fuel mix for derived heat production in Europe represents natural gas (37%), coal (25%), biomass (20%), and waste (10%). Thus, more than 60% of heat is generated from fossil fuels combusting [1]. The competitiveness of fossil fuels-based heat production is decreasing because of the rapidly increasing price of carbon allowances, which nearly reaches 60 EUR per ton of CO_2 in the first half of 2021 [2].

Renewable sources for heat production as an alternative to fossil fuels are relatively limited, depending on each country's conditions. Another zero-carbon emission heat generation represents nuclear sources – large conventional power plants or SMRs project for combined heat and electricity production or the new innovative concept – TEPLATOR.

Spent nuclear fuel production and storing involve a significant cost for NPP's operators. Nevertheless, only a minor part of fuel energy is utilised for electricity production, and the rest remains in the stored fuel assembly. The TEPLATOR concept is able to generate heat from this already irradiated fuel with an additional economic profit and without any expensive reprocessing process.

2 THE TEPLATOR CONCEPT

TEPLATOR is the heat-only producing nuclear concept for the district heating of the future. TEPLATOR will use already irradiated fuel assemblies from commercial light water reactors due to the heavy water-based moderation. Several units of TEPLATOR are proposed with various power ranges and temperature output (see Table 1). The TEPLATOR design will use only known and proven technologies, which leads to low construction costs and thus competitive heat energy production. The estimated final production heat price ranges between 2 EUR and 5 EUR per GJ depending on the unit installed output power [3].

Table 1: The TEPLATOR proposed units [3]

Unit	**Max power output**	**Max temperature output**	**Operation start**
TEPLATOR DEMO	50 MW	98 °C	2028
TEPLATOR FULL	170 MW	200 °C	2032
TEPLATOR HT	170 MW	420 °C	2035

Figure 1: The TEPLATOR visualisation [4]

3 THE TEPLATOR APPLICATION POTENTIAL

The TEPLATOR facility will produce approximately 1 PJ of heat energy per 50 MW of installed power output for one heating season (approximately nine months in a temperate climate). The TEPLATOR output will be fully regulable from 0% to 100% of nominal power. Considering the higher investment costs of nuclear facilities, the maximum TEPLATOR utilisation is assumed (85% on average for presented economic estimations), thanks to the thermal energy storage system application. The facility will be shut down during the months with the lowest heat energy demand for refuelling and maintenance.

The appropriate yearly heating demand (more than 1.5 PJ) can be identified only in large cities with more than 100 000 citizens. The TEPLATOR potential locality must meet the safety, legislation, and geological requirements for the nuclear facilities – the final location is expected in the nearby surroundings of the served city.

The TEPLATOR application potential is promising in countries with the existing district heating systems in operation, currently primarily based on fossil fuels. Then TEPLATOR will be connected through the current heat-piping network. The district heating popularity varies across Europe. The highest share of the population connected to the heat network can be generally found in the north-eastern part of Europe. In western European countries, the popularity of district heating is lower, but the total amounts of consumed heat are also significant and promising for the TEPLATOR application.

The TEPLATOR demonstration facility is proposed for countries with sufficient reserves of spent light water reactor fuel assemblies, thus with a nuclear power plant in operation or already shut down after long-term operation. Potential localities, which meet all the mentioned requirements represent cities in the Czech Republic, Slovakia, Germany, France, Finland, Bulgaria, and Hungary [1].

4 THE TEPLATOR FUELLING

4.1 Spent fuel use

TEPLATOR will use 55 already irradiated VVER-440 fuel assemblies. Depending on the unit power output, one fuel loading will be sufficient for up to two years of operation. The already spent fuel from local NPPs will be used without any costs for purchasing, only for transportation and handling. For this reason, the TEPLATOR DEMO facility is primarily proposed for countries with the existing VVER-440 reactors, i.e., the Czech Republic, Finland, Germany, Hungary, and Slovakia. Table 2 presents the reserves of VVER-440 spent fuel assemblies in all the mentioned countries. When the fuel is finally removed from the TEPLATOR core and cooled down, it will be stored in the existing dry or wet interim storage, depending on each country's condition and legislation.

Table 2: VVER-440 spent fuel reserves in EU countries (at the end of 2016) [5]

<table>
<tr><th>Country</th><th>NPP</th><th>Reactor pools</th><th>Interim storage</th><th>Storage type</th></tr>
<tr><td>Czech Republic</td><td>Dukovany</td><td>2 306</td><td>7 896</td><td>Dry cask</td></tr>
<tr><td>Finland</td><td>Loviisa</td><td>339</td><td>4 828</td><td>Pool storage</td></tr>
<tr><td>Germany</td><td>Greifswald</td><td>-</td><td>4 802</td><td>Dry cask</td></tr>
<tr><td>Hungary</td><td>Paks</td><td>1 800</td><td>8 707</td><td>Dry vault</td></tr>
<tr><td>Slovakia</td><td>Jaslovske Bohunice</td><td rowspan="2">1 336</td><td rowspan="2">11 766</td><td rowspan="2">Pool storage</td></tr>
<tr><td></td><td>Mochovce</td></tr>
<tr><td>Total</td><td colspan="4">43 780</td></tr>
</table>

Each currently operating VVER-440 reactor core contains 349 additional fuel assemblies, and approximately one-fifth of the core assemblies are replaced every year. This continuous spent fuel production together with the existing reserves of more than 40 000 fuel assemblies represent a nearly unlimited resource of the potential TEPLATOR fuel for hundreds of years of its operation.

The spent fuel transportation will be performed via existing licensed casks. In the Czech Republic, the newly designed cask ŠKODA 440/84 for spent VVER-440 fuel storage at Dukovany NPP has been licensed by the Czech State Office for Nuclear Safety also for railway transportation [6]. In the Slovak Republic, the spent VVER-440 fuel from both NPPs is regularly transported to the Interim spent fuel storage (for Jaslovske Bohunice on-site for Mochovce off-site) via transport container TK C-30 on a special railway wagon [5].

The expected costs of the spent fuel transportation and handling are included in the TEPLATOR estimated operation and maintenance costs of 1 150 000 EUR per year [3].

4.2 Fresh fuel use

For countries, which do not currently operate any NPP, there is a possibility of fresh fuel use. This fresh fuel will be slightly enriched to 1.2% of uranium-235, and the operation condition will be the same as for the spent fuel use. Table 3 and the following equations (1 to 8) [7] describe the fresh fuel price estimation.

Table 3: Fresh fuel price estimation data [8]

Uranium costs ($P_{URANIUM}$)	70 USD/kg U_3O_8	**Product ($x_{PRODUCT}$)**	1.2% ^{235}U
Conversion costs ($P_{CONVERSION}$)	20 USD/kg	**Feed (x_{FEED})**	0.711% ^{235}U
Enrichment costs ($P_{ENRICHMENT}$)	55 USD/SWU	**Tail (x_{TAIL})**	0.25% ^{235}U
Fabrication costs ($P_{FABRICATION}$)	300 USD/kg	**U in FA ($UinFA$)**	approx. 135 kg

$$M_{FEED} = \frac{(x_{PRODUCT} - x_{TAIL})}{(x_{FEED} - x_{TAIL})} = \frac{(0.012 - 0.0025)}{(0.00711 - 0.0025)} = 2.06 \quad (1)$$

$$V(x) = (2 \cdot x - 1) \cdot ln \frac{x}{(1 - x)} \quad (2)$$

$$V(x_{PRODUCT}) = (2 \cdot 0.012 - 1) \cdot ln \frac{0.012}{(1 - 0.012)} = 4.30 \quad (3)$$

$$V(x_{FEED}) = (2 \cdot 0.00711 - 1) \cdot ln \frac{0.00711}{(1 - 0.00711)} = 4.87 \quad (4)$$

$$V(x_{TAIL}) = (2 \cdot 0.0025 - 1) \cdot ln \frac{0.0025}{(1 - 0.0025)} = 5.96 \quad (5)$$

$$SWU = M_{PRODUCT} \cdot V(x_{PRODUCT}) + M_{TAIL} \cdot V(x_{TAIL}) - M_{FEED} \cdot V(x_{FEED}) \quad (6)$$

$$SWU = V(x_{PRODUCT}) - V(x_{TAIL}) + M_{FEED} \cdot (V(x_{TAIL}) - V(x_{FEED})) =$$

$$= 4.30 - 5.96 + 2.06 \cdot (5.96 - 4.87) = 0.59\ [SWU/kg]$$

$$Price_{ENRICHED} = (P_{URANIUM} + P_{CONVERSION}) \cdot M_{FEED} + P_{ENRICHMENT} \cdot SWU = \quad (7)$$

$$= (70 + 20) \cdot 2.06 + 55 \cdot 0.59 = 217.85\ [USD/kg]$$

$$Price_{FA} = (P_{ENRICHED} + P_{FABRICATION}) \cdot UinFA = (217.85 + 300) \cdot 135 \quad (8)$$

$$\approx 70\ 000\ [USD]$$

The full TEPLATOR core loading contains 55 fuel assemblies. Then the final fuel price for one loading is approximately 3 300 000 EUR. Considering the spread of all the costs included in the uranium enrichment process and also the final price's dependence on the fuel manufacturer contract conditions, the fresh fuel price is estimated between 3 000 000 EUR and 3 500 000 EUR. The fresh fuel use for the TEPLATOR heat generation will increase the final producing price of heat energy by no more than 2 EUR per GJ (see Table 4).

4.3 Final heat production prices

Table 4: Final heat production prices [3]

Unit	Spent fuel use	Fresh fuel use
TEPLATOR 50 MW	4.69 EUR/GJ	6.18 EUR/GJ
TEPLATOR 100 MW	2.53 EUR/GJ	3.65 EUR/GJ
TEPLATOR 150 MW	1.81 EUR/GJ	2.81 EUR/GJ

5 CONLUSIONS

The Central Europe Region shows interesting potential for the TEPLATOR application. The TEPLATOR district heating solution is the way for the replacement of conventional outdated fossil fuel-based district heating plants and represents zero-emission heat production of the future.

Central European countries with the VVER-440 reactors in current operation or decommissioning (the Czech Republic, Slovakia, Hungary, and Germany) have sufficient spent fuel reserves for the TEPLATOR long-term operation. TEPLATOR will then utilise the already discharged fuel from NPPs for additional energy production and economic profit. Estimated production prices of heat will vary between 1.81 EUR/GJ and 4.69 EUR/GJ depending on the unit power output.

Another perspective EU country with VVER-440 in operation and the high popularity of district heating is Finland [1]. Countries without any power reactor in operation (for instance

Poland) or without suitable spent fuel reserves will be able to use fresh slightly enriched fuel with minimal additional costs. Then the final production price will increase to 2.81 EUR/GJ up to 6.18 EUR/GJ.

The presented prices do not include any costs for heat energy distribution, which are very variable and will be analysed in further studies. On the other hand, European countries' average consumer heat energy prices vary between 10 EUR/GJ and 29 EUR/GJ without VAT [1]. The TEPLATOR considered application localities require an existing DH network in operation, and just the current fossil fuels-based heat source will be replaced with the TEPLATOR technology. Then presented production prices of heat generated by TEPLATOR are evidently fully competent to the current heating plants for both fuel supply solutions.

The further TEPLATOR core designs will enable different light water reactor fuels utilisation and consequently diversify possibilities of its applications across Europe.

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