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Nuclear process heat application options: Highlights from the European GEMINI+ project

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ABSTRACT

The European Nuclear Cogeneration Industrial Initiative (https://www.nc2i.eu) has run the GEMINI+ project (https://www.gemini-initiative.com/geminiplus/) from September 2017 through February 2021 with the objective of supporting the industrial demonstration of a cogeneration High Temperature Gas-cooled Reactor (HTGR) power plant. This should help de-risk further projects and accelerate deployment. Recently, the Polish government has reconfirmed its interest, in particular to reduce the country's carbon footprint and its dependence on natural gas imports both for heating purposes and as a feedstock for chemical products.

The GEMINI+ project has performed several studies about how to use process heat from an HTGR for a variety of industrial purposes. These are of interest for most industrialized countries, and they often enable the integration of nuclear energy in Hybrid Energy Systems with variable renewables:

- Nitrogen fertilizers and chemical products.
- Hydrocarbon or ammonia synthesis.
- Dry reforming of methane with CO_2 to produce syngas as a feedstock for numerous chemicals.
- Hydrogen production for integration of nuclear energy in Hybrid Energy Systems.

This paper provides an overview of these studies and concludes with an impact analysis by evaluating the market and CO_2 savings potential of these technologies.

1. Introduction

Greenhouse gas emissions in EU28 amounted to 4457 Mt/yr CO_{2eq} in 2017 (Eurostat). Although electricity generation is primary energy intensive, it represents only 18 % of global energy consumption (OECD), whereas almost the entire rest of energy consumption is covered by fossil fuel. This means that even the hypothetical full decarbonization of global electricity generation would be insufficient to meet the most recent climate change mitigation targets.

Clearly, a credible decarbonization strategy must include the substitution of fossil fuels in industry. The most rapid and cost-effective avenue to emission reduction is to replace with priority the most carbon-heavy fossil firing and/or fossil feedstock in the most energy and CO_2-intensive industries, not only in power generation. In an earlier European project, a market analysis has identified a process steam demand of 87 GWth in EU28 (Bredimas, 2012) and greater than 7 GWth by the 12 biggest chemical sites in Poland alone.

Much of this demand can be delivered by High Temperature Gas-cooled Reactors (HTGR). Owing to HTGR development programs in particular in the UK, Germany and the US, later in a number of European and national R&D projects in China, Japan, South Korea and other countries, HTGR technology has reached a relatively high Technology Readiness Level (Fütterer et al., 2020). This clearly enables freezing of technology options and specifications, development of a supply chain and construction of a demonstration machine in the short to mid-term. Beyond high efficiency electricity generation, the attractiveness of

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HTGR for non-electric applications was recognized early on as well, for instance in the former German program until the 1980 s, in the US NGNP program, by the South African PBMR project, the Japanese GTHTR300C design or the Chinese HTR-PM600 concept. The inherent safety features of the HTGR enable a reduction of the Emergency Planning Zone and the co-location of nuclear and industrial plants on the same site. A range of chemical processes and hydrogen production methods were thoroughly analyzed. Specifically hydrogen production methods are today investigated in international cross-cutting projects (Fütterer et al., 2014) with experts from renewable and nuclear energies working side-by-side.

While the largest market for process heat is currently in the form of steam at approx. 550 °C, there is a substantial and growing market for bulk hydrogen with enormous potential for further growth.

This market potential and a number of those near-term technical options for extending the use of a cogeneration HTGR beyond steam supply at 550̊C were assessed that require only minor technology changes.

The baseline for a cogeneration HTGR in this study is the GEMINI+ concept. It is a hexagonal block type HTGR delivering 180 MWth (gross) at a rather conventional helium outlet temperature of 750 °C (Hittner et al., 2021).

The scope of this paper is on the following GEMINI+ studies about how to use process heat from an HTGR for a variety of industrial purposes, which are of interest for most industrialized countries:

- Nitrogen fertilizers and chemical products
- Hydrocarbon or ammonia synthesis
- Dry reforming of methane with CO_2 to produce syngas as a feedstock for numerous chemicals
- Hydrogen production for integration of nuclear energy in Hybrid Energy Systems

The paper concludes with an impact analysis by evaluating the market and CO_2 savings potential of these technologies.

2. Nitrogen fertilizers and chemical products

The European chemical industry, being one of the largest thermal capacity sectors, is a manufacturing success story, a wealth-generating segment of the economy, and a valuable part of Europe's economic infrastructure. European chemical industry continues to grow, and it aims to offer solutions towards achieving a competitive low-carbon and circular economy inside and outside Europe.

2.1. Market overview

Within the EU, the chemical industry, including the pharmaceuticals, rubber and plastics, is the largest sector, generating about 16 % of the total added value of EU production (CEFIC, 2020). The chemical industry is geographically concentrated, with about 70 % of the chemical companies being located in only seven countries, i.e. France, Germany, Italy, Spain, Poland and the UK. The European heat demand in industry had been quantified by the EUROPAIRS project (Bredimas, 2012), and the final energy use with energy efficiency improvements in the European chemical industry was estimated at around 3000 PJ from 2010 to 2050 (CEFIC, 2013). The peculiarity of the chemical industry is that energy sources, such as oil and natural gas, being the main energy vectors today, are used not only as energy carriers but also as feedstock.

More than 130 chemical sites were identified in Europe to quantify and map the power and process heat demand (Gradecka et al., 2015). It was determined that the thermal needs of the majority of chemical sites range from 100 to 200 MWth with electrical needs of less than 100 MWe (Ståhl et al., 2015). The process temperature of steam networks is usually in the range 200–500 °C at pressures of 0.2 – 3 MPa. For instance, the total heat demand of the 12 largest chemical plants in Poland was identified as more than 7000 MWth, and it was concluded that the thermal requirements of a single chemical plant could be covered in most cases by an HTGR delivering 165 MWth equivalent of steam (Wrochna and Malesa, 2017). Such a plant would replace existing boilers of the same capacity and plug directly into existing steam distribution networks on chemical production sites. This is a relatively simple, quick and cost-effective innovation towards displacing fossil fuels.

Fertilizer production, which is one of the chemical sub-sectors, is energy-intensive and highly dependent on natural gas. It is estimated, that fertilizer production accounts for approximately 1.2 % of global world energy consumption, ~90 % of which is consumed for nitrogen-based fertilizers (International Fertilizer Association (IFA), 2014). Nitrogen fertilizers require large amounts of fossil fuels, i.e. 1.5 tons of oil equivalents to make 1 ton of fertilizer. The EU fertilizer manufacturers alone consume about 13 billion m^3/yr of natural gas. In terms of carbon footprint, the EU is amongst the world's most carbon efficient in this field: emissions in ammonia production are ~ 2 t CO_2 per t NH_3 (2011), similar to the specific emissions of steel. On average, one-third of emissions from natural gas-based ammonia production is related to fuel combustion and two-thirds are associated with the use of fossil fuel as the feedstock to produce hydrogen for ammonia synthesis (Fertilizers Europe, 2012). Therefore, if the energy needed for fertilizers could be delivered as heat from an HTGR instead of burning natural gas for that purpose, emissions of approx. 8 Mt/yr of CO_2 could be saved without taking into account the effect of methane saved from leaking into the atmosphere.

2.2. Manufacturing process parameters

Nitrogen fertilizers come in many different forms, rich in nitrogen, including many types of liquid and solid products, among which the most common ones are ammonia, ammonium nitrate, and urea. Ammonia is produced by reacting nitrogen from the air with hydrogen from natural gas at high pressure and temperature. Ammonia (anhydrous) is stored as a liquid under pressure or cooled. It is often converted to other types of fertilizers for ease of handling (Fig. 1).

First, nitric acid is obtained by mixing ammonia and air in a reservoir, followed by absorption of nitric oxide gas in water. Concentrated

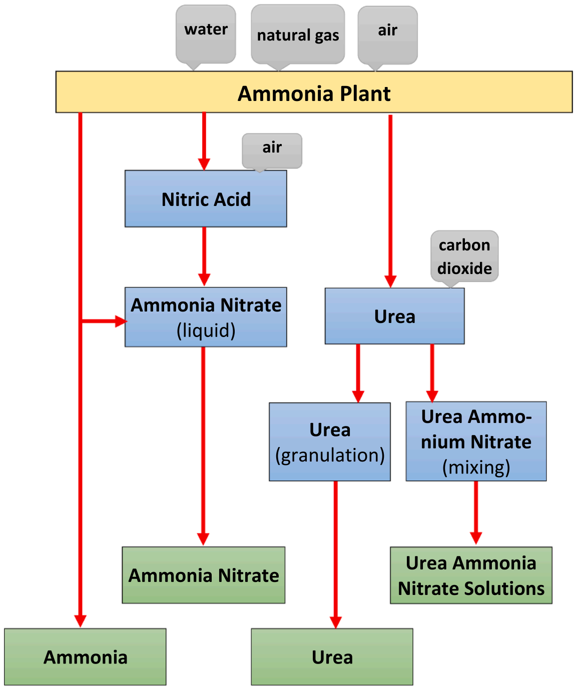

Fig. 1. Production route for nitrogen fertilizers.

nitric acid and ammonia gas are then mixed together to give ammonium nitrate. Urea is obtained by reaction of ammonia under high pressure with carbon dioxide. Both ammonium nitrate and urea can be further concentrated and converted into a solid form. The next step in the process can combine urea with ammonium nitrate solution to form liquid urea ammonium nitrate (https://www.yara.com/crop-nutrition/why-fertilizer/production-of-fertillizer/ ; Accessed 20 June 2022).

Among the various types of fertilizers, nitrogen fertilizers require the most energy for the preparation of raw materials. More than 90 % of the total energy demand is needed for the production of ammonia (Table 1), other types of fertilizers require less energy. Thus, steam is used at various pressures and temperatures to maintain chemical processes at a fixed temperature. The reaction temperature does not exceed 600 °C at a maximum process pressure ~ 10 MPa, and is readily delivered by HTGR.

2.3. HTGR process heat for fertilizers

Nuclear energy can deliver process heat for a variety of industrial applications including the chemical industry, as well as for the production of nitrogen fertilizers thus avoiding large amounts of CO_2 emissions. The heat source required for fertilizer production is usually obtained by partial combustion of natural gas and by burning all purge gases. This heat can be replaced by nuclear heat from HTGR. The heat carrier in chemical plants is often steam at temperatures of ~ 450–550 °C. HTGR can readily deliver steam in this temperature range. This steam can be used for three purposes: heat transfer, as a reactant, and/or for flexible power generation in the required fractions. Ammonia, a key product in the nitrogen fertilizer manufacturing process, requires a large amount of hydrogen to produce it, today mainly produced by steam methane reforming of natural gas. The use of nuclear process heat can save large amounts of natural gas and the corresponding emissions.

Major emissions associated with nitrogen containing fertilizers production are:

- nitrogen oxide (NO_x) and nitrous oxide (N_2O) parasitically produced during nitric acid production; because these molecules are potent greenhouse gases and air pollutants, they are catalytically reduced in tail pipe converters and their emission requires careful monitoring;
- CO_2 emitted by steam methane reforming (combustion for heat and chemical reaction) of natural gas to produce the hydrogen needed for the Haber-Bosch process;
- CO_2 emitted when natural gas is combusted to run the Haber-Bosch process for ammonia synthesis; this heat could be replaced by nuclear process steam.

Fertilizer production is thus an area where natural gas and the concomitant emissions from using it as an energy carrier could quite easily be eliminated with steam-generating HTGR. Emissions could be further reduced once HTGR are designed to produce bulk hydrogen as feedstock for ammonia. However, this development was until recently hindered by cheap natural gas and relatively low CO_2 taxes.

3. Hydrocarbon synthesis for HTGR system integration

This section identifies innovative chemical processes that are suitable for coupling with an HTGR of the GEMINI+ design. For optimum utilization of available heat, these processes have to match the process steam supply parameters recalled in Table 2.

Other criteria were that the processes should enhance sustainability by reducing CO_2 emissions, substitute fossil feedstock, raise recycling quota or store energy from variable energy sources. Furthermore, the processes should have a high TRL allowing implementation in the short term.

From this review, two processes were identified for closer consideration: Polymer Cracking Process (PCP) and the extraction of montan wax.

3.1. Polymer cracking process

This process was developed in parallel at the University of Hamburg (Kaminsky, 1989) and from a consortium led by British Petroleum (BP) (BP Chemicals, 1994; Greencircle Polymers Ltd., 2016). In Hamburg, a laboratory-scale test facility was used. The consortium built a test facility in Grangemouth, Scotland in 1994, which is still in operation

Table 2
GEMINI+ process steam supply.

Parameter	Value
Mass flow rate	64 kg/s
Pressure	13.8 MPa
Temperature	540 °C
Useable power	165 MWth
Annual operation time	7000–7500 h

Table 1
Main process parameters for production of nitrogen fertilizers.

Type of product, chemical formula	Reaction	Process parameters		Specific energy requirement (net / average with BAT**) [GJ(LHV)/t of product]	Heat demand [% of total energy]
		T [°C]	p [MPa]		
Ammonia (Am), NH_3	Haber-Bosch process $N_2 + 3H_2 \rightarrow 2NH_3$	(350 – 500)*	(10 – 25) *	~37 / 29 (International Fertilizers Association (IFA), 2009)	90
Urea (U), $CO(NH_2)_2$	$2NH_3 + CO_2 \rightarrow NH_2COONH_4 \rightarrow H_2O + NH_2CONH_2$	190	14–17	3.7 /3.2 (Fertilizers Europe, 2000a)	9
Ammonium nitrate (AN), NH_4NO_3	$HNO_3 + NH_3 \rightarrow NH_4NO_3$	100–180	~0.4	0.5 / 0 (Fertilizers Europe, 2000b)	1
Urea ammonium nitrate (UAN)	mixing (U + AN)	ambient	0.1	0.04 / 0 (Fertilizers Europe, 2000a)	~0
Nitric acid (NA), HNO_3	Ostwald Process (not stoichiometric here) $NH_3 + O_2 \rightarrow$ $NO_x(N_2O) + H_2O \rightarrow$ $NO + O_2 \rightarrow$ $NO_2 + H_2O \rightarrow$ $HNO_3 + NO$	~230	1	−2.3 / −3.1 (Fertilizers Europe, 2000c)	exothermic reaction

* high temperature and low pressure in optimum mode are favorable for the ammonia synthesis reaction.
** Best Available Techniques.

today.

In PCP, plastics waste is pyrolyzed in a fluidized bed reactor. Due to the nature of the reactor type, short dwell times of the plastics in the reaction room ($2-3$ s) are possible. These short dwell times allow the depolymerization of the plastics mainly into monomers thus enabling optimum recycling of plastics waste. The advantages of PCP in comparison to the most used state-of-the-art thermo-mechanical recycling are (Hunold + Knoop Kunststofftechnik, , 2017).

1. Expanding the range of recyclable plastics beyond thermoplastics only, which represent only about 50 % of the EU plastics waste (Plastics - the Facts, 2017).
2. The Grangemouth results show that mixed plastics can be handled (Tukker et al., 1999) and energy and water for sorting and cleaning of the waste could be saved (CVP Service Technology, 2013; Gu et al., 2017). In addition, potential environmental pollution with cleaning agents can be avoided (CVP Service Technology, 2013).
3. PCP allows a large product range from the recycled waste while classical plastics recycling yields fibers, thus limiting the application of this product (Garcia and Robertson, 2017).

The principle of PCP is illustrated in Fig. 2. The shredded educt is transported from the reservoir (1) with a heated conveyor screw (2) into the reactor (3). The reactor contains fluidization particles, e.g. sand, and is fluidized by inert gas or steam. The pyrolyzed products are separated and withdrawn from the process via a cyclone (4, 5), a condenser (6, 7) and a membrane separator (10), respectively for solids, liquids or gas. The energy for the process is provided by a pump (9) and a heater (11). The heater can be designed as a heat exchanger, coupled with external steam supply from an HTGR.

From the different types of plastics, polymethyl-methacrylate (PMMA) was chosen for a closer examination. PMMA is a ubiquitous transparent polymer, widely used in construction, car industry, computer screens, optics, medicine and other applications. The pyrolysis of PMMA requires temperatures between 450 °C and 490 °C matching well the available steam temperature. Additionally, this process shows high conversion rates (up to 97 %) from PMMA to Methyl methacrylate (MMA). MMA is a relatively valuable type of plastics and its recycling saves significant amounts of CO_2 (https://cefic.org/a-solution-provider-for-sustainability/chemical-recycling-making-plastics-circular/chemical-recycling-via-depolymerisation-to-monomer/new-innovative-process-for-recycling-end-of-life-pmma-wastes; Accessed 20 June 2022), because its production generates 3.75–4.78 kg CO_2 per kg of PMMA (Kerscher, 2016), which makes PMMA about twice as CO_2-intensive as steel.

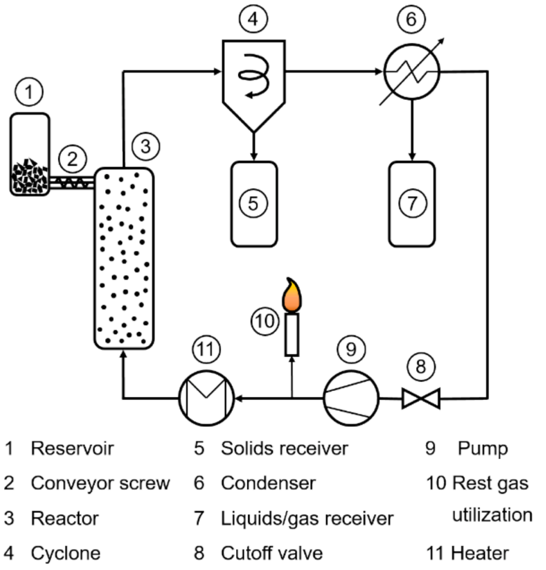

Fig. 2. Schematic of the PCP.

Some outcomes of the Hamburg test facility for PMMA recycling are shown in Table 3. In the range between 450 °C and 490 °C, good conversion rates between 91 % and 97 % are achieved. This is true for pure PMMA as well as for mixed PMMA of different colors, which would otherwise be considered waste that cannot be recycled with conventional methods (Kaminsky et al., 2006).

To assess the potential of coupling with nuclear process steam, numbers from existing research were taken (Kaminsky et al., 2006). The required heat for melting and depolymerization of the pure PMMA of 0.6 kWh/kg, the heating of the fluidization gas is 0.2–0.4 kWh/kg and losses amount to 0.5 kWh/kg. All values are related to the PMMA feed. As a result, the recycling of 1 kg pure PMMA consumes up to 5.4 MJ. Disregarding transportation losses, a chemical facility coupled with one GEMINI+ reactor could process 118.46 t/h ± 8.45 t/h of PMMA waste. Assuming continuous operation, such a plant could triple the currently recycled European PMMA waste (Plastics - the Facts, 2017) and save 3–4 Mt/yr of CO_2 compared to the production of virgin PMMA. This is one example where the use of nuclear process heat with an HTGR could save significantly more CO_2 by using it for process heat applications than for generating electricity.

The identified risks for coupling are: (I) process stability, (II) upscaling of the process and (III) availability of PMMA waste.

(I) Research has shown, that the process is vulnerable to build-up of bituminous compounds (Kaminsky, 1989). An educt loaded with such compounds, can adhere to the conveyor screw, the reactor and the process path. This necessitates regular and intensive cleaning operations and a subsequent reboot of the process. Cleaning and separation of the educt can minimize the problem. On the other hand, the Grangemouth test facility shows that mixed educts with impurities are with some limitations manageable (Tukker et al., 1999).

(II) Due to the nature of a fluidized bed reactor, such a reactor is scalable only within strict limits. For large diameters of the reaction room, the required velocity of the fluidization gas and the pressure loss are unsolvable physical and economic challenges (Stieβ, 1997). A possible solution to recycle maximum amounts of PMMA with minimum energy is the use of several chemical reactors in parallel. This modular approach also improves process stability and facilitates maintenance.

(III) PCP for PMMA waste could in principle triple the recycling capability with a single HTGR coupled facility. However, there are alternative recycling methods for PMMA under development, which could lead to competition for plastics recycling and limited availability of waste. To avoid this, a small adjustment of the process sequence would allow the recycling of polyethylene and polypropylene plastics, opening the process capabilities to the most used kinds of plastics. PCP of poly-olefin mixtures require higher temperatures of about 730 °C (Kaminsky, 1989). The fluidization gas could be preheated with the heat of the nuclear reactor. Burners, firing directly the chemical reactor, can cover the required difference of about 200 K. They are fuelled by the

Table 3
PMMA pyrolysis with PCP (Kaminsky et al., 2006).

	T [°C]	Pure pellets			Waste
Products		450	490	590	490
Gas [wt%]		0.37	2.63	42.46	7.36
Liquid (MMA) [wt %]		98.48(97)	97.08 (95)	57.27 (55)	92.13 (91)
Carbon black [wt %]		0.15	0.29	0.27	0.51

generated off-gas (10 in Fig. 2). At laboratory scale, the process produced enough gas to bridge the temperature gap between 530 and 730 °C by itself. The implementation of such processes could make an end to the current practice of exporting European plastics waste to other continents.

3.2. Montan wax extraction

This process is a type of thermo-chemical coal conversion (Herdegen et al., 2018). The produced wax can be used as lubricant or bulk material in plastics production or as protection cover for fruits. It can be processed to paraffin, olefin or their waxes with refinement techniques, e.g. steam distillation.

Mined raw lignite is crushed in a mill and subsequently dried in a tube dryer to 18 % maximum humidity. For wax extraction, particle sizes between 0.5 and 4 mm are required. Percolation is the classical approach for the actual wax production (Herdegen et al., 2018). In a multi-stage process, the montan waxes are washed out of the coal with the help of toluene. The toluene is placed in a cross overflow at 80 °C on the lignite, which slowly conveys on a belt. This process is repeated until the solvent is saturated with waxes. The toluene is heated to operating temperature before every use. In the end, the loaded solvent is heated to extract the waxes and to regenerate the toluene. The de-waxed lignite can then be used for power generation, but it could also be gasified or liquefied, e.g. to jet fuel.

To assess the coupling potential, three main energy consuming process steps were identified: (1) drying of the lignite, h (2)eating of the solvent for the belt extractor and (3) desolvation of the toluene.

(1) For the drying of the wet, raw lignite, a rotary dryer without significant heat losses is assumed (Krokida et al., 2006). Prior to the extraction process, the coal has to be dried from a humidity of about 50 % to less than 18 %. The following simplified equation gives the ratio of required heat (Q_1) [kJ] to mass of raw lignite input (m_L) [kg]:

$$\frac{Q_1}{m_L} = \Delta T_1 \bullet \overline{c_{p,air}} \bullet \frac{(X_{L,in} - X_{L,out})}{(X_{air,out} - X_{air,in})} \tag{1}$$

where ΔT_1 [K] is the temperature difference of the air, used to dry the lignite, which has to be heated from ambient temperature up to 80 °C. And $\overline{c_{p,air}}$ [kJ/(kg K)] is the specific, average heat capacity of the air. The variable X represents the water content of the air and the lignite at the inlet and the outlet, respectively.

(2) For the heating of the toluene required on the belt extractor, the specific ratio is:

$$\frac{Q_2}{m_L} = c_{p,tol} \bullet \frac{V_{tol}}{m_L} \bullet \rho_{tol} \bullet \Delta T_2 \tag{2}$$

where ΔT_2 [K] is the temperature difference of the toluene, heated from temperature after use of 50 °C up to 80 °C, the extraction temperature. The specific heat of toluene is $c_{p,tol}$ [kJ/(kg K)] and its density ρ [kg/m^3].

(3) As the specific heat capacity of toluene is just given for 80 °C (Grolier et al., 1993), the equation for the desolvation of the toluene is nearly the same, as the one for (2), but the toluene is heated from 80 °C to 110 °C:

$$\frac{Q_3}{m_L} = c_{p,tol} \bullet \frac{V_{tol}}{m_L} \bullet \rho_{tol} \bullet \Delta T_3 \tag{3}$$

Summing up the three partial results ($Q_1/m_L = 21.53\,kJ/kg$, $Q_2/m_L = 134.4\,kJ/kg$ and $Q_3/m_L = 134.4\,kJ/kg$), a heat per input lignite mass of $Q_S/m_L = 290.33\,kJ/kg$ is necessary for the extraction. With the selected assumptions, a maximum of about 15.3 Mt/yr of lignite could be processed in the coupled plant. This would correspond to a tenth of the current annual German lignite production or a quarter of the Polish (EURACOAL, 2019).

The identified risks for a coupling are: (I) availability of lignite, (II) a too small sales market, and (III) corresponding with (II), the economic efficiency.

(I) Currently, an approximate wax fraction of as much as 10 % in bituminous coal is required, which is found only in few deposits in the world (Wei et al., 2014). Therefore, current research focuses on the use of coal with lower wax content (Herdegen et al., 2018), thus expanding the usable lignite reserves to nearly every European storage location, which have an average wax fraction of about 5 %.

(II) The imagined facility could produce 750 kt/yr wax. This corresponds to approximately-three times the annual production of the German company ROMONTA, supplying about 90 % of the world market for montan wax (Kilian, 2015). Montan wax production is currently suffering from high-energy costs and rising CO_2 prices, as the current heat is supplied by lignite-fired plants. This is an actual downside in the competition with synthetic, bio or other fossil-based waxes. With the coupling of the process with an HTGR, the montan wax generation could contribute to the fast growing world wax market, with expected growth rates between 3 % and 6 % between 2017 and 2026 (Maximize Market Research PVT. ltd., 2019; Roy, 2018). Additionally, ongoing research is investigating new fields of applications, for example the use of new bleaching technologies to widen the range of usage (Wei et al., 2014; Kilian, 2015).

(III) The economic challenges were already mentioned. Moreover, the coal dust, generated during the process, is currently burned for power production, which is expected to finish in countries implementing a coal phase-out. Current research on polygeneration is looking into options for using this carbon feedstock in combination with a CO_2-free hydrogen/oxygen source to produce a wide range of products.

4. Dry reforming of methane using CO_2 to syngas

Dry reforming of methane to produce syngas is a way to use natural gas deposits with high CO_2 content. Alternatively, it can be considered a form of Carbon Capture and Utilization (CCU) where CO_2 is valorized to form other products.

The reaction $CO_2 + CH_4 \rightarrow 2CO + 2H_2$ is endothermic at 4.35 MJ/kg ($2CO + 2H_2$) and is performed industrially at high temperature (815–960 °C depending on the used process).

Already in 2010, the global syngas production corresponded to the equivalent of more than 70 GWth, 45 % of which was used to produce chemicals and 38 % to produce liquid fuels (Ampelli et al., 2015). This fundamental and widespread process in the chemical industry can be achieved with novel catalysts (hydrotalcite derived materials) already in the range 550–650 °C thus making it accessible for using process heat from HTGR (Motak et al., 2018).

CO_2 conversion to fuels, rather than organic chemicals, is rightly expected to play a major role in CO_2 emission management strategies. The hydrocarbon fuels market is very large (much larger than the market of organic chemicals), and around 5–10 % of current total CO_2 emissions can be recycled for the production of new hydrocarbon fuels, which could be used for applications, which are difficult or impossible to electrify such as aviation. This could achieve a worldwide CO_2 emission reduction of approx. 1.75–3.5 Gt/yr.

Processes for CO_2 conversion are energy-intensive (Fig. 3). To make sense, they require this energy to be CO_2-free (renewables or nuclear). These processes are likely a key element of sustainable development towards a low-carbon economy because many of the products will remain essential in the future.

Currently, the lack of stable catalysts is slowing further

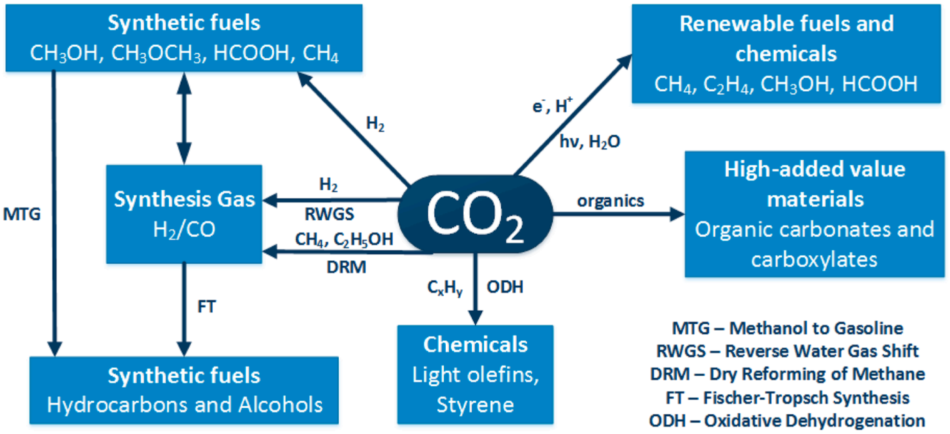

Fig. 3. Catalytic routes for CO_2 transformation into fuels and chemicals requiring energy in the form of sunlight, heat, electricity or hydrogen.

commercialization of dry methane reforming and the use of heat from HTGR for this purpose. Various candidate catalysts have been studied in the last decades. Since CO_2 is a stable, non-reactive molecule, it requires a highly active metal catalyst. Noble metals were very promising materials, but their high price and limited availability directed the research towards nickel-containing catalysts. Nickel-based catalysts show similar activity to those of noble metals, however, they tend to undergo deactivation due to formation of carbon deposits. Thus, the main challenge concerning such catalysts is to increase their stability. Various approaches and solutions have been proposed, including increasing nickel-support interactions, increasing surface basicity, decreasing nickel particle size and increasing nickel dispersion, which may be realized via application of appropriate support or addition of promoters. In view of these facts hydrotalcite-derived materials have been proposed. Their catalytic properties may be tailored by controlling composition of the catalyst precursor, synthesis method and promotion by various metal species.

5. HTSE for dynamic peak shaving

Cogeneration is an enabling technology for Hybrid Energy Systems (HES), which integrate several energy sources, in particular large fractions of variable renewables. Examples for such opportunities can be found in literature and often involve hydrogen as a storable (intermediate) product. The overall efficiency and cost of hydrogen production are decisive for the feasibility of the HES.

The aim of this analysis was to check the suitability of high temperature steam electrolysis (HTSE, typically at 750–1000 °C) in this context. HTSE is one of the most promising, efficient and flexible hydrogen production methods, which can be powered by a combination of heat and electricity from an HTGR, which is why it was selected here. HTSE does not employ toxic materials, precious metals, rare materials etc. and upscaling HTSE to industrially relevant scales is not restricted by a foreseeable material shortage.

It was also investigated whether HTSE can be used for “peak shaving” which is the dynamic adaptation to short-term demand–supply mismatches in the electric grid.

The on-site produced electricity is expected to be much cheaper than electricity bought from the grid. HTGR can indeed be designed for load following at a 5 %/min ramp rate and can indefinitely, although not economically, operate between 20 and 100 % name plate power. However, most engineers recommend keeping the reactor power constant and perform load switching on the secondary side instead. Constant power supposedly minimizes the risk of thermal fatigue with a negative impact on service life and was assumed here.

For peak shaving, a consumer reduces power consumption quickly and for a short period of time to avoid a spike in consumption. This is either possible by temporarily scaling down production, activating an on-site power generator or relying on a battery. HTSE is preferred over other technologies because it can adapt more rapidly to power variations than chemical processes with high thermal inertia such as the sulfur-iodine process or steam methane reforming (Keçebaş et al., 2019; Keçebaş et al., 2019).

Solid Oxide Electrolyzer Cells (SOEC) can be used for HTSE. SOEC are reversible and can of course be operated as an electrolyzer, but also as a fuel cell, which reduces investment costs. However, the fuel cell mode achieves only approx. 1/5 of the electrolyzer output. SOEC can also electrolyze CO_2 or co-electrolyze H_2O and CO_2 mixtures to form syngas (Keçebaş et al., 2019). Recycling of smoke stack CO_2 or capture from air and subsequent electrolysis are studied as an alternative for synthesizing CO_2-neutral synthetic hydrocarbons (Ebbesen et al., 2009). Co-electrolysis in SOEC makes very efficient use of electricity and heat and features high reaction rates. The produced syngas can be converted into a broad array of hydrocarbons by Fischer-Tropsch synthesis. Another option is the co-electrolysis of nitrogen and water producing valuable nitrogenous chemical substances such as ammonia.

It has to be kept in mind that some steam heating is needed for hot idling operation of SOEC, which is necessary because the thermal ramping tolerance for HTSE cells is rather low, usually a 60 K/h gradient is acceptable for either heating or cooling, so that a cold start from ambient to operating temperature at about 800 °C would take as much as 13 h.

Two presented simple case studies account for a rough estimate of the basic economy of HTSE-HTGR connection.

- Case 1: HTSE is working in SOEC mode (hydrogen production), electricity is purchased at baseload price. All produced hydrogen is sold at an assumed price of 3 EUR/kg.
- Case 2: HTSE is in SOEC mode (hydrogen production) in periods with baseload electricity price (7000 h/yr), or in SOFC mode (electricity production) in periods with peak electricity price (1000 h/yr). Most hydrogen is sold, but during periods with peak electricity price the produced hydrogen is reconverted to electricity and sold at the peak electricity price.

Both case studies show no return of investment, which is caused mainly by the low life expectancy and high cost of HTSE and of auxiliary equipment. Key to the feasibility of HTSE, especially for peak shaving, is thus the stretching of service life and cost cutting.

The degradation behavior of active materials was studied in a test rig, able to measure performance decrease caused by degradation of electrolysis cells with time and with changing operating conditions. This work is reported in (Tkáč et al., 2019).

HTSE technology is not mature yet. In particular, high investment costs and short service life of key components put it at a disadvantage to other possible peak-shaving technologies, or even to low-temperature electrolysis. Unlike HTSE, where we clearly see a significant potential for cost decrease, we do not expect hydrogen tanks and compressors to go down in price significantly.

However, the potential of HTSE is such that it deserves the currently ongoing further development in many countries worldwide, which could make it the preferred choice for peak shaving in the future.

6. Concept of a hybrid energy system for an application in the polish industry

Hybrid Energy Systems (HES) combine different energy sources and consumers to optimize efficiency and to iron out demand–supply mismatches. HES with cogeneration HTGR are recognized as an avenue towards the decarbonization of Polish industry, which is one of the largest CO_2 emitters in the EU. This section presents HES based on the HTGR specifications defined in the GEMINI+ project. An HTGR is coupled to a representative chemical facility in Poland consuming energy in the form of heat, electricity and hydrogen (Pawluczyk et al., 2019).

Two base cases are presented, one considering coupling with High Temperature Steam Electrolysis (HTSE) and the other with allothermal Steam Methane Reforming (SMR) for hydrogen production. Thermochemical cycles for hydrogen production are not yet considered here. In both cases, the HTGR supplies the required steam and electricity. For comparison, a third case assumes hydrogen production by Low-Temperature Electrolysis (LTE) with Polymer Electrolyte Membrane (PEM) electrolyzers. The three cases are summarized in Fig. 4.

Hydrogen production is energy-intensive, which is why a relatively large fleet of HTGR units is necessary to replace fossil-fueled boilers for hydrogen production. The use of HTSE would be more sustainable than the other options because it consumes a moderate amount of primary energy while being CO_2-free. The HES with SMR can be easily coupled with the HTGR, it is least primary energy-intensive. Although less CO_2-intensive than classical autothermal SMR, allothermal SMR still has a significant CO_2 footprint despite the use of HTGR produced steam and of nuclear electricity. Assuming no CO_2 capture, this could reduce CO_2 emissions by 15.4 % in the considered INL concept of SMR + HTGR (Wood and Boardman, 2010), which, with further process optimization could be increased, theoretically to 35 % (Verfondern, 2007). The concept with LTE is very energy-intensive, it requires a large number of electrolyzers, and additional reactors would be required to meet the heat demand of the chemical facility.

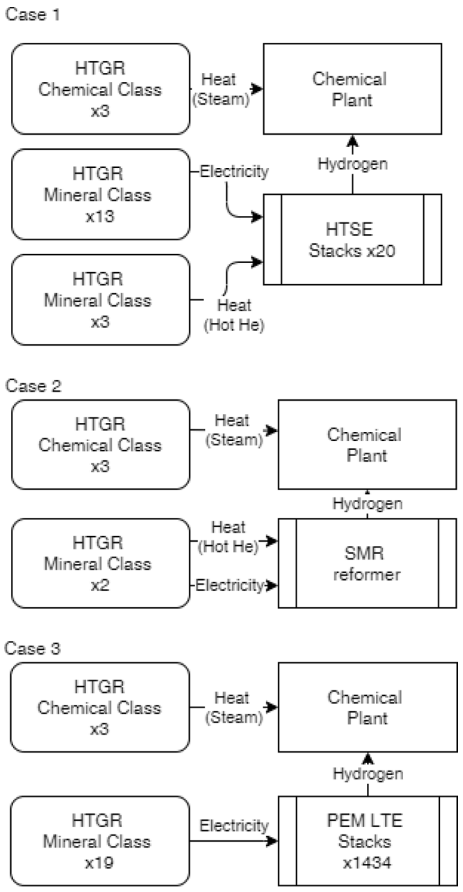

Fig. 4. Different HES concepts with HTGR.

6.1. HES concepts with HTGR

The representative Polish chemical plant consumes a combination of ~ 450 MWth, 30 MWe and up to 28.7 t/h H_2. The aim was to replace the existing fossil-fired boilers with a minimum number of HTGRs and to calculate the expected savings of natural gas and emissions of CO_2.

The considered HTGR is of the GEMINI+ design delivering 180 MWth (165 MWth net in the form of steam) but using two different Balance of Plant systems (Amezcua, 2019): The "Chemical Class" (CC) version produces only high-temperature steam (heat), while the "Mineral Class" (MC) version is based on a helium Brayton cycle producing heat (helium) and/or electricity.

The assumptions for power conversion efficiency and hydrogen production efficiency were the following:

CC HTGR – a unit generates 180 MWth and 165 MWth net for steam with 13.8 MPa and 540 °C.
MC HTGR – a unit with 180 MWth, 85.5 MWe, and 750 °C hot helium. In Case 2, electricity production is reduced and some helium is fed to the SMR process.
HTSE – a single electrolyzer stack consumes 51.2 MWe (including helium pre-heating and other consumptions) and 29.9 MWth of heat. It produces 1.45 t/h H_2.
LTE – a single stack produces 20 kg/h H_2 and consumes 1.15 MWe.
Allothermal SMR – scaled from an INL process (Wood and Boardman, 2010) a plant generating 28.7 t/h H_2 would require natural gas feed of 114292.6 m^3/h, and 2 MC HTGRs to deliver 10 MWe electricity and 259.6 MWth nuclear process heat; the whole process would generate 5920 t/d CO_2.

Three systems were proposed (Fig. 4).

- Case #1 is a set of 16 MC-HTGRs providing electricity and heat for operation of twenty SOEC HTSE stacks and 3 CC-HTGRs providing hot steam for the plant.
- Case #2 has two MC-HTGRs providing electricity and heat for SMR (based on (Wood and Boardman, 2010) and three CC-HTGRs producing hot steam.
- Case #3 employs 19 MC-HTGRs producing electricity to run an LTE hydrogen plant with PEM stacks and 3 CC-HTGRs producing hot steam.

6.2. HES comparison of concepts

Table 4 compares the proposed solutions in terms of products and consumables against the current industry reference, which is autothermal SMR. All cases are covering the hydrogen demand as this was the primary constraint. Since the turbine in the chemical plant is powered by the steam produced from the boilers and common steam header, the electrical output from the HTGR would be the same for Case #1 and #2.

All cases are able to produce 90 % of the plant maximum steam

Table 4
Comparison of the cases.

Case:	1 HTGR +HTSE	2 HTGR +SMR	3 HTGR +LTE
Number of HTGRs for H_2 production	16 MC	2 MC	19 MC
H_2 production [t/h]	~28.9	~28.7	~28.7
HTGRs for steam production [-]	3 CC	3 CC	3 CC
Net heat production [MWth]	405	405	405
electricity consumption [MWe]	1023	10	1650
Hot He consumption eq. [MWth]	567	260	0*
NG consumption eq. [Mm^3/yr]	0	1001.2	0
CO_2 emission [Mt/yr] **	0	2.16*	0
CO_2 emission avoided [Mt/yr] **	2.5	0.34	2.5

NG – Natural Gas, eq. – equivalent.
* for comparison: autothermal SMR without HTGRs ~ 2.5 Mt/yr.
** Neglected 10 % steam demand equal to 45 MWth which would cause an additional ~ 0.085 Mt/yr CO_2.

demand with 3 CC-HTGRs and the rest could be covered by a small fossil boiler to avoid construction of a 4th reactor. The other reactors are fully dedicated to hydrogen production.

In Case#1, 3 out of 16 MC-HTGRs are dedicated to producing heat for all HTSE stacks, while the remaining 13 MC-HTGRs maximize electricity production necessary to operate the stacks. Interestingly, HTSE consumes 600 MWe (equivalent of ~ 7 MC reactors with 1260 MWth) less than the LTE option for the same hydrogen production. However, HTSE is still a costly and immature technology with relatively high risk.

Case#3 is producing electricity for the required 1434 PEM stacks (1.15 MWe each) and additional 3 CC-HTGRs (in total 22) are used to satisfy the steam demand. LTE is an established technology with no risk, but considering that there is no heat demand, the use of an HTGR for this specific purpose may not be a priority, unless the HTGR can produce electricity very cheaply.

Case #2 requires substantially fewer reactors in comparison to Case#1 and Case#3, but the price to pay is the production of 5920 t/d CO_2. Using conventional autothermal SMR process with electricity supplied by fossil fuels, the NG consumption would be higher by ~ 15.4 % and the emissions higher by 492 t/d CO_2.

Electrical, heat and primary energy consumptions related to a unit of hydrogen produced are presented in Table 5. The use of SMR is the dirtiest in terms of CO_2 emissions, but also the most energy efficient with almost no electrical energy and 55 % less primary energy required than in the HTSE option. In terms of primary energy, the HES with LTE is the most energy-intensive solution consuming greater than 60 % more electrical energy and overall greater than 30 % more primary energy than HES with HTSE.

Future techno-economic analysis will encompass other variants, technologies (such as Cu-Cl or S-I cycles for H_2 production), sensitivity cases, and more complex HES systems, e.g. load following, production of cold for industrial or residential refrigeration, and integration with renewables.

Table 5
Specific energy consumption (kWh/kgH_2) of different nuclear-assisted H_2 production methods.

Case:	1 HTGR +HTSE	2 HTGR +SMR	3 HTGR +LTE
Electricity	35.4	0.4	57.5
Heat	20.1	48.5*/9.92**	~0.0
Primary energy	108.7	49.4*/10.92**	143.7

For NG: heat of combustion 36 MJ/m^3.
For electricity: power conversion efficiency 40%.
* all NG feed treated as primary energy.
** when NG is not considered as source of primary energy.

7. Market in Poland

The Polish market presents attractive possibilities for HTGRs. Most of the industrial heat is supplied by pulverized coal boilers (67 %) (Polish Society of Professional Combined Heat and Power Plant, 2019), with a rising contribution from natural gas, identifiable by 16 planned CCGT units. Industries such as fertilizer production, oil refining or paper industry, are very prominent in Poland, they are good candidates for being powered by nuclear reactors and represent significant CO_2 reduction potential. The market for industrial heat ranging between 250 °C and 550 °C is more than 7 GWt in large facilities alone (shown in Table 6) (Ministry of Energy of Poland, 2017), with most of them on just four sites belonging to two conglomerates – Grupa Orlen and Grupa Azoty. Replacing this mostly coal-fired energy by HTGR would save approx. 21 Mt/yr of CO_2. Additionally, the demand for hydrogen is very high at approx. 1 Mt/yr. Because autothermal SMR produces H_2 at a CO_2-intensity of approx. 7 $kgCO_2/kgH_2$, this would lead to a further reduction of 7 Mt/yr of CO_2.

Attractiveness of HTGRs in Poland is furthered by comparatively high prices for imported natural gas as well as the struggling domestic coal sector. While Poland has large but deep coal reserves, their exploitation is increasingly costly and dangerous for the workers, leading to higher prices thus lower demand in favor of coal imports. Natural gas is an increasingly important fuel in Poland, but most of it is bought from Russia, leading to high dependency. Efforts are undergoing in Poland to diversify sources of the fuel, including new pipelines to Norwegian gas deposits and construction of LNG terminals, in order to ensure security of gas supply and to stabilize pricing.

A techno-economic analysis was performed, which considered cogeneration of heat and electricity with gas and coal boilers, CCGTs and HTGRs. The size and price of each type of boiler were adjusted to 165 MWth. Levelized costs of heat and electricity were calculated for each technology as well as the sensitivity of said costs to changes of various cost components: overnight capital cost, construction time, discount rate, fuel and emission costs, and load factor. Two most sensitive cost components were selected for each technology and offset by probable ranges of values to visualize the plausible ranges of levelized costs of products.

It is well known that for coal and gas technologies, emissions and fuel costs are the most impactful components of LCOE and LCOH, followed by the load factor. In contrast, the costs from HTGRs are dependent primarily on overnight cost and load factor, followed by the capital cost, which, in turn, depends on construction time. When discussing levelized costs, it is important to mention the importance of the discount factor. We assume here the value of 5 %, which is relatively lenient towards nuclear reactors but within values found in the literature. The value

Table 6
List of chemical facilities in Poland requiring industrial heat in the range of 250 °C and 550 °C with the largest heat consumption.

Facility	**MWth**
PKN Orlen	2153
Anwil S.A. – Grupa Orlen	997
Orlen Południe Zakład Trzebinia	93
Orlen Południe Zakład Jedlicze	62
International Paper Kwidzyń	692
Grupa Azoty Puławy	755
Grupa Azoty Police	481
Grupa Azoty Tarnów	558
Grupa Azoty Kędzierzyn	557
Grupa LOTOS	465
LOTOS Jasło	74
PCC Rokita	160
Total	**7047**

chosen reflects favorable financing of long-term investments.

Under standard assumptions of our analysis, HTGRs can deliver heat and electricity at costs competitive with CCGTs and coal boilers, particularly if the cost of energy from coal were to include transportation costs, omitted in the calculations due to their high variability (see Fig. 5). Energy cost from natural gas is driven almost exclusively by the fuel price which is relatively high in Poland making it little attractive for baseload, especially when factoring in security of supply aspects.

The range of plausible (Fig. 6) LCOH for each boiler shows that, under the right circumstances, every technology can become competitive. Gas boilers appear as an exception in this scenario due to the assumed high default load factor of 90 %, which places the technology in a weaker position while its strong flexibility and low CAPEX make it particularly suitable as peak load and backup generator.

The high capital cost and low sensitivity to fuel price changes make HTGRs a very good candidate for baseload and baseload only operations – because load factor has a dramatic effect on LCOH. It is in contrast with coal or gas technologies, which see almost no change to their LCOH until about 60 % load when placed on the same graph as HTGRs.

The competitiveness of HTGRs for heat and electricity production in our scenario does not translate directly into competitiveness of HES with HTGRs for hydrogen production. The assessment considered four types of hydrogen production technologies (S-I, HTSE, LTE and SMR) in conjunction with up to four types of previously analyzed heat generation methods.

Fig. 7 clearly shows SMR as the most cost-effective way of industrial hydrogen production – the levelized cost of hydrogen is the lowest, the thermodynamic efficiency is the highest, the technology is mature and it requires comparatively minimal capital investment. For the S-I cycle combined with HTGR to compete, the price of natural gas would have to reach 17 EUR/GJ. For comparison, in the current geopolitical situation

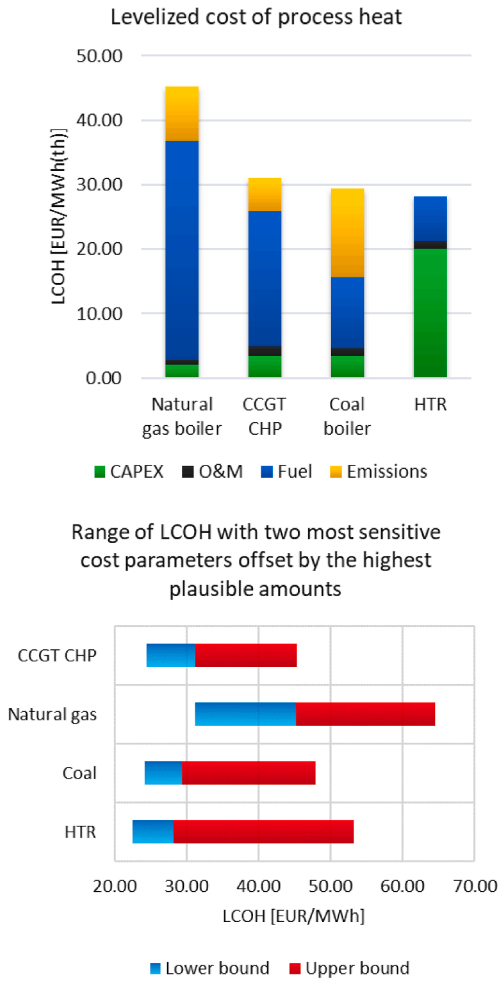

Fig. 5. Breakdown of costs of process heat from different technologies and probable range of total levelized cost (Chmielarz, 2020).

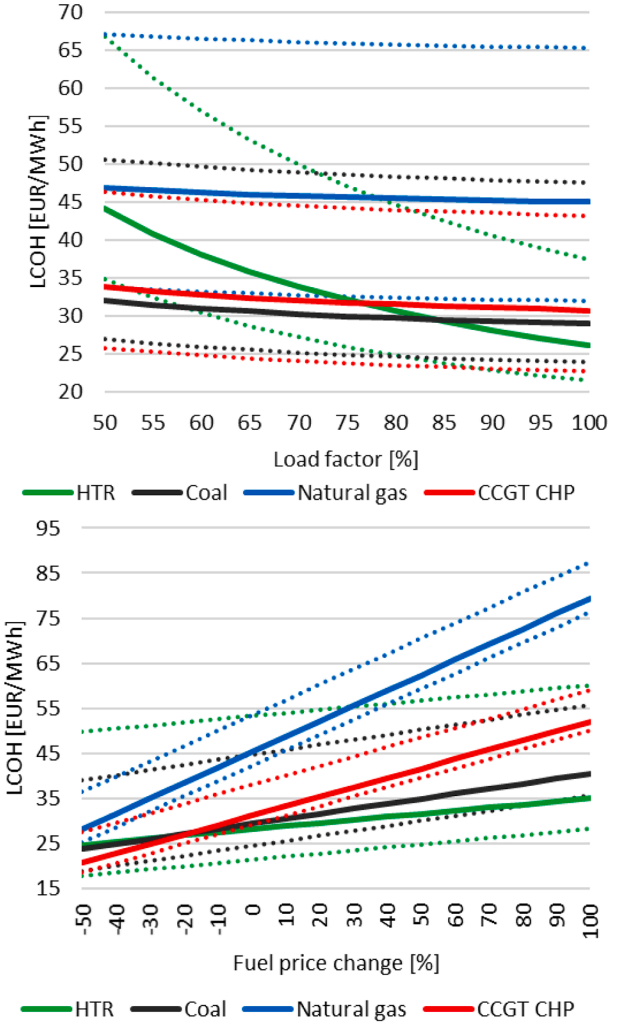

Fig. 6. LCOH as a function of load factor (top) and fuel price (bottom) with minima and maxima calculated through plausible offsets of two most sensitive parameters for each technology, indicated by dotted lines (Chmielarz, 2020).

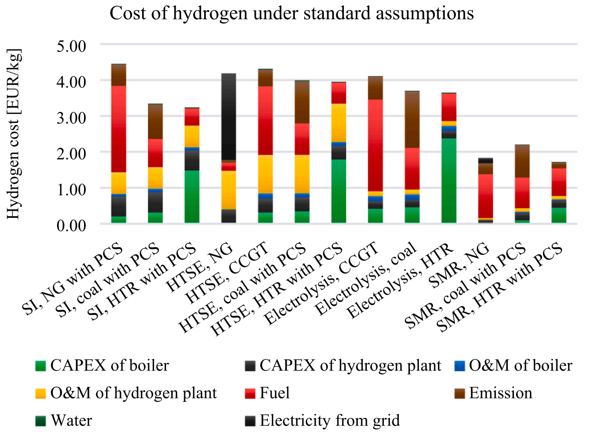

Fig. 7. Breakdown of cost components of levelized cost of hydrogen using different technologies (Chmielarz, 2020).

(June 2022), the natural gas prices by far exceed these economic break-even conditions with a very high and volatile natural gas price at around 28 EUR/GJ after having peaked at 63 EUR/GJ in March 2022 (https://tradingeconomics.com/commodity/eu-natural-gas; Accessed 20 June 2022).

Ways to enhance the competitiveness of HES through decreased capital and operational costs for HTSE and S-I cycles will have to be implemented, particularly in conjunction with HTGRs, as well as through upscaling the hydrogen production plants.

Note that since the time of writing this manuscript, its review and publication, natural gas prices have seen historically unprecedented increases to the point that essentially all technically feasible replacement technologies would be competitive. In addition, industrial investment decisions will likely include, more than in the past, considerations regarding security of supply on top of highly volatile economic assessments.

Hybrid systems based on fossil-fueled heat generation and without HTGRs make neither economic nor environmental sense as SMR can produce hydrogen with less emissions at lower cost. Electrolysis, HTSE and thermochemical cycles (such as S-I) with HTGRs are solutions without GHG emissions. S-I and conventional electrolysis with HTGRs are, based on currently available data, the most affordable CO_2-free sources of hydrogen. The comparison here does not consider purity or pressure of the delivered hydrogen. The reasoning behind this approach is that different applications require different qualities of hydrogen in terms of purity and pressure and fixing them would not be universal. Both pressure and purity are very important for some applications, such as fuel cells. S-I and HTSE can deliver hydrogen both at high pressure and purity thus reducing the effort for purification and compression. Electrolysis and SMR, however, lose a few percent of efficiency and their cost would increase when taking due account of purification and compression.

8. Conclusions

In this paper, we have presented and analyzed a number of near-term nuclear process heat applications with good timeliness and significant potential impact to contribute to the European “Green Deal” efforts towards climate change mitigation. It appears that some of these process heat applications have an even stronger CO_2 savings capability than replacing fossil-fired electricity generation with nuclear power. The CO_2 emission savings would also translate into significant costs savings for industry. During the time of writing this article, the European Emission Trading System has increased the pricing of emissions from approx. 25 to more than 80 €/t CO_2.

- Ammonia production: if in a first step only the required heat could be delivered by an HTGR instead of burning natural gas, emissions of approx. 8 Mt/yr of CO_2 could be saved. If the H_2 feedstock could be produced in addition, the CO_2 emission cuts could be approximately tripled.
- Plastics recycling: as an example, the application of nuclear process heat for plastics recycling could yield, in the specific case of PMMA, savings of 3–4 Mt/yr of CO_2 compared to the production of virgin PMMA. This technology could set an end to the current practice of shipping very large amounts of European plastics waste to other continents. It is also an example where the use of nuclear process heat in what is apparently a niche application could achieve significant impact.
- Dry reforming of methane with CO_2 and nuclear process heat to produce syngas as a feedstock for numerous chemicals and synthetic hydrocarbons can globally cut CO_2 emissions of the order of several Gt/yr. A similar effect could be obtained by the co-electrolysis of steam and CO_2 to produce syngas. This would enable the continued use of hydrocarbons in areas which are difficult to electrify, e.g. in aviation.

Nuclear production of hydrogen can reduce the current carbon intensity of SMR from 7 tCO_2/tH_2 to 0. It has an extremely large market and CO_2 reduction potential, including for integration of nuclear energy in Hybrid Energy Systems. This is because hydrogen is being used in massive quantities both as an energy carrier and as feedstock for chemical products. The efficiency chain from nuclear heat to hydrogen depends on the hydrogen production method with delivery pressure and purity to be factored in because both weigh heavily on the energy balance. Hydrogen production with HTGRs has potential to compete with SMR using thermochemical cycles (e.g. S-I) or HTSE if the competing methods manage to reduce their CAPEX significantly, for example through upscaling, and their operational costs, e.g. by using materials with higher durability. However, our study implies that, from a pure energy efficiency point of view, nuclear hydrogen production is possibly not the most effective first target for CO_2 reduction by using nuclear power because it is very primary energy intensive.

Poland presents a good opportunity for HTGRs due to two main factors - its large refining, fertilizer and pulp and paper industries as well as incentives associated with security of supply and pricing of fuels and emissions. HTGRs can be competitive if the capital costs during the sensitive planning and construction phase can be kept low and if these reactors can be operated with a high load factor. This contrasts with other technologies where most of the risk is related to operations – fuel and emission costs.

The selected case studies in this paper demonstrate once more the gigantic effort required to decarbonize the industry sector, especially in the areas of process steam and hydrogen production. But the cases also indicate the equally gigantic potential benefits from these efforts. GEMINI+ assumes correctly that process steam production for replacement of standard fossil boilers is a priority, because there is a large existing market and it is technologically a relatively low hanging fruit. If, however, at the same time cogeneration of steam, electricity and hydrogen production are required, the optimum reactor size may actually be larger than 180 MWth as assumed for GEMINI+. This would lead to enhanced benefits from the established economy of scale instead of a presumed economy of replication, which is yet to be demonstrated.

Nomenclature CAPEX	CAPital EXpenditure
CC	Chemical Class
CCGT	Combined Cycle Gas Turbine
CCU	Carbon Capture and Utilization
CHP	Combined Heat and Power
DRM	Dry Reforming of Methane
EU28	European Union, when it still had 28 member states (before the UK left)
FT	Fischer-Tropsch synthesis
GTHTR300C	Gas-Turbine High Temperature Reactor 300 MW for Cogeneration (JAEA)
HES	Hybrid Energy Systems
HTGR	High Temperature Gas-cooled Reactor
HTR-PM600	High Temperature Reactor Pebble Bed Module 600 MW
HTSE	High Temperature Steam Electrolysis
LCOE	Levelized Cost of Electricity
LCOH	Levelized Cost of Hydrogen
LTE	Low Temperature Electrolysis
MC	Mineral Class
MMA	Methyl methacrylate
MTG	Methanol To Gasoline
MWth	Megawatt thermal
MWe	Megawatt electric
NG	Natural Gas
NGNP	Next Generation Nuclear Plant
ODH	Oxidative De-Hydrogenation
OECD	Organisation for Economic Cooperation and Development
PBMR	Pebble Bed Modular Reactor
PCP	Polymer Cracking Process
PEM	Polymer Electrolyte Membrane
PMMA	Polymethyl-methacrylate
RWGS	Reverse Water Gas Shift reaction
S-I	Sulfur-Iodine process for thermochemical hydrogen production

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Nomenclature	
CAPEX	CAPital EXpenditure
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolysis Cell
SOFC	Solid Oxide Fuel Cell
TRL	Technology Readiness Level

CRediT authorship contribution statement

Michael A. Fütterer: Conceptualization, Investigation, Writing – review & editing, Supervision. **Raimondas Pabarcius:** Methodology, Formal analysis, Investigation, Writing – review & editing. **Sebastian Hübner:** Methodology, Formal analysis, Investigation, Writing – review & editing. **Ludwik Pieńkowski:** Methodology, Formal analysis, Investigation, Writing – review & editing. **Wojtek Brudek:** Methodology, Formal analysis, Investigation, Writing – review & editing. **Piotr Darnowski:** Methodology, Formal analysis, Investigation, Writing – review & editing. **Michał Pawluczyk:** Methodology, Formal analysis, Investigation, Writing – review & editing. **Błażej Chmielarz:** Methodology, Formal analysis, Investigation, Writing – review & editing. **Martin Šilhan:** Methodology, Formal analysis, Investigation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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