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NC2I-R D431 Deployment scenarios

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Summary

This study aimed to estimate and compare several deployment scenarios for the utilization of HTRs in industrial cogeneration. Earlier studies in the Nuclear Cogeneration Industrial Initiative project already identified industrial sectors suitable for HTR cogeneration. In the near future chemical industry was seen as a most prominent sector as it already uses cogeneration, the required temperatures correspond to the output of an HTR and the power capacity of several parks is large enough to be compatible with the size of an HTR.

Mid to long-term solutions for the utilization of electricity and heat provided by HTR are Coal-to-Liquid and Carbon Capture and Storage which utilize the heat in the pressure and temperature suitable for a HTR. The applications for the utilization heat from High Temperature Reactors will increase to e.g. metal and non-metallic mineral industries as well as to hydrogen production if the temperature of the heat could be increased up to 700-1000°C.

Besides delivering heat and electricity to industrial sites HTR can also provide electricity to the grid and heat to the nearby cities as a district heat. There are 4398 districts in Europe which have existing district heating network with annually sold heat/cold of 1009 PJ/year. The challenge with district heating is that the heat demand is not constant throughout the year but the consumption is the smallest during summer months which would require the HTR to adjust its production accordingly by running in an uneconomical part-load or by producing more electricity instead which would reduce the overall efficiency of the plant. Instead of covering all the district heating demand, HTR could cover part of the district heat demand that stays stable throughout the year while also serving the nearby industry or industries with a higher temperature heat.

Around 60% of all energy intensive industrial activities in EU27 are located close to cities with district heating network and a decent heat demand. The approach to identify favourable synergy regions for district heating [12] identified almost 650 zones where energy intensive industrial activities are located close to an existing district heating system. The amount of chemical and petrochemical activities was 151. Based on the study it can be seen that quite many industrial cogeneration plants could also supply the close cities with district heat. The closeness of district heating network could make the planned heat output from a cogeneration plant larger than would be only in the case of a plant which only supplies the heat to the industrial process. Therefore the smaller sites identified in the European site mapping [7] might be also interesting for HTR cogeneration if they produced also district heat. In the case of nuclear, the safety distances between the nuclear plant and population centre needs to be taken into account.

Deployment scenarios were utilizing the findings from deliverables D411 Economic assessment and business modelling and D431 Site mapping when evaluating the near and long-term potential for HTR development in Europe. The economic results and energy prices from HTR were compared against the projected price development in the IEA's World Energy Outlook from 2014. Based on the different scenarios with different price development for carbon price the HTR could be feasible in the market by 2024-2025.

The deployment scenarios for the nuclear cogeneration were built based on the WEO's scenarios. Besides the WEO's price estimates the effect of policies and emissions targets has been estimated on a country level by estimating which countries are likely to adopt nuclear cogeneration as a part of their generation portfolio. Also different industrial sectors adopting the technology were estimated.

The competitiveness of cogenerated industrial heat in HTR reactor has been estimated against the heat produced in gas- or coal-fired heat-only boilers. The cost of heat production in HTR cogeneration process has been calculated by valuing the simultaneous electricity production against the estimated wholesale

electricity prices. Therefore the heat production costs have a strong dependence on prevailing wholesale market prices.

Based on the fuel price forecasts the heat provided by HTR could be competitible against the heat produced in coal and natural gas fired heat-only boilers around 2025. This however, is strongly depending on the future development of electricity prices on the market.

The effect of different HTR scenarios on employment and carbon emissions were estimated by comparing the scenarios to the state-of-art situation where the heat and electricity consumed by the industry are produced with traditional coal and gas-fired CHP plants and heat-only boilers. The alternative carbon emissions for electricity have been estimated based on the average carbon imposture on electricity in IEA Europe countries. The calculations indicated that the overall CO_2 reduction resulting from the adoption of HTR cogeneration could be almost 18000 million tons of CO_2 by 2050 in the base scenario.

The nuclear cogeneration will generate local labour since capital intensive investments will replace expensive imports of fossil fuels to Europe. An estimate indicates that by building a generation fleet of HTRs approximately 200 000 man-years could be created in Europe by 2050.

Approval

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1 Introduction

The objective of the European Nuclear Cogeneration Industrial Initiative (NC2I) is to demonstrate an innovative and competitive energy solution for the low-carbon cogeneration of heat and electricity based on nuclear energy. The targeted outcome is the commissioning within 10 years of a nuclear cogeneration prototype to deploy this low-carbon energy technology in several energy-intensive industries.

The aim of the task on deployment scenarios is to identify future nuclear cogeneration markets beyond near-term applications so that they can be included in a long-term transition model up to 2050. Of particular interest could be nuclear-assisted coal-to-liquid or syngas processes with reduced CO_2 emission. Possible synergies with CO_2 capture and/or recycling will be identified and the impact on the economics of the process will be addressed. Scenarios for different kinds of gradual deployments of nuclear cogeneration up to 2050 is developed and their impacts on resource, jobs creation, economic growth, European exports and CO_2 emission savings in industry is assessed.

In a task of European site mapping heat intensive industrial sites in Europe that can be potential location for HTR demonstrator were identified. The subject was to localize and characterize chemical and petrochemical sites within Europe which can be a potential market for deployment of the HTR's. It was established that benefits of nuclear cogeneration can be utilized by industrial consumer of process steam at high and intermediate parameters, industrial consumer with on-site CHP unit or need for one and sites with aging steam boilers. The main processes compatible with HTR capabilities are:

- refinery distillation steam,
- refinery distillation superheated steam,
- petrochemicals - reaction enthalpy,
- steam as utility for industrial complex, and
- paper steam (drying).

In total 132 sites were located within Europe. The chemical and petrochemical industries are dominant and represent respectively 30% and 35% of the mapped sites. Remaining sites are metal processing plants and pharmaceutical plants.

Information on heat and electricity consumption of the processes was requested from industrial sites and 57 answers were received. Majority of sites providing the answers use less than 100 MWth, that is 20 sites. In the category of more than 100 MW_{th}, 8 sites were located. The last significant category was about 500 MW_{th} including 9 sites.

The electrical power demand is distributed somewhat in more uniform manner. The smallest demand – up to 50 MWe was reported by 20 sites of 57 who answered the request for the information. Each of next categories, respectively 51-100 MW_e, 101-200 MW_e and 201-400 MW_e, reported between 4 and 6 sites.

2 Heat markets

2.1 Current status of heat markets

Heating and cooling represent almost half of the total energy consumption in the EU. In addition to its size, it has large potential for primary energy efficiency, in terms of both final consumption and system efficiencies. Rapidly developing technologies are introduced at a varying pace in different member states, depending largely on societal and customer expectations and on the flexibility and business orientation of the sector as a whole. Furthermore, natural gas is most commonly used directly as a fuel to provide heating for individual houses, underlining security of supply concerns.

2.1.1 Nuclear cogeneration

Nuclear cogeneration is a proven technology. Mainly the nuclear cogeneration has been by utilising the waste heat from water reactors. In 2006 more than 1000 GWh of low-temperature nuclear heat was produced in Bulgaria, Czech Republic, Hungary, Romania, Slovakia and Switzerland. [1]

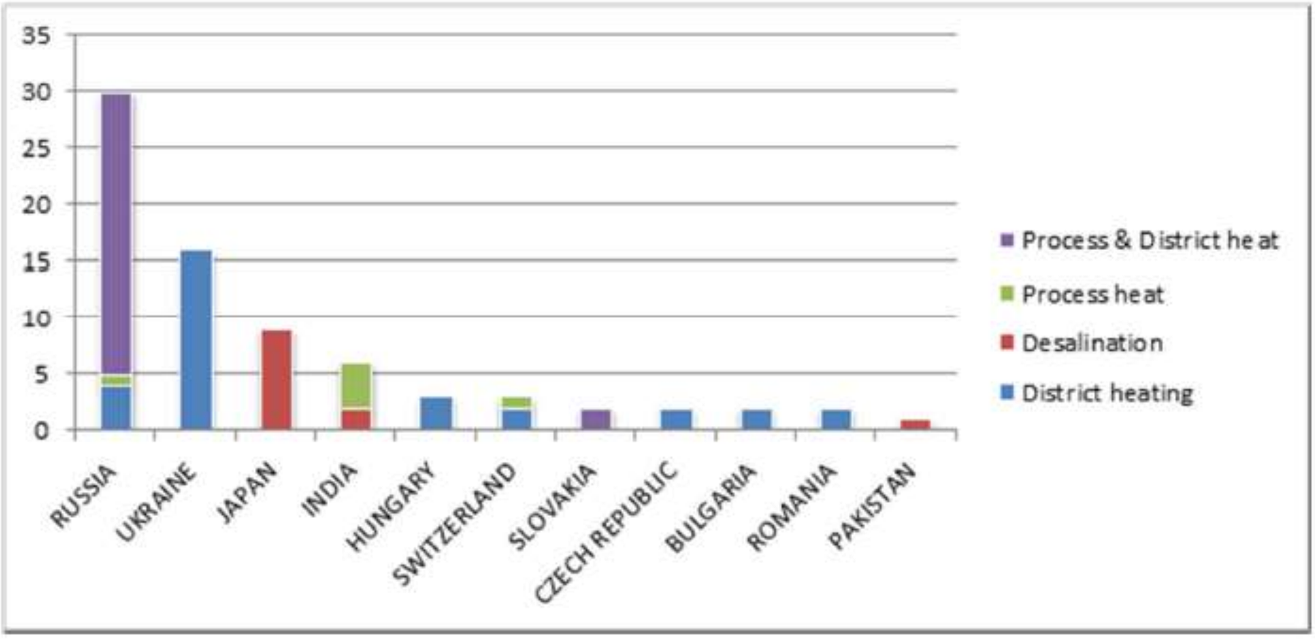


Figure 2-1 Number of reactors used for both non-electric purposes and for electricity production [2]

A few nuclear power plants in operation already supply process heat to industrial customers. The largest projects implemented are in Canada (Bruce, heavy-water production and other industrial/agricultural users) and in Kazakstan (Aktau, desalination). Many reactors, which currently produce only electricity, could be converted to co-generation. The conversion to co-generation could be technically feasible if the heat amount is sufficient and close enough. [3]

Nuclear co-generation can also be a supply option for district heating. In the case of medium and large nuclear reactors electricity would be the main product due to the relatively low load factors in the district heating markets. This has been done in Russia, Ukraine, the Czech Republic, Slovakia, Hungary, Bulgaria, and Switzerland, using up to about 100 MW_{th} per power station [4]. Smaller reactors could more easily be optimized against the local heat demand.

High temperature reactors provide significant perspectives for medium and high temperature cogeneration applications. The HTR technology builds on the developments in Germany in the 1980s, as well as research in UK and USA, re-established and revived in several national and European Framework Programme projects from the year 2000 onwards including the ARCHER project (2011-2014). [1]

The coupling with end-users of HTR for high temperature cogeneration has still to be developed. The EUROPAIRS project has established direct contacts between the conventional process industry and the nuclear community and has developed key performance indicators. It has also identified operational envelopes for the coupling and assessed the general licensing aspects on dedicated case studies (hydrogen, refining). Additionally, the establishment of an HTR demonstrator coupled to industry has been regarded as essential by the industry in EUROPAIRS, to enable market breakthrough by risk reduction and the more reasonable deployment horizon of demonstrator follow-ups. [1]

2.1.2 Industrial heat markets

European industrial heat markets are characterized with a wide diversity of loads with respect to temperature levels, branches, countries, and energy supply. Industrial processes differ from one another and the energy supply differs from country to country due to local conditions.

The Heat and cooling demand and market perspective [5] study divided the European heat demand into three temperature intervals in the industrial sector. The low temperature heat demand covers heat loads below 100°C including processes as washing, rinsing, food preparation as well as space heating of the industrial facilities and hot water preparation. The medium temperature, covering the range between 100°C to 400°C, corresponds to drying or evaporation processes which are usually produced by steam. The high temperature heat with temperature over 400°C is generally used for the transformation processes i.e. reduction of the ore, calcination, electric induction etc.

The estimated energy demand identified in the EU's heat and cooling demand and market perspective study [5] in the EU-27 Member States is presented in the following figure. The heat demand has been estimated based on the 2009 final energy data from Eurostat.

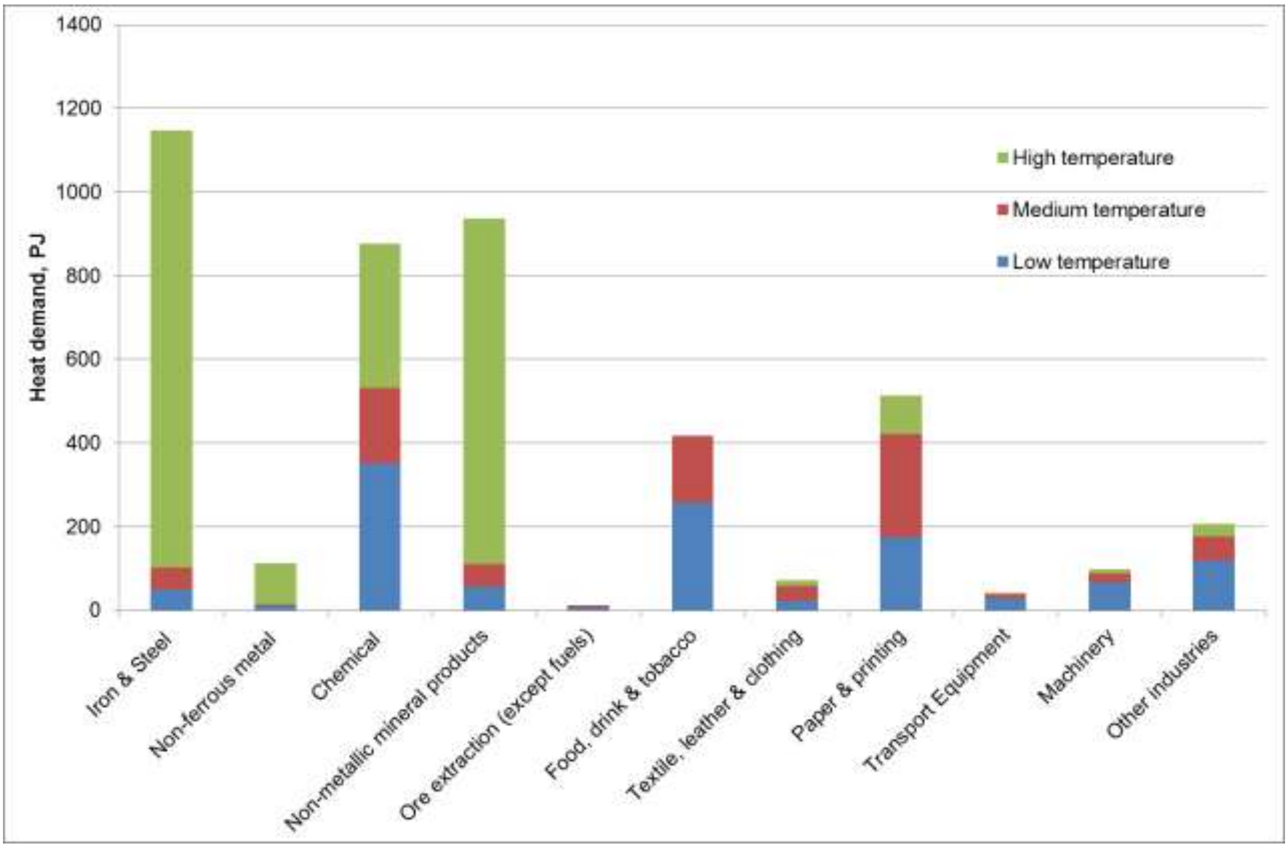


Figure 2-2 Industrial heat markets in the EU [5]

Industrial sectors consume steam as process heat, ingredient of chemical reaction or working fluid for electricity production. The European heat market was further studies in EUROPAIRS project where the majority of industrial sites located within EU had a demand between 10 and 500 MWth of steam at various temperatures. [6]

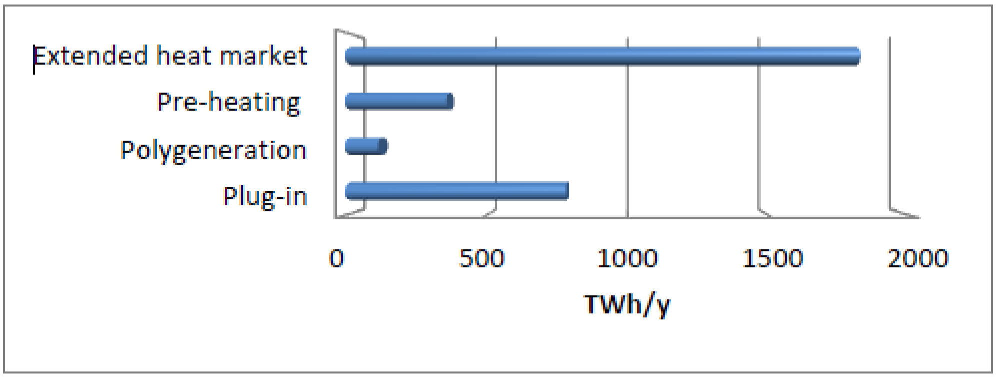


Figure 2-3 European heat market [6]

Technical limitations for short term deployment of HTR reactors in cogeneration indicate temperature below 750°C at the HTR core outlet. Based on temperature restrictions all applications requiring steam temperature above 570°C can be eliminated for near term horizon deployment. The temperature requirements of different Industrial processes are presented in Figure 2-4.

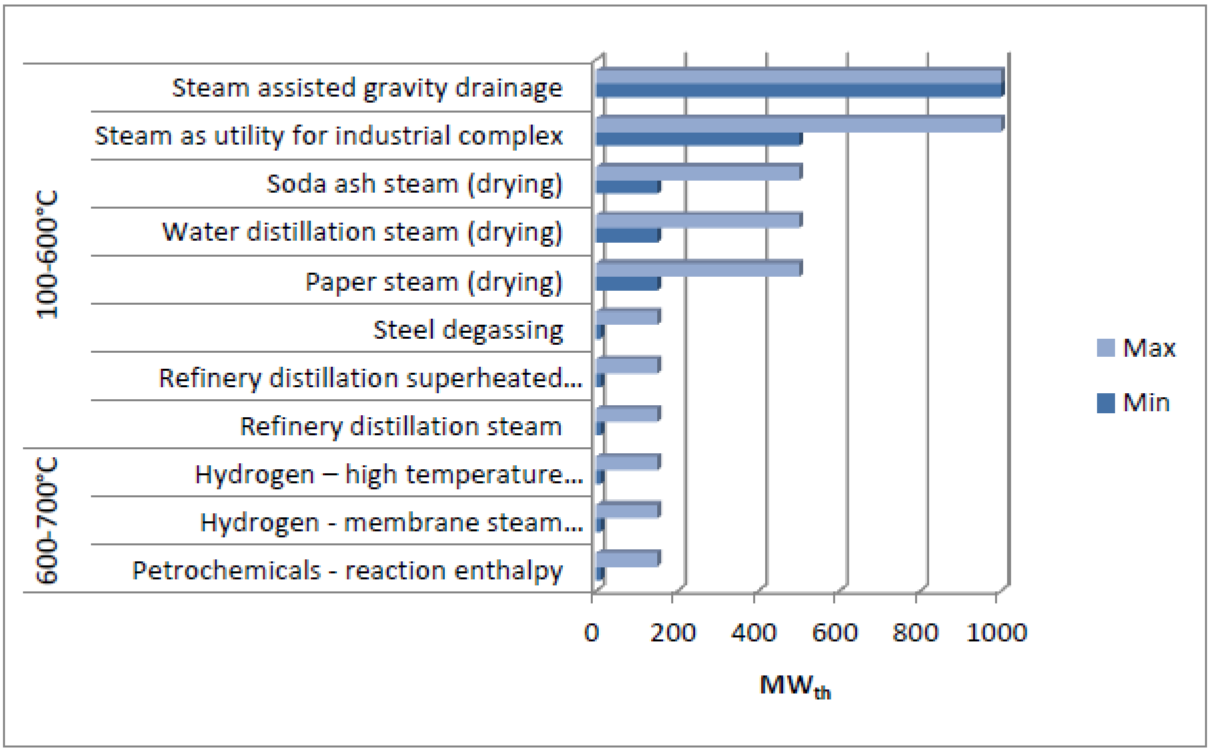


Figure 2-4 Heat demand for various processes [6]

The low and medium temperature demand is almost half of the total heat demand in the EU and therefore the chemical industry has been selected as a most interesting sector for a HTR demonstrator. In EU each chemical installation has a lifetime of 30-40 years and after this time is replaced with new system. The European site mapping [7] identified over 90 individual chemical clusters which business infrastructure located mainly in Benelux, Germany, UK, France, Italy and Spain. For industrial branches including chemical clusters the price and availability of energy is fundamental aspect for profitability of the investment. Nuclear CHP unit could replace conventional CHP units usually located at the cluster, or in its direct vicinity if proven profitable.

Operational conditions, availability and life time of HTR is compatible with chemical sites. The existing infrastructure of steam supply on site can be used for peak power production and/or as a backup supply during HTR's maintenance periods.

The task of European site mapping [7] was to localize and characterize chemical and petrochemical sites within Europe which can be a potential market for deployment of the HTR's. The benefits of nuclear cogeneration can be utilized by industrial consumer of process steam at high and intermediate parameters, industrial consumer with on-site CHP unit or need for one and sites with aging steam boilers. The main processes identified to be compatible with HTR were:

- refinery distillation steam,
- refinery distillation superheated steam,
- petrochemicals - reaction enthalpy,
- steam as utility for industrial complex,
- paper steam (drying)

In Europe total of 132 sites were located. The chemical and petrochemical industries were dominant and represent respectively 30% and 35% of the mapped sites. Remaining sites are metal processing plants and pharmaceutical plants.

The Figure 2-5 represents division of identified sites based on their thermal power demand. Majority of the sites use less than 100 MWth, that is 20 sites. In the category of more than 100 MWth, 8 sites were located. The last significant category was demand around 500 MW_{th} and in this category 9 sites were located. The electricity demand of the sites is quite evenly distributed. The smallest demand – up to 50 MW_e was reported by 20 sites. The next next categories i.e. 51-100 MW_e, 101-200 MWe, and 201-400 MW_e, reported between 4 and 6 sites.

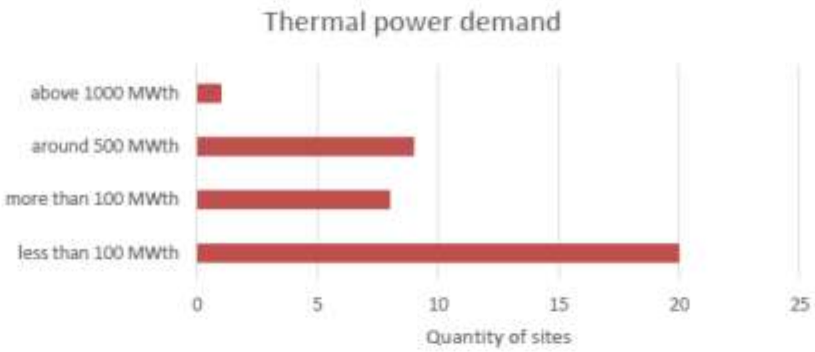


Figure 30 Sites categorized by thermal power demand

Figure 2-5 Sites divided by heat demand [7]

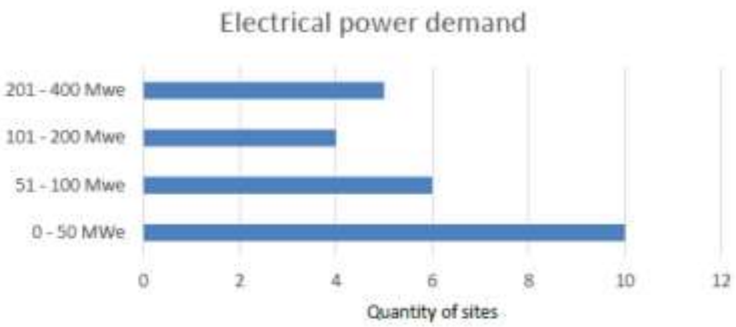


Figure 31 Sites categorized by electrical power demand

Figure 2-6 Sites divided by electricity demand [7]

ECSPP has collected European chemical parks on a map the most dense concentration of the parks is the the Benelux area and in Gemany [8].

Figure 2-7 Chemical parks in Europe [8]

Figure 2-8 Chemical parks in Europe, focus on the chemical parks in Germany, Belgium and The Netherlands [7]

2.1.3 District heat markets

European district heat markets were identified in the Heat Roadmap Europe study in 2011 and second prestudy in 2013 [9]. Study was a pre-study for expansion of district heating in EU27 performed for Euroheat & Power. The heat market for residential and service sector was estimated at 3300 TWh/year. The market share for district heating for buildings is about 13% resulting in a heat deliveries of 430 TWh/year. Besides the district heat deliveries, 220 TWh/year is delivered from industrial CHP plants for industrial use.

District heating systems exist all over Europe, but the share of district heating differ significantly between the countries. District heating covers 13% of the of the European heat market for buildings in the residential and service sector but is even 40-60 percent in some Scandinavian and Baltic countries. The market share of DH in the industrial sector is about 9% [9]. The European district heating systems have networks containing distribution pipes with a total trench length of almost 200 000 km.

In EU 60 million people are connected to district heating systems. The spread of European district heating technology can be seen in Figure 2-9, where the red dots mark a city with at least one operating district heating system [10]. The map is based on the District Heating and Cooling Database made by the Halmstad University. The database does not cover all district heating systems in Europe but the deficit consists mainly of small systems in Germany, France and Poland.

The district heating systems supply only part of the heat demands in the cities. Around 57% of the EU's citizens live in areas having at least one district heating system. As a European average, district heat constitute about 15% of current urban heat markets, while these fractions can reach as high as above 90% in some cities with mature district heating systems.

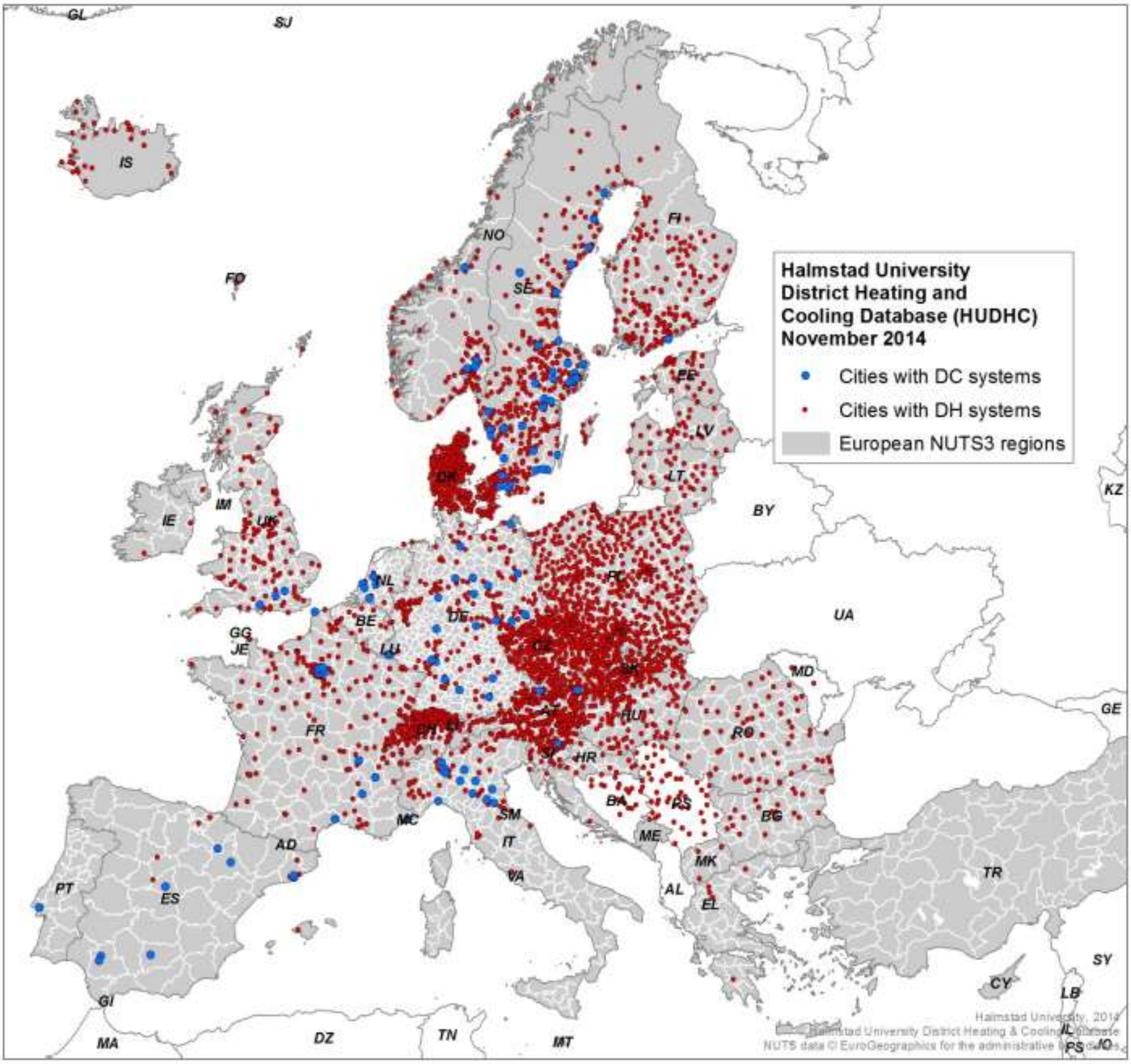


Figure 2-9 European cities (3871) with one or more district heating system (4398) and 107 cities with district cooling systems currently in operation as stored in Halmstad University District Heating and Cooling Database, November 2014 [10]

A demand curve for district heating is not the most optimal towards nuclear plant's operation where high availability is a prerequsite. However, nuclear cogeneration plant's could be designed for flexible operation between heat and electricity when the plant would produce more electricity during the times when the heat demand is smaller. This would reduce the overall efficiency a bit but would guarantee the fyll time operation of the plant. The other option would be that the nuclear power plant would only supply the base load required for hot service water which is required all year round. That would require somewhat larger city to be supplied with district heat i.e. in Finland the based load of around 100 MW of district heat is in cities with around 90 000 customers connected to the district heating network. On the other hand, the district heat could be a by-product from a HTR supplying industries with process steam and the excess heat might be sufficient to cover the need for the domestic hot water which demand is almost contant all the year round.

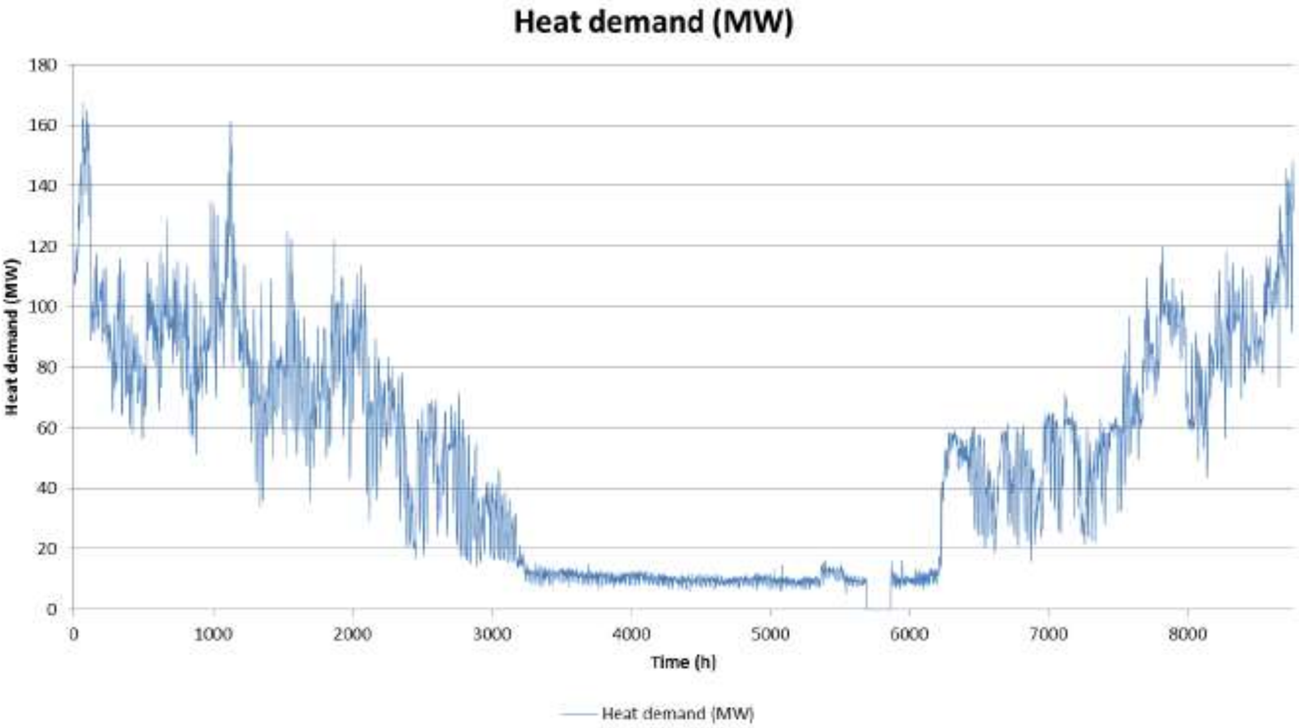


Figure 2-10 Typical annual heat demand pattern of a Polish district heating system [11]

European zones where the need for both industrial heat and district heat exists has been mapped by a study made by a cooperative group of reseachers from the Department of Development and Planning at Aalborg University in den,mark and from the School of Business and Engineering at Halmstad University in Sweden [12]. In the study the viable transmission distances were calculated from all district heating cities recorded in the HUDHC (Halmstad University District Heating and Cooling) database. The study identified heat synergy opportunirty zones where the transmission distance between the sites with energy intensive indusrial activities and city with existing district heating network was 30 kilometres at the maximum. The identified heat synergy opportunirty zones are presented in the following figure.

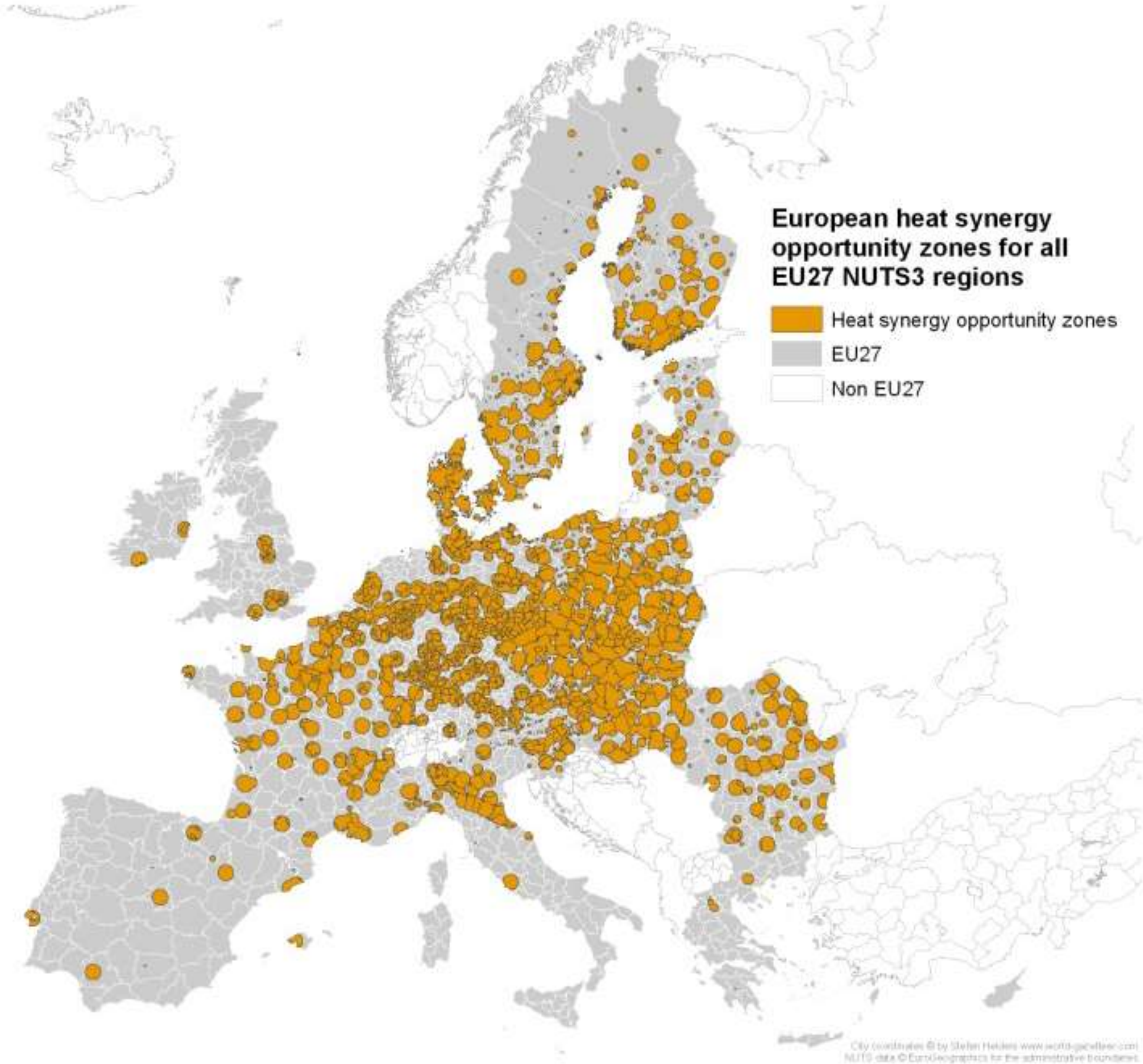


Figure 2-11 European heat synergy opportunity zones [12]

Approximately 60% of all energy intensive industrial activities in EU27 are located close to cities with district heating network and a decent heat demand. The approach to identify favourable synergy regions for district heating [12] identified almost 650 zones where energy intensive industrial activities are located close to an existing district heating system. The amount of chemical and petrochemical activities was 151. Based on the study it can be seen that quite many industrial cogeneration plants could also supply the close cities with district heat. The closeness of district heating network could make the planned heat output from a cogeneration plant larger than would be only in the case of a plant which only supplies the heat to the industrial process. Therefore the smaller sites identified in the European site mapping [7] might be also interesting for HTR cogeneration if they produced also district heat. In the case of nuclear, the safety distances between the nuclear plant and population centre needs to be taken into account.

The amount of all cities and areas identified as heat synergy opportunirty zones are presented in the following Table.

Table 2-1 General properties of assessed heat synergy opportunity zones (HSOZ) in EU27 [12]

	Total	HSOZ	%
European NUTS3 regions and land areas			
NUTS3 regions	1303	979	75
Tatal land area (km^2)	4 267 644	1 283 185	30
Energy intensive industrial activities			
Chemical & petrochemical	231	151	65
Iron & steel	140	101	72
Non-ferrous metals	30	17	57
Non-metallic minerals	421	204	48
Paper, pulp & printing	172	110	64
Fuel supply & refineries	191	63	33
Thermal power generation activities			
Combustion installations	961	595	62
Waste-to-Energy	410	280	68
Grand total	**2556**	**1521**	**60**

2.2 Prospects for future heat markets

2.2.1 Existing technologies

The JRC study [13] estimated the useful heat consumption of the industry to be 4434 PJ in 2009. Based on PRIMES scenarios projections, the estimated useful heat demand was estimated to be 5 045 PJ in 2020 and 5 020 PJ in 2030 [13]. These estimations were based on the trends foreseen by PRIMES in the Reference scenario. The scenario included the emissions trading system and assumed that national targets under the Renewables directive 2009/28/EC and the GHG Effort sharing decision 2009/406/EC would be achieved in 2020. The following figure shows that the main changes in the useful heat demand is expected to happen in the high range of temperatures for the iron and steel industry and for the non-metallic mineral industry. A notable increase of the heat demand for the food, drink and tobacco industry is expected in the consumption of the low and medium range of temperatures and decrease in the pulp and paper industry. The heat demand in the chemical industry was expected to remain as almost the same as in 2009.

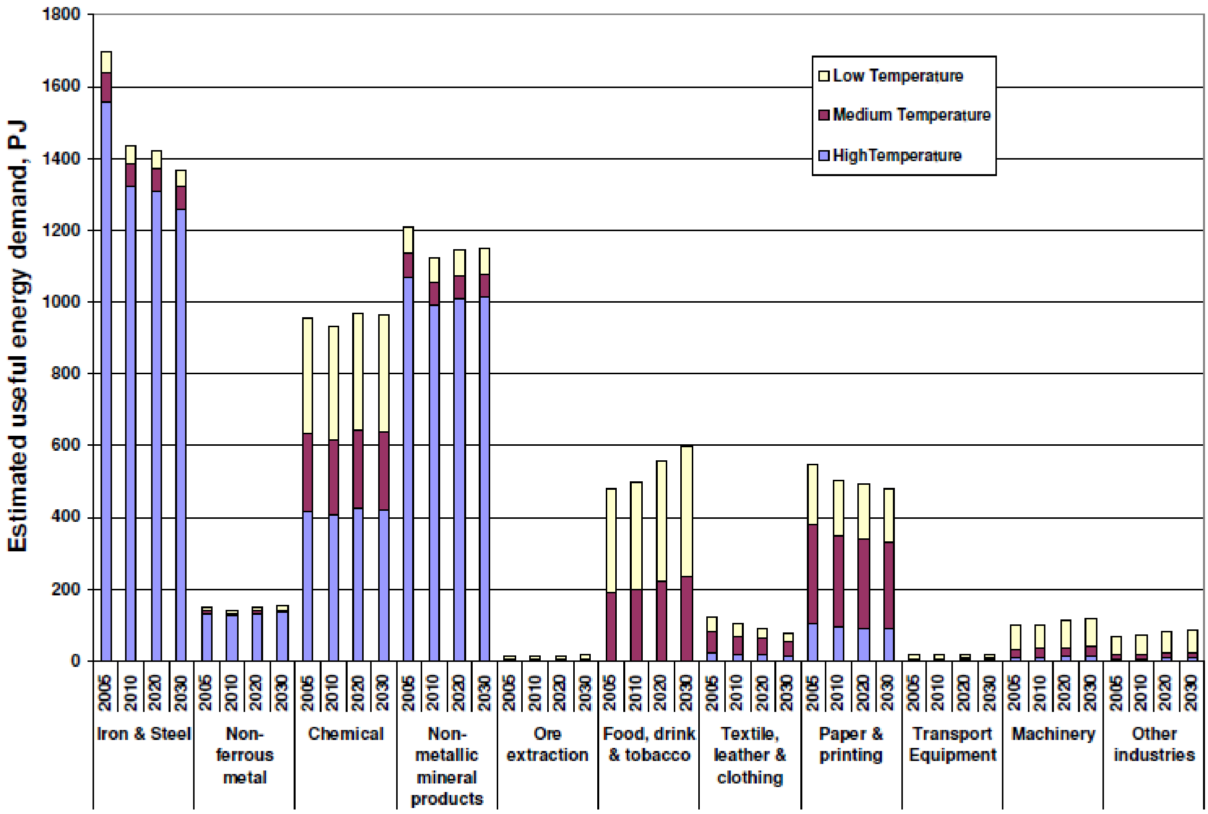
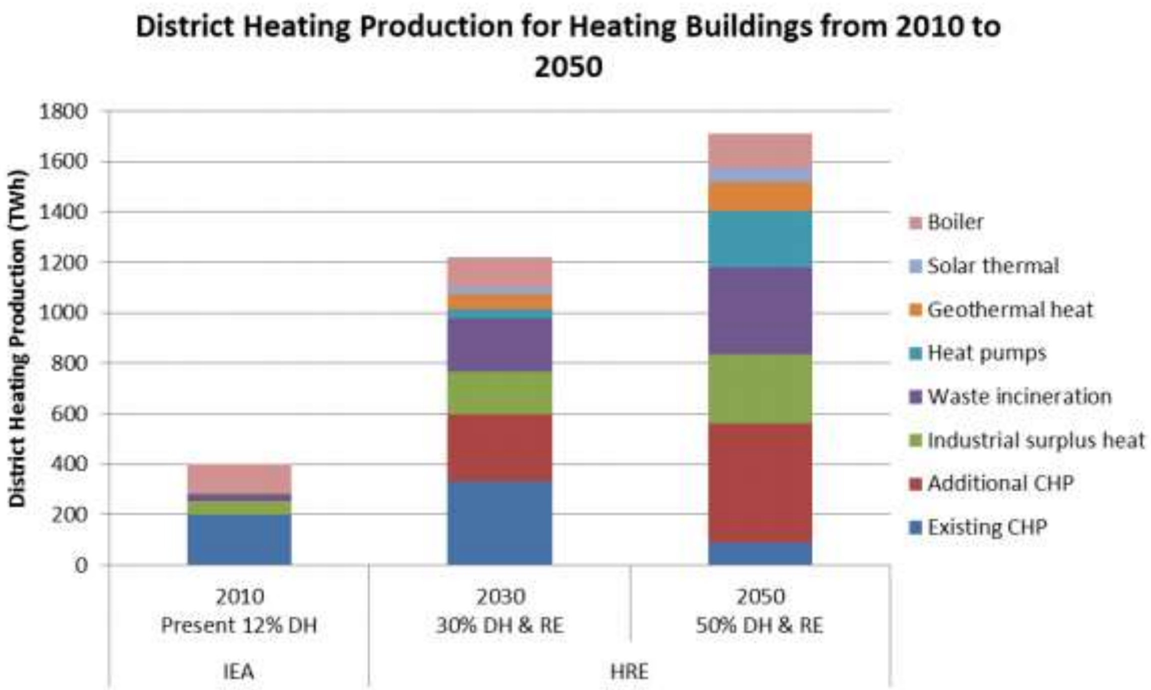


Figure 3.2 Estimated useful heat demand in the European Industry

Figure 2-12 Estimated heat demand in the European industry

As can be seen from the figure above the heat market is not expected to increase partly due to improved energy efficiency but, on the other hand, it will not decrease significantly either.

The district heating demand estimates done in the first initial pre-study for expansion of district heating [14] estimated increases in district heating demand. Increases are expected to be based on the expansions of district heating systems and they are to be covered by the increased usage of CHP, industrial excess heat, waste incineration, geothermal, and solar thermal heat.



<u>Figure 2-13 District heating production for heating in buildings in EU27 in 2010, 2030 and 2030 if district heating and CHP were expanded to 30% in 2030 and 50% in 2050 in combination with the expansion of industrial excess heat, waste incineration, geothermal, and solar thermal heat for district heating [14]</u>

2.2.2 Coal-to-Liquids

Technology description

Coal to liquid (CTL), also referred to as coal liquefaction, is a conversion of bituminous or sub-bituminous coals to a liquid fuels like gasoline or diesel. Although this technology is generally more expensive than producing fuels from crude oil, it is potentially very attractive as the coal reserves are more than ten times more abundant, and are more evenly distributed than oil reserves.

Conversion of coal to liquids is done by increasing the hydrogen to carbon ratio from H/C ~0.8 (typical bituminous coal) to H/C ~2 (final hydrocarbon fuels). This result can be achieved either by rejection of carbon or by addition of hydrogen. The first method is known as the indirect coal liquefaction (ICL), the second one as the direct coal liquefaction (DCL). In the ICL coal is gasified to form a mixture of H2 and CO (syngas) which after adjustment of H_2/CO ratio and removal of sulfur and CO_2 is converted to hydrocarbon liquids in a Fischer-Tropsch synthesis unit. In the DCL hydrogen is added to crack the coal structure to hydrocarbon liquids. Direct liquefaction works by dissolving the coal with a special catalyst in a solvent at high temperature and pressure and reacting it with hydrogen. This process is highly efficient, but the liquid products require further refining to achieve high grade fuel characteristics. The indirect liquefaction has substantially lower efficiency than the direct one (40-45% vs 60-65%), but less complicated processes are involved. The capital costs of ICL plant are generally higher, but 60-80% of them is connected with syngas production and cleaning. ICL can be used for production of a number of various high quality ultra-clean products: conventional fuels like petroleum and diesel, alternative fuels like methanol and dimethyl ether (DME), synthetic waxes and lubricants or chemical feedstocks.
The DCL process dissolves coal at high temperature and pressure (around 450°C and 170°C). The ICL process includes two main steps: first, the production of syngas resulting from coal gasification (requiring temperatures around 800°C); then, the syngas is converted into hydrocarbons using the Fischer-Tropsch (FT) synthesis. Both processes have advantages and drawbacks: the DCL process is more efficient but lead to products that require additional treatments before use. The products resulting from the ICL process can be

used directly and this process benefits from a long experience - more than 50 years in the Sasol industrial plant in South Africa, when the DCL process still needs to be scaled-up.

From these two basic methods only ICL has been implemented in a big commercial scale, whereas the implementation of DCL has been abandoned for many years. In the last decade some new projects (DCL and ICL) have been launched in China. However, the world-wide deployment of the conventional CTL is limited by two very important drawbacks:

- the energy required in chemical processes is produced by burning feedstock
- huge CO_2 emissions are 7-10 times higher than in petrochemical production.

It is expected that both of these problems can be solved while implementing a nuclear-assisted method where the required process heat (~850°C) is supplied from the high temperature nuclear reactor (HTR). It should be noted, that the mentioned above methods will require these temperatures in different process stages. In the nuclear-assisted ICL (NA-ICL) the highest temperatures are in the gasification step whereas the subsequent Fischer-Tropsch synthesis runs in temperature range 180-350°C. The process temperatures in NA-DCL are generally not higher than 500°C, and high temperature is required only for the emission-free hydrogen generation.

Although the temperature of coolant leaving the HTR core can be even higher than 850°C, the most serious problems are related to the high-temperature heat transport to the remote chemical installation. Such high temperatures require the use of special materials, much more expensive than the conventional steel. In this situation another solutions have been proposed, where the heat is transported by the steam loop at 530-550°C, and finally the temperature is raised by conventional heating or by using the mechanical heat pump. In this case the proven heat transport technologies could be applied, but the efficiency would be lower comparing to the high temperature gas transport loop. In the case of external heating either the efficiency will be significantly lower (electrical heating) or the process will be not emission-free (gas heating). The alternative configuration with mechanical heat pump can offer theoretically slightly better efficiency than electrical heating, but because of difficult working conditions serious material problems can be expected.

The technologies required for successful deployment of NA-CTL are not ready for commercialization and a lot of intensive R&D work is required. But expected progress in clean hydrogen production methods will allow for rapid development of NA-DCL methods.

Opportunities and threats

The use of heat from a HTR for thermo-chemical processing of coal could substitute the presently used burning with flameless processes. That would result in an economical use of the raw material and radical reduction in the emissions of CO_2 and other harmful gases. Developing this method would also bring other long-term and strategic advantages like changing the technological profile of the fuel and energy sector, making it a flexible and diversified system, which would guarantee a much higher level of strategic safety, but also be ready to enter the era of hydrogen fuel in the future. In such a system new opportunities are open, connected with processing of natural gas, or, reversely, producing its substitute. Introducing the solution would make it possible to implement and further develop the nuclear reactors technology of the highest generation in Poland, in a way that would be blended in with traditional energy technologies, alleviating the existing social resistance in this area. Synergetic combining of coal and nuclear power industries will have multiple positive consequences for the whole energy sector and the economy as a whole. Poland, due to its leading position in coal exploitation and the lack of significant resources of liquid fuels is predestined for introducing the discussed technology in Europe.
On the other hand, the lack of energy producing nuclear reactors based on the second and third generation technology can even be seen as an advantage. That is because the high-temperature reactors, based on different technologies are not complementary but rather competitive for the existing technologies. Besides, maintaining different types of reactors in one country involves doubling a lot of work, legal regulations etc. Introducing new type reactors in Poland would then be possible without a potential conflict of interests with the existing technology. Certainly, a problem to overcome is re-creating and developing the scientific and technological staff necessary to implement the fourth generation reactors. Such a task will require significant investment – first of all from the state – in education and scientific research. Such investment is strongly desired, as they will provide for the modernization of the economy towards the most modern and technologies. [15] Moreover, both the DCL and ICL process require heat. However, in a CTL plant, coal used as feedstock would perfectly be used as fuel for the cogeneration plant (it would make easier logistics and safety issues).

Future markets

Several forecasts have quantified the future production of coal-to-liquids. Depending on the scenario chosen (rather optimistic or not) the future production of CTL is estimated between 0.3 Mbarrils/day and 5.5Mbarrils/day by 2025. The following table summaries the different forecasts:

Table 2-2 Different forecasts for future production of coal-to-liquids

Source	Year	Production (Mb/d)
National Coal Council	2006	2.7 Mb/d by 2025
Annual Energy Outlook	2015	0,71 by 2040
National Petroleum Council	2007	5.5 Mb/d by 2025

There is some interest in CTL technology around the world, especially in China. China has the most active CTL programme in the world with large scale ICL and DCL R&D programmes supported by the industrial company Shenhua Energy Company. However, in 2008, the Chinese National Development and Reform Commission (NDRC) ordered that all CTL projects, except the DCL and IDCL demonstrations involving the Shenhua Group in Inner Mongolia and the Ningxia Hui Autonomous Region, should be stopped. The objective was initially to produce 10Mton annually of crude oil equivalents by 2010 from domestic coal. The total output was expected to reach 30 million tons of crude oil equivalents by 2020.

2.2.3 Carbon Capture and Storage

Technology description

Carbon Capture and Storage (CCS) refers to the capture, transport and storage of CO_2 that would otherwise have been emitted from commercial facilities excluding the power sector. Once captured, the CO_2 is either geologically stored to permanently isolate the CO_2 from the atmosphere, or can be utilised in industrial applications. Carbon Capture and Storage (CCS) technology has been seen as an important technology for the energy sector to reduce its CO_2 emissions but it can be applied to other energy intensive sectors as well like the cement industry. There are three main technical solutions for CO_2 captures: pre-combustion, post-combustion and oxyfuel. These processes are described in the NC2I-R deliverable D4.11 “Economic assessment and business modelling” [16].

Opportunities for HTR

The CCS technology is meant to be coupled to an industry to reduce the CO_2 emissions. Different industries, of interest for the HTR technology are looking at CCS to reduce their emissions especially, the chemical industry, the steel industry and the CTL industry. The coupling CCS-chemical industry presents interesting opportunities for high-temperature cogeneration since the process would require additional heat and the chemical industry is large in Europe. The steel and iron industry are running at a slow pace in Europe but constitute a potential market outside of Europe, especially in Asia. Finally, CTL appears as one important application for the CCS technology. This coupling could require heat from HTR but as said above, the CTL technology still needs to be implemented in Europe and could use coal a as heat source rather than nuclear energy, making logistics and safety issues easier.

Future markets

According to the vision described by the IEA in 2013 [17], CCS could be deployed at relatively low cost on processes such as coal-to-liquids and chemicals in non-OECD countries, especially in China, in Africa and in the Middle East by 2020. For OECD countries, CCS could be coupled to gas processing. Higher cost-applications of CCS in power generation in OECD countries and in iron and steel production in non-OECD countries also need to be undertaken as early as 2020. The ETP 2012 2DS [18], forecasts that by 2050, a total of over 950 GW of power generation capacity would be equipped with capture, or 8% of all power generation capacity globally. Nonetheless, industrial applications are also important in the 2DS scenario, especially the iron and steel manufacture and the biofuel production, since they would account for 45% of the total volume captured and stored between 2013 and 2050. The figure below shows the forecast of CO_2 captured and stored.

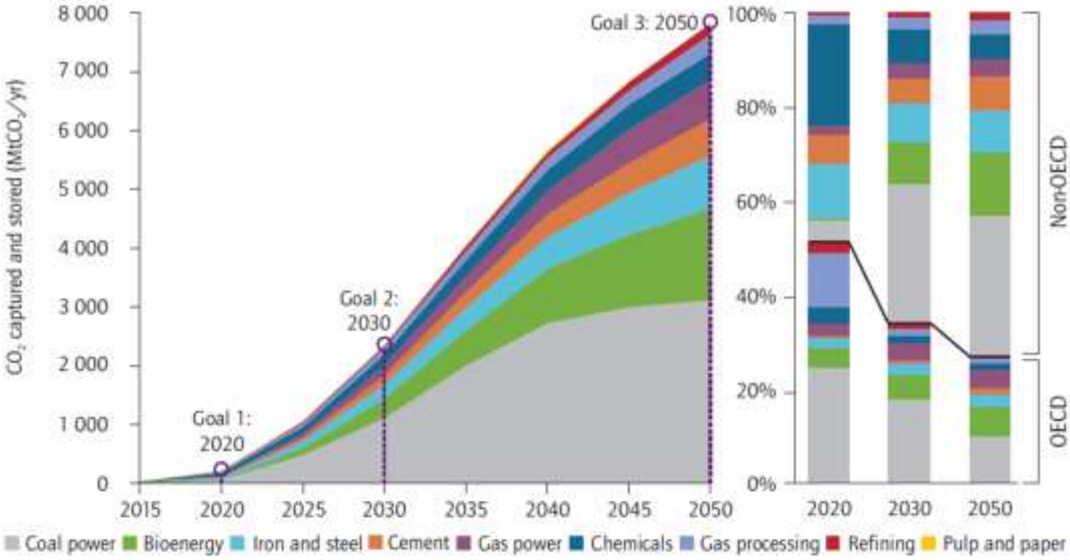


Figure 2-14 CCS in the power and industrial sectors

The potential for the use of CCS in the cement industry comes from the fact that this industry has its CO_2 emissions concentrated in few locations and at the same time the concentration of CO_2 in their flue gas is twice the concentration found in coal-fired plants (about 14-33% compared to 12- 14%) [19]. It is noteworthy to mention that cement emission are 5% of anthropogenic worldwide emissions [13].

2.2.4 Hydrogen

Technology description

The world hydrogen production is not precisely monitored, but is estimated at around 45 million tons, or 500 million Nm^3, per year. Ammonia and methanol production is by far the largest consumer of hydrogen, accounting for 58% of global consumption. Petroleum refineries accounted for the next 37%, and 5% was used in other applications, like: hydrogenation of processed foods, thermal treatment of metal components, production of glass or semiconductors, space propulsion etc. It is commonly expected that in near future hydrogen will play important role as an environmentally friendly energy carrier. Finally, the perspectives of all coal-to-liquid technologies depend on the progress in new, emissions-free hydrogen production methods.

At present only 4% of hydrogen is made by environmental-friendly but expensive alkaline electrolysis. The remaining 96% is produced from fossil fuels giving rise to huge carbon dioxide emissions. Depending on the feedstock, each tonne H_2 produced is equivalent to release of 7-11 tonnes of CO_2. Currently, the most common method of hydrogen production is stream methane reforming (SMR).

It is expected that the high temperature nuclear reactors can be used as a clean source of process heat required for emission-free hydrogen production. The most promising methods comprise:

- nuclear-assisted methane reforming
- polymer electrolyte membrane (PEM) electrolysis
- high temperature electrolysis
- thermochemical water splitting

The nuclear-assisted steam methane reforming (NA-SMR) can produce hydrogen at reasonable cost, but the technology is not emission-free. In fact, the CO_2 generation can be significantly lower than in conventional SMR, but further reductions require more R&D on membrane reactor technologies. The nuclear-assisted dry- and combined methane reforming are very promising as they can remove CO_2 converting it with CH_4 (and steam) in syngas which may be used in subsequent Fischer-Tropsch synthesis. These methods could be combined with NA-SMR allowing for relatively cheap hydrogen production and elimination of CO_2 emissions. However, the both methods are currently not mature enough, and for the effective large-scale deployment intensive R&D is still required.

In high temperature electrolysis, also referred to as steam electrolysis or solid oxide electrolysis, some amount of the total energy required is supplied as heat, which is much cheaper than electric energy. In addition, the high temperature accelerates the reaction kinetics, reducing the energy loss due to electrode polarization, thus increasing the overall system efficiency. The process temperatures depend on the electrolyte used. For often reported $BaZrO_3$ electrolyte it is 500–800°C, but some more complex materials were successfully operated at 460–600°C.

Thermochemical water splitting is the conversion of water into hydrogen and oxygen by a series of thermally driven chemical reactions. Among more than 200 thermochemical cycles that have been studied for the past 35 years, only a few have been identified as promising for emission-free hydrogen production. The thermochemical cycles are expected to have higher efficiency than water electrolysis, and in some publications the hydrogen production cost is estimated below 2.0 $/kg. On the other hand, the DOE cost targets for thermochemical hydrogen production are assumed at 3.9-5.5 $/kg in 2014 and <3.0 $/kg in 2019.

Hydrogen has multiple applications in various industries: refining, ammonia production, the chemical industry, glass making electronics. In addition, hydrogen as a clean energy carrier can be used in transport through fuel cells or to facilitate distributed power generation.

The main production route (95%) used to produce hydrogen is the steam reforming using fossil fuels (mainly natural gas or naphta). The steam reforming process is the only process currently used at an industrial scale. Many other production routes are under development. Two methods, supported by the Fuel Cells and Hydrogen – Joint Undertaken (FCH-JU), are particularly of interest for HTR, since they require high temperature steam: high-temperature electrolysis and sulphur-iodine thermochemical cycle.

Table 2-3 Comparison of hydrogen production routes

	Steam methane reforming	**High Temperature electrolysis**	**Thermochemical cycles**
Heat required	700-850°C	850°C	600-900°C
Status	Industrial scale	Under development	Under development
Advantages	Low production costs	No carbon emission High efficiency	No carbon emission Highest efficiency
Disadvantages	Carbon emissions polluting Low efficiency	High energy demanding	Dangerousness of reagents

At the moment, there is no optimal method of emission-free and cheap production of hydrogen. The only technology available is the low-temperature alkaline electrolysis, but the hydrogen cost is significantly higher than from conventional SMR (without CCS). The other technologies – especially the ones operating at higher temperatures – theoretically can have better efficiencies, but currently none of them is ready for commercial application. It should be noted that in complex cogeneration systems the conventional low-temperature electrolysis can be utilized as a back-up.

Opportunities for HTR

The production of hydrogen is a serious opportunity for HTR since the different production routes require large amount of heat. The current steam methane reforming is well established and the efficiency has been improved over the years. Entry barriers for nuclear cogeneration can be then difficult to overpass. Other techniques to produce hydrogen are under development and represent an opportunity for nuclear cogeneration. High-temperature electrolysis takes place at temperatures around 850° and requires large amount of electricity and heat. A nuclear cogeneration installation answers these constraints and constitutes a real technical solution. Thermochemical cycles to produce hydrogen are also under development and require high-temperature heat. The main disadvantage of this option is the future safety since it involves highly corrosive, expansive and harmful reagents which may make the coupling with a nuclear reactor difficult.

The development of the innovative processes (electrolysis and thermochemical cycles), and thus the coupling with HTR will depend on the future market of hydrogen. This future market will depend on the carbon policies chosen by the governments.

Future markets

In the World Energy Technology Outlook from 2006 [20] the European Commission estimated the production of hydrogen higher around 370 Mtoe in 2050. In this reference case scenario, hydrogen production represents only 3% of the total final energy consumption – equivalent to 9% of final electricity consumption. In Europe, the hydrogen production comes to 60 Mtoe. As shown on the figure below, production is mostly from renewable sources, non-fossil fuels and nuclear.

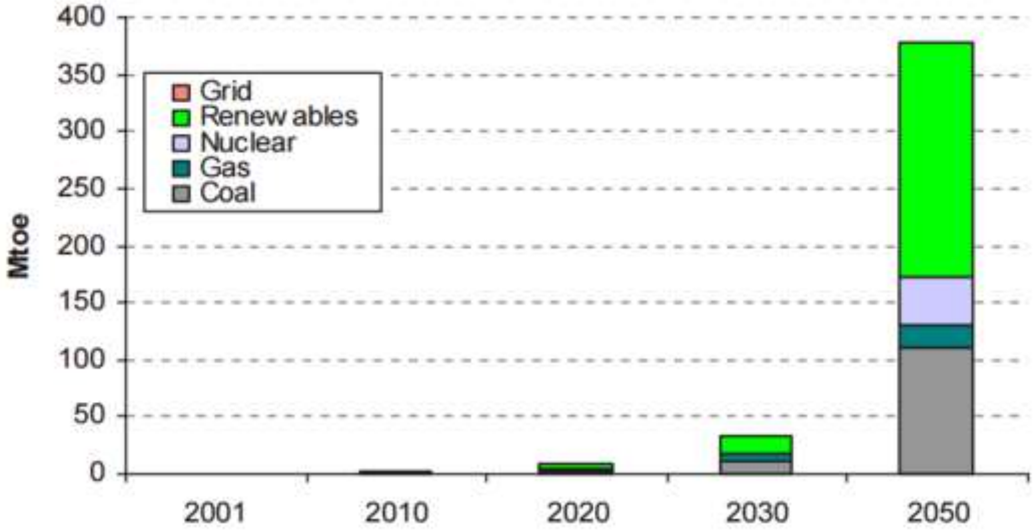


Figure 2-15 Hydrogen energy production by technology

However, in the Carbon Constraint Case, considering more ambitious carbon policies that aim at a long-term stabilisation of the concentration of CO_2 in the atmosphere close to 500 ppmv by 2050, the world hydrogen production reaches almost 600 Mtoe. The production mainly comes from renewable sources. Nonetheless, nuclear accounts for more than 100 Mtoe.

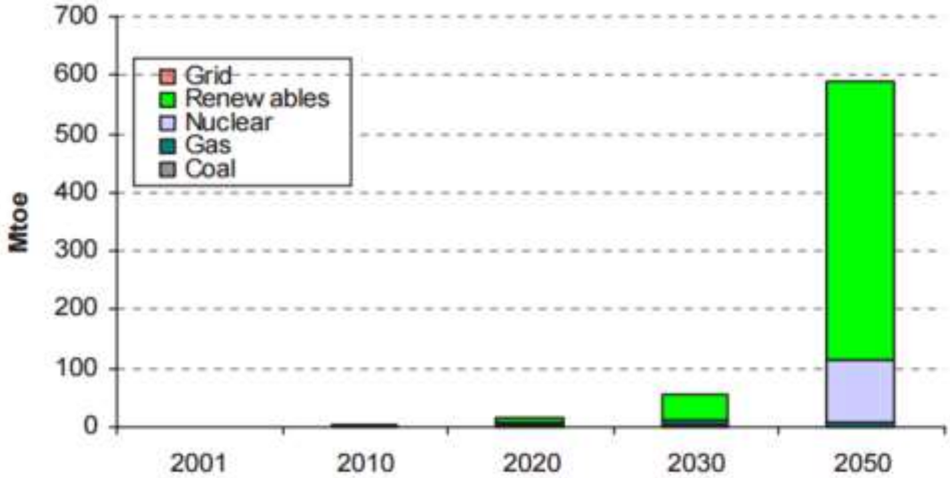


Figure 2-16 World hydrogen production – Carbon Constraint Case

2.2.5 Hybrid Energy Systems

Technology description

Energy markets in Europe are rapidly changing and new renewable like wind and solar generation are entering on the market. The increase of intermittent generation will put new stress on the grid and more flexible generation is needed on the market to balance the difference between consumption and production. The energy system has been based on fossil fuels and the supply side has been flexible and reliable. Large amounts of fossil fuels has been stored on the supply side in liquid, gas, and solid forms. When the usage of wind and solar increases and old fossil fuel plants are being decommissioned the stored energy resources are lost as wind and solar have no natural form of storage.

One of the keys in achieving an affordable low-carbon energy system in the future is to identify new forms to store energy and/or create flexibility that will enable to increase the share of intermittent generation from wind and solar power. Flexibility can be increased by utilizing energy storages, such as electricity or thermal storage or storable gaseous and liquid fuels. At the moment he electricity storage is approximately 100 times more expensive than thermal storage, while thermal storage is ~100 times more expensive than gas and liquid storage. [21] Therefore, thermal, gas, and liquid storages seem to be preferable option to electrical storage when balancing the production of wind and solar. By connecting the electricity, thermal, and transport sectors, it is possible for the electricity sector (e.g. nuclear, wind and solar) to utilise these cheap forms of energy storage.

Hybrid Energy Systems integrate energy conversion processes for optimized energy management and to increase reliability, security, and sustainability of the system. The benefits of Hybrid Energy systems are [22]

- Effective integration of renewable energy by overcoming the challenges of variable production and transmission constraints
- Utilization of nuclear energy beyond the production of only base load power
- Better utilization of carbon fuels, including natural gas and biomass, for the production of transportation fuels with reduced GHG impact
- Efficient utilization and conversion of resources into infrastructure compatible products.

Opportunities for HTR

Integrated Hybrid Energy Systems combining nuclear and renewables should be tailored towards regional resources and markets in order to optimize the use of thermal and electrical energy. Prioritization and analysis of key options is necessary to identify the best synergies in a specified region. Nuclear-renewable energy systems can be divided into five categories: thermal energy generation (i.e. nuclear reactor); power conversion (electricity generation); renewable resources and related systems; industrial processes; and interface or storage technologies [23]. Besides the nuclear reactor and its optimal size the other subsystems vary depending on the resources and market opportunities. As HTR reactors can be optimized to different heat and electricity outputs they can offer flexible source of energy to balance the system needs at different times. Also a number of industrial processes are available for possible integration such as natural gas to liquid fuels plants, production of hydrogen through electrolysis, and production of potable water.

Hybrid Energy Systems could optimize the use of thermal and electrical energy against available resources and local markets. Optimized operation of such hybrid systems would improve the flexibility in the system, decrease the constraints in the grid and allow the operation of both renewable and nuclear power sources at levels that maximize economic benefit. The share of renewable electricity could thus be increased to near maximum potential while avoiding the need for fossil or nuclear plants to operate as standby dispatchable plants. The excess generation could support e.g. the production of clean transportation fuels from domestic resources. [22]

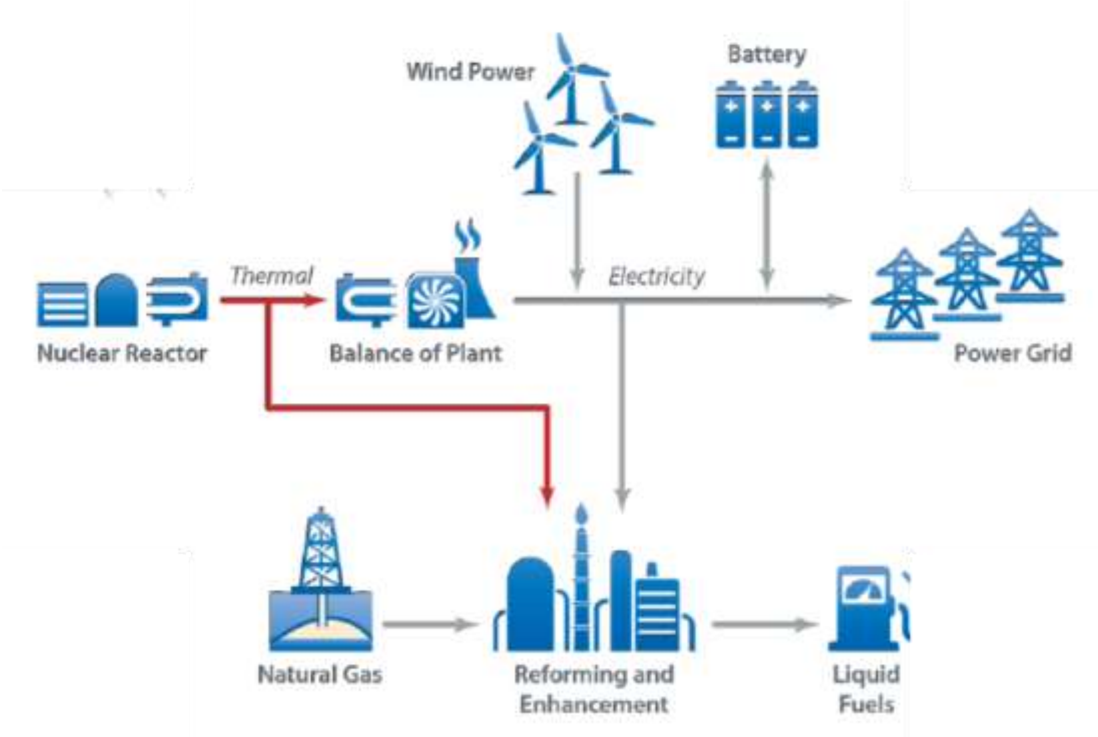


Figure 2-17 Example on nuclear and wind generation sources to produce electricity and to support a natural gas to liquid fuels plant [22]

Future markets

Research work is needed to reduce the system costs of advanced energy systems. Design, development, and deployment of tightly coupled integrated energy systems face numerous challenges that must be addressed. Technical challenges related to system integration could be approached via system modeling and simulation and hardware testing. Additional challenges relate to e.g. financing (demonstration of a feasible business model) and regulatory issue. Prototype development and eventual commercialization can take place when technology gaps are decreased and a clear implementation path is defined.

3 SWOT on nuclear cogeneration

The main strengths, weaknesses, opportunities and threats of nuclear cogeneration are listed in Table 3-1. General drivers for industrial cogeneration are that it improves the economics of electricity only or heat only production, it secures the energy supply for industrial complexes, and can accommodate seasonal variations of electricity demand.

The challenge is to ensure the reliability and availability in order to guarantee the continuous delivery of electricity and heat for the process purposes. Current industry trend has rather been to buy energy instead of building it and thereby avoid risks related to energy production.

Table 3-1 SWOT on nuclear cogeneration

Strengths	***Weaknesses***	***Opportunities***	***Threats***

• Long tradition of cogeneration in energy intensive industries
• Cogeneration increases the plant's feasibility to electricity only plant
• Liberalised markets -possibility to sell the excess electricity to the markets
  • Secure energy supply for industrial complexes
• Minimized heat losses
• Improved energy (fuel) efficiencies
• Provides CO_2 free high temperature steam
• Enhanced energy security
• CHP since long applied in many industries
• Stable fuel price
• Direct and indirect employment
	• Low electricity prices weakening the feasibility
	• Lack of harmonized licensing and regulatory principles
	• Requirement only for a small amount of heat 1-300 MWth, majority < 10 MWth
	• Risks in building new energy generation capacity
	• Handling of spent nuclear fuel
	• Concerns regarding potential accidents
	• High up-front capital
	• Challenging financing
	• Long-lead times
		• Possibilities to utilize excess heat in district heating of near-by cities
		• Trigeneration
		• Improve economics
		• Meet demand for energy-intensive non-electric products (desalination, hydrogen,…etc).
		• Accommodate seasonal variations of electricity demand
			• Continued low electricity prices
			• Low carbon price levels
			• Low energy prices
			• Bureaucracy
			  • Disparity between characteristics of nuclear reactors & heat markets :
			  • Reliability & availability: no unexpected outages & Max availability
			  • Large vs small NPPs (industrial park vs decentralized industries)
			  • Wide range of processes or industries
			  • Planning schedule for complete projects (long vs short)
			• High capital costs
			• Safety distances of nuclear

Many of the strengths, weaknesses, opportunities and threats of nuclear cogeneration are the same as for conventional nuclear power. However, as the size of HTRs are smaller e.g. the constraints on grid are smaller and the likelihood of possible accidents is smaller due to increased safety measures and the impact would also be smaller due to the smaller plant size.

Nuclear energy is recognized as a CO_2 free source for base-load generation. Besides, the cogeneration increases energy efficiency as the efficiency of the CHP plant is higher compared to conventional nuclear power plants. The cost of uranium has a limited impact on the production costs and therefore, compared to gas and coal fired plants, nuclear generation reduces the risks related to fuel prices.

The security of supply for uranium is based on resources coming in a major part from politically stable countries. Nuclear fuel may also be easily stored in small volumes offering additional guarantees on availability of nuclear power plants.

The major part of the nuclear fuel supply chain is based in the EU. European companies are global leaders in nuclear fuel fabrication, enrichment, reprocessing and recycling activities which supports high level of security of supply. [23] Nuclear plants have long lifetimes and they generally have high capacity factors and their overall environmental impact is lower than for fossil fuels. Social benefits of nuclear power include direct employment and stable and predictable cost of energy.

The amounts of used fuel waste from nuclear power generation is small in volume but challenging with regard to its long term confinement. The long-term waste management needs to solved which could also increase acceptability of nuclear. At the moment there is no final repository for high activity waste yet in operation. In 7 out of 16 Member States with NPPs final disposal facilities for Low and Intermediate Level Wastes (LILW) are in operation. [23]

Nuclear cogeneration is capital intensive, therefore the licensing and construction time as well as construction costs have significant impact. Possible delays in nuclear projects can result in substantially higher financing costs, causing cost overruns.

Public acceptance creates uncertainty in the licensing process of nuclear plant. Negative public opinion may delay, obstruct or stop nuclear energy projects. The impact of low frequency accidents could be high and such accidents may affect nuclear acceptability world-wide. Therefore plant safety is built on precautionary measures and safety functions protect the plants in the event of incidents and failures, and limit the consequences of severe accidents.

Sufficient human resources and knowledge on nuclear design, construction, and operation are critical to economical use of nuclear energy. Preserving and transferring the gained knowledge to next generations is a challenge for the nuclear industry as fewer plants have been in construction in Europe in the recent years.

4 Deployment scenarios for nuclear cogeneration

Scenarios for gradual deployments of nuclear cogeneration have been evaluated against the price scenarios in the IEA's World Energy Outlook in 2014 [24]. WEO has three scenarios: Current policies, New policies and 450 scenarios.

The New policies scenario is the central scenario of WEO 2014 taking into account the policies and implementing measures adopted in the middle of 2014 which affect energy markets. The New policies scenario also includes relevant policy proposals even though all the measures needed for the implementation has not yet been fully developed. This scenario has been hereby seen as a base scenario.

The Current policies scenario assumes no changes in current policies adopted as of mid-2014 and represents a business-as-usual future. The scenario provides a baseline picture of how markets would evolve without any new policy invention. The 450 scenario sets out an energy pathway consistent with the goal of limiting the global increase in temperature to 2°C by limiting concentration of greenhouse gases in the atmosphere to around 450 parts per million of CO_2. The 450 scenario assumes a set of policies that limit the greenhouse gas emissions from energy sector to be consistent with the goal.

The price development of the scenarios has been presented in the following Table. CO_2 price assumptions are given for European Union covering power, industry and aviation.

Table 4-1 Price development in the World Energy Outlook scenarios from 2014 [24]

WEO 2014		New policies			Current policies			450		
		2020	**2030**	**2040**	**2020**	**2030**	**2040**	**2020**	**2030**	**2040**
Natural gas	$/MBTU	11.1	12.1	12.7	11.5	13.2	14	10.5	10	9.2
Coal	$/tonne	101	108	112	107	117	124	88	78	77
Crude oil	$/barrel	131	181	244	136	205	286	123	151	185
CO_2	$/tonne	22	37	50	20	30	40	22	100	140

The wholesale price of electricity covering the generation cost and a margin is system specific and depends on the market design, the power mix, the cost of fuels, the extent of environmental levies, and the extent of connectivity with other power systems.

According to WEO 2014 wholesale electricity prices and their future trends vary across the European Union. The prices were not presented in the scenario. In order to evaluate the likeliness of HTR cogeneration in the European electricity generation the average price level of electricity is however needed. Therefore the electricity prices has here been estimated based on the typical merit order on the electricity markets where in general the gas-fired combined-cycle power plants are setting the price. Here no fixed costs have been included but it has been estimated that the prices are set on markets where there is no immediate need for new capacity and therefore the prices are set based on only the variable production costs.

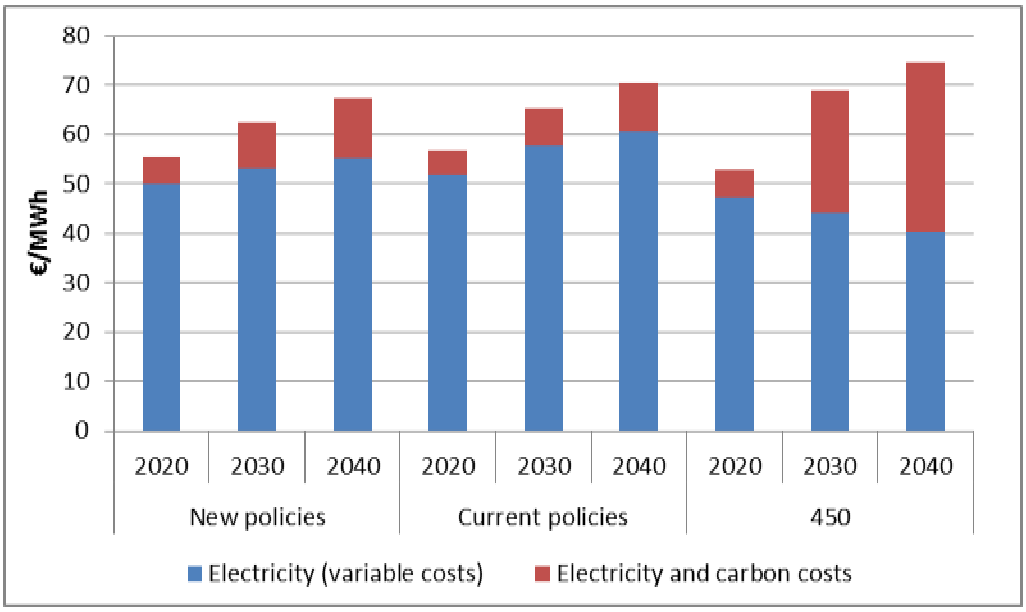


Figure 4-1 Estimated electricity wholesale prices and related carbon costs based on the typical merit order on the electricity markets

Countries estimated as potential adopters of nuclear cogeneration are the countries which have existing nuclear reactors or have plans for new builds. The numbers of adopting countries differs in different scenarios based on the feasibility of the nuclear cogeneration and industrial sectors expected to introduce the technology. The amount of reactors to be build have been estimated based on the study on industrial site mapping [7], demand of industrial process heat and district heating demand in the specific country. It has been assumed that in an individual country the share of nuclear cogeneration as the source of the process heat cannot exceed 40% and the overall share cannot exceed 20% of the heat demand when also the district heating demand has been taken into account. This means that in the countries which have a lot of district heating the amount of reactors can be a bit higher in relation to the industrial heat demand.

Table 4-2 Existing and planned nuclear reactors in EU27

Country	No. of operating reactors[1]	Under construction[1]	No. of planned and proposed reactors by June 2014[2]
Belgium	7		
Bulgaria	2		1
Czech Republic	6		3
Finland	4	1	2
France	58	1	2
Germany	9		-
Hungary	4		2
Lithuania			1
The Netherlands	1		1
Poland			6
Romania	2		3
Slovakia	4	2	1
Slovenia	1		1
Spain	7		
Sweden	10		
United Kingdom	16		11

[1] European nuclear society, https://www.euronuclear.org/info/encyclopedia/n/nuclear-power-plant-europe.htm, referred 8 June 2015

[2] World Nuclear Association, http://www.world-nuclear.org/info/Country-Profiles/Others/European-Union/, referred 8 June 2015

The deployment scenarios for the nuclear cogeneration have been built based on the WEO's scenarios. Besides the WEO's price estimates the effect of policies and emissions targets has been estimated on a country level by estimating which countries are likely to adopt nuclear cogeneration as a part of their generation portfolio. Also different industrial sectors adopting the technology has been estimated. The deployment scenarios and used estimated are presented in Table 4-3.

Table 4-3 Assumptions used in the scenarios

Scenario	Price estimates	Countries adopting HTR cogeneration	Industries adopting HTR cogeneration	Carbon price within electricity price
Base scenario	WEO 2014: New policies scenario	Poland and existing nuclear countries (excl. Belgium, Germany and Sweden)	Chemical industry, district heating, new technologies (CtL, CCS, H_2)	No
Low carbon price scenario	WEO 2014: Current policies scenario	Poland and existing nuclear countries (excl. Belgium, Germany and Sweden)	Chemical industry, district heating	No
High carbon price scenario	WEO 2014: 450 scenario	Poland and all existing nuclear countries (incl. Germany and Sweden), Croatia, Serbia, Ukraine	Chemical industry, Iron & Steel, Non-ferrous metal, Non-metallic mineral products, Ore extraction, district heating, new technologies (CtL, CCS, H_2)	No

The most suitable industrial sites (market restrictions, environmental aspects, business case) were identified in the task 4.2 of this project and were presented in the deliverable D4.21 Site Mapping [7]. The heat and electricity consumption of the sites were studies and their suitability for HTR cogeneration were analysed by also considering the need for the replacements of existing boilers and CHP plants. However, as the development work of the HTR technology still needs to take steps before the commercialization of the technology, most of the identified replacements are likely to be made before the HTR technology is available. On the other hand, there are generally several boilers in the site to guarantee the uninterrupted delivery of process heat so new needs for replacements are likely to occur before the expected commercialization of HTR technology after 2025.

Based on the site mapping and technical information received from 57 sites, 15 sites are big enough to consume the whole heat production of 2x250 MW HTR plant which steam generation is estimated at 387 MWth. Some of these sites are, however, big enough for a capacity of 4x250 MW HTR plant. 9 sites consume more than 200 MW of process heat which seem also quite suitable especially is the excess heat could be supplied as e.g. district heat or if additional heat consumers are close by e.g. industrial park. The rest of the identified sites were quite small for HTR cogeneration (consumption less than 200 MW_{th}) but could be considered if other industrial heat consumers are located close enough or if an moderate size district heating network is in reach.

Table 4-4 Identified chemical plants in Europe based on their heat consumption [7]

Heat consumption	> 385 MW_{th}	200-385 MW_{th}	<200 MW_{th}	NA	Total
Austria				3	**3**
Belgium		1		1	**2**
Bulgaria			1	0	**1**
Denmark			1	0	**1**
Finland				2	**2**
France			2	7	**9**
Germany	1	1	5	38	**45**
Hungary	1	1	9	0	**11**
Ireland				1	**1**
Italy				4	**4**
Netherlands	2	2		4	**8**
Poland	8		5	0	**13**
Romania			4	0	**4**
Slovakia	1		1	0	**2**
Spain	1		1	1	**3**
Sweden				2	**2**
Switzerland				2	**2**
United Kingdom	1	1		4	**6**
Croatia		1	2	0	**3**
Serbia		2		0	**2**
Ukraine	1		1	0	**2**
No. of sites	**15**	**9**	**33**	**69**	**126**

4.1 Base scenario

The base scenario is based on fuel and CO_2 price projection for New Policies Scenario of IEA's World Energy Outlook [24]. The electricity prices have been estimated based on marginal production costs of a gas-fired Combined Cycle with Gas Turbine (CCGT) power plant.

The competitiveness of cogenerated industrial heat in HTR reactor has been estimated against the heat produced in gas- and coal-fired heat-only boilers. The cost of heat production in HTR cogeneration process has been calculated by valuing the simultaneous electricity production against the estimated wholesale electricity prices. The heat production cost from gas- or coal-fired heat-only boilers are based on the cost presented in the deliverable D4.11 Economic modelling [16] and fuel price estimates of WEO 2014.

The heat production cost comparison has been presented in the following Figure. Based on the used price developments heat generated by HTR is becoming more lucrative from 2025 onwards as the CO_2 emission prices are increasing.

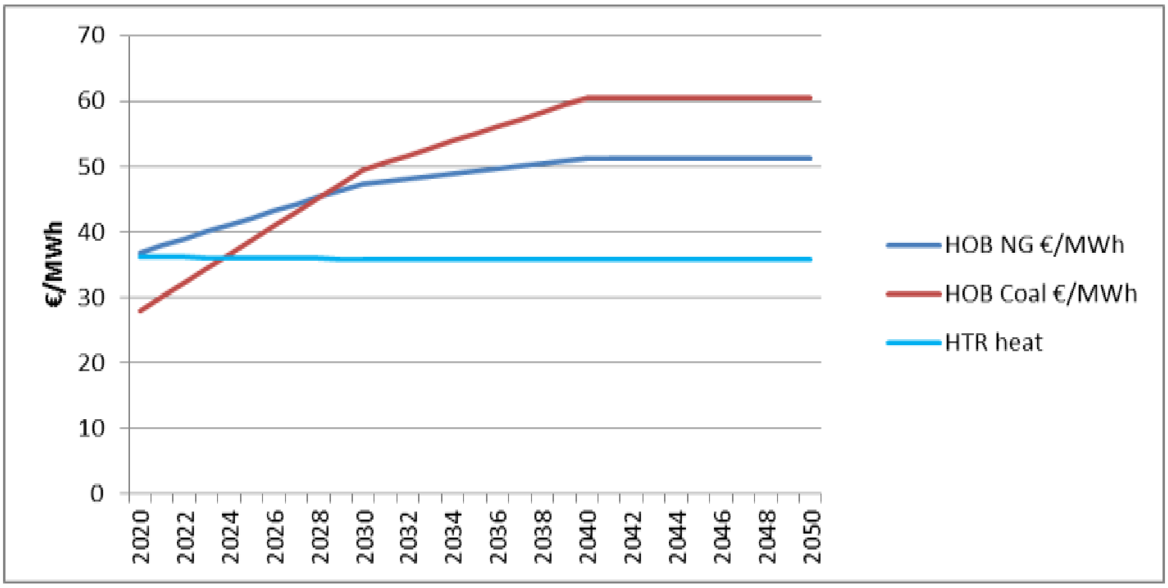


Figure 4-2 Heat production cost comparison in Base scenario

The deployment scenario has been estimated based on the assumptions presented in the Table 4-3 and based on the above cost competitiveness. In the base scenario it has been assumed that adopting sectors for HTR cogeneration is chemical industry and additional heat from the plants can be sold to district heating. The adoption of new technologies like Coal-to-Liquids, CCS and hydrogen production are expected to take place after 2040.

Countries targeted for HTR deployment having existing nuclear plants or plans for new ones and high consumption within the chemical industry represent 54% of the overall heat consumption in the chemical industry sector in the EU. In reality the final deployment will depend on the energy market development and political atmosphere in each country.

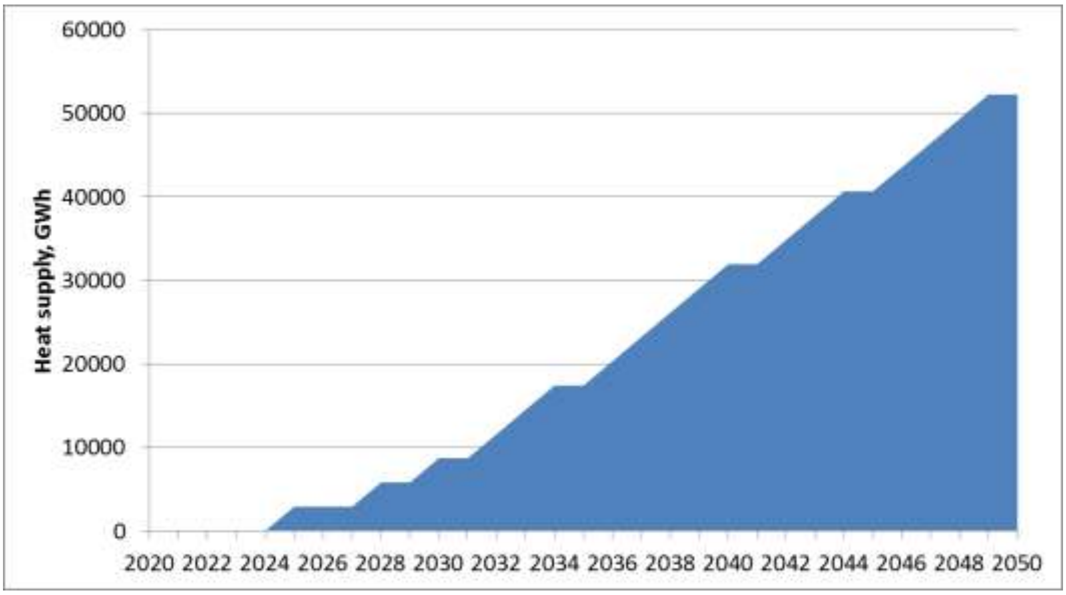


Figure 4-3 Nuclear cogeneration deployment in the Base scenario

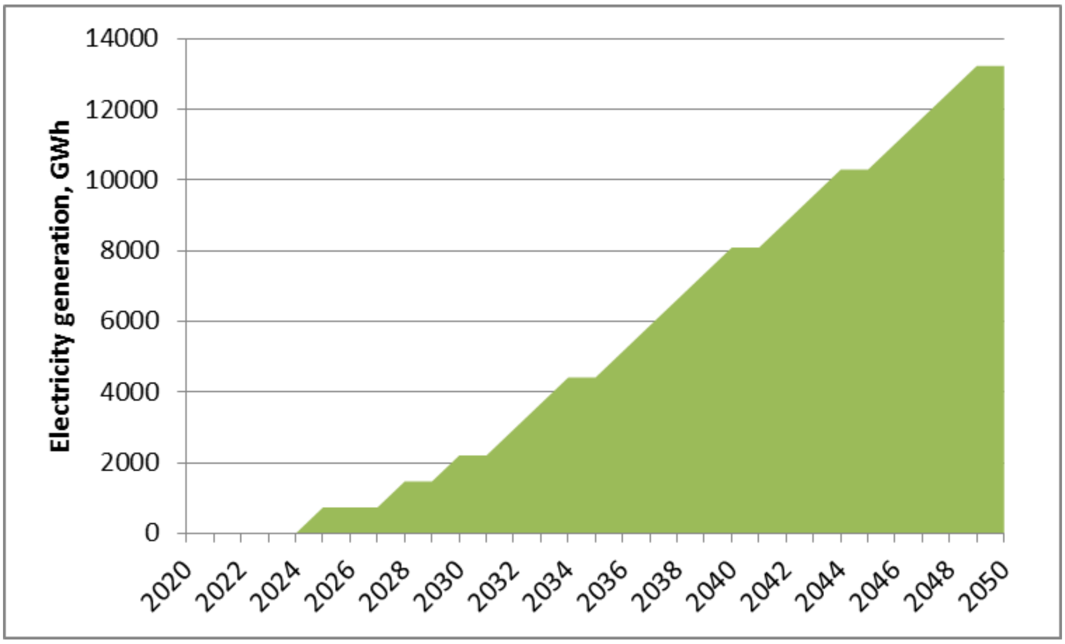


Figure 4-4 Electricity generation by HTR cogeneration in HTR in the Base scenario

The more detailed data behind the scenarios is presented in Annex 1.

4.2 Low carbon price scenario

The low carbon price scenario is based on fuel and CO_2 price projections of Current Policies Scenario of World Energy Outlook [24]. The electricity prices are based on marginal production costs of a gas-fired CCGT power plant.

The competitiveness of cogenerated industrial heat in HTR reactor has been estimated as in the base scenario against the heat produced in gas- or coal-fired heat-only boilers. The production cost comparison has been presented in the following Figure. Based on the used price developments heat generated by HTR is becoming more lucrative after 2023 as the fuel and CO_2 emission prices are increasing.

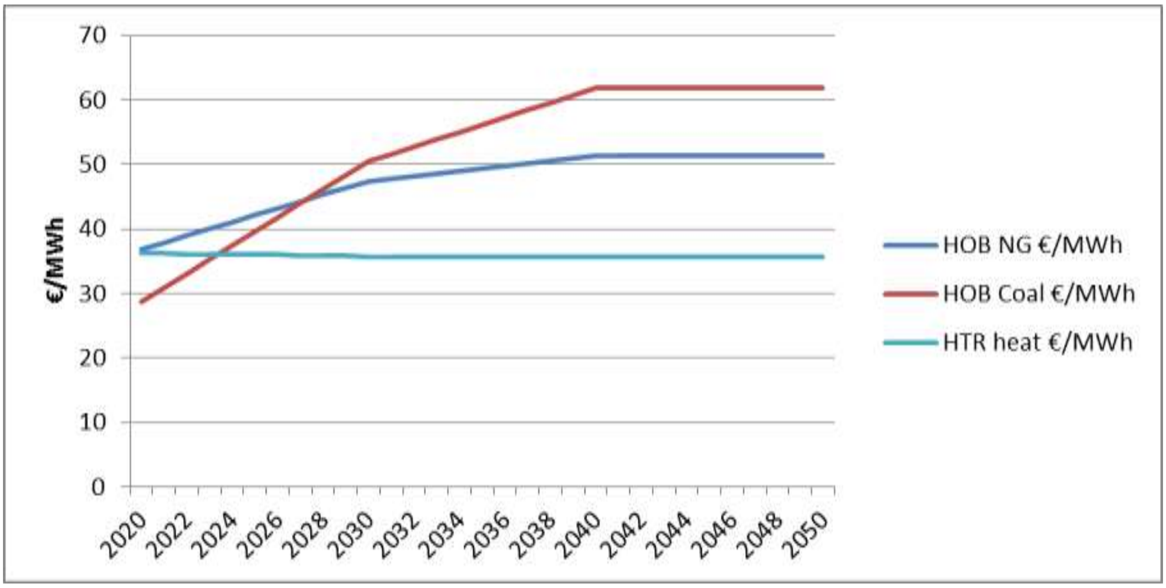


Figure 4-5 Heat production cost comparison in Low carbon price scenario

Compared to Base scenario in Low carbon price scenario the heat generation in HTR comes more lucrative sooner which is due to the higher electricity prices in Low carbon price scenario. Low carbon prices are, however, likely to slow down the investments in CO_2 free and new technologies.

The deployment scenario has been estimated based on the assumptions presented in the Table 4-3 and based on the above cost competitiveness. The adopting sectors for HTR cogeneration are assumed to be chemical industry and district heating as in the Base scenario. The adopting countries are the ones with existing nuclear plants or plans for new ones and high consumption within chemical industry. However, as the carbon price is lower than in the Base scenario the adoption of new technologies like Coal-to-Liquids, SMR, CCS and hydrogen production are expected to be slower and take place after 2050.

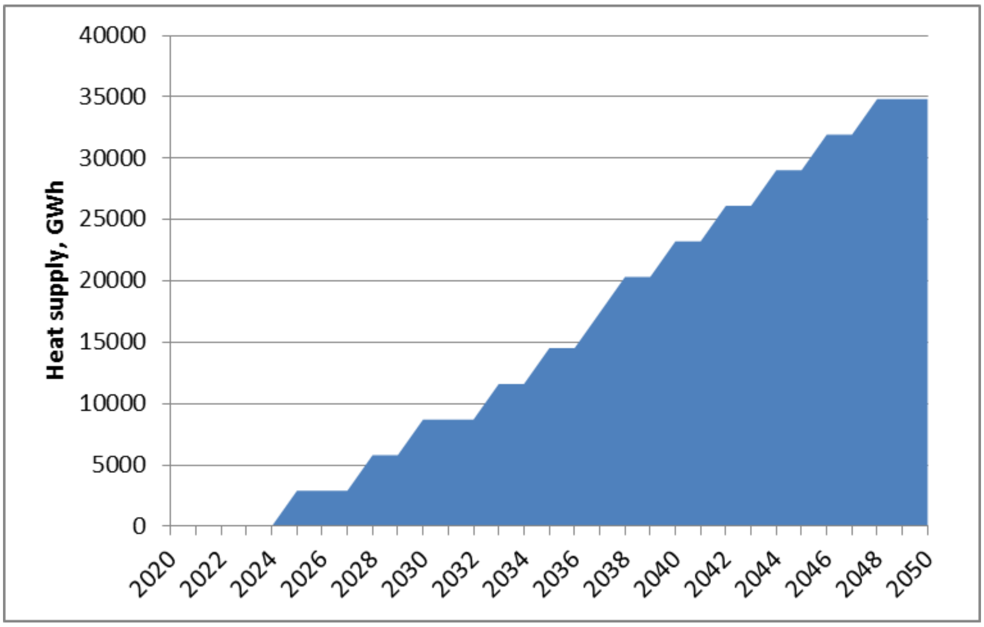


Figure 4-6 Nuclear cogeneration deployment in the Low Carbon Price Scenario

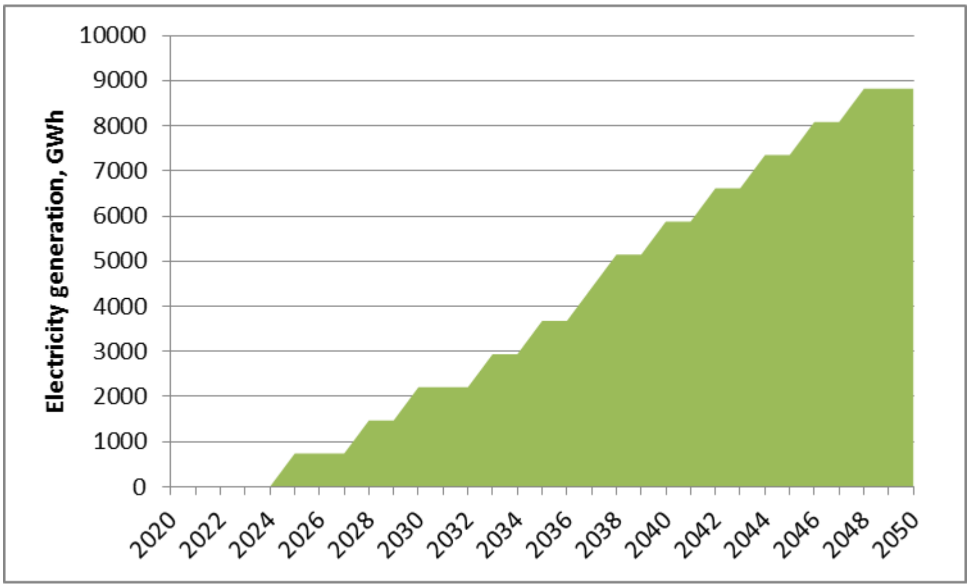


Figure 4-7 Electricity generation by cogeneration in HTR in the Low Carbon Price Scenario

The more detailed data behind the scenarios is presented in Annex 1.

4.3 High carbon price scenario

The base scenario is based on fuel and CO_2 price projection for 450 Scenario of World Energy Outlook [24]. The electricity prices has been estimated based on a marginal production costs of a gas-fired Combined Cycle (CCGT) power plant.

The competitiveness of cogenerated industrial heat in HTR reactor has been estimated against the heat produced in gas- or coal-fired heat-only boilers. The cost of heat production in HTR cogeneration process has been calculated by valuing the simultaneous electricity production against the estimated wholesale electricity prices. The heat production cost from gas- or coal-fired heat-only boilers are based on the cost presented in the deliverable 4.11 Economic modelling [16].

The heat production cost comparison has been presented in the following Figure. Based on the used price developments heat generated by HTR is becoming more lucrative after 2025 as the CO_2 emission prices are increasing.

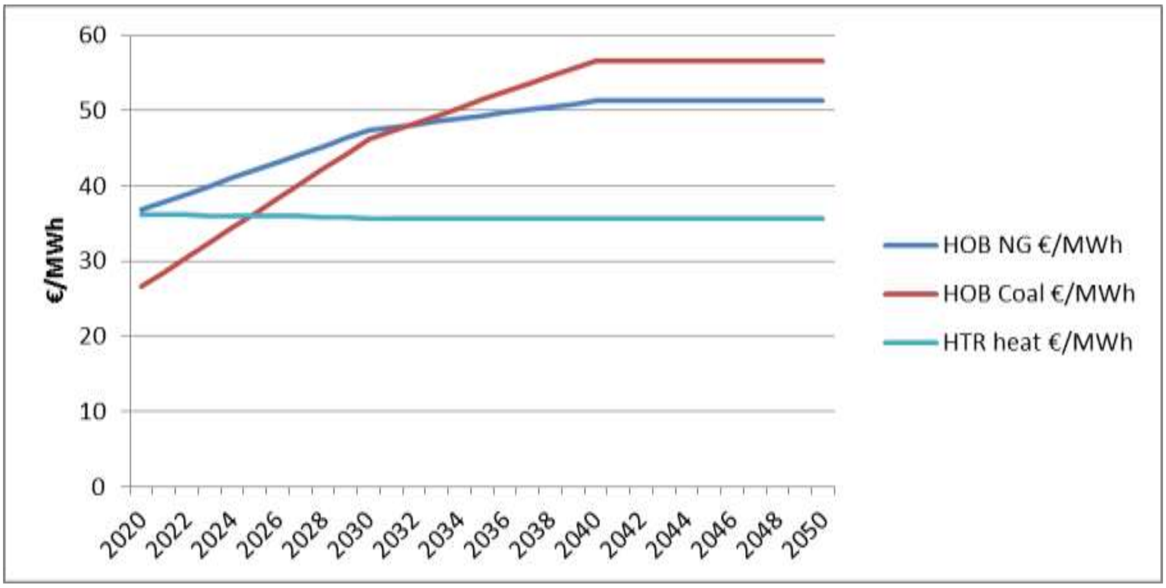


Figure 4-8 Heat production cost comparison in the High carbon price scenario

The deployment scenario has been estimated based on the assumptions presented in the Table 4-1 and based on the cost competitiveness presented above. Even though the carbon prices are high, the fossil fuel prices are low and electricity prices on the market are moderate as there's a lot of renewable generation with low variable costs on the market. This affects that the markets are not remarkably better for HTR development compared to Base scenario or Low carbon price scenario although the high carbon price is expected to encourage the development of low carbon technologies (e.g. CtL, CCS, H_2).

It has been assumed that adopting sectors for HTR cogeneration are chemical industry, iron & steel, non-ferrous metal, non-metallic mineral products, ore extraction, district heating, and new technologies such as CtL, CCS, and H_2. It has been expected that the output temperatures of HTR have been increased making the steam values suitable also for metal industries. The adoption of new technologies are expected to take place after 2040.

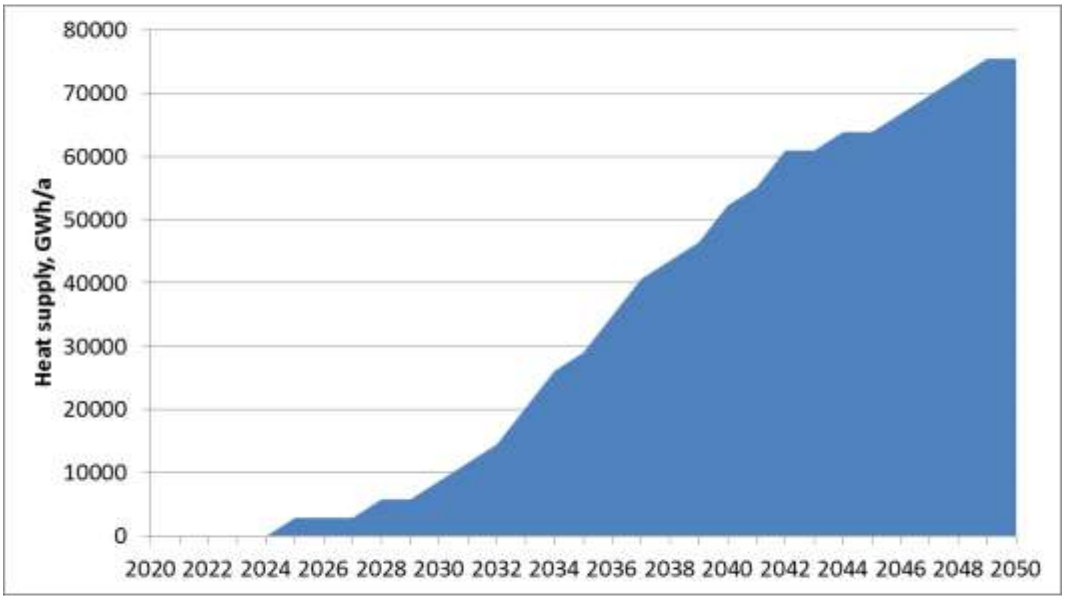


Figure 4-9 Nuclear cogeneration deployment in the High Carbon Price Scenario

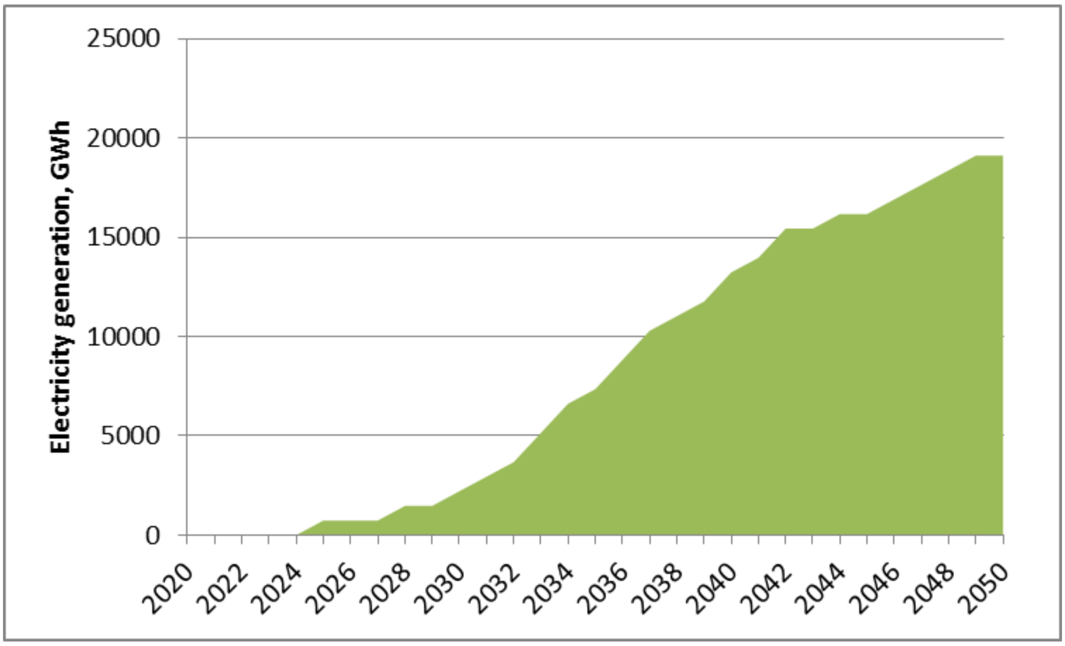


Figure 4-10 Electricity generation by cogeneration in HTR in the Low Carbon Price Scenario

The more detailed data behind the scenarios is presented in Annex 1.

4.4 Effect of scenarios on employment and carbon emissions

The manufacture of HTRs, the construction of sites, and the annual operation will create positive economic effects. Here the assessed economic impacts are the ones related to employment and carbon emissions. The possibilities for technology exports has not been considered here.

The effect of different HTR scenarios on employment and carbon emissions have been estimated by comparing the scenarios to the state-of-art situation where the heat and electricity consumed by the industry are produced with traditional coal and gas-fired CHP plants and heat-only boilers. The alternative carbon emissions for electricity have been estimated based on the average carbon imposture on electricity in IEA Europe countries i.e. 450 kgCO_2/ton [25].

The manufacturing of HTRs is expected to take place in Europe having a positive impact on European employment and economy. The amounts of needed man-years for the manufacturing and construction is hard to estimate and will depend on the amount of sites under construction, local licensing conditions etc. therefore the amounts used for manufacturing and construction are the same as the ones presented for 100 MW SMR [26], which is likely to be on the low side for 2x250 MW HTRs.

Table 4-5 Employment in HTR scenarios

	Manufacturing	Construction	Annual operations, man-year/a	Total man-years in 2020-2050
HTR	5 687	1 238	337	
Base scenario	102 366	22 284	76 499	201 149
Low carbon price scenario	68244	14856	55 942	139 042
High carbon price scenario	147 862	32 188	117 613	297 663

The development of employment in annual operations in different scenarios is presented in the following Figure.

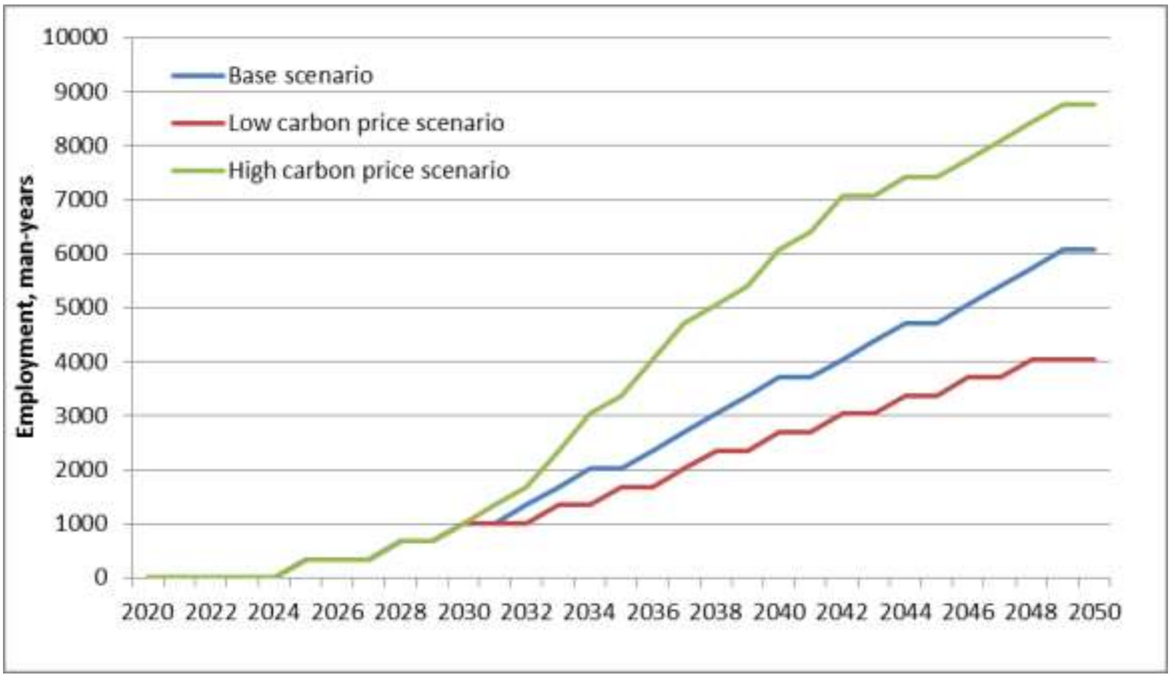


Figure 4-11 Development of employment in different scenarios

The annual addition of employment has been evaluated against the heat and electricity generation in traditional coal and gas fired CHP plants and heat-only-boilers. It has been estimated that 50% of electricity production from HTR is replaced with gas CHP and 50% with coal CHP and rest of the heat production is covered by gas HOBs.

Table 4-6 Effect of scenarios on employment

	No. of reactors	No. of personnel	No. of personnel in traditional plants	Addition in employment, man-years/a
Base scenario	18	6066	928	5138
Low carbon price scenario	12	4044	619	3425
High carbon price scenario	26	8762	1340	7422

The effects of HTR deployment on carbon emissions has been presented in the following Table and Figure. The avoided emissions on electricity generation has been compared against the average carbon imposture on electricity in IEA Europe countries i.e. 450 $kgCO_2/kWh_e$ [25] and the avoided emissions in heat supply has been evaluated against heat generation in heat only boilers (220 $kgCO_2/kWh_{th}$).

Table 4-7 Avoided carbon emissions in HTR scenarios

Mt/a	No. of reactors	Heat	Electricity	Total
Base scenario	18	11 500	6 000	17 500
Low carbon price scenario	12	7 700	4 000	11 700
High carbon price scenario	26	16 600	8 600	25 200

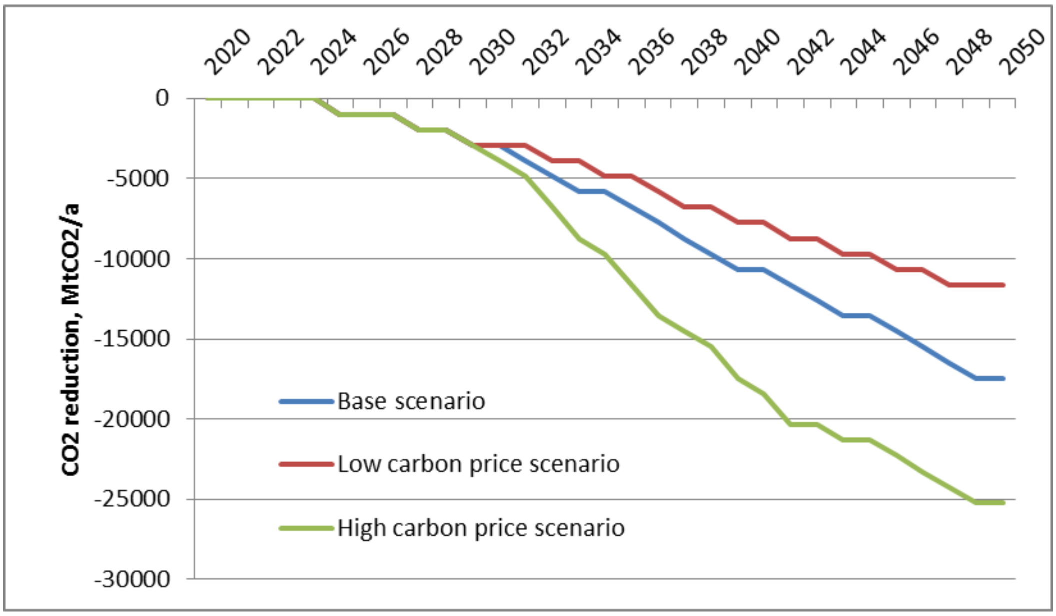


Figure 4-12 Effect of scenarios on carbon emissions

5 Conclusions

The energy system is changing in Europe for a variety of reasons, such as climate change, security of energy supply, and new renewables on the market. The achievement of these goals will require a rapid transition from a fossil fuel based energy system to a carbon free energy system. It will require new solutions on electricity sector but also on heat sector to reduce the fossil fuels used in heat production.

There is a potential market for HTRs in Europe to provide heat and electricity to industries requiring low to medium temperature steam. Earlier studies in the Nuclear Cogeneration Industrial Initiative project already identified industrial sectors suitable for HTR cogeneration. In the near future chemical industry was seen as a most prominent sector as it already uses cogeneration, the required temperatures correspond to the output of an HTR and the power capacity of several parks is large enough to be compatible with the size of an HTR.

Mid to long-term solutions for the utilization of electricity and heat provided by HTR are Coal-to-Liquid and Carbon Capture and Storage which utilize the heat in the pressure and temperature suitable for a HTR. The applications for the utilization heat from High Temperature Reactors will increase to e.g. metal and non-metallic mineral industries as well as to hydrogen production if the output temperature of the heat from HTR could be increased up to 700-1000°C.

The cogeneration will increase the efficiency of both the electricity and heat sectors. Since fossil fuels are substituted with nuclear cogeneration, the reduced usage of fossil fuels will give considerably reduced emissions of carbon dioxide for all heat sectors utilizing nuclear cogeneration. The energy imports will also decrease which will increase the future security of supply and give more positive balances of foreign exchange. The calculations indicate that the overall CO_2 reduction in the heating sector could be 18000 million tons of CO_2 by 2050.

The nuclear cogeneration will generate local labour since capital intensive investments will replace expensive imports of fossil fuels to Europe. An estimate indicates that approximately 200 000 man-years could be created in Europe by 2050.

As the energy system is changing and a higher proportion of variable renewable electricity will be on the market, a smart energy system is needed with flexible generation to balance the difference between the demand and supply. Flexible cogeneration can support the system by adjusting its electricity and heat output accordingly.

Abbreviations

Abbreviation	Signification
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
CTL	Coal To Liquid
DCL	Direct Coal Liquefaction
FCH-JU	Fuel Cells & Hydrogen – Joint Undertaking
GHG	Greenhouse Gas
HSOZ	Heat Synergy Opportunity Zone
HT	High Temperature
HTR	High Temperature Reactor
IAEA	International Atomic Energy Agency
ICL	Indirect Coal Liquefaction
LILW	Low and Intermediate Level Wastes
Mtoe	Million Tonnes of Oil Equivalent
MWe	Electrical Megawatt
MWth	Thermal Megawatt
NPP	Nuclear Power Plant
NUTS3	Nomenclature of territorial units for statistics 3 regions
PJ	Petajoule
SMR	Steam Methane Reforming
WEO	World Energy Outlook

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Annex 1

Energy production

BASE SCENARIO

Electricity generation in HTRs

GWh	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Belgium	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bulgaria	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Czech republic	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	735	735	735	735	735	735	735	735	735	735	735	1470	1470	1470
Finland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
France	0	0	0	0	0	0	0	0	0	0	0	0	0	0	735	735	735	735	735	1470	1470	1470	1470	1470	1470	1470	1470	1470	1470	1470	1470
Hungary	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Netherlands	0	0	0	0	0	0	0	0	0	0	0	0	735	735	735	735	735	735	1470	1470	1470	1470	1470	1470	1470	1470	1470	1470	1470	2205	2205
Poland	0	0	0	0	0	735	735	735	1470	1470	2205	2205	2205	2205	2205	2205	2205	2205	2205	2205	2205	2205	2205	2205	2940	2940	2940	3675	3675	3675	3675
Romania	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	735	735	735	735	735	735	1470	1470	1470	1470	1470	1470	1470	1470	1470
Spain	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	735	735	735	735	735	735	1470	1470	1470	1470	1470
United Kingdom	0	0	0	0	0	0	0	0	0	0	0	0	0	735	735	735	735	735	735	735	735	735	735	1470	1470	1470	1470	1470	1470	1470	1470
TOTAL	**0**	**0**	**0**	**0**	**0**	**735**	**735**	**735**	**1470**	**1470**	**2205**	**2205**	**2940**	**3675**	**4410**	**4410**	**5145**	**5880**	**6615**	**7350**	**8085**	**8085**	**8820**	**9555**	**10290**	**10290**	**11025**	**11760**	**12495**	**13230**	**13230**

Heat production in HTRs

GWh	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Belgium	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bulgaria	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Czech republic	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2902.5	2902.5	2902.5	2902.5	2902.5	2902.5	2902.5	2902.5	2902.5	2902.5	2902.5	5805	5805	5805
Finland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
France	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2902.5	2902.5	2902.5	2902.5	2902.5	5805	5805	5805	5805	5805	5805	5805	5805	5805	5805	5805	5805
Hungary	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Netherlands	0	0	0	0	0	0	0	0	0	0	0	0	2902.5	2902.5	2902.5	2902.5	2902.5	2902.5	5805	5805	5805	5805	5805	5805	5805	5805	5805	5805	5805	8707.5	8707.5
Poland	0	0	0	0	0	2902.5	2902.5	2902.5	5805	5805	8707.5	8707.5	8707.5	8707.5	8707.5	8707.5	8707.5	8707.5	8707.5	8707.5	8707.5	8707.5	8707.5	8707.5	11610	11610	11610	14512.5	14512.5	14512.5	14512.5
Romania	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2902.5	2902.5	2902.5	2902.5	2902.5	2902.5	5805	5805	5805	5805	5805	5805	5805	5805	5805
Spain	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2902.5	2902.5	2902.5	2902.5	2902.5	2902.5	5805	5805	5805	5805	5805
United Kingdom	0	0	0	0	0	0	0	0	0	0	0	0	0	2902.5	2902.5	2902.5	2902.5	2902.5	2902.5	2902.5	2902.5	2902.5	2902.5	5805	5805	5805	5805	5805	5805	5805	5805
TOTAL	**0**	**0**	**0**	**0**	**0**	**2902.5**	**2902.5**	**2902.5**	**5805**	**5805**	**8707.5**	**8707.5**	**11610**	**14512.5**	**17415**	**17415**	**20317.5**	**23220**	**26122.5**	**29025**	**31927.5**	**31927.5**	**34830**	**37732.5**	**40635**	**40635**	**43537.5**	**46440**	**49342.5**	**52245**	**52245**

Heat production in HTRs

GWh	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Chemical	0	0	0	0	0	2902.5	2902.5	2902.5	5805	5805	8707.5	8707.5	11610	14512.5	17415	17415	20317.5	23220	26122.5	29025	31927.5	31927.5	31927.5	31927.5	31927.5	31927.5	31927.5	31927.5	31927.5	31927.5	31927.5
Iron & Steel																															
Non-ferrous metal																															
Non-metallic mineral products																															
Ore extraction																															
New technologies	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2902.5	5805	8707.5	8707.5	11610	14512.5	17415	20317.5	20317.5
TOTAL	**0**	**0**	**0**	**0**	**0**	**2902.5**	**2902.5**	**2902.5**	**5805**	**5805**	**8707.5**	**8707.5**	**11610**	**14512.5**	**17415**	**17415**	**20317.5**	**23220**	**26122.5**	**29025**	**31927.5**	**31927.5**	**34830**	**37732.5**	**40635**	**40635**	**43537.5**	**46440**	**49342.5**	**52245**	**52245**

LOW CARBON PRICE SCENARIO

Electricity generation in HTRs

GWh	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Belgium	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bulgaria	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Czech republic	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	735	735	735	735	735	735	735
Finland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
France	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	735	735	735	1470	1470	1470	1470	1470	1470	1470	1470	1470	1470	1470
Hungary	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Netherlands	0	0	0	0	0	0	0	0	0	0	0	0	0	735	735	735	735	735	735	735	735	735	735	735	735	735	735	735	1470	1470	1470
Poland	0	0	0	0	0	735	735	735	1470	1470	2205	2205	2205	2205	2205	2205	2205	2205	2205	2205	2205	2205	2205	2205	2205	2205	2205	2205	2205	2205	2205
Romania	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	735	735	735	735	735	735	735	735	735
Spain	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	735	735	735	735	735
United Kingdom	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	735	735	735	1470	1470	1470	1470	1470	1470	1470	1470	1470	1470	1470	1470	1470
TOTAL	**0**	**0**	**0**	**0**	**0**	**735**	**735**	**735**	**1470**	**1470**	**2205**	**2205**	**2205**	**2940**	**2940**	**3675**	**3675**	**4410**	**5145**	**5145**	**5880**	**5880**	**6615**	**6615**	**7350**	**7350**	**8085**	**8085**	**8820**	**8820**	**8820**

Heat production in HTRs

GWh	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Belgium	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bulgaria	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Czech republic	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2903	2903	2903	2903	2903	2903	2903
Finland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
France	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2903	2903	2903	5805	5805	5805	5805	5805	5805	5805	5805	5805	5805	5805
Hungary	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Netherlands	0	0	0	0	0	0	0	0	0	0	0	0	0	2903	2903	2903	2903	2903	2903	2903	2903	2903	2903	2903	2903	2903	2903	2903	5805	5805	5805
Poland	0	0	0	0	0	2903	2903	2903	5805	5805	8708	8708	8708	8708	8708	8708	8708	8708	8708	8708	8708	8708	8708	8708	8708	8708	8708	8708	8708	8708	8708
Romania	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2903	2903	2903	2903	2903	2903	2903	2903	2903
Spain	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2903	2903	2903	2903	2903
United Kingdom	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2903	2903	2903	5805	5805	5805	5805	5805	5805	5805	5805	5805	5805	5805	5805	5805
TOTAL	**0**	**0**	**0**	**0**	**0**	**2903**	**2903**	**2903**	**5805**	**5805**	**8708**	**8708**	**8708**	**11610**	**11610**	**14513**	**14513**	**17415**	**20318**	**20318**	**23220**	**23220**	**26123**	**26123**	**29025**	**29025**	**31928**	**31928**	**34830**	**34830**	**34830**

Heat production in HTRs

GWh	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Chemical	0	0	0	0	0	2903	2903	2903	5805	5805	8708	8708	8708	11610	11610	14513	14513	17415	20318	20318	23220	23220	26123	26123	29025	29025	31928	31928	34830	34830	34830
Iron & Steel																															
Non-ferrous metal																															
Non-metallic mineral products																															
Ore extraction																															
New technologies																															
TOTAL	**0**	**0**	**0**	**0**	**0**	**2903**	**2903**	**2903**	**5805**	**5805**	**8708**	**8708**	**8708**	**11610**	**11610**	**14513**	**14513**	**17415**	**20318**	**20318**	**23220**	**23220**	**26123**	**26123**	**29025**	**29025**	**31928**	**31928**	**34830**	**34830**	**34830**

HIGH CARBON PRICE SCENARIO

Electricity generation in HTRs

GWh	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Belgium	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bulgaria	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Czech republic	0	0	0	0	0	0	0	0	0	0	0	0	0	0	735	735	1470	1470	1470	1470	1470	1470	1470	1470	1470	1470	1470	1470	2205	2205	2205
Finland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	735	735	735	735	735	735	735	735	735	735	735	735
France	0	0	0	0	0	0	0	0	0	0	0	0	0	735	735	1470	1470	2205	2205	2205	2940	2940	2940	2940	2940	2940	2940	2940	2940	2940	2940
Hungary	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Netherlands	0	0	0	0	0	0	0	0	0	0	0	735	735	1470	1470	1470	1470	1470	2205	2205	2205	2205	2205	2205	2205	2205	2205	2205	2205	2940	2940
Poland	0	0	0	0	0	735	735	735	1470	1470	2205	2205	2205	2205	2205	2205	2205	2205	2205	2205	2940	2940	2940	2940	3675	3675	3675	4410	4410	4410	4410
Romania	0	0	0	0	0	0	0	0	0	0	0	0	0	0	735	735	735	735	735	735	735	735	1470	1470	1470	1470	1470	1470	1470	1470	1470
Spain	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	735	735	735	735	735	1470	1470	1470	1470	1470	2205	2205	2205	2205	2205
United Kingdom	0	0	0	0	0	0	0	0	0	0	0	0	735	735	735	735	735	1470	1470	1470	1470	1470	2205	2205	2205	2205	2205	2205	2205	2205	2205
TOTAL	**0**	**0**	**0**	**0**	**0**	**735**	**735**	**735**	**1470**	**1470**	**2205**	**2940**	**3675**	**5145**	**6615**	**7350**	**8820**	**10290**	**11025**	**11760**	**13230**	**13965**	**15435**	**15435**	**16170**	**16170**	**16905**	**17640**	**18375**	**19110**	**19110**

Heat production in HTRs

GWh	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Belgium	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bulgaria	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Czech republic	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2903	2903	5805	5805	5805	5805	5805	5805	5805	5805	5805	5805	5805	5805	8708	8708	8708
Finland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2903	2903	2903	2903	2903	2903	2903	2903	2903	2903	2903	2903
France	0	0	0	0	0	0	0	0	0	0	0	0	0	2903	2903	5805	5805	8708	8708	8708	11610	11610	11610	11610	11610	11610	11610	11610	11610	11610	11610
Hungary	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Netherlands	0	0	0	0	0	0	0	0	0	0	0	2903	2903	5805	5805	5805	5805	5805	8708	8708	8708	8708	8708	8708	8708	8708	8708	8708	8708	11610	11610
Poland	0	0	0	0	0	2903	2903	2903	5805	5805	8708	8708	8708	8708	8708	8708	8708	8708	8708	8708	11610	11610	11610	11610	14513	14513	14513	17415	17415	17415	17415
Romania	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2903	2903	2903	2903	2903	2903	2903	2903	5805	5805	5805	5805	5805	5805	5805	5805	5805
Spain	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2903	2903	2903	2903	2903	5805	5805	5805	5805	5805	8708	8708	8708	8708	8708
United Kingdom	0	0	0	0	0	0	0	0	0	0	0	0	2903	2903	2903	2903	2903	5805	5805	5805	5805	5805	8708	8708	8708	8708	8708	8708	8708	8708	8708
TOTAL	**0**	**0**	**0**	**0**	**0**	**2902.5**	**2902.5**	**2902.5**	**5805**	**5805**	**8707.5**	**11610**	**14512.5**	**20317.5**	**26122.5**	**29025**	**34830**	**40635**	**43537.5**	**46440**	**52245**	**55147.5**	**60952.5**	**60952.5**	**63855**	**63855**	**66757.5**	**69660**	**72562.5**	**75465**	**75465**

Heat production in HTRs

GWh	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Chemical	0	0	0	0	0	2902.5	2902.5	2902.5	5805	5805	8707.5	11610	14512.5	20317.5	26122.5	29025	31927.5	34830	34830	34830	37732.5	37732.5	40635	37732.5	40635	40635	43537.5	46440	49342.5	52245	52245
Iron & Steel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2902.5	5805	8707.5	11610	11610	11610	11610	11610	11610	11610	11610	11610	11610	11610	11610
Non-ferrous metal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2902.5	5805	8707.5	8707.5	8707.5	8707.5	8707.5	8707.5	8707.5	8707.5	8707.5
Non-metallic mineral	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2902.5	0	0	0	0	0	0	0
Ore extraction	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
New technologies	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2902.5	2902.5	2902.5	2902.5	2902.5	2902.5	2902.5
TOTAL	**0**	**0**	**0**	**0**	**0**	**2902.5**	**2902.5**	**2902.5**	**5805**	**5805**	**8707.5**	**11610**	**14512.5**	**20317.5**	**26122.5**	**29025**	**34830**	**40635**	**43537.5**	**46440**	**52245**	**55147.5**	**60952.5**	**60952.5**	**63855**	**63855**	**66757.5**	**69660**	**72562.5**	**75465**	**75465**