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Safety Assessment of Non-Electric uses of nuclear energy

Overview of potential applications for nuclear energy

2025 Oct 1st

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N. & Name	**Overview of potential applications for nuclear energy**				
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Description of the related task and the deliverable	This report provides a comprehensive overview of non-electric applications of nuclear energy, highlighting sectors where nuclear technologies have limited current use but significant future potential. It aims primarily to offer an introductory perspective, outlining market potential and technical feasibility across various industries. This overview serves as the foundation for subsequent, more detailed sector-specific analyses. The sectors examined include district heating, desalination, data centers, industrial applications (focusing on the chemical industry, industrial heat for energy-intensive industries, and food and drink), agriculture, ship propulsion, and space applications. The report includes initial case studies to illustrate promising opportunities for nuclear applications beyond electricity generation. It briefly assesses the viability of the nuclear energy, especially in the context of the evolving European energy landscape, and outlines critical recommendations for future detailed research, technological advancements, and supportive policies to facilitate CO_2-free industrial practices. The overarching goal is to identify and preliminarily assess a broad spectrum of potential nuclear applications, supporting more detailed studies in WP1 that will provide deeper evaluations of these opportunities.				
Participants	VTT				
Comments	–				

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Content

1. Energy demand in Europe by sector

Final energy consumption in 2022 in EU was 37 771 PJ (= 10 492 TWh). Figure 1 left-side pie chart shows the final energy consumption by sector, and the right side the corresponding greenhouse gas emissions of the area. The transport, household, and industry sectors account for 83% of the energy demand, while the largest emissions are accounted for by energy supply, domestic transport and industry, totaling 69%.

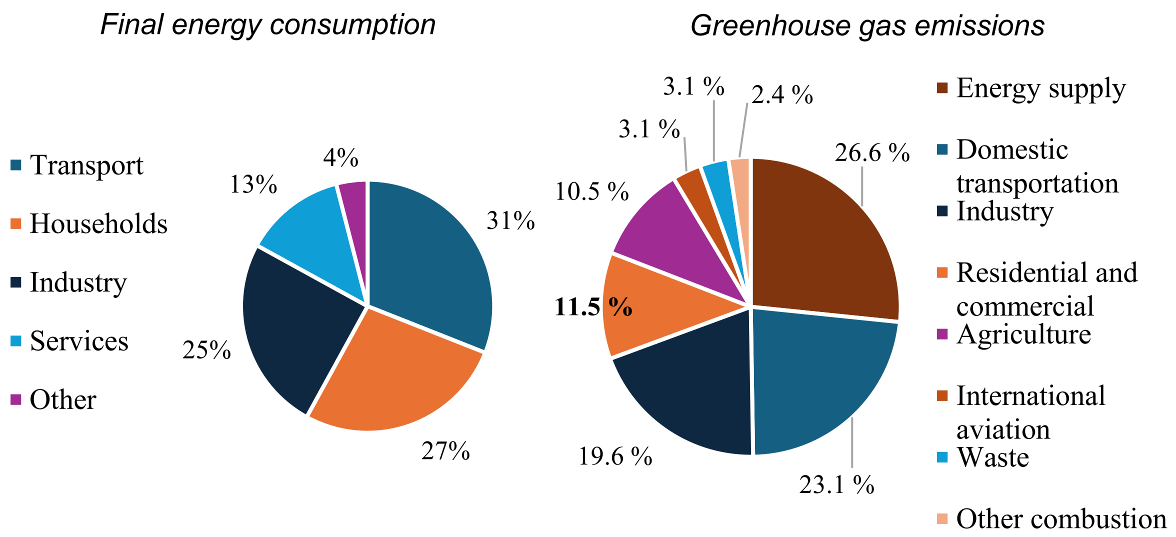


Figure 1. Left: Final energy consumption in EU by sector (2022) Eurostat [1]. International aviation and maritime bunkers are excluded from transport. Right: Greenhouse gas emissions by sector in the EU in 2022 [2].

By energy product, the final energy consumption is covered in large parts by fossil fuels; oil and petroleum products, and natural gas. Electricity is another major energy product, and in 2022 34,5 of net electricity generation was from renewable sources. Including nuclear, the share was 55,9 %. [3]

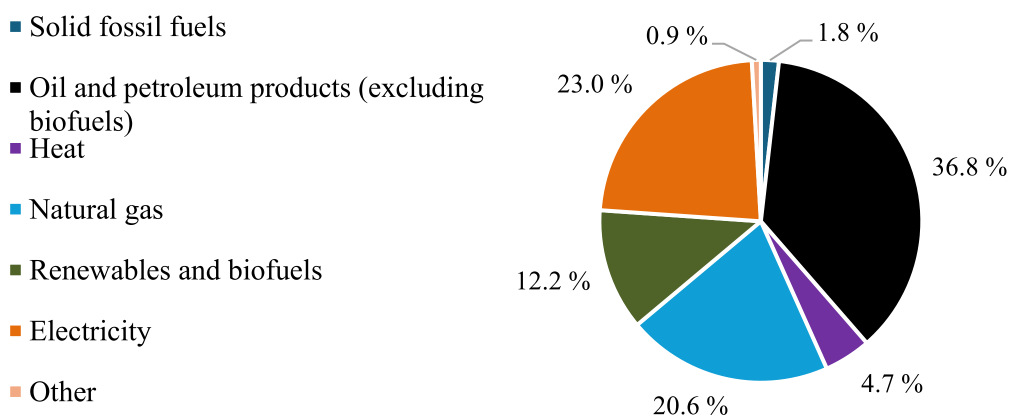


Figure 2. Final energy consumption by fuel in EU (2022) [4].

1.1 Energy demand projections

The IEA World Energy Outlook 2024 provides a region-specific scenario for the energy demand in the European Union until 2050. The STEPS scenario considers the stated policies of the European countries, however only accounting for those policies which have been pointed enough resources for implementation. Figure 3 presents the scenario results for energy demand development between 2023 and 2050, by energy product. The gross available energy declines by 23.4 % between 2020 and 2050. The share of fossil fuels decreases, and in absolute values the share of oil and natural gas experience a major drop by 2050. The share of renewables and nuclear would increase from 56.3 % in 2023 to 71.69 % in 2050, relative to the total energy demand.

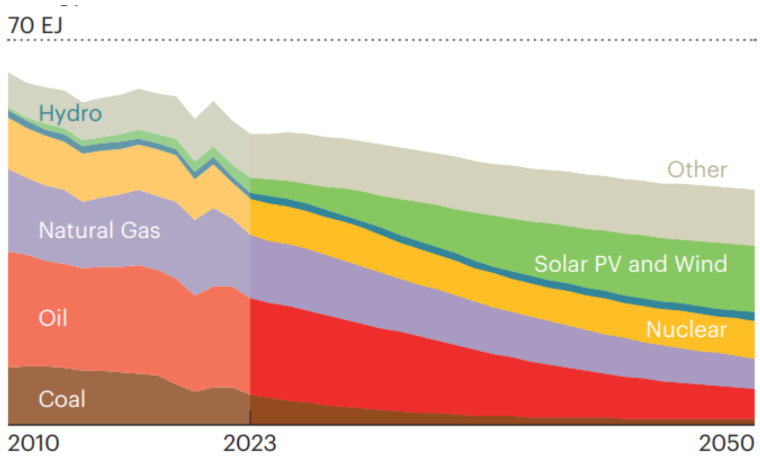


Figure 3. Energy demand in Europe in the "Stated Policies Scenario, STEPS" [5]. (gross available energy) Gross available energy = Primary production + Recovered & Recycled products + Imports – Export + Stock changes)

The STEPS scenario shows also a growth of low-emissions energy in the industry sector, which would grow from 25.5 % in 2023 to 48 % in 2050. Industry emissions show a 31.1 % decrease from 2023 to 2050, which would mean a drop from 0.52 $GtCO_2$ to 0.35 $GtCO_2$.

The EU reference scenario modelling from 2020 provides extensive insights to multiple greenhouse gas emitting sectors and their energy demand projections. The modelling has been carried out by examining the effects of policies, macroeconomic trends, fuel prices and technological trends together in the 27 member states. The modelling shows the effects of the policies existing at that time, i.e. does not show how climate neutrality is reached but how close with the existing policies it could be possible.[6] However, as the modelling was conducted in early 2020, many assumptions regarding especially fuel prices and carbon prices are outdated due to the energy crisis. Higher ETS prices may in fact accelerate energy efficiency measures as well as renewable energy investments, combined with the effects of the Russian aggression war in Ukraine to energy supplies, such as natural gas.

Figure 4 shows development of final energy consumption in the EU reference scenario. The modelling results show that the final energy consumption in the EU experiences a gradual decline after 2030 and declines with 8.5 % between 2020 and 2050.

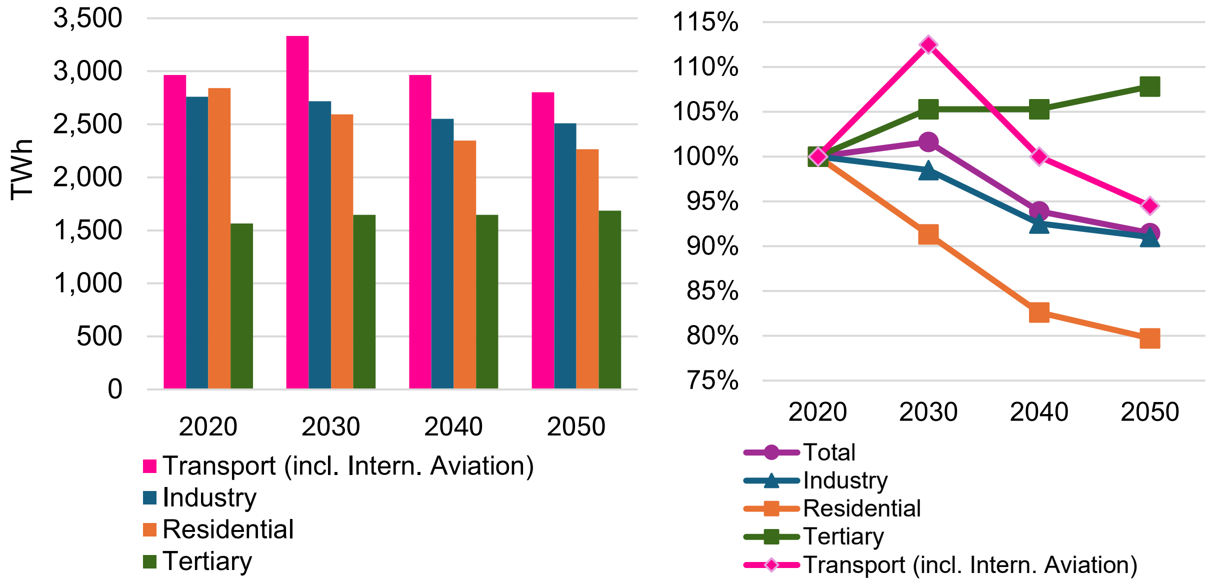


Figure 4. Final energy consumption in the EU reference scenario modelling from 2020 (left) and development in % compared to 2020 [6].

Residential sector: The largest relative change happens in the residential sector, where energy consumption decreases by 20 % between 2020 and 2050 due to energy renovation and efficiency leaps in space heating technology. Electrification, connections to gas networks and small increase in district heating (1-2 percentage points) are the leading trends in heating technologies. The market share of gas declines from 32 % to 25 % by 2050 and declines also in terms of absolute demand.

The industry sector also faces a decline in energy consumption, which can be attributed to structural shifts in the economy to service-based products and high-tech. Investments in the traditional industrial sectors also decrease, which is in part due to energy efficiency gains as well as sustainability focus. Energy efficiency gains and technological advancements also reduce the energy needs of energy-intensive industries. Nonetheless, energy-intensive industries are expected to mainly remain their production in the EU due to strong links with other EU industries that support their share, as well as digitalization and global competition which drive the sector's innovation and upkeep of competitiveness and efficiency. Industries which are counted to the energy-intensive industries are the following:

- Iron and steel
- Non-ferrous metals
- Chemicals
- Building materials
- Paper, pulp, and publishing

The only industry with projected growth is the tertiary sector, which includes, e.g., agriculture and services. Electrification is the major trend when covering energy demand, and its share increases from 43 % to 50 % between 2020 and 2050. Share of gas declines from 25 % to 20 %, and the rest is covered by renewables, district heating and oil.

Figure 5 shows the average annual decrease in energy consumption in the different industry sectors.

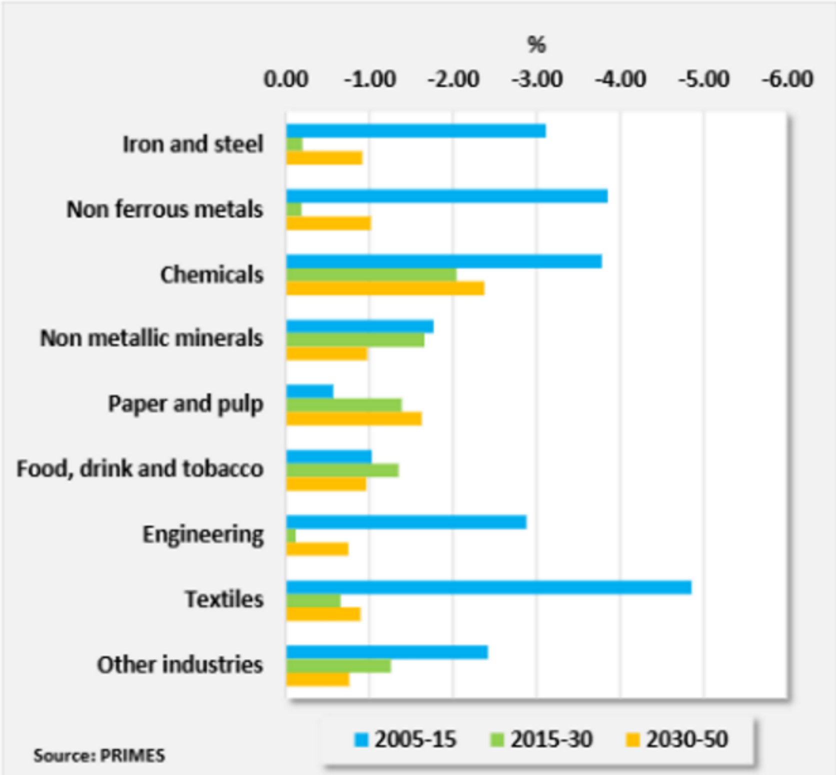
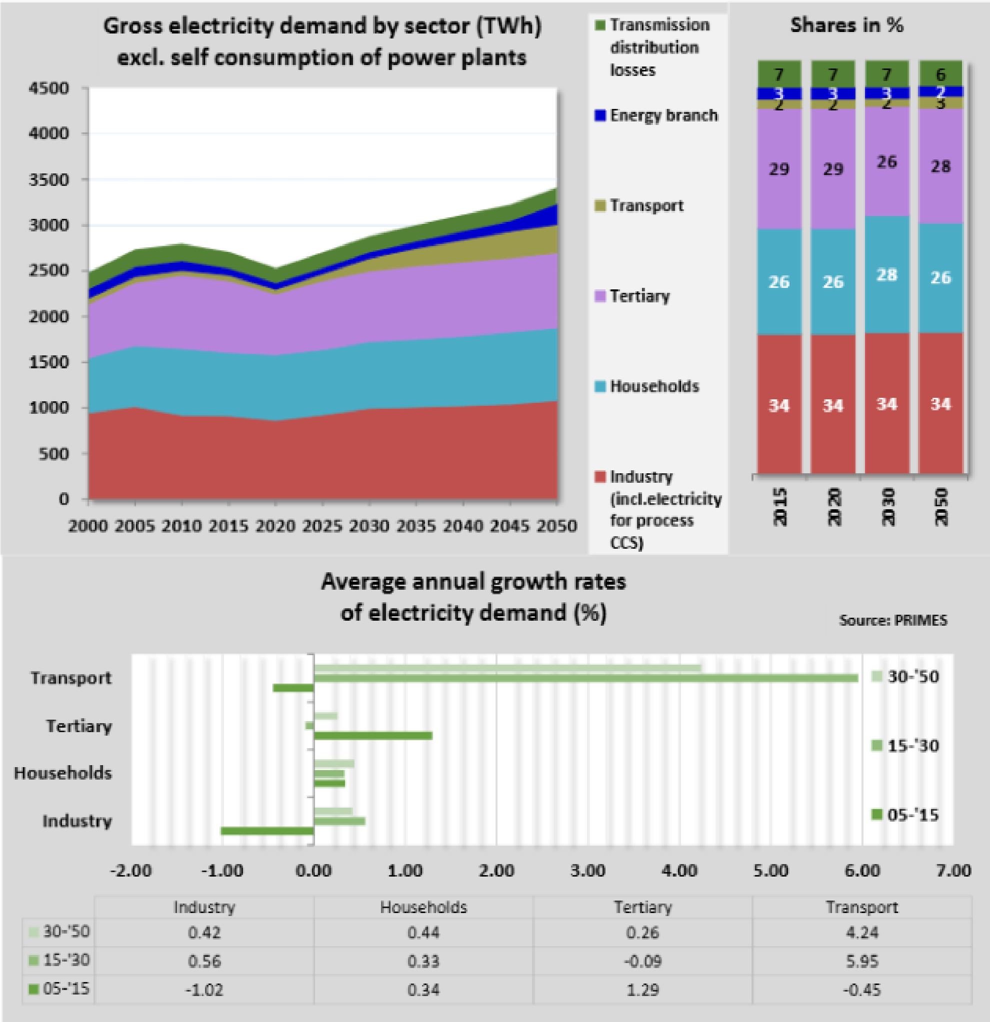


Figure 5. Decline in energy consumption in different industries in the EU reference scenario modelling [6].

Figure 6 shows the EU Reference Scenario modelling results in electrification of different sectors, which shows a continued trend in the final energy demand. This trend is driven by several factors, of which electrification of heating in buildings through heat pumps and increase of electric appliances in residential and tertiary sectors is a significant contributor. In addition, the transport sector experiences a notable rise in electricity demand due to the growing penetration of electric vehicles (EVs) and drives the absolute growth in gross electricity demand by 2050. The energy branch sees increased electricity consumption driven by hydrogen production for road transport. Industrial processing also gradually increases its electricity share, albeit at a slower pace.



	Industry	Households	Tertiary	Transport
30-'50	0.42	0.44	0.26	4.24
15-'30	0.56	0.33	-0.09	5.95
05-'15	-1.02	0.34	1.29	-0.45

Figure 6. Development in electricity demand by sector in the EU reference scenario modelling [6].

Also, the study by Seck et al. (2022) [7] **on the decarbonization of EU's energy system and the role of hydrogen** models future pathways to carbon neutrality by 2050. The energy demand projections are performed with JRC-EU-TIMES model, without considering the COVID-19 effects on the energy demand of the sectors.

The study assumes that production of energy-intensive industries largely remains at their current levels, or even grow a little, such as the cement, pulp and paper, and the lime industries, shown in Figure 7.

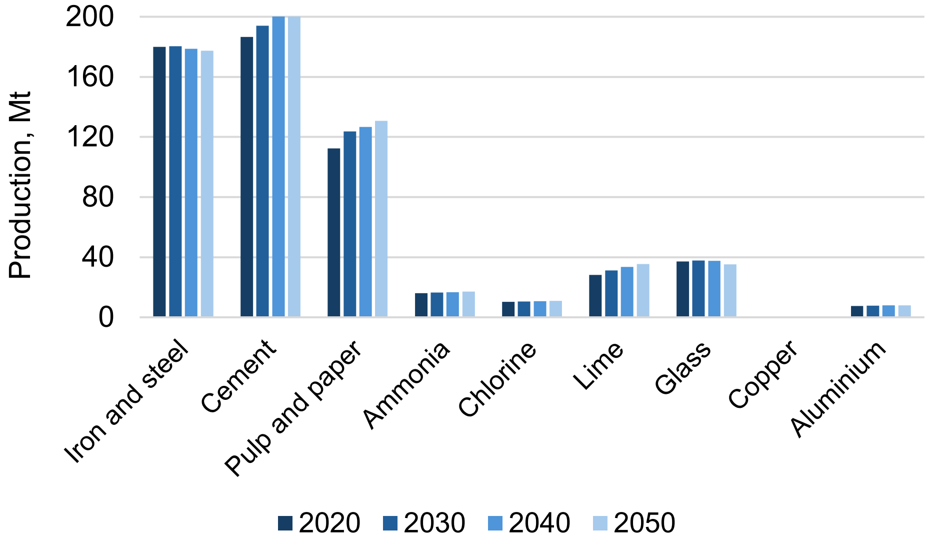


Figure 7. Projection on the production of energy intensive industry goods [7].

Figure 8 shows the gross final energy consumption (transmission losses and internal consumption of power plants included) from the same study, where the demand would decline 12.5% between 2020 and 2050.

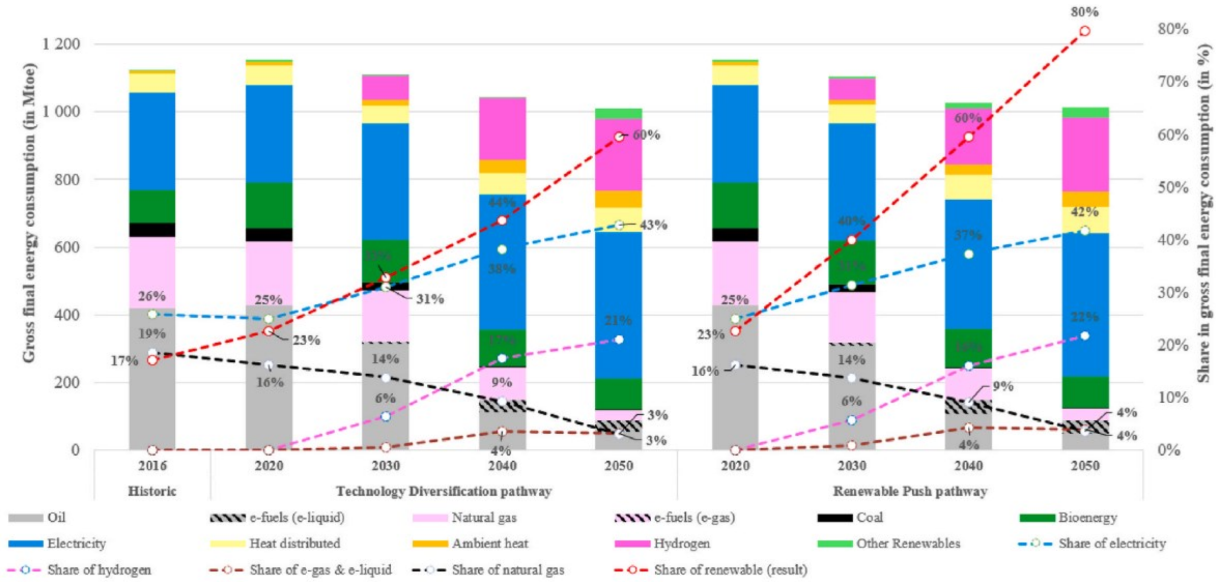


Figure 8. Gross final energy consumption in Seck et al. study [7].

Conclusions:

- Modelling scenarios show that final energy consumption decreases due to multiple factors; energy efficiency gains, shift in economic activity, demographics etc. Depending on the modelling scenarios, around 8-12 %.
- Residential sector energy demand has potential to decline by 20 % between 2020 and 2050 with energy efficiency gains, including renovation.
- Energy-intensive industries expected keep production in Europe due to links to other sectors, but energy efficiency and fuel switching can decrease the final energy consumption by around 9 % between 2020 and 2050.
- Electrification trends on many sectors, and is primarily driven by the transport sector (growing share of EV’s, and e-fuels).

2. Possible nuclear applications by sector

This section presents the potential applications for nuclear energy, by sector. The applications have been filtered by the temperature range of reactor output temperature. In this report, the applications will be limited to process temperatures of 500℃, as most reactor concepts in development fit to this range. In addition, sectors and applications with fairly constant energy demand are selected.

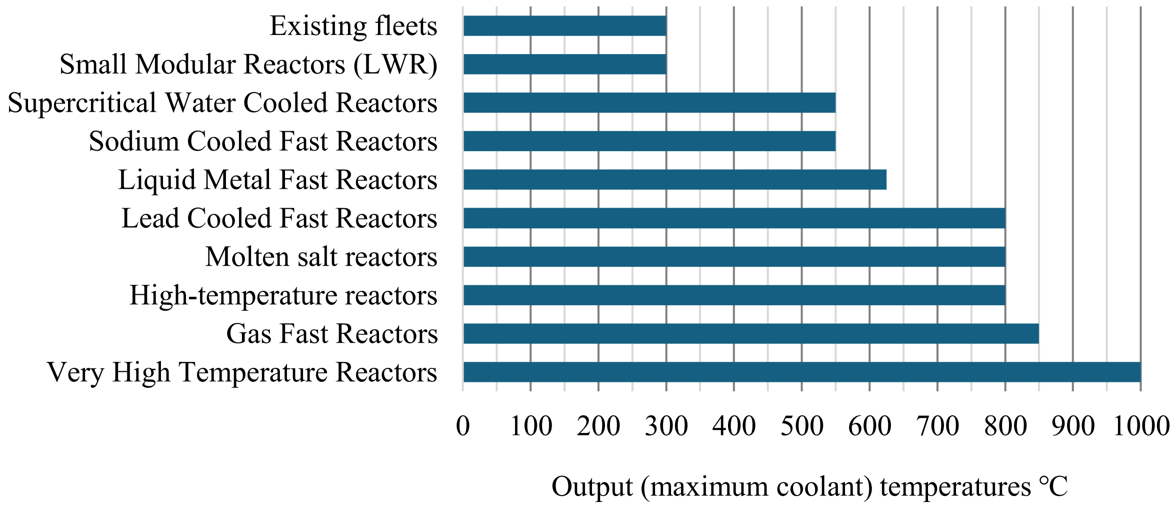


Figure 9. Output temperatures of different reactor variants. Most reactor types are in development, and thus the temperature ranges are indicative. [8], [9]

2.1 District heating

Heating and cooling account for approximately 50 % of the total gross final energy consumption in the EU [10]. Of this share, space heating and hot water take up around 31 %, and industrial heat 16 % [11]. In the residential buildings, the majority are supplied with individual heating solutions, such as natural gas boilers, which take up 36.8 % of the residential heating market. The share of district heat is around 10 %, counted in the heat category, seen in Figure 10.[12]

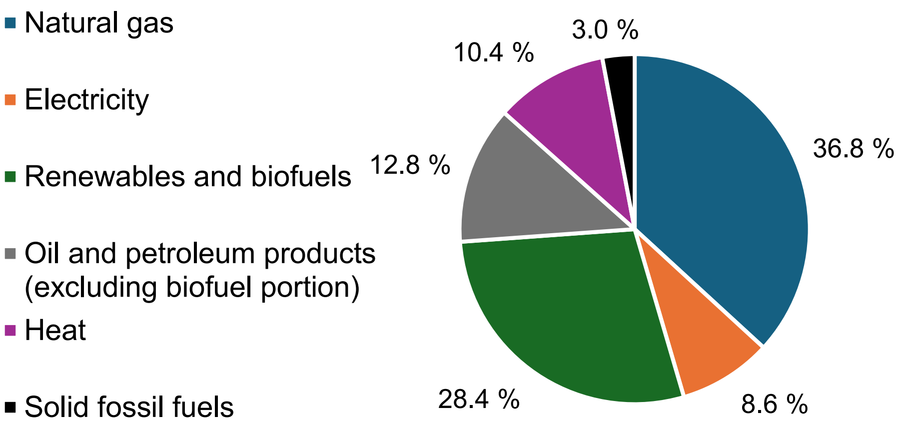


Figure 10. Final energy consumption in the residential sector in the EU in 2022 [12].

Nuclear heat could be integrated into district heat production, where heat is produced centrally and distributed in heating networks to the consumers. The temperature level in district heating networks depends typically on the outdoor temperature and is at its highest around 100 ℃ in most networks, making this application suitable for nuclear. Table 1 lists examples of typical maximum district heat temperatures in different European countries.

Table 1. Maximum temperatures of district heating networks in different European countries [13].

Country	Temperature
France	110 ℃
Denmark	70–80 ℃
Germany	Up to 130 ℃
Czechia	Up to 130 ℃
Finland	115 ℃
Poland	130 ℃
Sweden	102 ℃
Italy	90 ℃

District heat supplies around 608 TWh of heat in Europe yearly, to approximately 77.3 M citizens. There are in total 19 037 district heating networks in 30 European countries. Market share of district heat varies by country, with the highest shares in the northern European countries. [13] The largest countries by district heat sales (2022 and 2017) are presented in Figure 12.

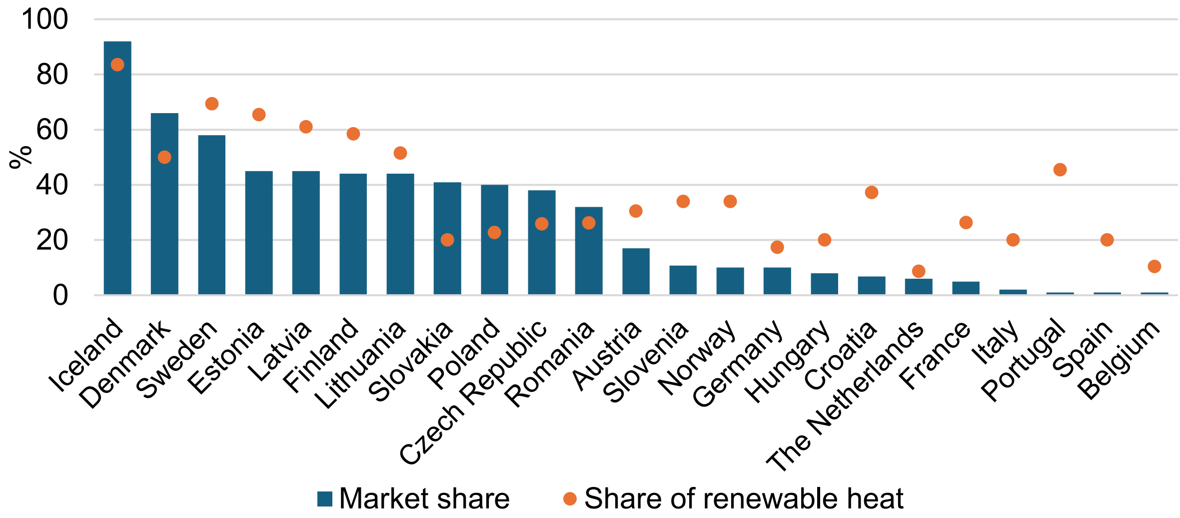


Figure 11. Market share of district heat among heating solutions for residential and service sector and share of renewable heat in final consumption for heating and cooling [13].

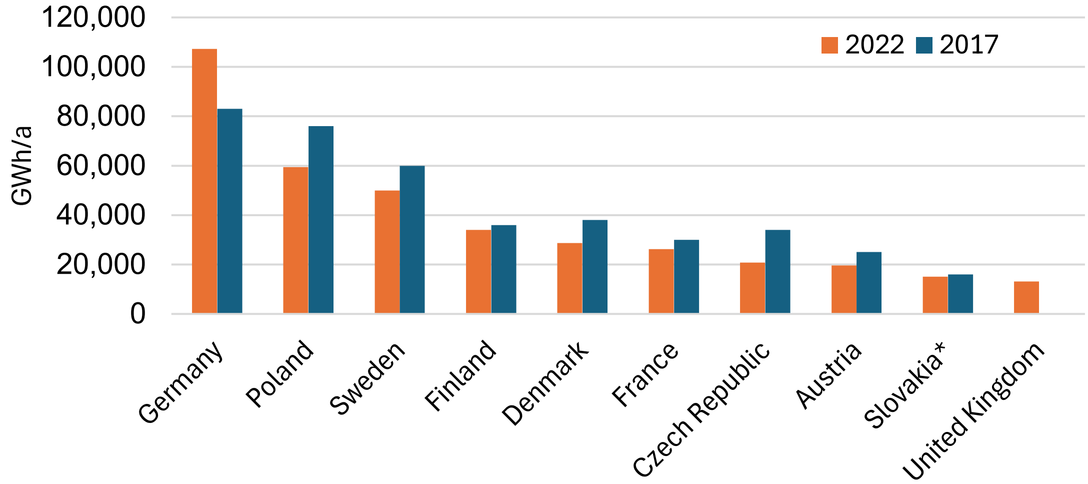


*Figure 12. Largest district heat producers in 2022 and 2017. *Slovakia's value from 2022 and 2015. [13]*

Fuel mix also varies greatly between countries in district heat production, which also affects the emissions intensity of district heat in different countries. The varying share of renewable energy in DH can be seen in Figure 11. On the European level, district heat is produced largely with bioenergy, coal, oil and peat, as well as natural gas. Countries with the highest shares of renewable energy in district heating are northern European (excl. Norway) and Baltic countries.

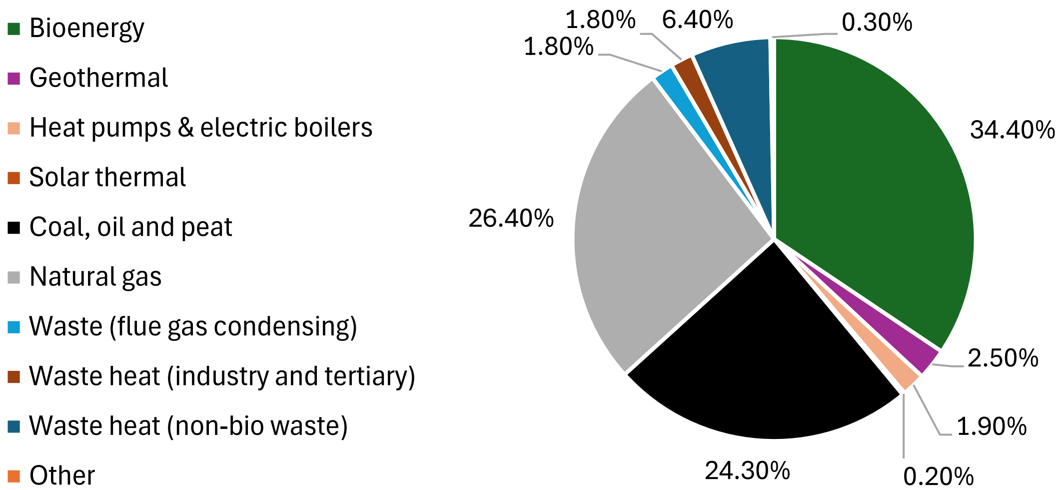


Figure 13. Energy sources for district heat production in Europe in 2022 [14].

Raising the share of renewable energy and waste heat use in district heating and cooling is addressed in EU's Energy Efficiency Directive, where definition for efficient district heating and cooling has been defined. All systems with more than 5 MW heat or cold output must fulfill the requirements, which change in steps until 2050. While high-efficiency cogeneration is still allowed in 2040, after 2050 only renewable energy and waste heat are included in the definition.[15] From the efficient district heating viewpoint, it is unclear whether nuclear heat could be counted in these categories. An alternative way to define efficient district heating and cooling is by system emissions intensity, by which nuclear heat could possibly be included [15].

District heat demand

The heating needs naturally vary by country, where northernmost countries have higher number of heating degree days. Heat demand also varies by season, and depending on the location, the winter peak loads can be multiple times higher than summer's. For instance, in Helsinki, Finland, in the beginning of the winter in 2024, the district heat production could reach approximately 9 times higher than the production in the summer [16]. Due to this varying demand, SMRs would probably be used to supply mostly the base load, which stays rather constant. Due to this variability in demand, it is challenging to evaluate the market potential for SMRs in district heating, as they cannot replace all capacities in a district heating network. Figure 14 presents the total district heat demand in Finland, demonstrating the variability of the demand.

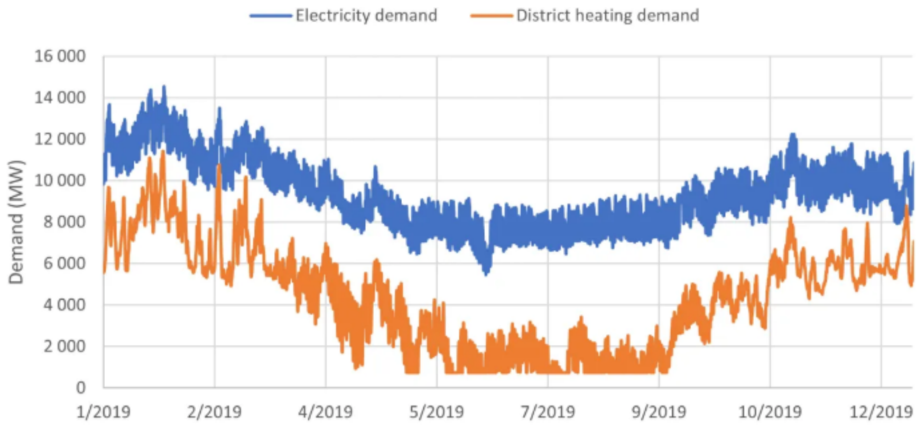


Figure 14. Total district heat and electricity demand in Finland in 2019 [17].

2.2 Desalination

Desalination is a process that addresses global water scarcity by converting saline water from seas and oceans into freshwater. This technology is increasingly significant as climate change and rising water demand exert pressure on freshwater resources. Projections indicate that numerous regions in the EU, particularly southern European Member States, will face severe water shortages by 2050. The PESETA IV project estimates that the population exposed to severe water scarcity could increase from 50 million to 65 million people with a 3°C rise in global average temperature.
[18]

Desalination technologies are designed to remove dissolved inorganic substances from seawater, brackish water, or wastewater. These technologies can be broadly categorized into three major groups [19]:

- Thermally-Activated Systems: Heat is used to either boil or freeze seawater or brackish water, converting it to vapor or ice to separate salts from the water.
  - Examples include multi-stage flash distillation (MSF), multiple-effect distillation (MED), vapor compression distillation (MVC), humidification-dehumidification desalination (HDH), solar distillation (SD), and freezing (Frz).

- Pressure-Activated Systems: These systems use permeable membranes that let the water pass through, leaving salt behind.
  - Examples include reverse osmosis (RO), forward osmosis (FO), electro-dialysis (ED), and nanofiltration (NF).

- Chemically-Activated Desalination Systems: These include ion-exchange desalination (I.Ex), liquid-liquid extraction (LLE), and gas hydrate (G.Hyd) and other precipitation schemes.

Among these technologies, the **most common and commercially used are reverse osmosis (RO), multi-stage flash distillation (MSF), and multi-effect distillation (MED)**. Reverse Osmosis uses semipermeable membranes to separate freshwater from seawater. It has become the most widely used desalination technology. Multi-stage flash distillation involves heating seawater and then flashing it into steam in multiple stages. It is commonly used in regions with low-cost thermal energy. Multi-effect distillation, like MSF, uses multiple stages to evaporate and condense seawater. It is known for its high energy efficiency and is used in various industrial applications. [20]

Table 2. Technical data of commercial desalination technologies [20].

Technology	Average Capacity [10^3 m^3/day]	Input	Recovery Ratio	Water Quality [ppm]	Energy Consumption		Water Cost [$/$m^3$]
					Electrical [kWh/m^3]	Thermal [kJ/kg]	
MED	0.6–30	SW	0.25	10	1.5–2.5	230–390	0.52–1.5
TVC	10–35	SW	0.25	10	1.5–2.5	145–390	0.87–0.95
MSF	50–70	SW	0.22	10	4–6	190–390	0.56–1.75
MVC	0.1–3	SW		10	6–12	no	2.0–2.6
SWRO	1–320	SW	0.42	400–500	3–6	no	0.45–1.72
BWRO	Up to 98	BW	0.65	200–500	1.5–2.5	no	0.26–1.33
ED	Up to 145	BW	0.9	150–500	2.64–5.5	no	0.6–1.05

Note: SW is the abbreviation of Seawater; BW brackish water.

*TVC = thermal vapor compression; MVC = mechanical vapor compression; ED = electro-dialysis

One challenge in desalination industry is the high energy consumption of the processes. State-of-the-art reverse osmosis (RO) systems consume around 2 kWh/m^3, and further reductions are challenging to achieve. [21] The main challenge with existing desalination plants is to switch the energy source to renewables, as in 2020, the proportion of renewable energy used in desalination was around 1 % [18]. However, desalination requires a steady energy input, as the process (particularly RO) is continuous, which causes requirement for energy storage and/or buffer storage systems. Due to this, nuclear electricity, heat, or hybrid systems could provide a reliable energy source to the process, which requires temperatures around 100-130 ℃ [8]. However, the unit sizes of desalination plants can vary a lot, from smaller than 1 MW to tens or even hundreds of MW, which has to be considered when considering nuclear energy for the application.

Desalination capacities in Europe and market outlook

In the EU, desalination has developed in response to territorial water shortages, with facilities supplying up to 3.4 x 10^{12} m^3 of desalted water annually. There are approximately 2178 desalination plants in the EU, with Spain (41%), Greece (19%), and Italy (18%) having the highest numbers.[18] Moreover, Spain holds over 60 % of the desalination capacity in the EU [21]. Most of the desalinated water in the EU is used for public water supply (71%), followed by industrial applications (17%), power plants (4%), and irrigation (8%) [18].

The European desalination market is expected to expand due to climate change caused water availability fluctuations. The moderate growth observed between 2010-2020 deviates from the sector's global growth during the same period, which almost doubled its capacity. This deviation is partly due to existing infrastructure, and partly due to the different needs of regions in Europe. For example, already established water supply systems and desalination plants reduce the immediate need for additional capacity, such as in Spain. Moreover, as these countries that have faced water shortages have invested in desalination, future development concentrates on maintaining and upgrading existing facilities. Island regions in

Europe, on the other hand, focus on acquiring small and medium-sized plants (small and medium size: under 10 000 m^3/day, large: 10 000-50 000 m^3/day). The new desalination capacity in the EU typically is now small and medium-sized facilities. [21] Figure 15 shows the desalination capacity investments and installed capacity between 2000 and 2025. Figure 16 shows the locations of desalination plants in Europe in 2024.

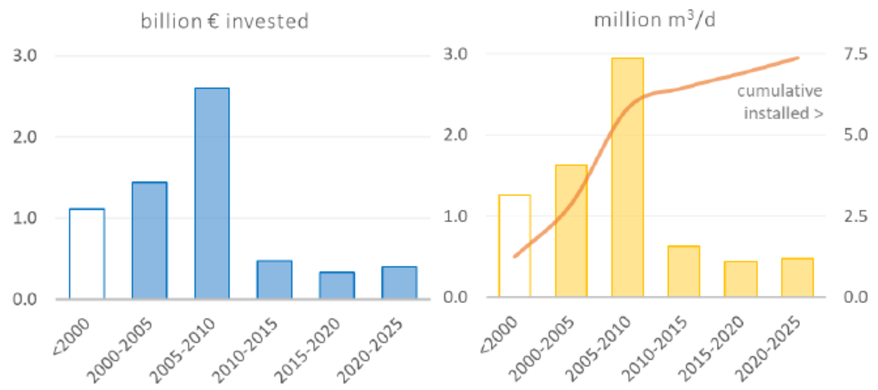


Figure 15. Desalination capacity investments and installed capacity [21]

Figure 16. Geographical illustration of EU desalination plants' locations [18].

2.3 Data centers

Data centers are facilities, which house computer systems and related components for storing, processing and managing large amounts of data. Data centers' energy consumption is mainly based on electricity, and is consumed mainly in three processes: computing, cooling of the computing equipment, and networking infrastructure, of which computing and cooling take the largest part. The breakdown of energy requirements in data centers is shown in Figure 17.

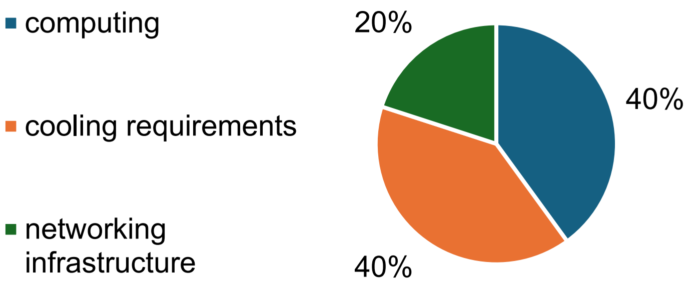


Figure 17. Data center energy needs.

Cooling in data centers is usually based on a terminal cooling sub-system, which has the task of removing heat from the indoors of the data center to outside. A part of the cooling system is the mechanical refrigeration subsystem, which covers the technologies providing the cold supply like chillers, pumps, and cooling towers. Figure 18 presents the cooling methods of data centers. Cooling is typically based on either air-cooling, liquid cooling, or free cooling. In air-cooling, cold air comes from the air conditioner unit and and travels through an air circulation system. Liquid cooling involves a liquid coolant which can come to direct or indirect contact with the computer equipment, and free cooling essentially uses cold sources from the outside environment, like cold air or water, to enhance the cooling.

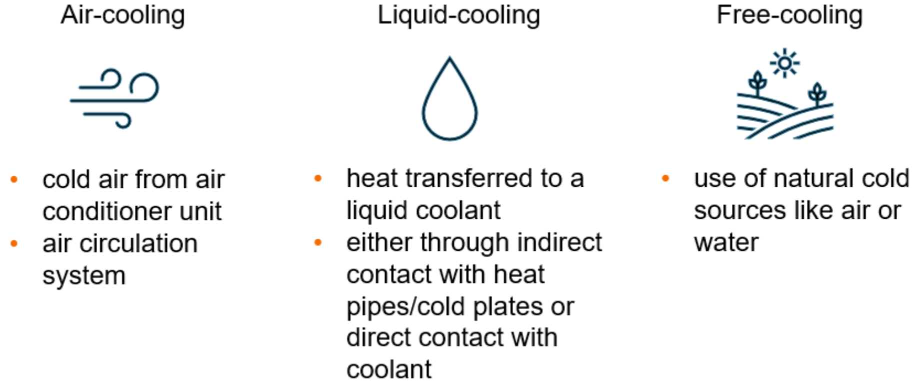


Figure 18. Cooling methods of data centers [22].

Data center load

Data center size measured in power demand can vary significantly. Large, hyperscale data centers typically have power demands between 50 and 300 MW. Co-location or cloud data centers on the other hand are typically below 50 MW, and enterprise data centers are below 2 MW. [23], [24] The average size of a data center is according to IEA around 5-10 MW, whereas hyperscale centers exceed 100 MW [25].

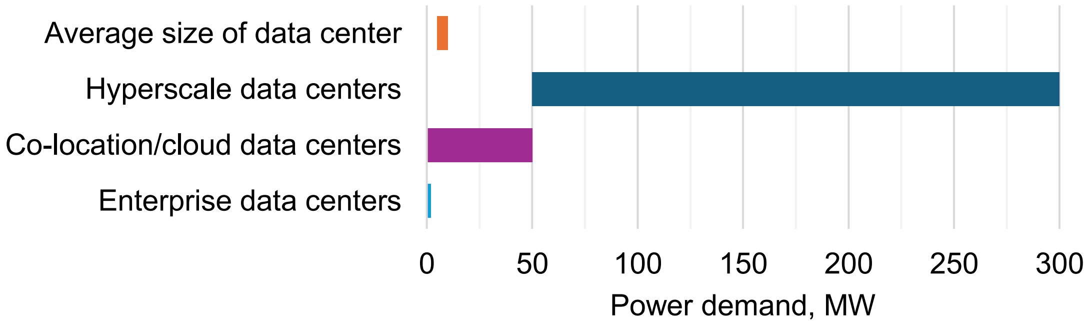


Figure 19. Data center sizes by power demand [23].

Data centers operate throughout the year, with constant loads both on the daily and yearly scale, which do not have large variation between summer and winter. This applies particularly to hyperscale and cloud centers, meaning that the facility needs a constant power supply. If the data center shares some other spaces, like office space, the load curve can have more variation, resulting from office hours. In general, data centers require high availability, close to 100 %, meaning that they are typically supplied also with UPS systems (uninterruptible power supply) or back-up generators.[26]

Figure 20 shows how by type, hyperscale and cloud data centers have increased their share of overall electricity use in data centers from 13.9 % in 2010 to 65.2 % in 2018, globally, whereas the electricity demand between those years has risen only 5.7 %. [27] Similar shares apply to the EU in 2022, as the hyperscale and cloud data centers had around 65 % share, and the enterprise data centers had a 35 % share [28].

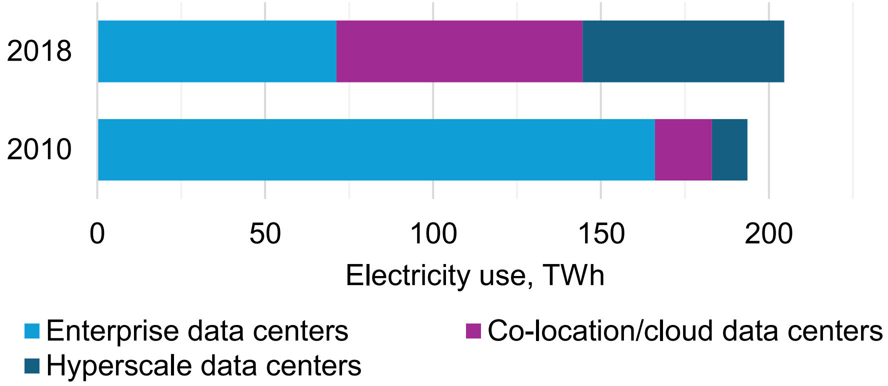


Figure 20. Shares of data center types by electricity use in 2010 and 2018 [27].

Historically, the energy demand growth of data centers has been balanced by, for instance, energy efficiency improvements and did not experience significant growth until 2019, after which the global electricity demand doubled from ~200 TWh to 400 TWh in 2023 (excluding crypto currency) according to Goldman Sachs Research. IEA estimates that in 2022, the global data center electricity consumption was 240-340 TWh, which also excludes cryptocurrencies. This corresponds to 1-1.3% of the global final electricity demand.[29] In the EU, data centers consumed 45-65 TWh of electricity in 2022, which corresponds to 1.8-2.6 % of total electricity use in the EU [28]. Figure 21 shows the number of data centers in the EU by country in 2024.

Future data center energy demand growth is challenging to estimate. Trends affecting growth are first and foremost artificial intelligence and machine learning, as well as blockchain technologies. According to IEA, as the demand for data handling has increased, 20-40 % yearly energy demand growth has been estimated for the past few years. The growth of data center energy use probably stays moderate in the few upcoming years, but in the longer-term estimates are harder to make due to uncertainties, such as enhancements in energy efficiency in blockchain technologies, as well as AI development.[29] According to a McKinsey & Company report, with the prevailing trend, the data center power demand could rise from their current energy demand estimate of 62 TWh in 2024 to over 150 TWh by 2030 in the EU [30].

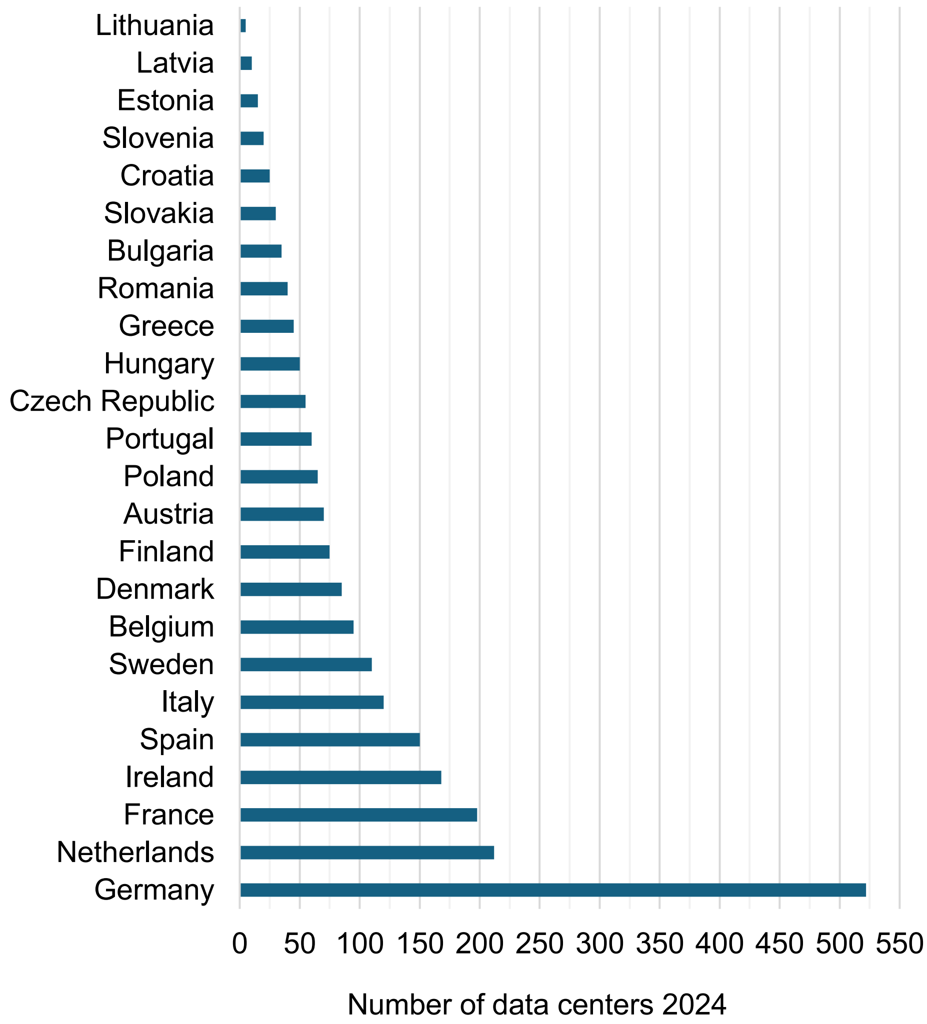


Figure 21. Number of data centers in EU countries in 2024 [31].

2.4 Industrial sector

Industry consumed around 25.1% of the final energy in the EU in 2022. As shown in Figure 22, most industrial energy, 64%, comes from natural gas and electricity, after which the most common energy products are oil and petroleum products.

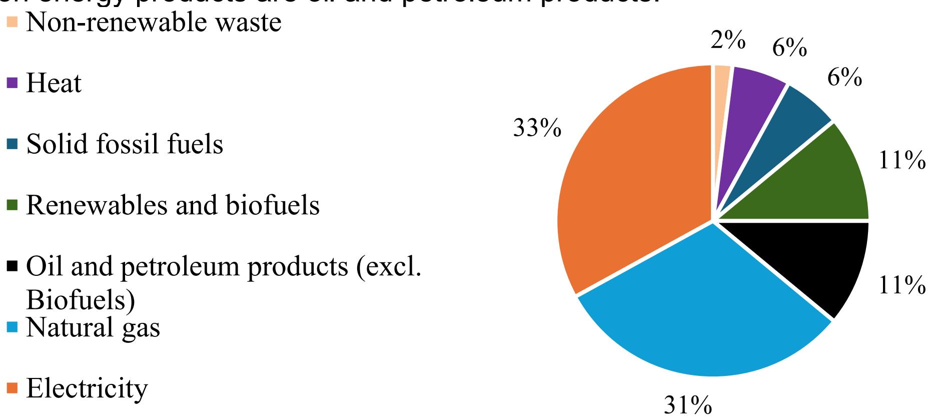


Figure 22. Final energy consumption in the industry sector by energy product in EU (2022) [32]

The largest industrial sectors in terms of final energy consumption are presented in Figure 23. As shown, chemical and petrochemical industries, non-metallic minerals, paper, pulp and printing, as well as food, beverages and tobacco industries all exceed 1000 PJ (>277.8 TWh) annual demand. Furthermore, Figure 24 shows the temperature level needs for industrial heat of these sectors. Of the larger industries, food and tobacco, pulp and paper, and the chemical sector have heat demands, of which 50% or more stay below 400 ℃, making them particularly suitable for nuclear applications.

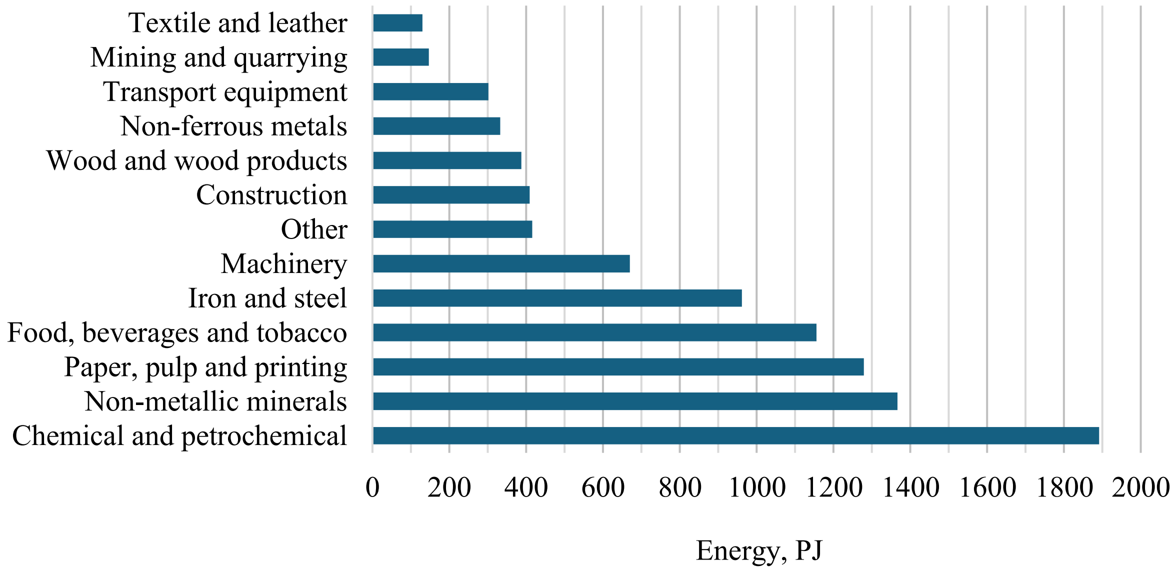


Figure 23. Final energy consumption by industry sector in EU (2022) [32].

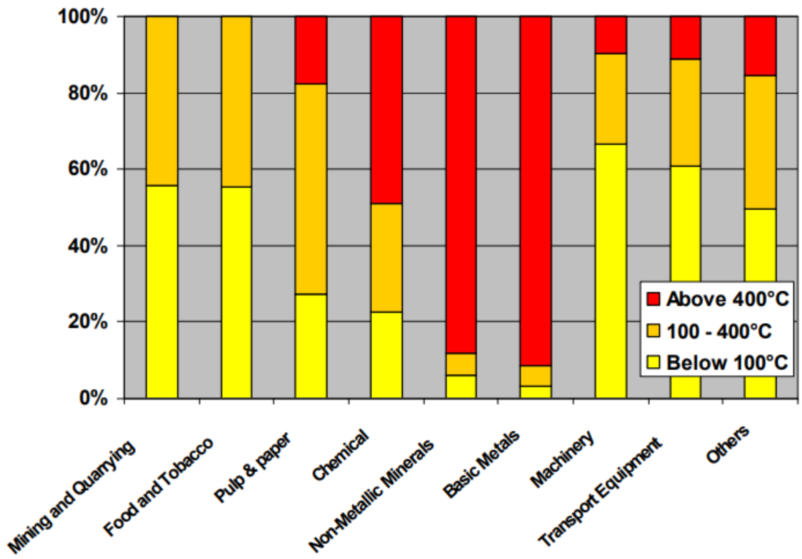


Figure 24. Industrial heat demand by temperature level and sector [33].

Figure 25 shows average plant unit sizes in different industries in terms of heat use (in MW) in the US, as well as their respective annual emissions. Moreover, Figure 26 presents the distribution of unit sizes in the petroleum, chemical, paper and plastics and rubber manufacturing industries. As shown, potash, soda ash and borate industries, along with paper and board mills, tend to have the highest heat uses, from 250 to 300 MW_{th}, whereas pulp mills, petrochemical industry, iron and steel mills and ethyl alcohol manufacturing have the smallest heat uses, around tens of megawatts.

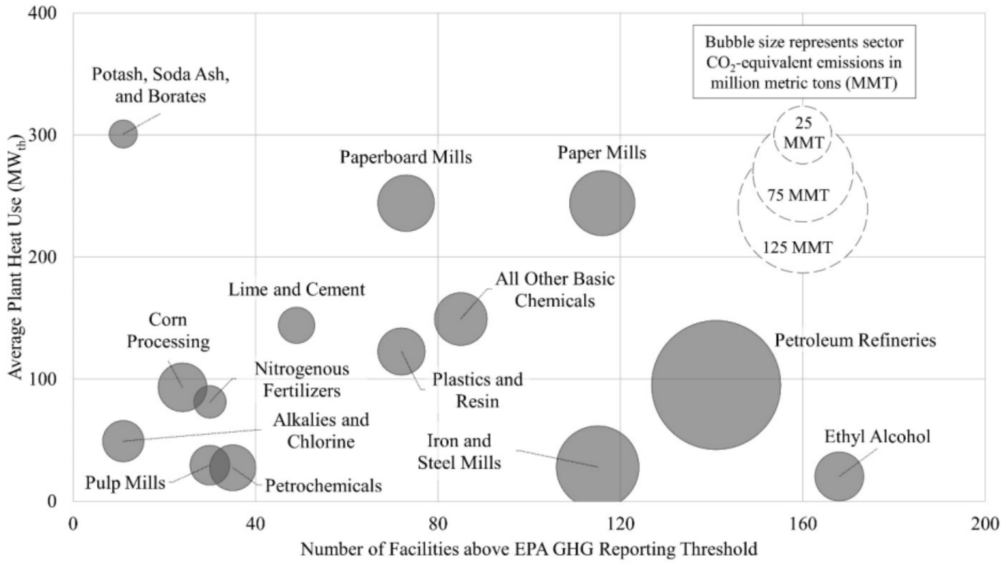


Figure 25. Average plant heat use in different industries in the US that exceed a reporting threshold of the Environmental Protection Agency [34].

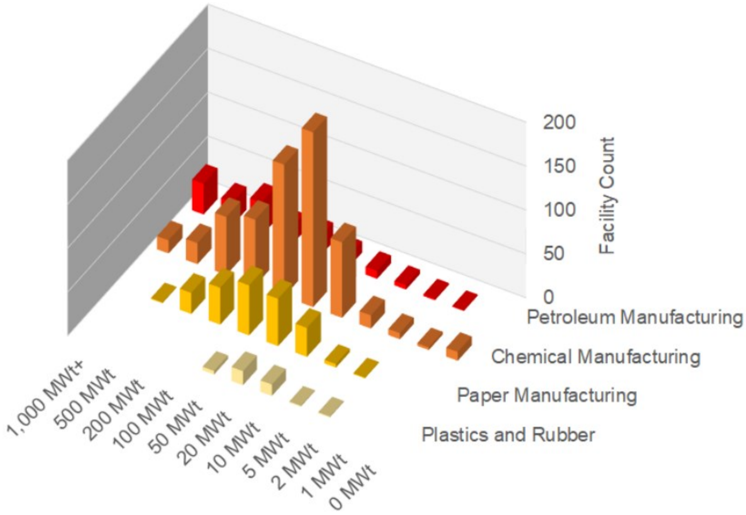


Figure 26. Plant heat consumption distribution in the US, for petroleum, chemical, paper and plastics and rubber manufacturing industries [34].

In the following subsections, application-specific process temperature requirements are provided in sectors, which could be suitable for nuclear applications.

2.4.1 Chemical industry

Chemical and petrochemical production is a prominent industrial sector in the EU, where the energy acquired for the processes is mainly from natural gas (33 %) and electricity (30 %). Furthermore, oil and petroleum products and heat account for 17 % and 14 % of the final energy consumption [35].

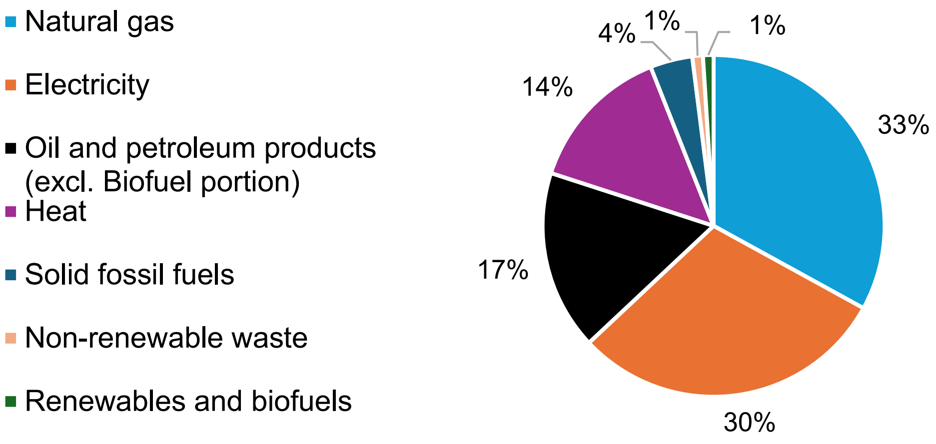


Figure 27. Total final energy consumption in the chemical industry in 2022 [35].

The EU is the leading region in chemical exporting globally. Most of the EU27 chemical sales come from petrochemicals (26 %) and specialty chemicals (27 %) as shown in Figure 28, and they account for the majority of chemical exports from the EU as well (Figure 29) [36], [37]. Specialty chemicals include e.g. coatings such as paints and varnishes, dyes and pigments, and pesticides and agrochemical products.

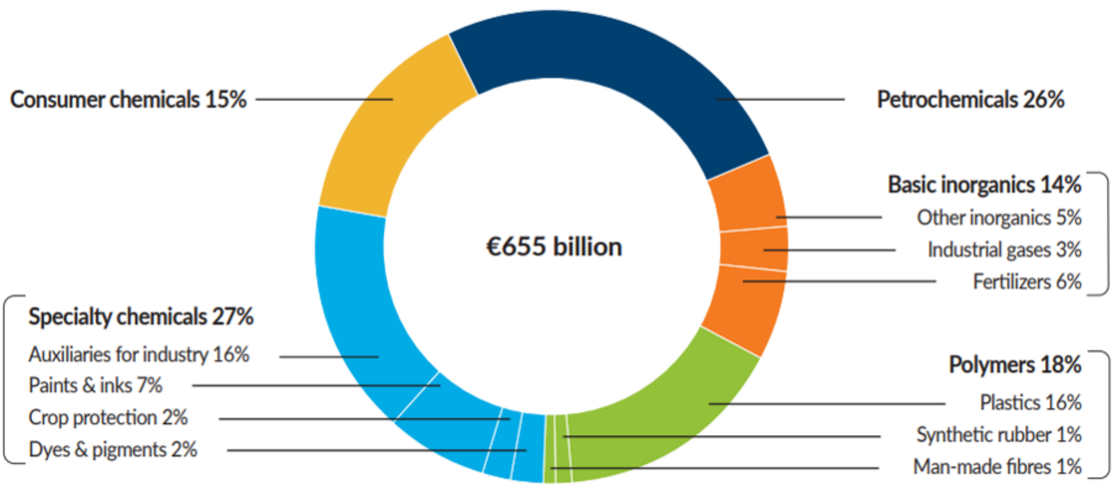


Figure 28. EU27 Chemical sales in 2023 [38].

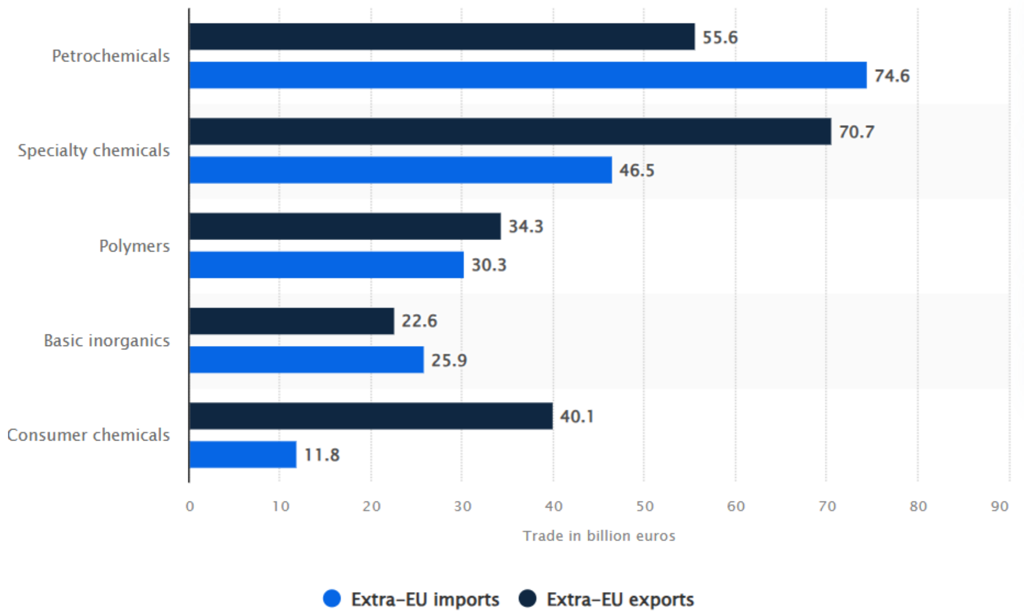


Figure 29. EU chemical imports and exports in 2023 [37].

Error! Not a valid bookmark self-reference. lists common chemical compounds and their required process temperatures. It is important to note, however, that the challenge in the chemical industry is, that many compounds are used as a feedstock to produce other compounds or products, or that the compound is a downstream product of other compounds. This requires more investigation to understand how the production chains work; are there typically multiple chemical products in the production chain that are produced in the same facility, and how is the energy use arranged. For example, if an upstream product requires high process temperature levels, it can be that the downstream product utilizes lower-grade waste heat from the upstream process to run its own process. Therefore, some of the listed products can already be a part of an efficient energy loop, where nuclear could not replace the heat source in the very highest temperatures, nor would it be needed downstream. Also, industrial heat pumps have a competitive edge in these kind of production chains, where they enable utilizing waste heat.

Table 3. Common chemical compounds, hydrogen and e-fuels with process temperatures up to around 500 ℃.

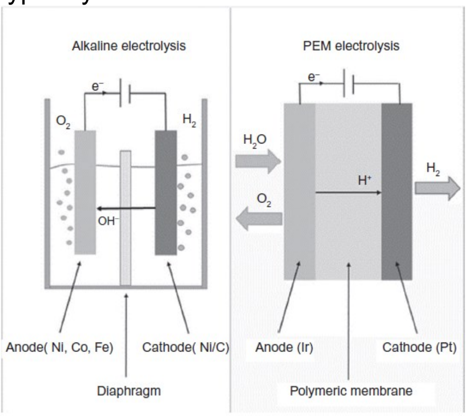
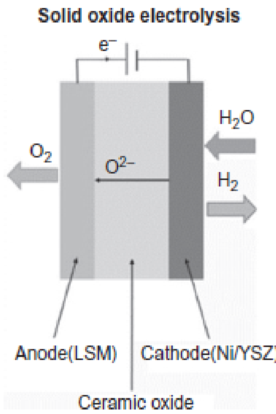
	Temperatures (℃)	**Notes**	**Reference**
Petrochemicals/plastics			
Vinylchloride	100-200	Steam as energy carrier	[8], [39]
Ethylene glycol (MED/DEG)	~100-250		[40]
Ethylene oxide	220-300	1-3 MPa	[41]
Ethanol	300 (from ethylene) 266 (In plant biomass residues furnace CHP) 233 (steam/distillation) 454 (steam/power production)	**Continuous or batch production**	[8], [42]
Benzene	Houdry Detol process: 480-590 Catalytic reforming ~500	40-60 bar	[43]
Ethylbenzene (ethylene + benzene)	liquid phase alkylation 240-270		[44]

	vapor phase alkylation ~400		
Cumene (of benzene)	25-361		[45], [39]
Bisphenol A	75-199	Steam as energy carrier	[39], [46]
Cyclohexanone	100-180		[47], [39],
MTBE	~100		[39], [48]
Phthalic anhydride	350-420 (salt melt) 220-240 (hot oil)		[39], [49]
Terephthalic acid (PTA)	120-200	15-30 atm, steam as energy carrier	[39], [50]
Acrylonitrile (ACN)	400-500		[39], [51]
Chlorine	177	**Continuous process.** Energy needed for steam/drying and heating of brine	[42]
Phosphoric acid	70-110 (wet process, which is most common)		[52], [53]
Sodium hydroxide	electricity (chlor-alkali electrolytic process) with temps at 66-75, evaporation around 100-150	**Can be produced from desalination brine. Chlorine is produced in the same process. Continuous process.**	[54], [55]
Synthesis gas from natural gas or naptha	400-800		[8]
Methanol	200-300	3.5-10 MPa. **Continuous process.**	[56], [42]
Hydrogen			
Low temperature electrolysis	electricity		
High temperature electrolysis*	800 700-1000	*Very high temperature processes	
Steam methane reforming*	700-1000 600-800	*Very high temperature processes	
E-fuels			
e-Ammonia	350-550	100-450 bar. Haber-Bosch synthesis	[57]
e-Methanol	200-300	50-100 bar	[57]
e-Methane	250-400	5-50 bar	[57]
Ammonia			
Urea synthesis	180-280 190	Steam as energy carrier	[8],[39]

Hydrogen and e-fuels

Hydrogen is produced currently mainly for feedstock to various industrial sectors, such as transportation fuels, fertilizers, chemical industry, as well as steel and glass industries [58], [59]. Of the current end use of hydrogen in the EU, refining holds 57.3 % of the demand, and ammonia production 25.2 % [60]. In the future, hydrogen could play a central role in many sectors, such as hard-to-abate sectors like heavy transport and aviation. There, hydrogen would be utilized as feedstock to e-fuels, which are carbon neutral synthetic fuels. Hydrogen could be utilized also in the power and gas sector, in gas turbines, fuel cells and CHPs [59].

Hydrogen can be produced via several routes, and with different technologies. Below the main production methods are summarized, without the inclusion of thermochemical cycles for water splitting and radiolysis of water, which are not commonly used or are only at research level development.

<table>
<tr><th>Low-Temperature Water Electrolysis</th><th>High-Temperature Steam Electrolysis</th><th>Steam reforming</th></tr>
<tr>
<td>-Splits water into hydrogen and oxygen using electric current
-Two categories: alkaline liquid electrolyte (KOH or NaOH) and acid electrolyte with solid polymer as a proton exchange membrane (PEM)
-Operating temperatures <150℃, typically around ~90 ℃

</td>
<td>-thermal energy of feed steam lowers the electricity required in the electrolysis ~25-40%
-solid oxide electrolyte
-high temperatures required
-not yet a commercial technology

</td>
<td>-catalytic decomposition of light hydrocarbons (like methane) with superheated steam, resulting in syngas
-hydrogen fraction is increased with water-gas shift reaction, typically in two steps with different catalysts 1. 350-450 ℃ 2. 150-250 ℃
-high temperatures, pressures around 2.5-5 MPa</td>
</tr>
</table>

The most common route to produce hydrogen is steam methane reforming, with natural gas as feedstock. This route, however, emits carbon dioxide unless carbon capture is applied. Another option is electrolysis, where water is split with electric current to obtain hydrogen and oxygen.

Hydrogen could be produced with nuclear energy mainly with the low-temperature water electrolysis route, as high-temperature electrolysis and steam reforming in general require higher temperatures than what most commercial nuclear reactors can produce (600-1000℃). Also, high-temperature electrolysis is still in the development stages. [58] With advances in reactor designs and commercialization, also high temperature routes could open to nuclear energy. Hydrogen production could be a suitable application for nuclear electricity production for several reasons. Firstly, hydrogen production is energy intensive, and the electrolyzers have varying capabilities regarding flexible operation. With nuclear electricity, electrolyzer could acquire stable, low emission electricity, and operate with a constant load. Secondly, the unit size required in industrial-scale hydrogen production can range from tens to hundreds of MW, such as in refining, which would suit SMR unit sizes [8].

However, it is crucial to note that hydrogen production in the EU is regulated. Delegated acts regarding renewable fuels of non-biological origin (RNFBOs) restrict what is counted as renewable hydrogen, to which nuclear energy is not eligible. This also influences how e-fuels can be counted as renewable, and how they can be used in fulfilling targets in raising the share of renewable fuels in aviation and transport.

The table below shows some announced renewable and low-carbon hydrogen projects announced in Europe and their electrolyzer capacities.

Company/Project	Capacity	Reference
Air Liquide	200 MW	[61]
Galp	100 MW	[62]

Shell/Rephyne	100 MW	[63]

After hydrogen via electrolysis is produced, it can be further processed to fuel products, such as e-methanol, e-methane, and e-ammonia, as shown in Figure 30.

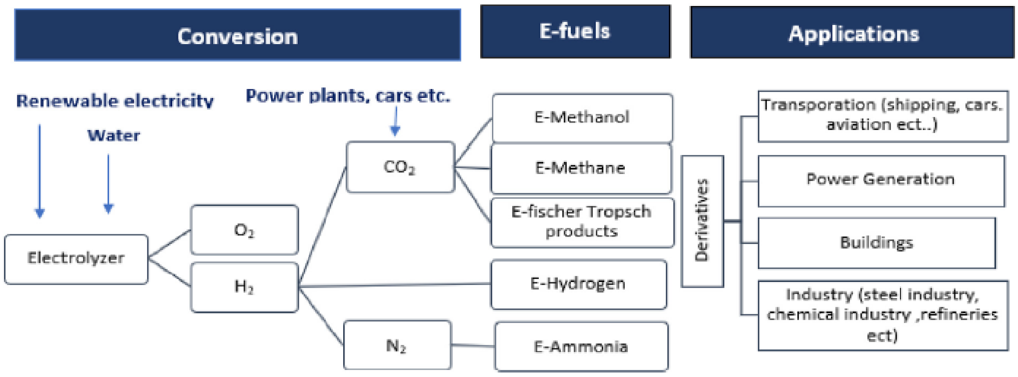


Figure 30. Power-to-fuel process steps [57].

E-methanol is produced through catalytic hydrogenation of carbon dioxide using renewable or low-carbon hydrogen. The reaction is exothermic and occurs around 200-300 ℃ and 50-100 bar. [57] The primary reaction is:

$$CO_2 + 3H_2 \rightarrow CH3_3OH + H_2O \qquad \Delta H_r = -49.2 \text{ kJ/mol}$$

E-ammonia is produced in the Haber-Bosch process by combining nitrogen with hydrogen with an iron-based catalyst. Nitrogen is obtained through membrane separation, pressure swing adsorption or cryogenic distillation, which is the most common method of the three. The process happens around 400-500℃ and pressure of 100-450 bar. [57] The primary reaction is:

$$3H_2 + N_2 \rightarrow 2NH_3 \qquad \Delta H_r = -91.8 \text{ kJ/mol}$$

E-methane, or syngas, is produced through the Sabatier process, which involves the hydrogenation of carbon dioxide using hydrogen. The reaction is highly exothermic and occurs at temperatures between 250-400 ℃ and pressures of 5-50 bar. The reaction, described below, requires significant amounts of carbon dioxide, 5.5 kg per kg of hydrogen. This amount of carbon dioxide is a challenge to acquire with carbon capture, as the installations can be located a long distance from renewable fuel plants, adding to the cost of CO transportation. [57]

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O \qquad \Delta H_r = -165 \text{ kJ/mol}$$

2.4.2 Industrial heat in other energy-intensive industries

Table 4 presents other energy intensive industries that have process temperatures potentially suitable for nuclear applications. In the **pulp, paper and board** industry, stand-alone pulp mills typically produce excess power, as they burn usually biomass-based residues from various processes, such as bark, limb, sawdust and black liquor. Consequently, it is improbable that these stand-alone pulp mills will experience significant advantages from the integration of low-carbon technologies. However, stand-alone paper and board mills have a high energy demand to mainly dry pulp with heat from steam (on average above 200 MW_{th} [34]), to which nuclear energy could be a good fit. Paper and board mills also typically operate continuously [42].

Table 4. Industrial heat sectors and uses with process temperature requirements up to approximately 500 ℃.

	Temperatures (℃)	Notes	Reference
Pulp, paper and board	200-400		[8]
Paper and paper board mills	177	**continuous process**	[42]
Pulp mills	200 150	Steam/heat to digester, bleaching, oxygen stage, multi-effect evaporator Team/pulp machine, multi-effect evaporator, chemical preparation. **Continuous process.**	[42]
Aluminium			
Leaching of aluminium hydroxide from bauxite by caustic soda	210-250	10 MPa	[8]
Separation of aluminium hydroxide from the caustic soda	process steam		[8]
Calcination to alumina	200-850	0.4 MPa	[8]
Soda ash	~350-450		[64]
Non-ferrous metals (lead, zinc)	350-500		[64]
Ceramics	100-350	drying	[64]
Mining			
Potash, soda, and borate mining	300	Continuous process. Steam/calciner, crystallizer, and dryer	[42]
Petroleum refineries	450-550		[8]

2.4.3 Food and drink

The food and drink sector contains many products, which require constant heat input with fairly low temperature requirements. Specifically, product categories which are required to be consumed fresh, such as dairy, meat processing, and bread and bakery, form a group which could be suitable for nuclear heat application. At the same time, many food and drink applications have cooling needs. However, the required unit sizes (MW) may be smaller than in other industries.

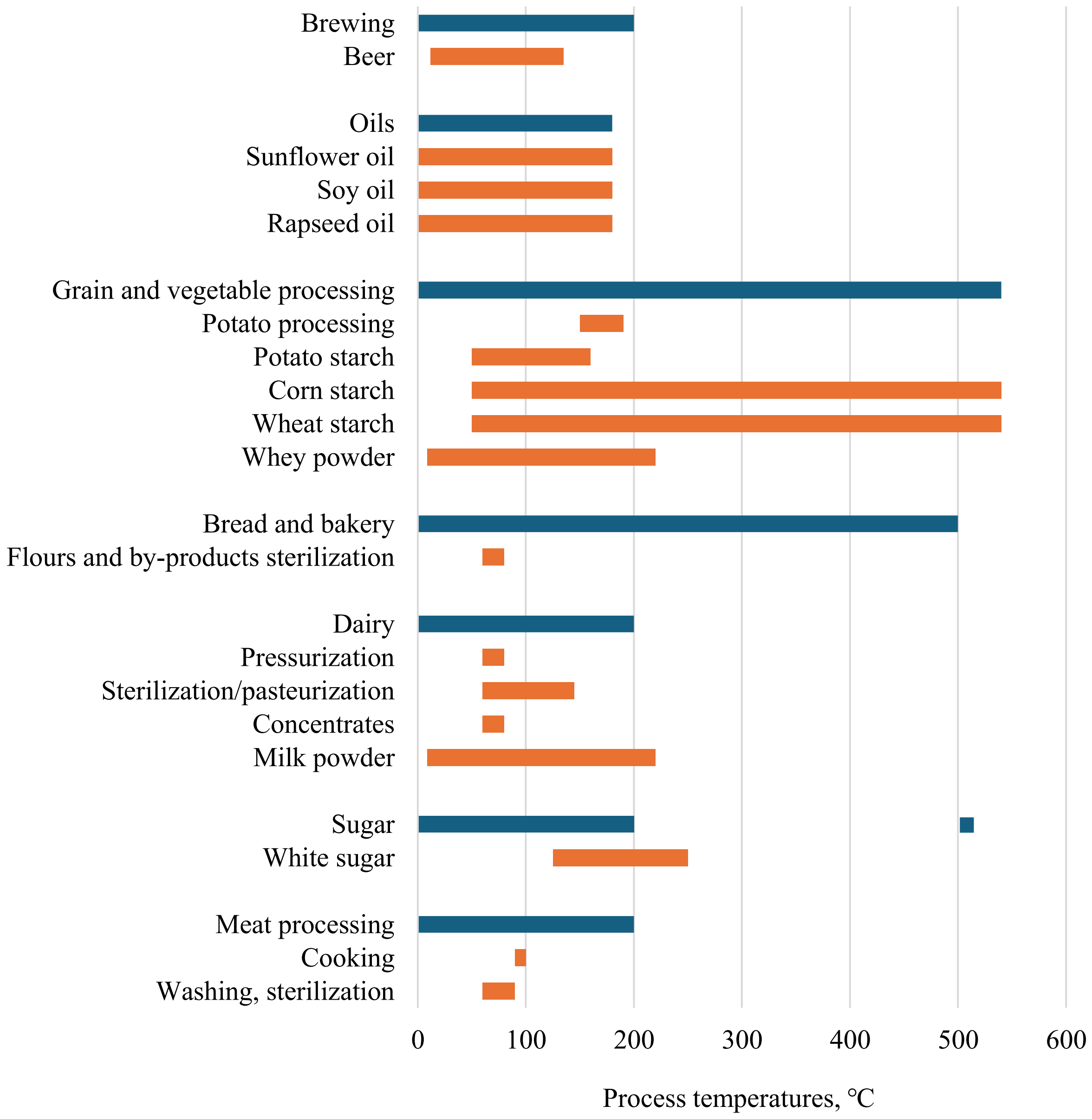


Figure 31. Food and drink sector process temperature needs. Temperature ranges have been collected from [65], [66], [67], [42].

2.5 Agriculture

In agriculture, energy is consumed directly with the use of machinery, such as cultivation of fields with tractors, and mainly the heating of greenhouses and livestock stables. In addition, indirect use comes from production of agrochemicals, farm machinery and equipment, and buildings. [68] Agriculture is thus tightly connected to the chemical industry, where fertilizer production is a prominent sector, as well as in the future, potentially more tightly with desalination through irrigation needs and growing number of droughts. According to Eurostat, in 2022 agriculture and forestry accounted for 3 % of total direct energy consumption in the EU (Figure 32). There is noticeable variance by country, with Netherlands topping the graph due to prominence in greenhouse production of fruit, vegetables and horticultural plants, and with agriculture accounting for 7.5 % of their national direct energy consumption.

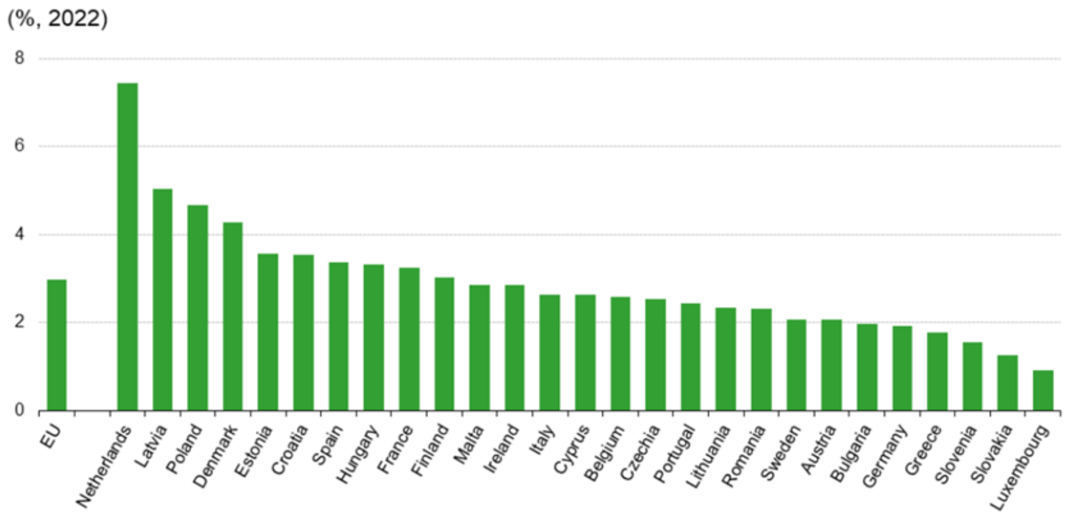


Figure 32. Direct energy consumption of agriculture and forestry in different EU countries compared as a share of total direct energy consumption in 2022 [68].

Figure 33, on the other hand, shows the fuel mix used in agriculture and forestry. As shown, fossil products like oil and petroleum play a significant role with an approximate 60 % share EU-wide. Some countries, like Greece and Netherlands, use electricity and natural gas instead for most of their energy needs in these sectors.

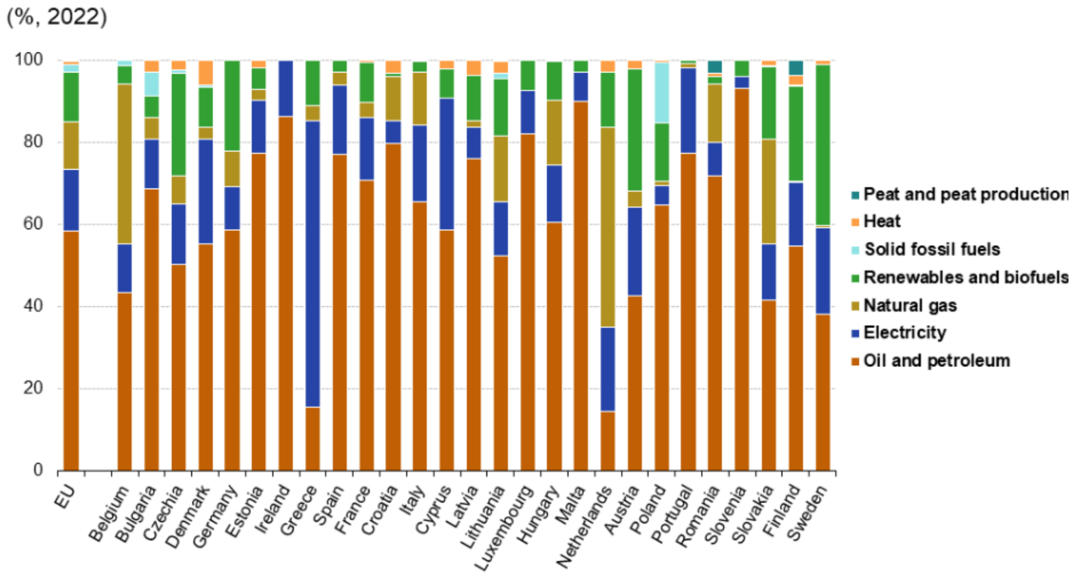


Figure 33. Fuel mix in direct energy consumption of agriculture and forestry in the EU in 2022 [68].

Greenhouses are one of the most energy-intensive consumers in agriculture, especially when compared to open-field agriculture. There are approximately 405 000 hectares of area covered either with glass or plastic greenhouses. [69] Greenhouse structure in the EU range from complex, energy-intensive systems that heavily regulate the indoor climate, to simpler structures resembling open-field practices. This variation is strongly influenced by local climatic and socio-economic conditions, where northern European greenhouses often require more heating and are more energy intensive. Various heating and cooling systems are used in greenhouses, including air heaters, central heating, boilers, cogeneration, natural gas, electricity, and heat pumps. Energy sources range from direct fossil fuels to cogeneration and geothermal heat pumps. Figure 34 shows that the energy needs and use cases vary significantly depending on the type of greenhouse. For example, the share of heating can range anywhere from 0 to 99 % of the total energy needs. Figure 35, on the other hand, shows these shares in a specific case, tomato farming in high energy intensity greenhouses, meaning with yearly energy consumption higher than 1000 GJ/ha (~278 MWh/ha). As shown, heating takes the largest share in energy consumption, with cooling needs as second. Finally, Figure 36 shows the energy consumption of greenhouses in Netherlands by crop.

Energy Consumption per Category	Range of Total Energy Consumption
Heating and cooling	0–99%
Irrigation	1–19%
Fertilizers	1–27%
Pesticides	0–6%
Lighting	1%

Figure 34. Shares of different energy needs in European greenhouses [69]

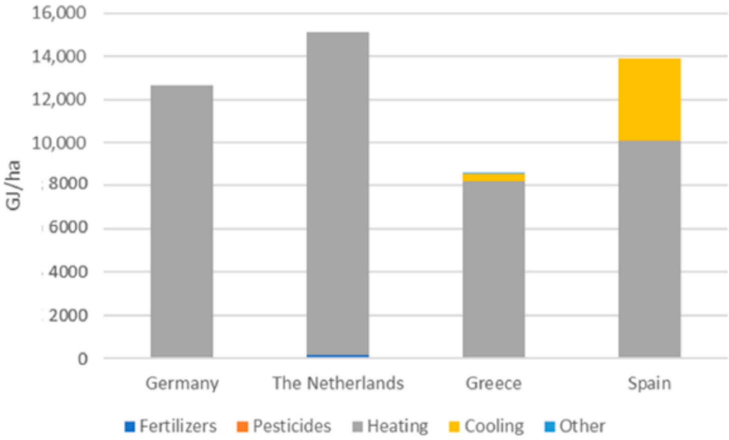


Figure 35. Comparison of energy consumption in high energy intensity greenhouses (>1000 GJ/ha) used for tomato production in different European countries [69].

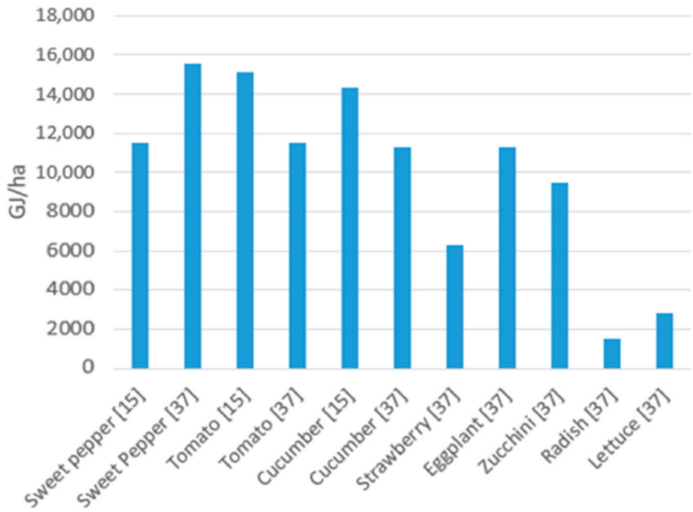


Figure 36. Yearly energy consumption of greenhouses per hectare per year in the Netherlands, categorized by crop [69].

The energy consumption in a greenhouse can vary during the seasons, as during summer the cooling needs can be higher than in the winter, when heating takes the major part. With around 11000 GJ/ha (or ~3056 MWh/ha) yearly energy consumption in a greenhouse in the Netherlands, the greenhouse energy demand is likely too low for any SMR.

2.6 Shipping

2.6.1 Current fleet of nuclear ships

Military vessels dominate current nuclear-powered ship propulsion. Nuclear reactors onboard ships provide steam power, offering prolonged operation without refueling, near-unlimited range, and high power output, essential for submarines and large vessels like aircraft carriers. Over 160 ships globally have used nuclear propulsion, mostly military submarines and a few aircraft carriers and icebreakers [70]. Nuclear propulsion allows submarines to maintain extended submerged operations and icebreakers to navigate polar regions effectively.

Today, the U.S. Navy leads with approximately 80 nuclear-powered ships, including all aircraft carriers and numerous submarines, achieving over 6,200 accident-free reactor-years due to rigorous safety standards. Russia operates about 40 nuclear submarines and a nuclear-powered cruiser, with historical experience building nearly 250 nuclear subs. Other countries with nuclear navies include France (one aircraft carrier and ten submarines), the UK (about 12 nuclear submarines), China (around 12 submarines), India (3 nuclear submarines in 2019), and Australia, which plans to acquire nuclear-powered submarines through the AUKUS alliance.

Commercial nuclear-powered merchant ships emerged in the late 20th century as demonstration and experimental vessels, primarily to test nuclear propulsion for civilian maritime applications. Four notable examples highlight their varied success:

The **NS Savannah**, launched by the United States, was a cargo-passenger demonstration ship operational from 1962 to 1970 [71]. It featured a 74 MW thermal reactor and was the first nuclear-powered merchant vessel, completing successful global promotional tours. Despite demonstrating technical feasibility, high operational costs and significant public concerns about safety and port acceptance led to its early retirement.

West Germany's **Otto Hahn** was a cargo vessel serving as a bulk and ore carrier, operational with nuclear propulsion from 1968 to 1979 [72]. Equipped with a 38 MW thermal reactor, it provided reliable service, covering approximately 650,000 nautical miles. Ultimately, the reactor was removed in 1979 due to economic factors, and the ship was converted to diesel propulsion by 1982.

Japan's **NS Mutsu** was an experimental nuclear-powered cargo ship, conducting trials between 1970 and 1992 with a 36 MW thermal reactor [73]. Although it successfully showcased Japan’s nuclear maritime technology, the ship faced numerous technical difficulties, political controversies, minor nuclear accident, and a strong public opposition. The reactor was eventually decommissioned, and the vessel was converted to diesel propulsion and changed its name to RV Mirai.

The Soviet Union's **Sevmorput**, an icebreaking container/cargo ship, began operations in 1988 and remains active after refurbishment in 2016 [74]. Featuring a 135 MW thermal reactor, it is the only commercially viable nuclear-powered cargo ship still operational today, primarily supporting essential logistics in the Arctic. Its continued economic success within this specialized niche demonstrates the potential viability of nuclear propulsion under specific conditions.

Russia operates the **Akademik Lomonosov**, the world’s first floating small modular reactor (SMR) barge, stationed in Pevek, Chukotka [75]. It supplies electricity and heat to this remote Siberian region using two KLT-40S reactors. Operational since 2020, it replaces aging infrastructure and now covers about 60% of regional energy demand. Russia plans to expand this concept with larger, next-generation floating reactors. It is a borderline electricity generation/shipping application yet listed in this chapter.

2.6.2 Shipping Energy Consumption and Emission Reduction Targets

As of early 2024, the global shipping fleet reached a total capacity of 2.35 billion deadweight tons (dwt), with oil tankers, bulk carriers, and container ships accounting for 71% of this capacity [76]. Fleet growth has slowed in recent years, averaging 3.7% annually since 2011, down from 7.1% between 2005 and 2010. Most fleet expansion has focused on purpose-built cargo ships.

Ownership is dominated by Asia, with China (310 million dwt) and Japan (242 million dwt) holding large shares, while Greece leads globally with 395 million dwt. European companies collectively own 35% of global capacity, compared to just 5% in North America. Developing countries, excluding China, own only a small fraction.

Ship registration continues to rely heavily on flags of convenience, with Liberia, Panama, and the Marshall Islands accounting for the majority. Notably, 87% of Greek-owned and 84% of Japanese-owned vessels are registered under foreign flags. Liberia has seen especially rapid registry growth since 2018.

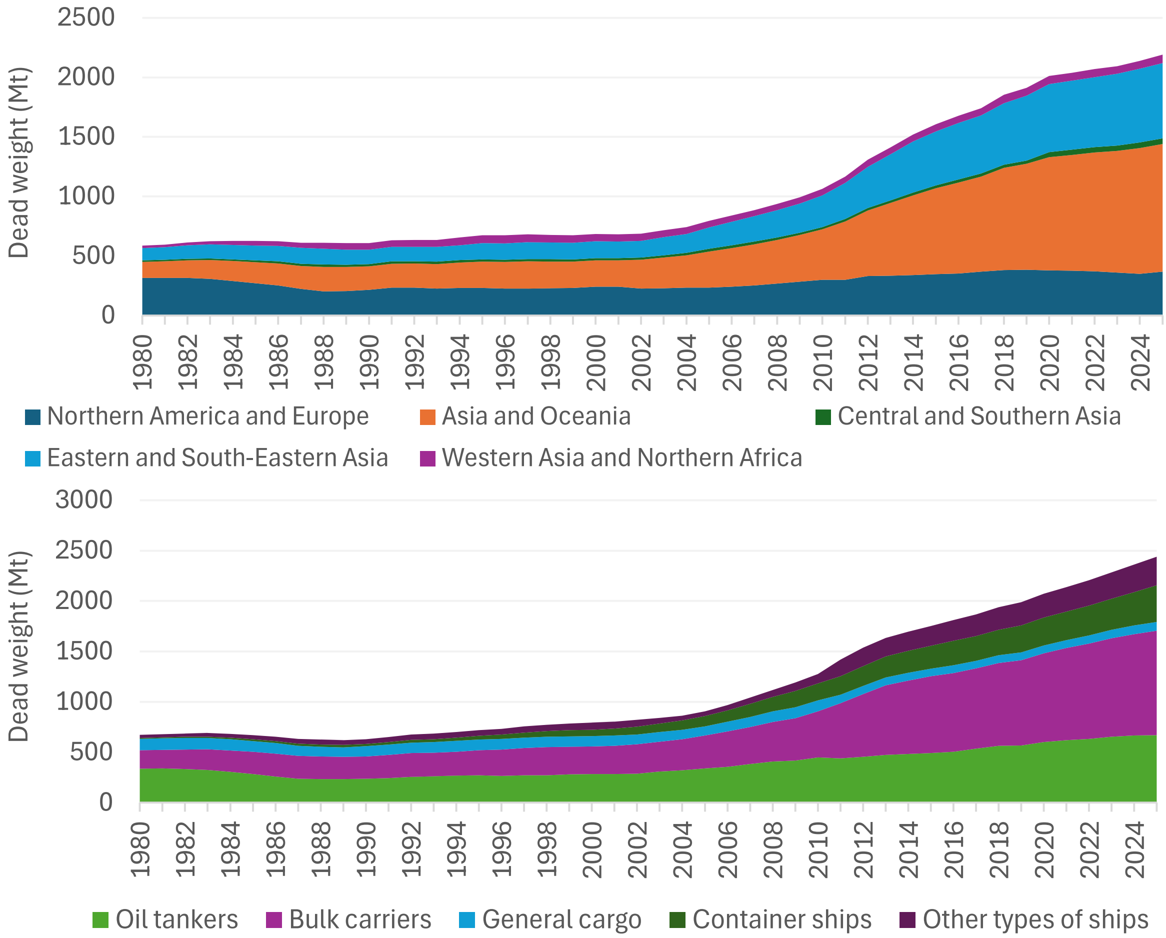


Figure 37. Global fleet capacity by owning countries, and by main vessel type [76].

Maritime shipping remains heavily dependent on oil-based fuels, with biofuels accounting for less than 0.5% of global use in 2022. To align with international climate targets, the sector must drastically increase the adoption of alternative fuels—such as biofuels, hydrogen, ammonia, methanol, and electricity. In the IEA's Net Zero Emissions (NZE) Scenario, the sector avoids the increase in the energy use, despite the increasing fleet capacity, and reaches 15% share of low-carbon fuels by 2030 [77]. While biofuels can be used in existing ships, broader uptake of other low-emission fuels will require major advancements in fuel production, bunkering infrastructure, onboard storage, and engine systems. Given the long lifespans of vessels, rapid innovation, retrofitting capabilities, and supportive policy frameworks are critical to driving this transition.

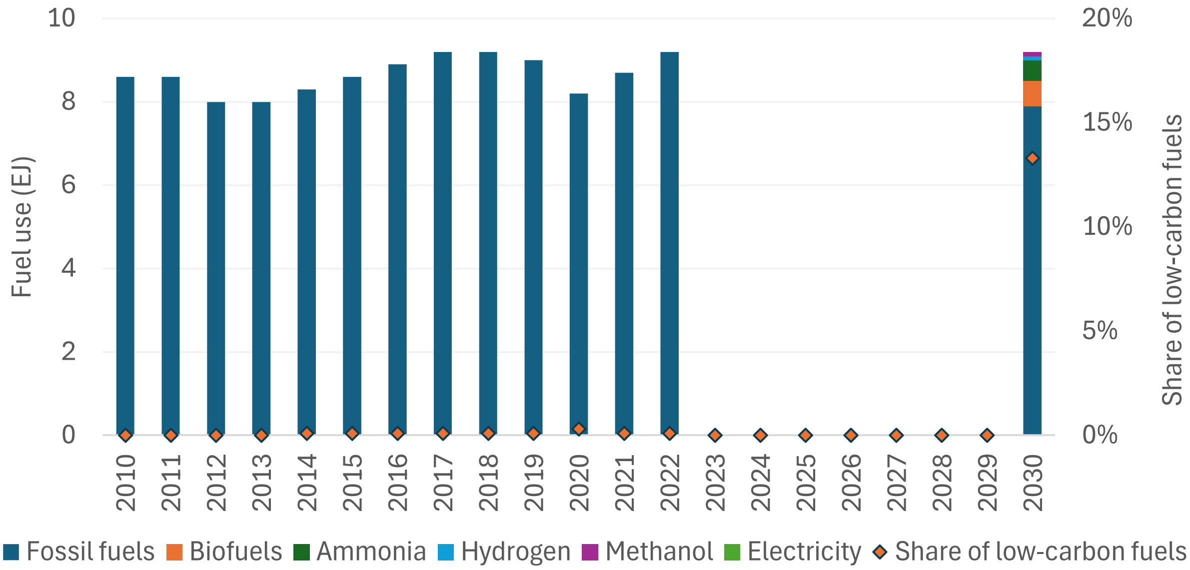


Figure 38. Energy consumption in international shipping by fuel in the IEA's Net Zero Scenario, 2010-2030 [77].

Global decarbonization efforts are advancing through coordinated international and private-sector initiatives. Key agreements like the Green Shipping Challenge (COP27), the Clydebank Declaration, and the Declaration on Zero Emission Shipping (COP26) aim to establish zero-emission shipping corridors and fully decarbonize maritime transport by 2050. At the same time, industry stakeholders are committing to low-carbon logistics. Companies participating in the CoZEV initiative aim to achieve zero-carbon ocean freight by 2040, while the Zero Emission Maritime Buyers Alliance (ZEMBA) seeks to procure near-zero-emission shipping services. Financial and operational alignment with climate goals is being reinforced through the Poseidon Principles and the Sea Cargo Charter, guiding investment and chartering practices toward sustainable outcomes.

Floating small-modular reactors (SMRs) highlight nuclear energy's potential to decarbonize long-haul shipping without the volumetric penalties of green fuels. Modern marine SMR concepts promise dense, zero-carbon power with multi-year refuelling cycles particularly suitable for ice-class tankers, Arctic routes, or energy-intensive container ships. Yet deployment faces steep hurdles: regulatory harmonization across flag and port states, public-acceptance concerns, safeguards against proliferation, and the high upfront cost of nuclear-qualified shipyards and crews. If these barriers can be addressed through international safety standards, specialized financing, and demonstrator projects, nuclear propulsion could have a role in future commercial shipping.

2.7 Space applications

Nuclear energy has significantly enabled space exploration by providing compact, long-lasting power sources and propulsion systems superior to solar and chemical alternatives. Historically, radioisotope thermoelectric generators (RTGs), utilizing radioactive decay (mostly plutonium-238), have powered notable missions, including NASA’s Voyager, Cassini, and Mars rovers (Curiosity, Perseverance) [78]. The U.S. also briefly experimented with nuclear reactors (SNAP-10A) and propulsion (NERVA), demonstrating feasibility but discontinuing due to shifting priorities. The Soviet Union extensively used small nuclear reactors (e.g., Bouk/Buk, TOPAZ-series) on military satellites, though accidents like Cosmos 954 underscored significant safety risks [79].

Currently, RTGs remain prevalent for missions beyond practical solar range, with NASA's MMRTGs powering Mars rovers. Radioisotope Heater Units (RHUs) are also widely used for instrument heating. Supply challenges of Pu-238 have driven the U.S. to restart its domestic production, while ESA explores americium-241 as an alternative fuel [78]. Modern reactor projects like NASA’s Kilopower (KRUSTY) demonstrated compact, reliable reactor concepts suitable for lunar and Martian bases, with future demonstrations planned via NASA’s Artemis program.

Nuclear propulsion development is actively progressing. NASA and DARPA’s DRACO project aims to demonstrate nuclear thermal propulsion (NTP) by 2027, promising significantly reduced transit times to Mars [80]. Nuclear electric propulsion (NEP), using reactors powering electric thrusters, offers high efficiency for deep-space missions, though low thrust currently limits human mission practicality.

Internationally, China and Russia are jointly pursuing lunar base nuclear reactors, aiming for operational capabilities in the 2030s [81]. China independently seeks a powerful (~1 MW_e) reactor prototype for Mars bases or orbital spacecraft. Russia advanced also a nuclear-powered "space tug" (Zeus) but had to cancel the project due to financial hurdles and a lack of suitable missions [82].

With ongoing technological and policy advancements, nuclear power and propulsion has a chance to start the transition from exclusively governmental projects into broader space industry utilization. However, commercial adoption of nuclear space technology faces significant regulatory, technical, and insurance-related hurdles. Private companies currently participate mainly through government contracts due to strict oversight, cost, and liability concerns. Nevertheless, industry involvement is expanding, with firms contributing innovative reactor designs and propulsion concepts. Streamlined regulations, clear liability frameworks, strong public-private partnerships, and global standards will be essential to commercial deployment.

3. Conclusions

In this report, potential applications of nuclear energy were explored through a literature review. The focus was on applications that utilize heat up to approximately 500°C. Both electricity and heat-only applications, as well as hybrid applications, were included in the review, such as desalination, data centers, and propulsion. The most suitable applications are those where energy demand is relatively steady and of a sufficiently large scale, requiring tens or hundreds of megawatts of power.

There are numerous potential applications for nuclear energy. The most promising ones appear to be district heating, desalination, data centers, certain industrial processes, and possibly space and ship propulsion. Industrial areas are another potential specific site for nuclear energy, as they collect several production facilities together, which aggregated energy demand nuclear energy could cover. This way, there would also be fewer limitations regarding the level of energy demand of the application.

Regarding industrial processes, much additional research is needed, particularly in the chemical industry, where many processes are interconnected. High-temperature heat used in upstream processes can be utilized in downstream processes, complicating the assessment of nuclear energy's feasibility. Since nuclear technologies may not reach the highest required temperatures, such production chains might not benefit from their integration, even if part of the production chain would operate within a suitable temperature range.

The food and beverage sector may have potential, as there are likely many continuous processes with fairly low temperatures. However, there is limited information on the sizes of these production facilities (in terms of MW demand), making it difficult to conclude an assessment of nuclear energy's potential. It seems likely that these processes are typically small severely limiting the potential of nuclear energy. Greenhouses are the most energy-intensive sites in agriculture, but even a large-scale greenhouse has relatively low annual energy consumption, typically only hundreds of MWh per hectare.

Many applications are such that industrial high and very high-temperature heat pumps are already a competitive option. Temperatures between 120–165°C have been achieved in some commercial industrial heat pumps, and development is underway for pumps operating at 160–200°C. Although heat pumps have much smaller unit size than nuclear reactors, the possible unit sizes of heat pumps have been increasing, further intensifying the competition.

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