Economic and Social Considerations for the Future of Nuclear Energy in Society

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Deliverable 2.2: Analysis of impact of societal and technological changes on the future energy market

Work Package 2

Lead Beneficiary: RATEN

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Contents

1 Executive Summary

One of the objectives of the ECOSENS project is to identify the possible roles of nuclear power in the mid-century and beyond. In the context of climate-neutral policies radical changes are required in how energy is provided and consumed. This transition involves structural changes in the European economy, extending beyond the energy sector, and new types of technologies to be developed and implemented. The strategies will impact society, either through the direct effects of technology use or indirectly through changes in patterns of consumption, daily behaviors, choices, and attitudes. Furthermore, these radical changes will have an impact on the environment, beyond a pure focus on climate change.

The deliverable is devoted to investigate the possible medium and long-term changes in the society and energy sector in order to create a basis for the identification of the possible roles of nuclear energy. The structure consists of four main chapters: Assumptions for the medium and long term, Driving factors and obstacles, Impact of disruptive technologies, and Impact of different crisis.

The ECOSENS **assumptions** quantify some predictive elements (such as demographics, GDP, standard of living) to obtain a projection of the future energy needs at European level. The investigations indicate a significant increase in electricity demand, despite expected large efforts to implement energy efficiency measures. A doubling of the electricity demand in 2050 compared to 2020 baseline figures appears very probable, due to the Green Transition objective of electrification of transport, heating and cooling, and greater use of electrical appliances. Economic growth, the trend towards a higher standard of living, and improvement in quality of life will be the second and third factors influencing electricity demand. The expected change in demographics will not impact significantly the energy demand. Overall, the assumed doubling of demand will greatly influence the energy generation portfolio. The decarbonization of the economy will create a market dominated by renewables with difficulties in balancing production and demand. In such conditions the development of energy storage systems together with the presence of a significant share of very stable energy are crucial for the security of supply.

A detailed discussion of **factors** influencing future developments of the European economy, market, energy sector, and society is presented. The influencing factors or drivers are described as demographic, environmental, economic, technological, political, social and cultural. The technological influencing factors are discussed in detail in the section devoted to the impact of disruptive technologies where eleven potential disruptors are considered: artificial intelligence, big data, Internet of Things, advanced robotics, material sciences, energy storage, additive manufacturing, drones, biotechnologies, blockchain, and geoengineering. Energy storage is seen to be the key **disruptive technology**. With increased energy storage capacity, excess electricity generated during off-peak times can be stored and used during peak demand periods, reducing the need for additional power generation. Without it, many of the advantages of the intermittent renewables become questionable.

Advanced robotics, additive manufacturing, material sciences, and biotechnologies may create a new paradigm in goods production, accompanied by a great decrease in classical manufacturing (relying on classical machineries and humans), more distributed/localized production, high-performance materials, and a new level in using the biological techniques. Most of the influences will act towards a reduction of energy consumption by energy efficiency, optimization of production, reduction in transport, redesign of factories with less human comfort and a more neutral environment appropriate for robots. Another group (Artificial Intelligence, Big Data, and the Internet of Things) will lead to an increase in electricity consumption in the short term, until the attainment of a mature phase when these technologies will output the best algorithms to construct the optimal solutions in terms of the sustainability performances.

A separate discussion is devoted to the potential impact of various crises (pandemic, economic, financial, geopolitical, energy supply, migration), and to the complexity arising from their co-occurrence. In the current context, due to globalization and high interdependencies crises have lost more and more of their local character, becoming seeds for global economic and societal crises. For example, the Covid-19 pandemic created a drastic decline in economies by the impact on consumption levels. Economic/financial crisis experienced in different historical contexts have shown that energy demand decreases up to 10-20%. Geopolitical crisis affects not only regional economies, but also supply chains including energy resources transactions. An energy supply crisis leading to higher prices, rationing, blackouts, economic repercussions, and disruptions in critical services can significantly impact energy demand and the energy market. Its consequences can affect quality of life by increasing costs, limiting access to essential services, and disrupting daily routines. Migration may be significant in coming years according to the evolution of climate change and of the attractivity of the EU. The arrival of many migrants in a particular region or country can lead to an increased demand for energy and create pressures on the local energy infrastructure and resources.

The present deliverable elaborates and details assumptions that were presented in a first working paper to participants in an ECOSENS international stakeholder webinar.[1] The next step will be to develop, on this basis, a plausible set of energy scenarios to understand the possible role of nuclear power in the European energy mix at the horizon of 2050.

[1] Cf. [Fourari], available online: https://ecosens-project.eu/decarbonizing-europes-energysystem-2-clarifying-non-linearassumptions-about-energydemand-to-2050/

2 Introduction

The energy sector stands as a complex arena, shaped by a myriad of interconnected forces, some with discernible patterns and others with volatile trajectories. Among the factors wielding a notable degree of predictability are demographics, consumption patterns, quality of life aspirations, and the consequences of decarbonization efforts. These elements provide a certain level of stability to energy forecasts. On the flip side, factors like technological advancements and economic shifts introduce a level of uncertainty due to their rapid evolution and the protracted nature of their implications on future projections.

The emergence of sophisticated algorithms and computational tools, bolstered by expansive networks capable of handling colossal datasets, has transformed predictive analytics. However, even in the face of these technological strides, foreseeing the exact contours of the future remains a formidable challenge.

The opening years of the present decade demonstrated the fallibility of predictions, as unforeseen events, such as the COVID-19 pandemic, energy crises, geopolitical conflicts, and financial turmoil, disrupted anticipated trajectories. These events underscore the inherent limitations in attempting to chart the course of a complex and interconnected world.

Adding to the complexity, technological progress significantly amplifies the complexity and intricacies of energy-related decision-making. The proliferation of data storage and processing capabilities reshapes the landscape by introducing layers of intricacy that policymakers, businesses, and analysts must grapple with.

ECOSENS seeks to predict the energy demand for the next decades to the mid XXI century, together with the available options to generate the required energy, and estimating the evolution of future energy markets in terms of driving forces. The synthesis of these contextual elements within the framework of ECOSENS contributes to a comprehensive evaluation of the conceivable role of nuclear power. This evaluation spans three pivotal timeframes: the forthcoming decades, the milestone year 2050, and the realm beyond it.

The energy sector is influenced by policies, consumers' behaviors, goals and actions to enlarge electrification, and energy efficiency measures, but also by the development of disruptive technologies (such as AI, IoT, 3D printing, big data, drones, biotechnologies, advanced material, etc.) and by economic and energy crisis. Additionally, the current classical growth-oriented paradigm of development may give way to one focused on a healthy economy designed to prosper but not necessarily to grow.

In such circumstances, predicting the role of nuclear power after 2050 is the most significant challenge of the analysis, together with the inclusion of influence by the regional market and economic interconnections and of social and environmental considerations.

In a world where change is the only constant, ECOSENS embarks on an odyssey of prediction. Through a fusion of data, analysis, and contextual understanding, it seeks to shed light on the energy landscape of tomorrow – a landscape shaped by both the calculable rhythms of demographics and the capricious tides of technology and circumstance. The journey is one of complexity, ambiguity, and continuous discovery, striving to decipher the ever-evolving script of the energy sector.

3 Assumptions on the medium- and long-term

3.1 Demographics

This section is devoted to a brief discussion on the possible evolutions of the demographics in Europe, for the next decades.

In April 2020 Eurostat published the population projections in the EU approaching the population size and structure for all European Union (EU) Member States and European Free Trade Association (EFTA) countries, covering the period 2019 to 2100 [1]. The study presents predictions on the size of population versus time considering three variables - births, deaths, and migratory flows – and a set of assumptions on future fertility, mortality, and net migration. The results are influenced by these assumptions and by used approximations (for example the flat values over the considered time horizon for the input variables) offering only a range for the possible demographic developments.

The first prediction is in terms of the evolution of the population's size. It is characterized by a modest grow within the current decade and a "**steady decline by the end of the century**" [1]. The EU-27 population is reported as 446.8 million in 2019. The maximum should be reached in 2026 as 453.3 million (+1.5 %). After that, a gradually decrease is expected with reported values as 441.2 million in 2050, and to 416.1 million in 2100. Details are presented in Fig. 2.1.1.

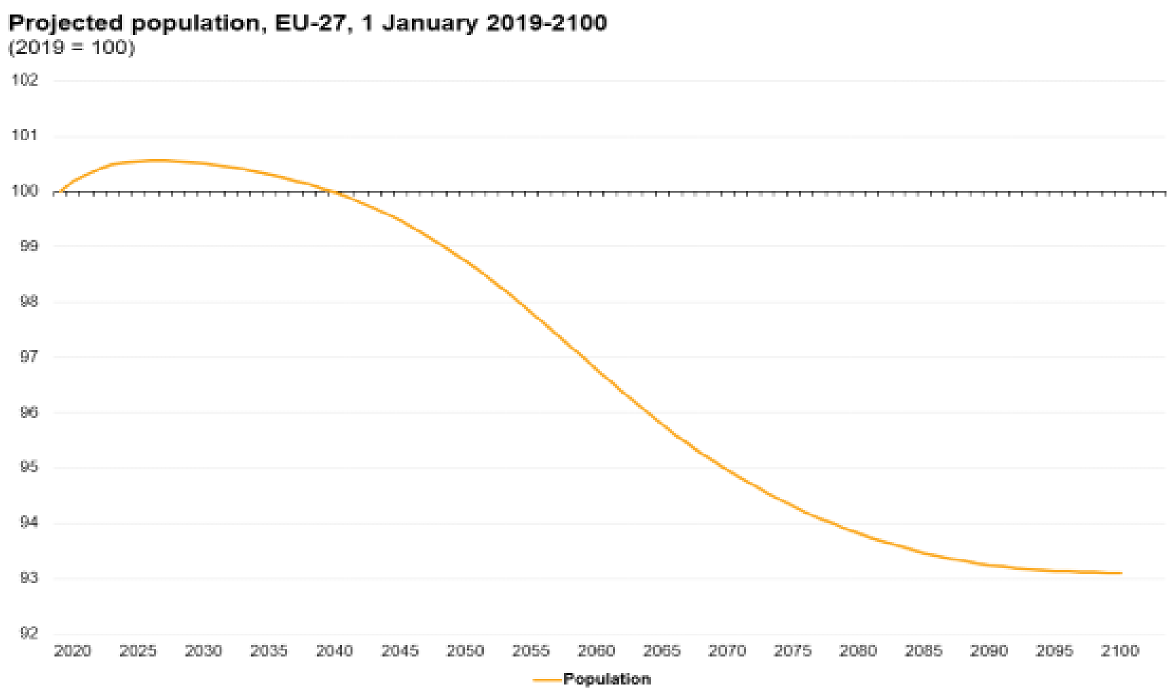

Fig. 2.1.1 Predictions for the evolution of the population of EU-27 in the period 2020-2100 (normalized at 100 as reference value for 2019) [2]

According with these predictions we may assume the size of EU-27 population approximatively constant until 2040, followed by a decrease of around -0.13 % per year between 2040 and 2050, and -0.11% per year for the period 2050 - 2100.

Considering the peculiarities per country it should be noted eleven Member States will have a population size in 2100 a little bit higher compared with 2019 (Belgium, Denmark, Germany, Ireland, France, Cyprus, Luxembourg, Malta, Netherlands, Austria, Sweden). The study mentioned the net migration as the main contributor.

The second important prediction is on the structural changes. The simulations on the baseline scenario shows a continuous increasing of the proportion of older persons in the total population, **"an ageing society"** characterizing the evolution from the entire analyzed period, "**over the next eight decades, the median age of the EU-27 total population is likely to increase by 5.1 years, from 43.7 years in 2019 to 48.8 years in 2100**" [1].

The main demographic groups: children (0-14 y), working-age population (15-64 y), elderly population (>65 y) will suffer important changes. The children segment will decrease from 15.2 % (2019) to 13.9 % (2100). The share of working-age population is predicted to decrease from 64.6 % (2019) to 54.8 % (2100), whereas the proportion of elderly segment in the EU-27 total population will increase from 20.3 % (2019) to 31.3 % (2100). A consequence of the ageing society will be the impact in the dependencies. According with the predictions by 2100 "there will be fewer than two persons of working-age for each elderly person" [1].

An important note for the shift towards older ages consists of the number of very old people (>80 y). It will be double in 2100, 60.8 million (14.6 %), compared with 2019, 26.0 million (5.8 %).

Assumption A1: Population growth	**Global**	7.8 b (2020) to 9.4 b (2050) with a tendency to slow down
	EU	from 0.45 b (2020) to 0.44 b (2050)

3.2 Gross Domestic Product

The perspective of the global economy by 2050 is approached in [3]. One of the main conclusions is about economic growth appreciated as "more than double in size by 2050, assuming broadly growth-friendly policies … and no major global civilization-threatening catastrophes". A repositioning of the counties in global GDP contribution is expected with China as the largest contributor in 2050, seconded by India. For the EU27 the contribution is estimated at "less than 10% by 2050, smaller than India" [3] an important relative decreasing from 15% in 2016. Other forecasts like [4] appreciated the top ranking will be China, US, EU-27, India.

The fastest growing economy in EU27 will be of Poland [3]. However, it should be noticed the estimated growing is strongly conditioned by the structural reforms to be implemented in the emerging markets in order "to improve macroeconomic stability, diversify their economies away from undue reliance on natural resources, and develop more effective political and legal institutions" [3].

For EU27, in the period of interest for our analysis (2020-2050) the annual rates of economic growth "will remain roughly in line with the advanced economy growth", around 1.5-2% [3], lower than the global average rate (2-3%).

According with the report of European Environmental Agency [5] in 2050 the GDP of EU-OECD countries is estimated to increase will around 67% compared with the level of 2020.

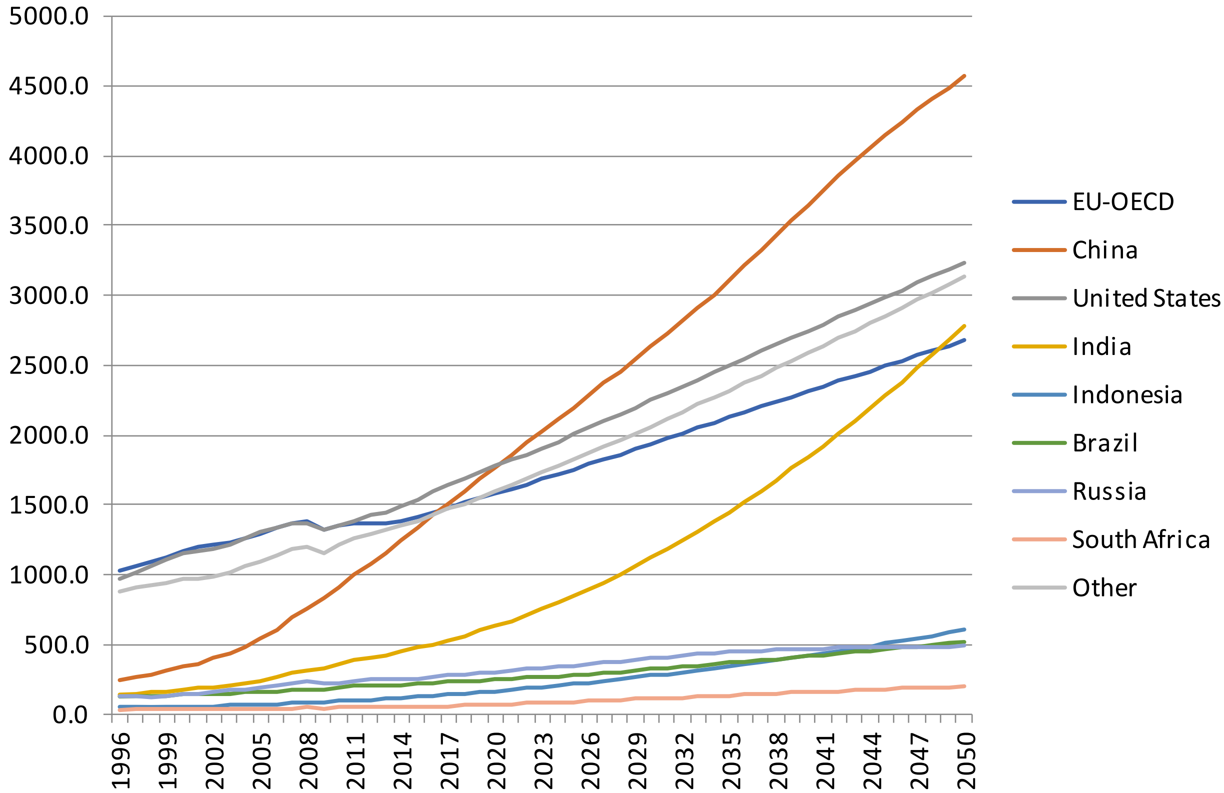

Fig. 2.2.1 Historic and projected GDP for different countries of the world (data from EEA, 2017])

Table 2.2.1 Projections for the economic annual rate growth (data from EEA, 2017])

			2024	*2025*	*2026*	*2027*	*2028*	*2029*	*2030*
			2.54%	2.59%	2.64%	2.68%	2.72%	2.74%	2.74%
2031	*2032*	*2033*	*2034*	*2035*	*2036*	*2037*	*2038*	*2039*	*2040*
1.94%	1.91%	1.88%	1.84%	1.80%	1.76%	1.72%	1.68%	1.65%	1.62%
2041	*2042*	*2043*	*2044*	*2045*	*2046*	*2047*	*2048*	*2049*	*2050*
1.59%	1.56%	1.53%	1.51%	1.49%	1.48%	1.46%	1.45%	1.44%	1.43%

Assumption A2: Economic growth	**Global**	>+100%, average annual rate of 2.5%
	EU27	+70% (2050 vs 2020) with an annual rate of 2.6% (2020-2030), 1.7% (2030-2040) and 1.4% (2040-2050)

3.3 Standards of living

The natural tendency of the social development is to improve the quality of life. The urgency of the measures to prevent the climate changes or at least to mitigate their impacts introduces some constraints. In [6] an important effort was dedicated to understand if it is possible to meet the 2050 climate targets in conditions of ensuring good living standards. The team involved in the work has developed an application ("Global Calculator") that includes a model of the lifestyle (consumption patterns, daily needs, diet, travels, etc) and its impact in the energy, materials and land requirements.

From the point of view of the comfort of the building, and increase of winter temperature (16 to 190C)

Based on the developed models and considering global data characterizing the current situation and the future evolutions the main answer is positive "yes, it is physically possible that all 10 billion people in the world could eat well, travel more and live in more comfortable homes, whilst at the same time reducing emissions to a level consistent with a 50% chance of 2°C warming" [6]. However, technological transformations and changings in the fuel use have to be rapidly implemented. The electrification of heat and transport seems to be in the center of these needs. On the other hand, a "smarter use of our limited land resources" is necessary.

According with [6] the following evolutions are plausible: (1) access to electricity will increase at 94% (2050) vs 84% (2014), (2) the winter average indoor temperature could rise to 19^0C (2050) compared with 16^0C (2014), whereas the summer average indoor will decrease to 24^0C (2050) compared with 27^0C (2014), both influencing the energy demand (heating and cooling), (3) people will own more appliances (e.g for washing machines from 0.8 (2014) to 1.0 (2050) units per urban household), (4) increasing of the travels, from 8300 km/capita (2014) to 12400 km/capita (2050), with an increase of 400 km of travels by air, and an increase of the travels share by car from 37% (2014) to 40-45% (2050), (5) the increasing in food equivalent consumption from 2180 kcal/capita/day (2014) to 2330 (2050) with impact in the land using.

Assumption A3: Standards of living: increasing progressively	**Global**	Relevant increase in access to electricity, heating&cooling, appliances in households, travels, food consumption
	EU27	Relevant increase in heating&cooling, appliances in households, travels

3.4 Impact of energy efficiency measures

Energy efficiency measures are driven by the climate policies (cutting the CO_2 emissions) and by the energy and geopolitics crisis (last two years). The effectiveness of energy measures is reflected in the values of the energy intensity indicators, overall economy and by sectors.

In 2018 the Energy Efficiency Directive (EED) entered into force, updating the 2012 directive (27/2012/EU). The EU energy efficiency target for 2030 of at least 32.5% (compared to projections of the expected energy use in 2030) was transposed in the national energy and climate plans (NECPs) for 2021-2030. In July 2021, the Commission adopted the integration of EED as part of the Green Deal package, which contains legislative proposals to meet the EU objective of at least 55% reduction in greenhouse gas emissions by 2030. A reduction of 36% for final energy consumption and 39% for primary energy consumption by 2030 compared to the 2007 (reference scenario) is targeted.

The EU considers the energy efficiency as the first priority in the practical applications, investment decisions, and policy. The objective stated in 2018 consists of a reduction of the consumption by 32.5% in 2030. In 2021 the target was redefined adding an additional effort of 9% reduction (2030 vs 2020), in absolute terms the "overall EU energy consumption should be no more than 1023 million tons of oil equivalent Mtoe of primary energy and 787 Mtoe of final energy by 2030" [7]. In 2022 the Commission has increased the ambition from 9% to 13% (reduction vs 2020), in absolute terms 980 Mtoe (primary energy), respectively 750 Mtoe (final energy consumption).

At global level [8] the world will use progressively less energy due to the implementation of energy efficiency measures. A global estimation shows a reduction with 13% than the total energy demand of 2020 (in absolute terms at a level of 500 EJ).

Assumption A4: Impact of energy efficiency measures	**Global**	A reduction of the primary energy consumption with 13% (vs 2020)
	EU27	A reduction of the primary energy consumption at least with 30% (vs 2020)

3.5 Impact of electrification

Electrification is a clear tendency of many energy markets, stimulated by policies oriented by the climate change crisis. Due to the progress of the decarbonization in the energy sector the most used approach is to transfer a large part of the heating&cooling sector energy consumption to the electricity and similarly for the transport sector. Today, the carbon-free electricity in based on nuclear power and renewable energy (hydro, biomass, wind and solar).

In 2019, globally, the electricity represents 19% of total final energy consumption [9]. A constant increase in weight is estimated by: improving the access to electricity, deployment of the electric vehicles, heat pumps, production of the hydrogen by electrolysis.

In 2050, the share of electricity could reach over 50% of total energy consumed, the use of fossil fuels being partially replaced by clean electricity [10]. The most important contributors will include transportation, space heating and cooling, as well as industrial processes such as hydrogen production.

The **transportation sector** offers extraordinary opportunities for electrification through the development of electric vehicles (EVs). The scenarios developed by the International Energy Agency (IEA) indicate a development of 125-220 million electric vehicles by 2030 [11]. According to Bloomberg New Energy Finance [12], 55% of new car sales and 33% of the global fleet will be electric by 2040. This will create a significant increase in electricity worldwide by 2030, for IEA scenarios of 400-900 TWh, and for BNEF predictions of 2,000 TWh in 2040 and **3,400 TWh by 2050** (with EV consumption representing 9% of total electricity demand).

The cooling of residential and commercial spaces will strongly stimulate global electricity consumption. In the period 1990-2016, the energy consumption for cooling the space tripled, amounting to 2,020 TWh. Most of the space cooling is served by devices such as air conditioning (AC) systems, household fans and dedicated dehumidifiers, with electricity providing almost 99% of energy consumption for this purpose. In 2016, almost 20% of electricity consumption in buildings around the world is consumed for space cooling [13].

By 2050, the **global cooling capacity of residential and commercial** systems will triple, from about 11,700 GW in 2016 to about **37,000 GW in 2050** [13]. Energy consumption for space cooling can reach up to 6,200 TWh [13].

Heating of living or business spaces represents approximately 50% of the global final energy consumption in 2018, while the final energy consumption for transport is 29%, and that of electricity 21% [14]. The predominant heat generation takes place by burning fossil fuels (77%), as a result of which the heating sector gives 40% of the total CO2 emissions. Structurally, about half of the heat demand is required by residential and commercial heating, and half by industrial processes. Much of this heat is generated by cogeneration and distributed through urban (DHS) or industrial heating systems. The transition from fossil fuel-based cogeneration to renewable or nuclear-based cogeneration can help achieve the goal of reducing emissions. From **the point of view of the electrification potential of heating, it does not seem to be significant, especially due to economic reasons**.

Considering the elements of electrification of transport, increasing the requirements for cooling, economic growth, as well as the development of new electrical applications for the **EU**, in the period 2020-2050 is estimated an increase in annual electricity production from 3500 to **4900 TWh** (about + 40%, with an average increase of + 1.1% / year) in order to reduce emissions [10].

An improved access to electricity is an important factor at global level, but with less importance at the EU level since the most of EU27 countries has a 100% access factor, and the others greater than 99%.

For 2050, the prediction for the energy mix in the EU estimates a share of electricity in the total primary energy of around 60% [15], compared with 23% at the level of 2019 (just before the drop due to the pandemics). For 2030 the target in electrification is estimated at 35% [15]. According with the ambition of Green Deal, EU entered into the Electric Decade.

The largest potential is represented by shifting from fossil fuel-based transport to electric vehicles (EVs), with an expectation of 130 million EVs (2050) vs 0.5 million in 2015.

From the point of view of the sectors of the economy, in the industry the electricity is expected to reach 50% from all used energy, whereas in the transport sector and building sector the electricity will represent 63% of the total energy consumption [15]. Currently, the EU's vehicle fleet consists of 63 million units (cars, vans, buses, trucks) [15]. It should be noted that an additional contribution will be achieved by the indirect use of electricity via hydrogen (and its derivatives) production based on electricity. The green hydrogen option will allow the greening of sectors difficult by direct electrification.

In absolute values, the large-scale electrification (industry, heating, cooling, transportation) will increase the demand of electricity in the EU from 2700 TWh to around 7000 TWh (2050) [16]

Assumption A5: Impact of electrification	**Global**	The introduction of EVs, increasing of the appliances, more cooling needs, and also the electrification in industry will produce a major increase of electricity, difficult to be estimated. At least 30% increase (2050 vs 2030) may be a realistic assumption
	EU27	A doubling of the electricity demand in 2050 vs 2020

3.6 Impact of energy decarbonization policies

Due to the urgency of climatic measures a large effort for the decarbonization of energy is expected. At world level, the decarbonization of the energy mix is predicted to be characterized by: (1) a global decrease of coal-fired power plants from 35% (2020) to 4% (2050) [8], (2) a global decrease of the gas-fired power plant from 24% (2020) to 8% (2050). It should be noted both types of plants have a crucial role in providing flexibility and backup in the electricity system.

In [8] the share of nuclear, in 2050, is estimated at 5%. The of energy will be almost renewables. According with IAEA [17] the contribution of nuclear power in 2020 was around 10% of the world's electricity. The scenarios developed by IAEA [17] shows a more optimistic view than [8]. The IAEA high case scenario predicted a doubling of the current nuclear capacity (393 GW(e), 2022) to 792 GWe [17].

Assumption A6: Decarbonization of the energy mix	**Global**	The share of energy based on fossil fuels will be significantly reduced.
	EU27	In 2050 the energy will be completely decarbonized (almost completely phase out of fossil fuel-based plants). Renewables will dominate the market.

3.7 Concluding remarks on the assumptions

A prioritization of the measures to be implemented in EU are presented in [18]:

(1) high efficiency of direct electrification in transport and heating implies that in most cases it is the preferable solution,

(2) green electrification of transport and heating, together with hydrogen and/or synthetic fuel production,

(3) no investment in fossil-fuel production, transmission or utilization, and quickly decommissioning of existing plants within the next decades,

(4) reinforcement of the engagements of MSs by upgrading of NECPs documents,

(5) infrastructure investment in decarbonization at the level of end-users.

In order to define the possible roles of nuclear power in the energy mix, in the EU, at the horizon of 2050, the assumptions presented in Table 2.1 are considered.

It should be noted the large uncertainties in the projections and in the estimations of the impact of the envisaged solutions. It is clear, at least now, there is no optimal solution. Therefore, we cannot discuss the cost of the implementation. The situation is more complicated due to the intervention of different factors for example the global energy crisis and the geopolitics created after the Russia's invasion of Ukraine, with a large impact in the natural gas imports.

The assumptions indicate a very probable increase of the electricity demand, despite the large efforts to implement energy efficiency measures. The economic growth and the tendency to increase the standard of life increase of quality of life will be the second, respectively the third factor influencing the increase of the electricity demand. The demographics will not impact significantly the energy demand. The decarbonization of the economy will create a market dominated by renewables with difficulties in the balancing the generation and the demand. In such conditions the development of the storage together with the presence of a significant share of very stable energy is crucial for the security of supply.

Table 2.1 Main assumption for the energy sector development in EU and globally

Assumption A1: Population growth	**Global**	7.8 b (2020) to 9.4 b (2050) with a tendency to slow down
	EU	from 0.45 b (2020) to 0.44 b (2050)

Assumption A2: Economic growth	**Global**	>+100%, average annual rate of 2.5%
	EU27	+70% (2050 vs 2020) with an annual rate of 2.6% (2020-2030), 1.7% (2030-2040) and 1.4% (2040-2050)
Assumption A3: Standards of living: increasing progressively	**Global**	Relevant increase in access to electricity, heating&cooling, appliances in households, travels, food consumption
	EU27	Relevant increase in heating&cooling, appliances in households, travels
Assumption A4: Impact of energy efficiency measures	**Global**	A reduction of the primary energy consumption with 13% (vs 2020)
	EU27	A reduction of the primary energy consumption at least with 30% (vs 2020)
Assumption A5: Impact of electrification	**Global**	The introduction of EVs, increasing of the appliances, more cooling needs, and also the electrification in industry will produce a major increase of electricity, difficult to be estimated. At least 30% increase (2050 vs 2030) may be a realistic assumption
	EU27	A doubling of the electricity demand in 2050 vs 2020
Assumption A6: Decarbonization of the energy mix	**Global**	The share of energy based on fossil fuels will be significantly reduced.
	EU27	In 2050 the energy will be completely decarbonized (almost completely phase out of fossil fuel-based plants). Renewables will dominate the market.

4 Driving factors and obstacles on medium- and long-term

At near and medium term, energy demand and production itself are influenced by **demographic, environmental, economic, technological, political** developments, **social and cultural** trends.

These structural forces act at individual and collective level, with regional or country peculiarities, offering opportunities and creating obstacles for the evolution of specific energy alternatives.

Demographic shifts such as aging populations, changes in the distribution of people around the world, and population growth can have great impacts on both energy demand and technological developments. Generally, such evolutions can drive changes in societal norms, values, and needs. For example, an aging population may lead to increased demand for healthcare technologies, while a younger population may drive demand for new forms of entertainment or communication.

The environmental concerns such as climate change, resource depletion, and other environmental issues will drive societal and technological changes as people seek to mitigate their impact and adapt to a changing world.

Economic factors, such as economic growth, recession, changes in the distribution of wealth around the world, unemployment rates, income levels, and consumer spending patterns, can also shape technological and societal change. For example, economic recessions may lead to a decrease in consumer spending and a shift towards cheaper, more practical technologies, while periods of economic growth may lead to increased demand for luxury goods and innovative technologies. The economic trends influence the energy demand in majority of the countries.

Technological advances can also drive energy demand and, more generally, societal and technological changes as people adopt new technologies and use them to solve problems and meet their needs in new ways. For example, the development of new technologies such as artificial intelligence, renewable energy sources, and advanced materials may lead to significant changes in how we live, move and work, with knock-on impacts on levels and modes of consumption.

Political changes, such as shifts in government policies, introduction of major legislation, or the emergence of new political movements, can also drive technological and societal change. For example, changes in environmental regulations may foster the development of new technologies that are more energy efficient or have a smaller carbon footprint.

Changes in social and cultural norms and values can also influence technological and societal development. For example, the rise of social media and the proliferation of online platforms for communication and self-expression may have changed the way people interact and communicate with each other, promoting new daily behavior patterns leading to new profiles of energy consumption.

In the ECOSENS energy mix sustainability assessment, the **first assumption** on the future is linked with the action of individuals, communities and governments **to improve the quality of life**, to create wellness and prosperity. The **second** is the **compulsory requirement for energy**, mainly in the form of electricity (but also considering heat and transportation) to satisfy the needs of the entire society.

4.1 Demographics

The assumptions on the possible evolutions of the demographics were presented in section 2.1. At the level of EU-27, after a modest growth within the current decade, a "**steady decline by the end of the century**" is predicted [1]. However, in the envisaged projection period the variation is not impressive, from 446.8 million (2019) to 441.2 million (2050).

A more important change is expected for the demographic structure, characterized by the ageing of the society, with an increase of the median age of the EU-27 of 5.1 years, from 43.7 years (2019) to 48.8 years (2100), with a significant reduction of working-age persons. The migration will help to delay the ageing process in some MSs, but may accelerate the ageing in other countries where the working-age population is very mobile in searching more attractive jobs. Such changes will impact the energy consumption patterns. However, these changes in the demographics may be considered as having a limited impact in the energy demand of the future, at the level of 2050.

In other circumstances, for example in case of crisis (geopolitical, climate, etc) the demographics may deviate from this previous presented scenario and impacts a lot the energy consumption. Therefore, even the demographic projection does not introduce major changes, the potential remains great the demographics should be considered as a key influencing factor on the energy demand and energy sector of EU-27.

4.2 Environmental

The last decades have brought continuously heightened awareness of the impacts of our civilization on the environment. Physical effects such as global warming, extreme weather, sea level rise, decreasing biodiversity are now self-evident facts for broad segments of society. Moreover, environmental degradation has now reached the potential to increase risks associated with the insufficient availability or affordability of food, water, and energy.

The goal of the Paris Agreement was to limit to 1.5 degrees Celsius the increase in global average temperature, but this objective seems to be impossible according to current trends. Nonetheless, to mitigate climate change or at least to rein in the possible consequences, the EU is taking firm action to achieve net zero with new energy technologies and carbon dioxide removal techniques.

According to [19] in 2020 the GHG emissions for EU-27 had declined to 32% of the reference level of 1990. It is remarkable EU reached the planned target for 2020 as early as 2018. In 2019 the massive replacement of coal by gas and renewable produced a decrease of 4% in the emissions.

In 2020 the effects of pandemic lockdowns, travel restrictions, and slowdown of economic activities led to a 10% reduction in GHG emissions [19] compared with the 2019 values. In 2021 the reduction continued even as restrictions were relaxed, with an estimation of -5% compared with 2020 [19].

The decarbonization objective was expressed in achieving climate neutrality in 2050, with a target of 55% reduction in emissions in 2030 compared with the 1990 reference level.

However, the EU-27 is responsible for only 7% of the world total GHG emissions [20]. Without a global coordinated effort, it is very difficult to reach the goal of the Paris Agreement.

In 2022 the context was drastically changed by the energy crisis and the Russian offensive on Ukraine, both introducing large perturbations in European and world economies. At the same time, the impacts of climate change caused more heatwaves, forest fires, droughts, floods, storms and tornadoes in the region.

In response to these challenges EU expressed the determination to accelerate the efforts to reach climate neutrality. Two specific targets were defined for 2030 and now there are negotiations with the MSs regarding the implementation pathways: (i) 40% of energy consumption from renewable sources, (ii) a reduction in energy consumption by 9% from 2020 levels by 2030, based on improvements in energy efficiency. Additionally, a rapid reduction of EU dependence on fossil fuels from Russia, the diversification of energy suppliers, and acceleration of the green transition are targeted. A “Fit for 55” Plan (centered on a 2030 objective) was established in view of four pillars [19]: (1) save energy, (2) diversify suppliers, (3) quickly substitute fossil fuels for other forms of energy by accelerating the clean energy transition, (4) smartly combine investments and reforms. In this plan the EC advances more ambitious targets such as 45% share of renewables in the total energy consumption, and 13% energy savings by energy efficiency.

In sum there is a high ambition for decarbonization to be supported by renewable energies; these orientations target a new structure of the energy production sector, and energy efficiency measures whose impact will be largely felt by final consumers.

Moreover, a crucial part of the decarbonization belongs to the transport and heating sectors, whose electrification can help to reduce GHG emissions, as electricity can be generated from a variety of sources including renewables like wind and solar. Electrification of transport means the use of electric vehicles (EVs) instead of fossil fuel-powered vehicles, while the use of electricity as the primary energy source for heating homes and other buildings can be achieved through the use of electric heat pumps, electric boilers, or electric resistance heating. However, both transformations imply a likely overall increase in demand for electricity, which can put pressure on the electricity grid and require the expansion of electricity production capacity (including the construction of new power plants) as well as the development of more efficient technologies for storing and distributing electricity.

It is important to consider the full lifecycle emissions of the various transport and heating technologies, including the emissions associated with electricity generation, in order to determine the most sustainable options.

4.3 Economic

Gross domestic product (GDP) as a measure of the total output of goods and services produced in a country or region is an important indicator of economic health and growth. As such it remains a crucial factor in the prediction of energy demand.

In recent years, GDP growth in EU has been relatively strong. However, it may be subject to fluctuations and economic challenges. Factors that can affect GDP include global and regional economic conditions, changes in government policies, shifts in consumer demand (not only in the energy sector). For near and medium term, the evolution of GDP may be affected by several global economic trends [21] such as: (1) the rise in national debt, (2) increasing complexity and fragmentation of the trade environment, (3) the global spread of trade in services, (4) new employment disruptions, (5) the continued rise of powerful companies. Some governments may have reduced flexibility in the economic context of large debt burdens, diversity and complexity of trade rules, and public pressure to face the challenges produced by demographic shifts, climate changes, and economic disparities.

The pandemic period slowed the EU economy. In the third quarter of 2021 the pre-pandemic value of EU-level GDP was recovered. For 2023, the perspective in the euro area is +2.7%.

The predictions for 2050 show a progressive increase in the share of the emerging economies in the total world GDP. According to [22] “Europe will steadily lose ground relative to the Asian giants. The EU’s share of world GDP is expected to fall from around 15% to just 9%, while China’s rises to around 20% and India’s to 15%. The US’s share of world GDP will also fall, potentially to around 12% by 2050”.

It is highly probable that economic and political power will shift to Asia, while “Europe and the United States will remain world leaders in science and knowledge-creation” [23].

Taking into consideration the evolution during the last two decades (Fig. 2.3.1), with some exceptions, GDP growth in EU was in the range of 2-3% per year. The two larger fluctuations are specific to crises (economic crisis 2008-2010, and pandemic crisis 2020-2021).

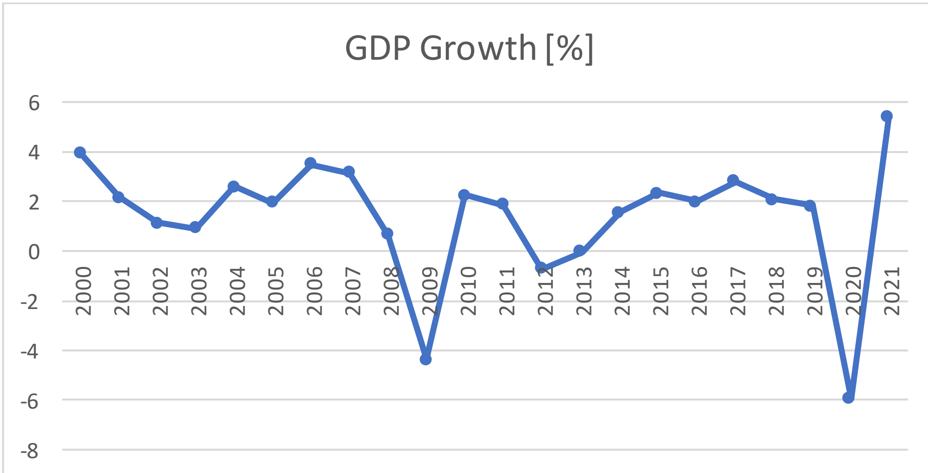

Fig. 2.3.1 GDP Growth of EU, 2000-2021 [24]

Assuming stability in EU construction and its role as a world technological leader, continuing economic growth in the range of 2-4% may be supposed, with possible fluctuations due to various future crises.

4.4 Technological

In the next two decades acceleration of the technological developments is expected, with high impact on the society, productivity, and environment. Such acceleration also has a high potential to create "new tensions and disruptions within and between societies, industries, and states" [25].

Technological developments may prove to have crucial influence on all the components of the energy sector: generating, transport, consumption. Novel technologies and materials can improve electricity generation performances, but also increase recovery levels in the extraction of oil and gas resources. Great improvements are forecasted in the efficiency of renewables (especially for photovoltaics) as well as in reduction of their production costs. In parallel, technological progress may improve the burning of fossil fuels to reduce their emissions, and enable a marketable method for carbon capture, storage and use.

Technological progress is a catalyst for economic growth, but also introduces disruptive forces on labor markets and drastically influences business models. At the level of society, technological development can produce significant changes in occupations and behaviors. Some jobs, especially those involving repetitive actions, will disappear from the market, and new jobs will be created, most of them probably in the service sector. New patterns for daily life may appear under the influence of the new technologies.

Some technological areas appear to have a great potential to transform both the economy and society. Development of these disruptive technologies is seen as likely to create new markets with new rules, set of values, and business models, as well as modifications to labor markets and practices. Disruptive technologies also have large capabilities to exploit the old technologies in new ways and produce impacts on the existing markets.

In [26] twelve areas are considered to produce disruptive impacts by 2025: "mobile Internet, automation of knowledge work (artificial intelligence, AI), the Internet of Things, cloud technology, advanced robotics, autonomous and near autonomous vehicles, next generation genomics, energy storage, 3-D printing, advanced materials, advanced oil and gas explorations, and renewable energy".

GESDA (Geneva Science and Diplomacy Anticipator) [27] engaged more than 700 scientists to identify and describe science trends and breakthrough predictions at 5, 10 and 25 years. Thirty-seven emergent topics touching all the sciences including economics were grouped under five major headings: Quantum Revolution & Advanced AI; Human Augmentation; Eco-Regeneration & Geoengineering; Science & Diplomacy; Knowledge Foundations. [28] continues a multiyear series by highlighting "breakthrough" technologies seen to promise significant impacts on daily life. The present list maps generally on the technologies highlighted by [26] and [27] by including four life science areas, generative AI and chips, drones, electric vehicles and battery recycling, and also the James Webb Space Telescope.

For the purpose of energy market predictions, the current study considers the following disruptive technologies:

1. Artificial intelligence (AI),
2. Big data (Bd),
3. Internet of Things (IoT),
4. Advanced Robotics (AR),
5. Material science (Ms),
6. Energy storage (Es),
7. Additive manufacturing (3Dp),
8. Drones (D),
9. Biotechnology (Bt),
10. Blockchain (Bch),
11. Geoengineering (Ge).

Their estimated impacts will be analyzed in detail in separate sections devoted to the influences of disruptive technologies on the energy sector, bearing in mind that even at the level of the EU, limitations of energy infrastructure may hamper the ability to support and enable rapid and broad spread of the technologies [29].

4.5 Political

The energy sector is quite dependent on political decisions. Factors of influence include, but are not limited to, actions by politicians (including policy decisions and legislation), and partisan or self-serving actions by individuals and groups. The main drivers (power balances, governmental structures) cannot be predicted at medium and long term due to great uncertainties in the evolution of society. In this study we will consider that political choices will be made in agreement with the future needs of societies and markets.

In the EU the coordination of the energy transition is achieved by the Energy Union strategy, launched in 2015 to provide "secure, sustainable, competitive, affordable energy" [30]. Five priorities dimensions are defined: (1) Energy security, solidarity, and trust, (2) A fully integrated European energy market, (3) Energy efficiency contributing to moderation of demand, (4) Decarbonizing the economy, (5) Research, innovation, and competitiveness.

In 2020 the European Green Deal was approved as a set of policy initiatives to reach the climate neutral by 2050 [31]. A review of the existing law and new legislation on the circular economy, building renovation, farming and innovation is targeted. In 2021 the European Climate Law was approved by European Parliament with an approved target for GHG reemission reduction with 55% in 2030 (vs 1990). The Fit for 55 package is a large set of proposed legislation detailing how the European Union plans to reach this target, including major proposal for energy sectors such as renewable energy and transport [32].

The investment effort for decarbonizing of EU energy system, by new electricity generating and green hydrogen production capacity, is estimated at 4.9 trillion euros, according to [33]. The new renewable capacity is estimated at 3.9 TW (2050), whereas for green hydrogen 1 TW of electrolysers is needed.

4.6 Social and cultural

The transition towards a climate neutral energy system has often been viewed "narrowly as a change in fuels and associated technologies" [34]. In reality it is producing important social changes. For example, the emergence of prosumers (persons producing some of the goods and services entering their own consumption) modifies the availability of energy resources for all social categories. The potential of prosuming is enormous, almost 25% of the EU electricity consumption may be generated from rooftop PV, "from a technical point of view, it is possible for almost every citizen in the EU to become a prosumer, either individually or in a collective" [35]. The current contribution is not published at EU level, but some illustrative data are available, for example Germany with the highest amount of installed capacity, around 22 MWe (2025) from prosumers (80% PV, 20% W) [35].

Decreases in energy costs will influence daily life by a redistribution of expenditures. At the same time, social changes resulting from the evolution of society, including the influences of technological development, will impact energy system development. For example, the AI deployment may create not only a new structure of the labor market, but may affect drastically the construction of the decisions (currently based on democratic dialogue in many countries, in the future very probable to be based on machine learning algorithms). In absence of a clear regulation framework an impairment of the democracy is also possible.

The recent evolutions in the energy systems confirms a progressive consolidation of the role of green energies. In correlation with the technological development, it is possible to achieve accessible and affordable technology at the level of each household. A sharp growth in the group of prosumers and a shift to decentralized energy production would influence the costs of energy and daily life. The more active role of citizens and local communities in consumer energy decisions contributes also to the overall level of democracy in a given context.

Social impacts of energy technologies must also comprise pre- and post-consumption life cycle phases. Both positive and negative impacts may be observed. Extraction of metals must sharply increase in order to produce technologies to meet clean energy targets (e.g. the volume of copper needed in the next 30 years is estimated to equal the entire volume mined in human history to date [36]). Extractive activities typically can bring economic development and jobs to a region, while abusive labor practices (including child labor) in some contexts must be counted on the down side in sustainability assessments. Mining activities to extract rare metals, or both fossil and non-fossil fuel materials, affect both natural ecologies and human habitats, as when indigenous groups are forced off their traditional land. This is observed not only in low income and less developed territories but also in Europe, for instance in Germany's North Rhine-Westphalia area where 50 villages have been partially or totally resettled over the years by the expansion of a lignite mine, and where 1000 climate activists occupied a village to be evacuated in 2023 [37]. Social unrest and rejection of energy-related decisions has impacts on both the economic ability to conduct pre-and post-consumer activities, and on the general societal good of trust between populations, civil society, economic, and policy actors. Cost and effort of ethically and legally required actions to restore or build inclusive energy governance are significant factors of influence to be accounted for.

4.7 List of retained influencing factors for development of the energy sector

Based on the previous discussion in Table 2.7.1 the list of the factors having major impact on the development of the energy sector is presented.

Table 2.7.1 List of influencing factors for the development of the energy sector

1.	Demographic	1.1 Size of population
		1.2 Ageing structure
		1.3 Potential labor force and participating labor force
		1.4 Urbanization
		1.5 Migration
		1.6 Healthcare expenditure
2.	Economic	2.1 GDP (overall size and per capita, growth rate)
		2.2 Distribution of GDP per sectors and subsectors
		2.3 Investment and capital accumulation
		2.4 Savings versus investments
		2.5 Financial environment
		2.6 Globalization
		2.7 Crisis (economic and financial, geopolitics, migration, sanitary)
3.	Technological	3.1 Energy intensity (average and per sectors)
		3.2 Disruptive technologies
		3.3 Productivity
		3.4 Decentralization of energy production (and large implementation of smart grids)
		3.5 Massive electrification (transportation, heat)
		3.6 Improvements in the intermittent energies (efficiency, siting, use of resources)
		3.7 Development of large storage capacities
		3.8 Improvements in the interconnections of energy systems
4.	Environment	4.1 Resources depletion (availability for future generations)
		4.2 Discovering new resources or improving extraction efficiency
		4.3 Pollution problems and their effect on health
		4.4 Climate change mitigation and adaptation
		4.5 Development of a sustainable food model
		4.6 Sustainable urban development and mobility
		4.7 Energy taxes

5.	Social and cultural	5.1 Decentralization of production by a large presence of the prosumers
		5.2 Changes of the occupational structure (dominance of smart work)
		5.3 New approaches to aggregate groups and community (post information society)
		5.4 New ways to build decisions (influence of the algorithms)
		5.5 Role of cyborgs (half-human, half-machine creatures)

4.8 List of technologies for medium- and long-term development

Considering the previous chapter discussions and the elements included in [38] a list of the key technologies for the energy sector on medium- and long-term was drafted (Table 2.8.1).

Table 2.8.1 List of key technologies in energy sector for medium- and long-term

1	Renewables	1.1 Photovoltaic, 1.2 Concentrated solar, 1.3 Wind on-shore, 1.4 Wind off-shore, 1.5 Small hydro, 1.6 Biomass
2	Nuclear	2.1 Large reactors (LR), 2.2 Small Modular Reactors (SMR)
3	Storage	3.1 Hydro pumping, 3.2 Batteries, 3.3 Hydrogen (and synthetic fuels)
4	Gas	Only for balance of the greed in case of insufficient storage
5	Disruptive technologies (for their impact on the energy system)	5.1 Artificial intelligence (AI), 5.2 Big data (Bd), 5.3 Internet of Things (IoT), 5.4 Advanced Robotics (AR), 5.5 Material science (Ms), 5.6 Energy storage (Es), 5.7 Additive manufacturing (3Dp), 5.8 Drones (D), 5.9 Biotechnology (Bt), 5.10 Blockchain (Bch), 5.11 Geoengineering (Ge).

5 Impact of disruptive technologies

The current section discussing the impact of disruptive technologies on the development and electricity demand. Considering the potential for the transformation of the energy sector the analysis was limited to the following eleven technologies: (1) Artificial intelligence (AI), (2) Big data (Bd), (3) Internet of Things (IoT), (4) Advanced Robotics (AR), (5) Material science (Ms), (6) Energy storage (Es), (7) Additive manufacturing (3Dp), (8) Drones (D), (9) Biotechnology (Bt), (10) Blockchain (Bch), (11) Geoengineering (Ge).

5.1 Artificial intelligence (AI)

From the point of view of energy consumption, AI will have at least three major effects:

(1) the possibility of optimizing energy consumption, including important effects in the effectivity of the energy efficiency measures, and in offering solutions for flexibility in the conditions of a high penetration of the intermittent renewables (iRES),

(2) a wide spread of electrical appliances and applications for most human activities,

(3) changes in occupational structure.

Looking to these potential impacting pathways, the most important impact of AI seems to be at the level of decision-making process, since the AI is largely able to support data-driven decisions. AI has the power to create the mechanism for instant reactions to the continuously changing factors, by using the machine learning process (MLP). The high variability introduced by a large fraction of renewables and by the influence of a decentralized production (greatly influenced by the prosumers) introduce a more difficult management of the dispatching, including the decision for storage on a duration ranging on some hours until a day.

At the level of the energy market, the short-term transactions (both day ahead and spot) represent a balance between demand and production. The long-term contracts are based on the predictability of a basic demand and robustness of the generation. AI is able to produce solutions for the electricity trading by a fast access and processing of historical market and weather data [39], by a better forecast using predictive algorithms and MLP, and integrating data about the evolution of the financial markets.

Moreover, the AI may help better predictive analytics to predict how energy demand will change in the next decades supporting a better decision for the necessary infrastructures to meet future energy needs. At the same time, the AI creates large capabilities for predictive maintenance of the equipment and components used in the energy system. A reduction of the unexpected outages is very feasible together with a reduction of the costs necessary to replace expensive energy assets or to perform laborious maintenance activities.

The AI may significantly contribute to a better efficiency and productivity in the energy sector. For example, oil and gas companies may use MLA to improve the optimal location for the wells. By using seismic data improvement in the drilling activities for oil and gas may be obtained.

Data digitalization creates a huge opportunity for the AI to play a vital role. By automating the collection of grids data, a vast amount of information is available for the machine learning algorithms (MLA). AI offer the chance to develop a smart forecasting, especially for the areas with large uncertainties, such as the output of the wind plants, evolution of the prices and consumption on turbulent markets. In terms of the functionality of the energy systems AI has a huge potential to identify the optimal solutions for balancing, and to avoid grid failures identifying the problems with enough time before they happen.

The AI development is directly connected with the large variety of sensors (included in the IoT) that may be installed to collect and transmit data about the functionality and performances of different equipment together with environmental data. Any source of data available for a system (such as data from programable controllers, data for human inspections, external data from interfaces like climate data, equipment usage history data, etc.) may augment the IoT data introduced as input for the predictive maintenance algorithms using the machine learning (AI) [40].The synergy between AI and IoT has a great influence on the predictability of the energy demand and may produce useful information for the decision-process targeting the production-consumption balance, including other measures such as power demand. The energy sector in developed countries has already started using AI and related technologies to enable communication between smart grids, smart meters and IoT devices [41]. An optimistic vision of the future imagines a world with all devices connected to the Internet, consumers and manufacturers, smart meters, consumer programming, including large consumers, creating an intelligent and optimal system with low energy intensity.

AI can contribute to the balancing of the intermittent production and floating consumption. At the level of electricity system AI will stimulate the decentralization and digitalization of the grids, by a considerable potential of support for the development of smart grids and smart homes (smart grids are carrying both electricity and data from the networks and final users).

A more efficient relationship between energy producers and consumers may be supported by customer engagement through AI. By using MLP the energy companies can produce useful information adapted to the customers variable needs, including possible way to reduce the consumption by changing their habits.

The development of the microgrids (small grids operating independently of the traditional energy grid) may be largely boosted by AI by using MLP to manage the energy flow toward optimal functionality. It is expected the microgrids will integrate easily the iRES local production in the classical energy grids and also to play an important role for energy security during emergencies.

The potential of using data from consumers and producers (including prosumers) is discussed in [42]. The exploitation of data can lead to the construction of optimal algorithms capable of contributing to the implementation of energy efficiency principles. In this sense, it is possible to reduce energy consumption, costs paid by users, better management of variable energy resources, planning, operation, and control of power systems.

Large companies tend to make the most of new technologies (AI, IoT, blockchain, cloud databases) to increase the efficiency of various processes. Other initiatives have a more global focus, for example Microsoft's IA Azure platform is already providing scientists with new tools for monitoring the environment in order to mitigate climate changes [42]. For example, DeepMind, a subsidiary of Google, applied the generation of algorithms, through neural networks machine learning, for a 700 MW wind farm in order to predict production 36 hours in advance [41].

On the other hand, it should be noted, at least in the initial phase of the optimization process, any exploitation of a huge amount of data collected from the real world and its transformation into algorithms necessary to optimize the targeted processes, based on learning, is an activity with high energy consumption. The dominant element in the energy consumption of AI is the deep learning process based on the processing of very large amounts of data. This type of machine learning uses very large mathematical models (the neural network method) with a huge number of parameters (from hundreds of millions to billions). Based on neural networks, complicated tasks can be performed such as classifying images, recognizing faces and voices, generating coherent and convincing texts. Behind these solutions there is a huge number of repeated attempts and trainings of the system which, by using a large number of examples (generated by adjusting the parameters), seeking a better solution and, finally, reaching the one considered as the optimal. The pace of learning can be considered fast over time, but slow in terms of the number of examples that are needed to generate the solution and consolidate the learning. The electricity consumed for these activities is generally associate with CO_2 emissions. Significant emissions associated with the machine learning process are mentioned, for example 192 t of CO_2 during the Google AI learning process of the game of chess [43].

Fortunately, after being trained, a deep learning model requires much less power. Many learning models can be implemented on smaller devices after being trained on large servers [43], including mobile devices, drones, laptops, and IoT devices. However, even small deep learning models consume a lot of energy compared to other software programs.

A pessimistic estimate [43] predicts that by 2030, more than 6% of the world's energy could be consumed by data centres. On the other hand, AI developers believe that the main cause of this consumption is generated by the fact that general processors are used, not adapted to the specific requirements of AI. For example, the development of the CS-1 processor (1.2 trillion transistors, 18 gigabytes of on-chip memory and 400,000 processing cores) allows running the entire deep learning model without having to communicate with other components, reducing, in this way, consumption. Major companies, such as IBM, are developing so-called green supercomputers (the Satori system) with low power consumption. Intense activity, over a period of one year, generates an amount of CO_2 that can be absorbed by 5 mature maples [43], i.e. a reduction of 50-60 times compared to the current computers.

On the other hand, AI systems can be trained to work in tandem with renewable resources. When the production of solar or wind energy is low, data centres can automatically reduce consumption by slowing down computing tasks and delaying low-priority AI tasks.

The influence of AI will have important effects on the traditional oil, gas and electricity industries [44], by profoundly transforming the way they operate. At the same time, AI will help analysts and energy market participants to understand extremely complex phenomena, from the behaviour of electricity networks to climate change effects [45].

AI will help to build a better understanding of how energy is supplied and distributed which will allow better predictions and decisions, with positive consequences in reducing the costs. Some examples for a better understanding: (1) machine learning can improve the ability to map and understand the value of underground oil and gas reserves, (2) dynamic regulation of the operation of the renewable energy systems, for example the automatic regulation of the relative position of the propeller to optimize the capture of the wind energy, (3) improvement of the quality of solar energy forecasting.

From the point of view of the occupational structure, by 2030, it is estimated that AI will influence more than a third of jobs in the European countries [46]. Some jobs will disappear, but new ones will be created. Between 40% and 50% of existing jobs could be partially of fully automated. The most affected jobs are those with low complexity tasks, standardized and repeatable, for example: assembly line workers, drivers, mining workers, cleaning workers. Employment will increase largely for occupations that require higher education and IT&C knowledge.

Some futurists believe that AI will have a drastic influence on the possibility of finding a job, “an important segment of society not being qualified for any activity on the market, automation and robots taking over these repetitive activities” [47].

From a structural point of view, the society will consist of some classes, depending on the relationship with AI: (1) AI developers, manufacturers, owners, (2) users of AI and robots, (3) providers of maintenance services for robots and AI, (4) other providers of service and activities, (5) as well as a relatively large class of "irrelevant persons" [47]. According to [47], there is a radical change "from a society based on the exploitation of labour to a society with a majority of irrelevant persons (the irrelevant)". For this category, the vision for a future society advances the idea of paying a guaranteed minimum universal income, based on taxes for the use of AI. The occupation of this large class will be that of pure consumers, a large part of their lives being filled with recreational activities, such as video games.

Undoubtedly, systems that incorporate AI have the ability to update quickly in the context of real-world conditions and are, in all probability, much more efficient systems. For this reason, after an initial period of consumption to transform data into learning, **there will be a decrease in energy consumption based on the use of AI and related technologies**. Efficiency will reduce energy demand and reduce emissions. **However, it cannot say exactly what the level of energy consumption would be. In [45] the reduction is estimated at "a few percent."** A much larger effect can take place at the level of reducing emissions, being advanced the reduction of 60% to 100% of emissions [45].

In Fig. 4.1.1 the main impacts of AI on the energy demand and energy system are presented.

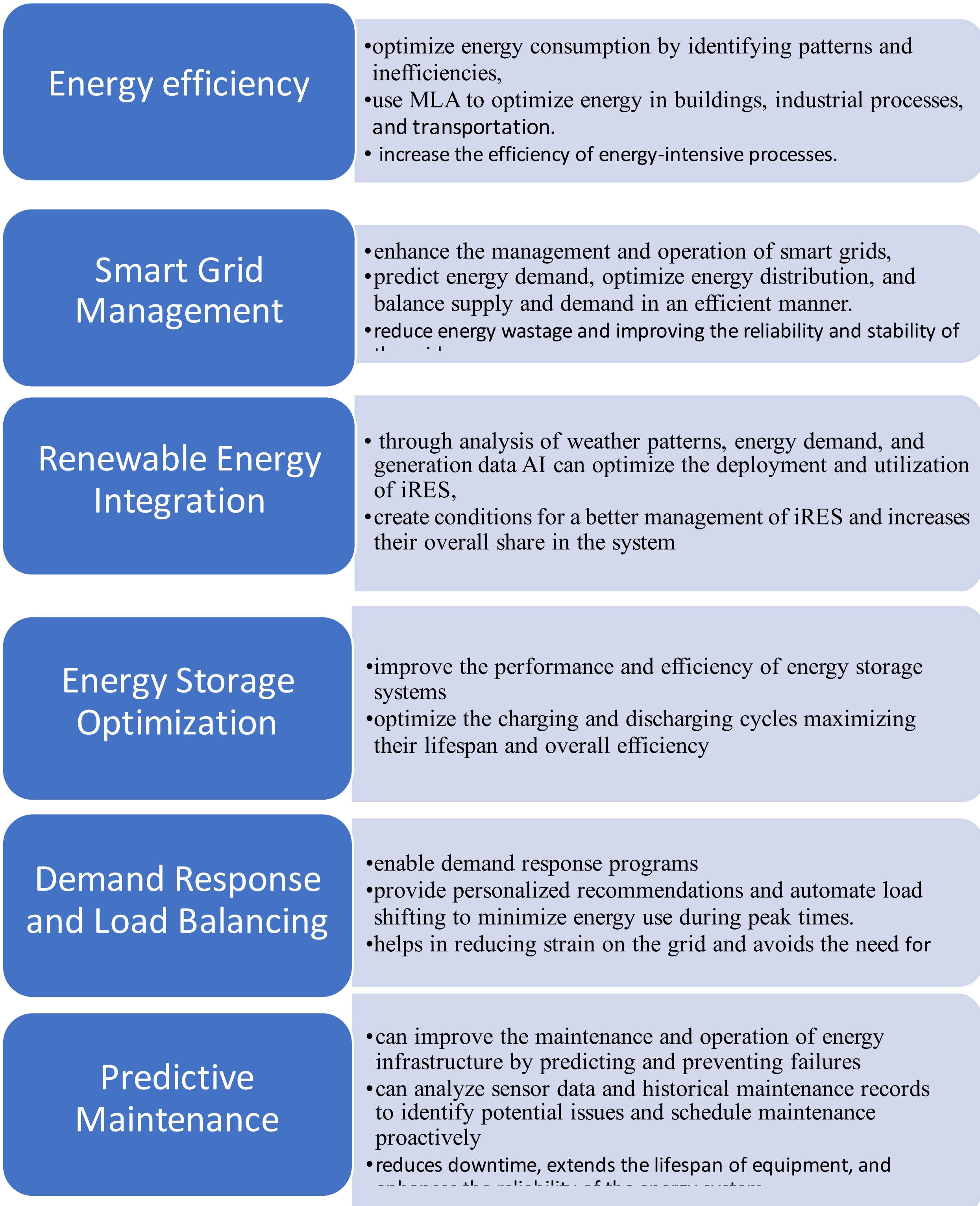

Fig. 4.1.1 Main impacts of AI on the energy demand and energy system

5.2 Big data (Bd)

Big data is a field dealing with large or complex data-sets to be delt by the classical software applications. Big data analysis includes capturing, storing, searching, sharing, transferring, visualizing, updating, analyzing processes. The volume (size), the variety (type, diversity), the velocity (speed of collection), and the complexity are the most important challenges of the big data.

Generally, large volumes (in the range of terabytes to petabytes) of low-density and unstructured data, sometimes having different qualities or unknown value, for example data generated by the social-media, web-sites, mobile apps, sensors, etc. Frequently the data are collected via data streams, in real time or near real-time needing a high-speed processing. From the point of view of variety, Bd are structured, semi-structured, and/or unstructured data types (text, audio, video, etc.) needing processing to identify the meaning and define the appropriate metadata. Bd often requires specialized tools, techniques, and technologies, such as distributed computing, parallel processing, machine learning, and data mining, to handle, process, and analyze such large and complex datasets.

Based on Bd it is possible to optimize the consumption (at the level of companies, municipalities, etc. The acquisition of data by smart meters is nowadays more and more used. The analysis of data may produce solutions for energy savings, for adapting the energy supply systems, or to prevent failures and ways to improve the functionality. The analysis of Bd may anticipate peaks in the energy use and avoids service outages [48].

In the field of iRES the weather data (hours of sunshine, intensities, wind speed, etc) are very important. Improving of the prediction involves the use of Bd, especially in the case of wind energy with impact in preparing the dispatching and storage functionality. A lot of factors influence the performances of iRES, such as the dust in suspension or the functional parameters of wind turbines, and may be in the focus of Bd [48].

In the last decade an increasing number of nuclear users and vendors have recognized the great potential of the big data to improve the economics and the safety of the NPPs. One of the most attractive areas is the use of big data in combination with the engineering knowledge to obtain safer and more resilient nuclear systems. The optimization of the maintenance and the component inventory are some of the direct applications of the big data in the nuclear sector due to the volume and diversity of the components. Collecting the data from a multitude of sensors together will be useful for the diagnostics and prognosis of the operational performances of the NPP.

Such development may have influence on the plant life management allowing a better use of the components, avoiding burdening states. At the same time, safety and security performances may be significantly improved.

Bd are strongly connected with AI in terms of the use of MLP/MLA to manipulate the data and to extract the meaningful elements according with the purposes.

In Fig. 4.2.1 the main impacts of Bd on the energy demand and energy system are presented.

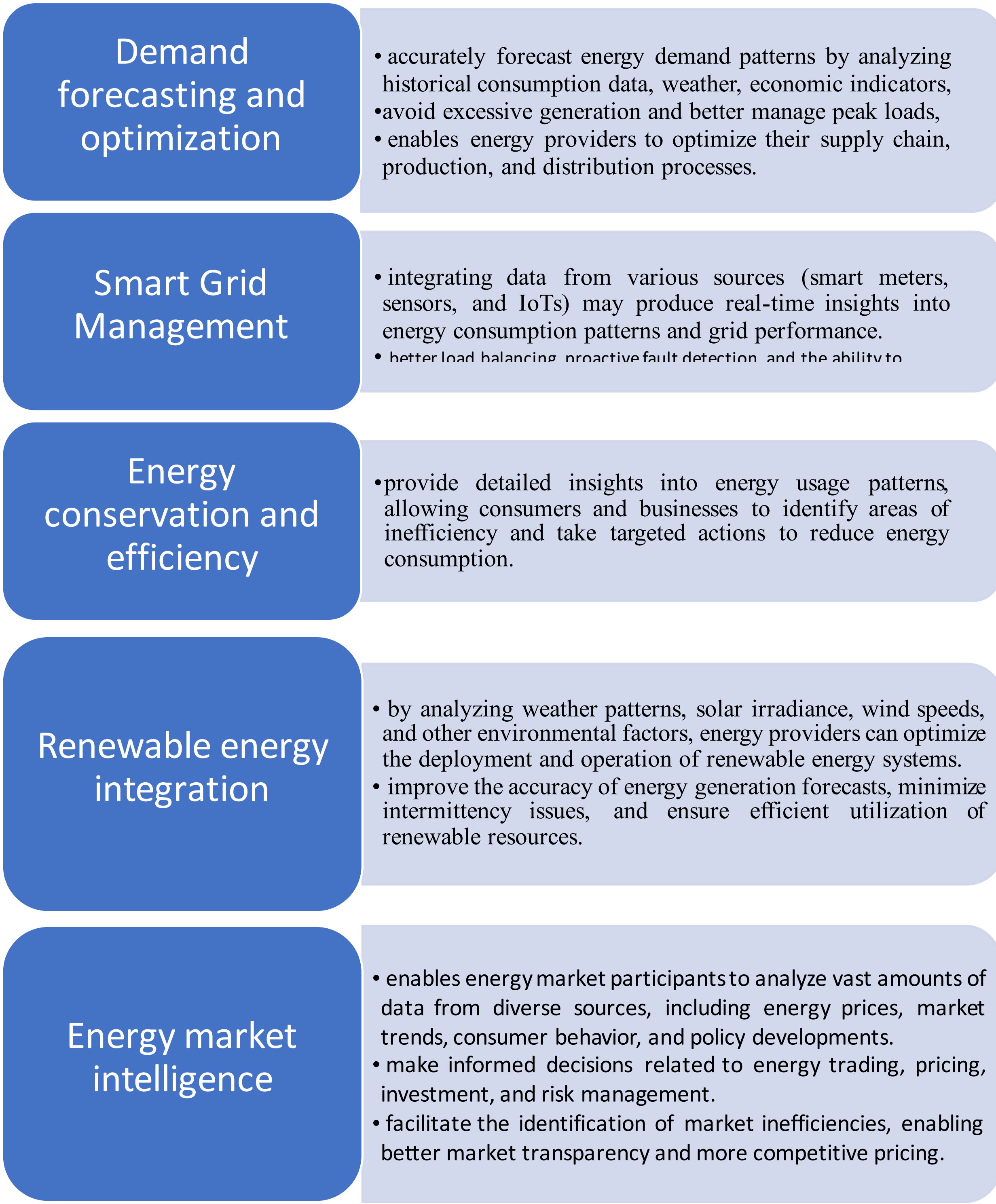

Fig. 4.2.1 Main impacts of Bd on the energy demand and energy system

5.3 Internet of Things (IoT)

Currently, the IoT is in a fast development based on sensors and monitoring systems (supervisory control and data acquisition, SCADA). In the energy sector is expected to grow with 11.8% (2025 vs 2020) [49]. The most common applications are related to real-time sensors monitoring of different parameters (temperatures, humidity, suspensions, etc.) influencing the energy production/transmission/consumption patterns. The deployment of IoT in the energy sector is driven by the needs of improvement for data management and of the system's agility.

In case of iRES the production of electricity is highly dependent on environmental factors such as temperature, wind, speed, light intensity, etc. IoT technology offers large capabilities to automatically collect the useful information to control and optimize the energy generation.

IoT technology is an innovative way to improve productivity, to recognize patterns, and to diminish the excessive consumption. It helps to improve the potential of the computing tools to analyze/predict the demand, as well the wastage of energy.

In case of the power transmission, the IoT advantages are capitalized in the smart grid configuration. Traditional grids are based on one-way communication, the transmission of power from the power station to the customer. In a smart grid a two-way communication is stated [50] based on the prosumer concept, and/or smart-meters. A better demand response approach is stimulated by providing consumers with meaningful information on the cost of the functioning of different appliances (in a market with variability of prices function on the period of the day) and on the particularity of the consumption patterns and way to optimize them. With the maturity of the IoT and modernizations at the level of energy market IoT may stimulate new business models including the transactions between similar prosumers (peer-to-peer) and a more adaptative pricing system.

On the other hand, predictive maintenance is more practicable due to the potential of information collected by IoT sensors (with large availability and affordable prices) and by using the synergic effect IoT-Bd-AI. The parameters for the monitoring of system may be easily captured, stored and processed.

IoT deployment enhances the reliability, resiliency, adaptability, and energy efficiency of energy systems, and improve the control of home appliances.

In Fig. 4.3.1 the main impacts of IoT on the energy demand and energy system are presented.

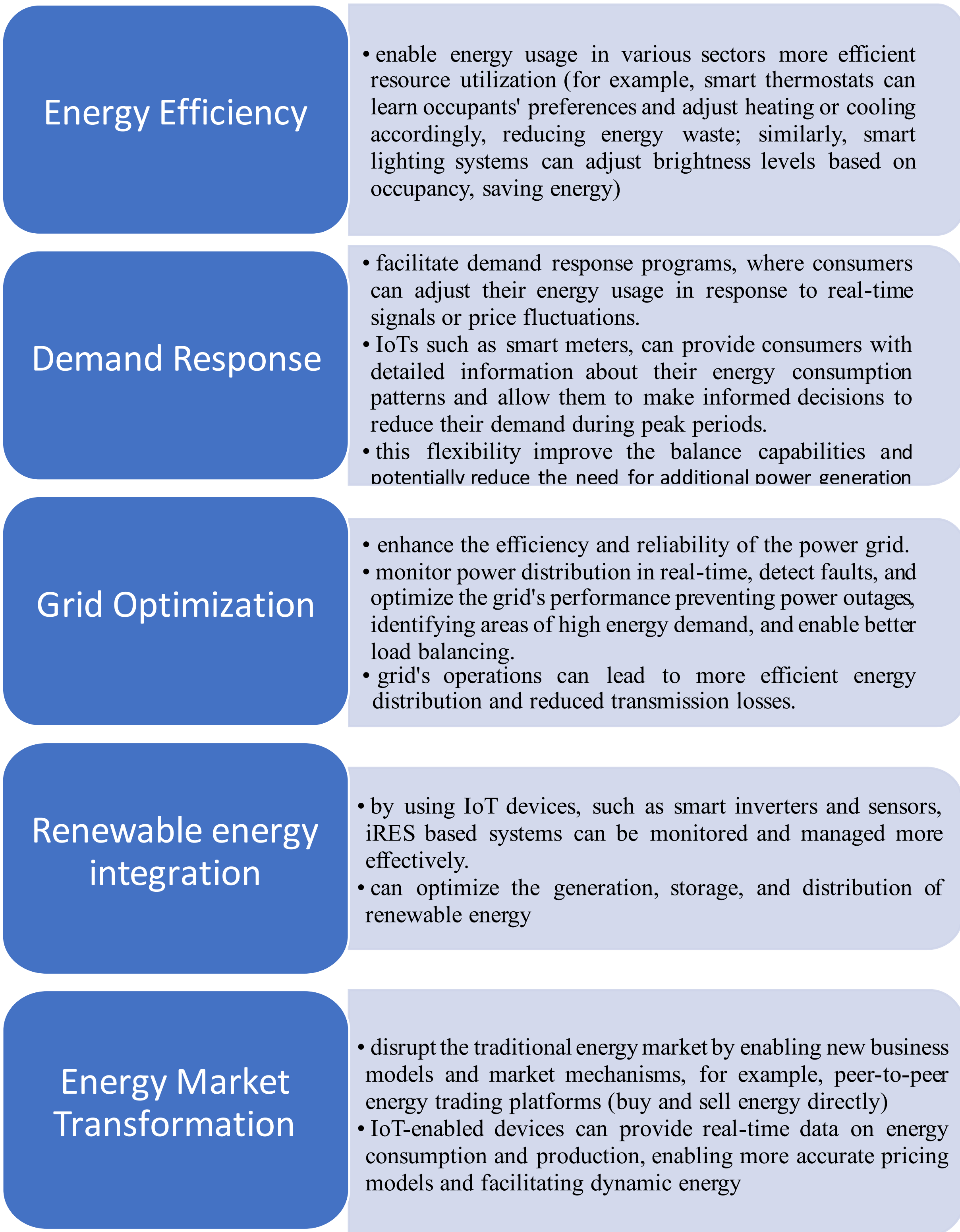

Fig. 4.3.1 Main impacts of IoT on the energy demand and energy system

5.4 Advanced Robotics (AR)

In the last decade a lot of industrial processes were shifted from classical manufacturing (machineries operated by humans) to systems using specialized robots. A societal 'roboticization' is envisaged in a new technological transformation. Such changes may significantly impact the energy demand and the energy system.

The replacement of tasks performed by humans with fully robotized tasks, even in case of high efficiency equipment, may increase the energy consumption. In [51] a modest increase with 0.5-0.8% is estimated. On the other hand, some energy savings are possible by reducing lighting (even fully light out factories), heating and cooling, water consumption, other materials used by the workers. However, the basic manufacturing represents 80 to 85% [52] of the total energy consumption for a factory, therefore the savings will be limited to around 10% even in the case of a fully robotized factory and with no needs of comfort light, water, temperature.

There is a continuous effort to optimize the performances, including the energy consumption, of the advanced robots, and to increase the lifespan. By choosing energy efficient components (motors, drives, and controllers) [53] a significant energy saving may be obtained. On the other hand, the optimization of the operating and maintenance may improve the energy performances. Robots with regenerative braking, energy recovery, and low-friction bearings [53] can help to minimize the energy consumption.

Deployment of advanced robots will produce great effects in productivity. Under these conditions, an acceleration of the growth of the gross domestic product is possible, which will stimulate a higher consumption. Therefore, increasing productivity can stimulate reaching a new level of energy consumption.

The use of advanced robots may be extended in many social sectors, including domestic applications, replacing some daily life human activities and services. In such case a small increase of the electricity consumption is expected with an estimation less than 0.5%.

Important potential is created by coupling AR and AI, especially by improving the operation based on machine learning and accumulation of previous operational experience.

The development of AR will improve the emergency intervention for all energy technologies. In case of nuclear, due to the hostile environment during the accidents, the development of performant AR will create the premises for an efficient intervention.

A set of factors are considered acting with high probability to decrease the electricity consumption [51]: (1) replacement of traditional machine tasks with more efficiently systems (AR), (2) reducing the needs for light, (3) better efficiency in the industrial processes. Other factors will act for the increasing of energy consumption: (1) moderate or large use of machine learning algorithms and Bd to act in complex processes or outside classical procedures, (2) improving consumerism (by a better productivity), (3) acceleration of the electrification (for example autonomous vehicles).

In Fig. 4.4.1 the main impacts of AR on the energy demand and energy system are presented.

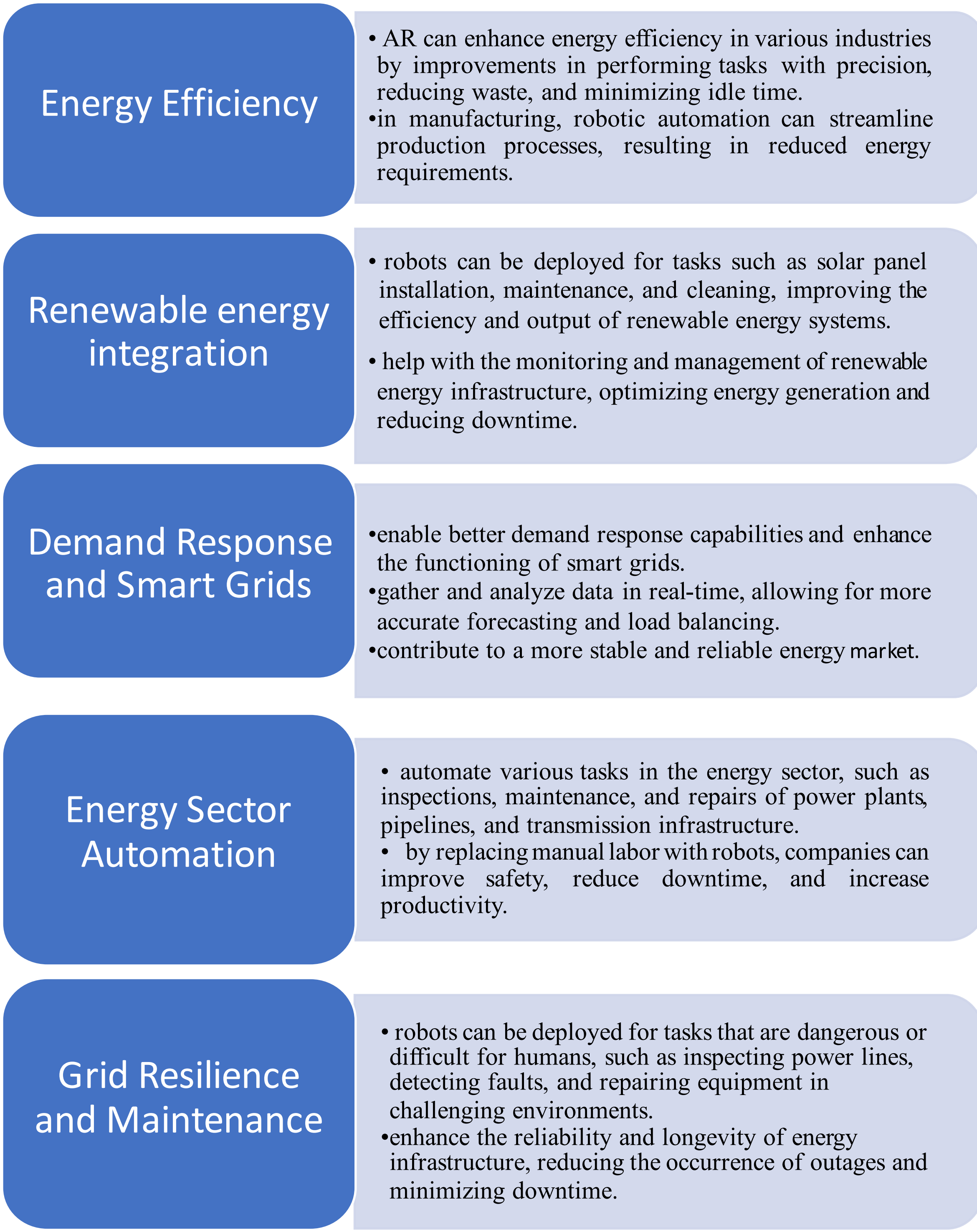

Fig. 4.4.1 Main impacts of AR on the energy demand and energy system

5.5 Material science (Ms)

The key importance of the advanced materials for the development and deployment of low-carbon energy technologies is clearly stated in the EU policies [54] "without continuous innovation in advanced materials, it would not be possible to increase the performance, reduce the cost and extend lifetime of low-carbon energy technologies".

The amazing development of Ms will influence the energy consumption especially by the new possibilities to reduce the energy losses. For example, the heat produced by large thermal or power plants will be transported easily at high distance to be used by the existing or by new clusters of consumers.

Significant progress has been made in the development and application of nanomaterials and nanotechnology. Currently it is possible to engineer materials at the nanoscale, offering unique properties and applications in fields like electronics, medicine, energy, and environmental protection.

The development of energy-storage materials [55] will open broad possibilities for the energy storage as a key factor for the use of iRES. Advancements in material sciences have facilitated the development of better energy storage solutions. For instance, improvements in lithium-ion batteries have increased their energy density and lifespan, paving the way for electric vehicles and grid-scale energy storage. Graphene, a single layer of carbon atoms arranged in a 2D lattice, has garnered immense attention due to its extraordinary properties. Scientists have been exploring various 2D materials and their composites, showcasing potential applications in electronics, sensors, and energy storage.

The development of energy efficient materials can support the reduction of the emissions in the construction sector by two factors [56]: (1) reduction of the energy loss due to with their various thermal properties (like heat storage, heat retention), (2) production of the materials by using processes with less energy consumption.

There has been a growing emphasis on developing environmentally friendly and sustainable materials. Biodegradable plastics, recycled materials, and bio-based composites are some examples of the strides made in this area.

On the other hand, the availability of the raw materials is a limitation factor for the development of the energy technologies based on the existing technologies. Currently [54], eight metals were classified as 'critical': Dy, Eu, Tb, Y, Pr, Nd, Ga, and Te; six materials were classified as 'near critical': graphite, Re, Hf, Ge, Pt, and In and should be monitored closely. The most of them are connected with vRES development, electric cars lighting, and fuel cell technology. For the nuclear industry the concerns are generated by the near-critical materials Hf and In.

A decreasing of the total consumption is expected based on the objective of Ms to develop such material and technologies.

Material science has the potential to significantly impact energy demand and the energy market through various advancements in materials and their applications. In Fig. 4.5.1 the main impacts of Ms on the energy demand and energy system are presented.

Energy-efficient materials

- contribute to the development of energy-efficient materials that reduce energy consumption in various sectors, for example advanced insulating materials can improve the thermal performance of buildings, lightweight materials in transportation can enhance fuel efficiency and reduce energy demand.

Energy storage

- contribute to the developing of advanced energy storage technologies such as batteries, supercapacitors, fuel cells.
- may enhance energy storage performance such as capacity, charging rates, and overall efficiency.

Renewable energy technologies

- enables the development of innovative materials for RES
- improve the efficiency and durability of solar cells, making them more cost-effective and widely accessible.
- novel materials for wind turbine blades can enhance their performance, leading to increased energy capture and reduced maintenance requirements

Energy harvesting

- Facilitates the energy harvesting technologies that capture energy from ambient sources such as sunlight, vibrations, or waste heat
- . develop efficient devices like solar panels, piezoelectric materials, and thermoelectric generators that convert these energy sources into usable electrical energy.

Energy infrastructure

- improve the durability, reliability, and efficiency of energy infrastructure components, for example, materials with enhanced corrosion resistance can extend the lifespan of pipelines, reducing maintenance needs and energy losses.
- advanced materials for power transmission cables can minimize electrical losses during long-distance energy transport, improving overall grid efficiency.

Fig. 4.5.1 Main impacts of Ms on the energy demand and energy system

5.6 Energy storage (Es)

The energy storage consists in processes and methods to capture the produced energy to be used later. Energy storage technologies are grouped into five categories: mechanical, electrochemical, thermal, electrical, and hydrogen. The most known energy storage technologies are: (1) batteries (rechargeable, flow-batteries, ultra-batteries), (2) hydro dams and hydro pumping, (3) hydrogen and synthetic fuel, (4) capacitors and super-capacitors, (5) thermal energy storage, (6) phase-change material, (7) flywheel energy storage, (8) springs, (9) compressed air energy storage, (10) solid mass gravitational, (11) biofuels, (12) hydrated salts, (13) thermal expansion, (14) ice storing tanks, (15) glycogen, (16) starch, (17) power to gas (methane, hydrogen, oxyhydrogen), (18) seasonal thermal energy storage.

The dispatching of the electricity should be achieved within milliseconds or seconds, and the duration of power back-up is ranging from a few minutes to many hours.

The integration of energy storage systems has the potential to bring significant impacts to the energy sector, both in terms of energy demand and the energy market. Overall, energy storage systems have the potential to significantly improve the energy sector by enhancing grid stability, enabling greater integration of renewable energy, improving energy efficiency, and providing new opportunities for market participation.

In condition of the large deployment of iRES, the energy storage become crucial, the long duration storage [57] will be obligatory to support future grids. Two classes of long-duration energy storage adapted to decarbonized grid are identified. The first one (lasting up to 20 h) is oriented to manage daily cycles. The second one (lasting for weeks or months) is necessary to manage seasonal cycles.

Energy storage offers the dispatchability characteristic but some limitations should be discussed. The technology is working in cycles charging-discharging and have two dimensions: one is the maximum energy for the discharge at a certain in time (expressed as power, and measured in kW or MW), the second is the total amount of energy for discharge before a new recharge (expressed as energy, and measured in KWh or MWh). The duration of the energy supply is dependent on the two terms (E=P*t).

In conditions of the large variability introduced by the recent deployment of iRES high storage capacities are needed to produce a real balance of the grid.

Currently, the hydro pumping is the most practicable high-capacity dispatchable energy storage, but tit is limited to those countries with appropriate landscape and raining regime. In order to understand the order of magnitude the largest hydro-pumping capacities in the world are Bath Count (Virginia, US) with 3000 MW, and Huizhou (China) with 2448 MW. In 2022 [58] China has the largest pumped storage hydropower capacity (more than 45 GWe), followed by Japan and the United State with around 22 GWe, respectively 19 GWe.

The promising storage capacity in batteries is in incipient phase, the largest capacity having 400 MW/1,600 MWh (Moss Landing, US). Despite the decrease of the price of the batteries, the method is not mature and introduce high consumption of materials, including rare elements, and produce a lot of emissions during the entire life cycle.

In Fig. 4.6.1 the main impacts of Es on the energy demand and energy system are presented.

Smoothing Energy Demand	• enables the capture and storage of excess energy during periods of low demand, which can then be discharged during periods of high demand reducing the need for additional power generation infrastructure and balancing the grid. • mitigates the consequences of the variability of iRES contributing to a stable and reliable energy supply, reducing the strain on the grid during peak demand periods
Peak Shaving	• can flatten the peak demand periods by providing additional power during those times reducing the strain on the grid and minimizing the need for expensive and often less efficient plants that are typically used to meet peak demand
Load Balancing	• absorbing excess energy during low-demand periods and releasing it when demand increases • enables a more efficient distribution of power, reducing transmission and distribution losses and optimizing the operation of the grid.
Integration of Renewable Energy	• addresses the intermittent nature of iRES by storage and promotes the wider adoption of RES and allows for a higher share in the energy mix. • contributes to a reduction in curtailment of RES, which occurs when excess generation is wasted due to a lack of demand or grid capacity.
Enhanced Grid Resilience	• can improve the resilience of the grid by providing backup power during outages and emergencies. •allow to supply energy during power disruptions, reducing the economic and societal impact of blackouts.
Changes in Energy Market Dynamics	• introduces new dynamics into the energy market contributing to different mechanisms, such as frequency regulation, demand response, and ancillary services. •creates new revenue streams and business opportunities for energy storage providers. • may affect the pricing dynamics in the energy market, potentially reducing price volatility and increasing market efficiency.

Fig. 4.6.1 Main impacts of Es on the energy demand and energy system

5.7 Additive manufacturing (3Dp)

Additive manufacturing produces the objects by adding successive layers of materials. The technique referred also as 3D printing is based on computer-aided-design (CAD) software or 3D object scanners to control the deposition of the layers and obtain a precise geometric shape. In the classical approach the object is obtained by successive removal of layers of materials, by milling, machining, shaping, curving or by casting.

The impact of the technique consists of a great simplification of the manufacturing process, a high ability to produce complex geometries, reduction of the wastes, high efficiencies, and reduction of the errors. 3Dp can completely revolutionize the modern manufacturing industry with a considerable cost reduction [59] allowing a highly customized fabrication of 3D objects "where both shape and composition can be tailored along with the material". The objects are directly created from their digital design by printing thin layers of material and fusing them together. Currently the main use of 3Dp is to create prototypes in some industries such as automotive, but the recent progress my shift the mass production from the traditional machining process to 3Dp. The 3Dp has a great potential to disrupt the manufacturing logistics, including the management of inventories.

An extensive development of 3Dp may dramatically change the supply chain, including the manufacturing in nuclear industry. Most of the components can be produced by additive manufacturing at the destination, reducing the transport efforts, duration, and the costs. In some decades it is expected the most of the components of a SMR or LR may be additive manufactured. The process is dependent only on the preparing the right alloys for the 3D printing of different parts/components. An important advantage will be the elimination of some constraints for the design due to the classical manufacturing process. The designer may approach the systems outside of the existing traditional structures. A great opportunity is open by 3Dp for the instrumentation and control. Sensors for real-time monitoring may be easily integrated into the components. Based on them, valuable information on the components'/systems' performance may be collected, including data for preventive operation or even autonomous operation.

This new technology offers high flexibility of the design and has a great potential for energy efficiency [60]. It allows rapid prototyping, and an acceleration of the deployment of complex components. As an example, the reduction in the production costs of solar panels is estimated up to 50% while increasing efficiency by over 20% [60].

By enabling the production of complex, customized, and lightweight components, additive manufacturing can contribute to energy efficiency, reduced energy demand, and transformative changes in the energy market. It's important to note that while additive manufacturing has the potential to bring positive impacts to the energy sector, there are still challenges to overcome, such as material limitations, scalability, and cost-effectiveness. However, continued advancements in additive manufacturing technologies and materials could help unlock its full potential in improving energy efficiency and transforming the energy market.

In Fig. 4.7.1 the main impacts of 3Dp on the energy demand and energy system are presented.

Energy Demand Reduction	• reduces energy demand by design optimization tools, creation of lighter and more efficient components, resulting in energy savings during operation. • elimination of traditional subtractive manufacturing techniques, which often involve material waste and high energy consumption
Distributed Energy Generation	• facilitates the development and deployment of distributed energy generation technologies • accelerates the adoption of decentralized energy generation by enabling rapid prototyping and manufacturing of RES components like solar panels, wind turbine blades, storage components
Enhanced Energy Storage	• contributes to the improvement of energy storage technologies by enabling the fabrication of intricate structures and complex geometries, • enhances the performance and capacity of energy storage devices, such as batteries and fuel cells
Customization and Localized Production	• allows for customization and for on-demand production • can create components tailored to specific requirements, improving overall system efficiency and performance. • localized production of energy-related components through 3D printing can reduce supply chain dependencies, lower transportation costs, and enable the production of spare parts on-site, increasing operational flexibility and reducing downtime
Disruption of Traditional Supply Chains	• could disrupt traditional supply chains in the energy sector • the reliance on long-distance transportation of components could decrease producing changes in the energy market dynamics, with a potential shift towards decentralized manufacturing hubs and a reduced dependence on global suppliers.

Fig. 4.7.1 Main impacts of 3Dp on the energy demand and energy system

5.8 Drones (Dr)

Drones are defined as unmanned aerial vehicles (UAVs) or unmanned aircraft systems [61]. Principally, a drone is a flying robot. It may be remotely controlled or may be autonomous by using a software-controlled flight plans coordinated with onboard sensors and GPS data.

The powerful development of drones was revealed by the current war between Russia and Ukraine. Initially developed for military purpose (anti-aircraft target practice, intelligence gathering and, more controversially, as weapons platforms) [61] the use was progressively extended in a range of civilian applications such as [61]: search and rescue, surveillance, traffic monitoring, weather monitoring, firefighting, personal use, photography and videography, agriculture, delivery services.

In terms of the energy market, the use of drones can introduce significant changes. Drones can reduce operational costs by streamlining inspection, maintenance, and monitoring processes. They can help energy companies identify and address issues more efficiently, minimizing expensive downtime and avoiding costly repairs.

On the other hand, drones can perform tasks in hazardous environments, reducing the risk to human workers. This can enhance safety standards in the energy sector and potentially lead to lower insurance costs.

In terms of environmental benefits, drones can contribute to environmental sustainability in the energy sector. By enabling proactive maintenance and reducing energy losses, they can help optimize energy production and reduce the overall carbon footprint of the sector.

It has to be noted the adoption of drones can lower barriers to entry for smaller players in the energy market. By reducing the need for extensive physical infrastructure and enabling remote operations, drones can create opportunities for new entrants to compete with established energy companies.

In the nuclear sector drones may be used for aerial monitoring including the critical infrastructure facilities, such as NPPs. The use of drones may be extended for the inspection of different nuclear facilities for example looking for the leaks in boilers, steam isolation valve rooms, rad-waste areas, or fuel recycling areas. On the other hand, drones equipped with adequate sensors may collect the dose data on contaminated areas, even in difficult to access indoor areas. Very important, the advanced drones can intervene in difficult contaminated areas reducing the human exposure during normal or accidental operation.

Overall, the integration of drones into the energy sector has the potential to improve efficiency, reduce costs, enhance safety, and promote environmental sustainability. While there may be some initial challenges related to regulations, privacy concerns, and technology adoption, the long-term impact of drones on the energy demand and energy market is expected to be positive.

In Fig. 4.8.1 the main impacts of Dr on the energy demand and energy system are presented.

Infrastructure inspection and maintenance

- better inspection of energy infrastructure such as power lines, wind turbines, and solar panels.
- providing real-time data on the condition of these assets, helping to identify maintenance needs and potential issues, allowing for timely repairs.

Enhanced efficiency in resource exploration

- improve significantly the aerial surveys and mapping of potential energy resources like oil and gas reserves
- can gather geospatial data, identify suitable locations for drilling or exploration, and assist in assessing the viability of energy projects.
- helps energy companies make informed decisions, optimize resource allocation, and improve overall efficiency.

Remote monitoring and control

- allows remote monitoring of energy infrastructure, including pipelines, transmission lines, and substations.
- offers real-time data on variables such as temperature, pressure, and flow rates, enabling operators to detect leaks, faults, or inefficiencies promptly, preventing energy losses, enhancing safety, and reducing the need for physical inspections and manual interventions.

Optimized maintenance and repair operations

- drones equipped with tools like robotic arms or even 3D printers can perform maintenance and repair tasks in difficult-to-access locations for example replacing faulty components on wind turbines
- reduces the need for human intervention and minimizes equipment downtime, contributing to a more stable energy supply

Data collection and analysis

- can gather vast amounts of data related to energy production, consumption patterns, and environmental factors to be analyzed to identify trends, optimize energy distribution, and improve demand forecasting.
- by leveraging drone-generated data, energy companies can make data-driven decisions, reduce wastage, and better align supply with demand.

Fig. 4.8.1 Main impacts of Dr on the energy demand and energy system

5.9 Biotechnology (Bt)

The development of biotechnologies will have important effects in: (1) demographic changes (which may influence global and local energy consumption), (2) technical developments (new solutions for energy generation and product development).

According to UN estimates, the world's population is constantly growing. In 2050 it will reach about 9.7 billion inhabitants [62], and in 2100 about 11.2 billion [62].

For Romania, the population has a decreasing trend [63]. Considering an average life expectancy in 2020 of 76.2 years (with an increase to 80.4 years in 2050), a birth rate of 1.68 children (in 2020) per woman of childbearing age (1.73 in 2050), as well as a ratio of boys / new-born girls of 51.4% / 48.6% simulation shows an evolution from 19.2 million in 2020, to 18.3 million in 2030, 17.3 million in 2040 and 16.3 million in 2050, respectively, i.e. a decrease of approximately 1 million people per decade. Estimates are even less optimistic in National Energy and Climate Plan (NECP), of 18.0 million in 2030 and 17.4 million in 2035, the lower values being generated by taking into account a migration phenomenon with a predominance of emigration.

The decreasing tendencies of the population at state level are characteristic, for this period, of most European countries, where the significant increase of the living standard determined an aging of the population and a decrease of the birth rate.

On the one hand, population decline at the level of demographic declining states will lead to a decrease in household electricity consumption and a possible contraction of their economy, and on the other hand, global population growth will raise the issue of food security and global energy consumption. From the point of view of social concerns, conventional production techniques alone cannot meet the future demand for food for the future population. For this reason, research on plant growth techniques tends to focus on finding methods with maximum yield, in ever-changing climatic conditions. Specialists are convinced that food security can be improved by diversifying agriculture, using more species for cultivation, but especially by developing biotechnologies [64].

An important direction for the analysis of the energy market is the cultivation of species favorable to the production of biofuels, in order to produce more efficient energy. Moreover, certain biotechnologies can contribute to improving access to hard-to-exploit resources. For example, using these technologies, oil that is difficult to exploit from depleted deposits (they contain about 60% of the initial amount of oil) can be converted to natural gas, which is easier to exploit [65]. At the same time, coal gasification techniques, as well as those for recycling organic waste are already available. Currently, industrial biotechnology uses enzymes and microorganisms to produce chemicals, food and feed, detergents, paper and pulp, textiles and energy with a direct impact in avoiding the use of fossil resources as a raw material, but in some cases competing with resources that could be used for food. This problem, especially in the case of biofuels, can be solved by using inedible biomass as a single raw material.

An extremely important aspect, the use of medicine and biotechnology to increase life expectancy, has raised many discussions and concerns in recent years. Through synergistic effects, artificial intelligence and biotechnology can restructure society and the economy, offering a totally different perspective from that of the industrial age. According [47] IA and Bt give mankind "the power to reshape and redesign life". If the industrial revolution has brought to humanity the power to change the nature, Bt gives solutions to alleviate the aging of the body, including the creation of “a-mortality” (the individual is not yet immortal, because some serious accidents can lead to death before medical intervention). In [47] the idea of the possibility of "brain design", "continuous upgrading", "life creation", as well as "control over our inner world" is discussed as very probable options. The author is extremely pessimistic about the consequences, because "people have always been much better at inventing tools than using them wisely."

Such a perspective will lead to important demographic changes, especially regarding the age structure, to polarizations that may accentuate the phenomenon of migration. On the other hand, the fusion of AI and Bt can quickly take billions out of the labour market, "undermining both freedom and equality" [47].

Regarding the duration of life, there are opinions of specialists who support the idea of a biological determination of the maximum duration. In [66] there is a limitation of life expectancy to 115 years, the probability of exceeding this age being extremely low. More generally, there are three visions of longevity called "futuristic", "optimistic" and "realistic" [67]. Futurists believe in a continuous extension of life expectancy, as biotechnological progress, towards immortality and eternal youth. Optimists support the increase in life expectancy, a process started in the last century, with a linear increase of 2.5 years per decade. And they are convinced of medical and biotechnological progress and do not consider an upper limit for life. Realists, on the other hand, are convinced of a bio-determination of the limits, and the continuous increase of life expectancy is implausible for them. In [68], based on studies on the role of renewed neuro-stem cells (NSCs) and experiments performed on mice, the hypothesis of the possibility of extending the limit to values over 125 years is stated.

The effect of increasing life expectancy may produce a short-term increase in population, but in the long run it will decrease, due to the limitation of the possibility of reproduction in the population in the young age segment. If, however, the development of biotechnology will lead to human upgrading, including by significantly prolonging the fertility period (by postponing old age) then we can expect an effect of population growth, including in countries in the demographic decline.

In terms of impacts on the energy demand and energy market, the application of Bt can lead to a reduced energy demand. The increased use of biofuels and other renewable energy sources can reduce the demand for fossil fuels, helping to mitigate environmental issues associated with their extraction and combustion.

On the other hand, a diversification is expected on the energy market. Biotechnologies can enable the emergence of new players in the energy sector, such as biofuel producers and microbial energy system developers. This can foster competition and diversify the energy market, potentially leading to greater energy security and stability. A shift towards decentralized energy production is possible. Bt solutions, such as microbial fuel cells and biogas generation systems, can be deployed at smaller scales, enabling decentralized energy production.

Biotechnologies can facilitate the integration of circular economy principles in the energy sector. By utilizing organic waste as feedstock for bioenergy production and adopting efficient waste management practices, the energy sector can contribute to a more sustainable and resource-efficient economy.

In Fig. 4.9.1 the main impacts of Bt on the energy demand and energy system are presented.

Biofuel Production

- enhances the production of biofuels, such as biodiesel and bioethanol, by optimizing the cultivation of energy crops and improving the efficiency of biofuel conversion processes, reducing the demand for fossil fuels and lowering greenhouse gas emissions

Energy Crop Development

- develop genetically modified crops that are more suitable for energy production and can be engineered to have higher biomass yields, improved tolerance to environmental conditions, and enhanced energy content.

Microbial Fuel Cells

- enables the development of microbial fuel cells to convert organic matter directly into electricity.
- provides decentralized and sustainable power generation, particularly in areas with abundant organic waste sources.

Biogas Generation

- optimizes the production of biogas through anaerobic digestion of organic waste materials.
- can increase the utilization of this renewable energy source for electricity and heat generation, reducing the reliance on fossil fuels.

Energy Storage

- contributes to advancements in energy storage technologies, for instance, microbial electrochemical systems can be used to develop microbial batteries that store energy in microbial cells.
- offers new opportunities for efficient and sustainable energy storage, helping to address the intermittent nature of renewable energy sources

Energy Efficiency and Waste Management

- can play a role in improving energy efficiency and waste management practices, for example, genetically engineered microorganisms can be employed to break down organic waste more effectively, reducing the energy required for waste treatment and facilitating the recovery of valuable resources.

Fig. 4.9.1 Main impacts of Bt on the energy demand and energy system

5.10 Blockchain (Bch)

The Bch was developed to perform a new digital type of transactions' recordings with the aim to prevent any voluntary/involuntary falsification of the data (for example of the documents certifying ownership). The Bch was stimulated by the last decade fast cryptocurrency development. The principle is to use many recordings in different computers that are linked in peer-to-peer networks.

The Bch technology is a large electricity consumer, for example in case of the most widely known cryptocurrency Bitcoin the usual process called mining becomes a concern for the emissions. The Bitcoin may be obtained by buying and selling on the existing or through the mining process involving the solving of a complex mathematical problem by computing. "If Bitcoin is assumed to be a country, it will rank 38th globally for energy consumption, with 90.2 metric million tons of carbon dioxide" [69]. It should be noted Bitcoin represents today only about 0.2% of the world's financial assets [70], therefore the potential to increase (including emissions) is appreciable.

In terms of total electricity consumption, the mining for Bitcoin was appreciated (March 2023) between 62 to 209 TWh per year [70] with "a central estimate of 128 TWh", representing around 0.5% of total world consumption. The situation is aggravated by the dominant use of fossil-based electricity for mining in the most important mining countries (China, US, Kazakhstan) [70].

The blockchain technology may increase cyber security for the data recorded. On the other hand, it may create a more effective and efficient interface with regulators. It is acting as a trusted platform to record transactions and distribute information among the parties without the control of a central entity. No files are used to store the digital records, instead they are represented by transactions written on a cryptographic hash.

Some important applications are already identified in the nuclear sector such as: (1) the fuel supply chain, involving many stakeholders including mining, processing, purchasing, operation, spent fuel storage etc, (2) effective management of the nuclear materials used in construction, operation and post-operation of a NPP, even after the decommissioning, (3) recording events within a single facility or company (security access, safety events, etc). All of these are contributing to a better transparency and will reduce the risks of fraud.

Blockchain technology has been used to create power purchase agreements (PPAs), a type of financial contract between energy buyers and energy sellers. Blockchain technology makes these contracts more efficient because it reduces transaction time, costs less to use than traditional PPA platforms, and is built on a highly secure platform

Overall, blockchain technology has the potential to revolutionize the energy sector by decentralizing energy trading, improving efficiency, enhancing transparency, optimizing grid operations, and promoting renewable energy adoption. In Fig. 4.10.1 the main impacts of Bch on the energy demand and energy system are presented.

Fig. 4.10.1 Main impacts of Bch on the energy demand and energy system

5.11 Geoengineering (Ge)

The Ge is considered in the present analysis due to the great potential to influence the energy demand even its controversial character, Ge includes a set of **deliberate large-scale interventions** at the level of the planet to reduce the effects of the climate changes. There is a large spectrum often grouped in two categories: (1) Solar Geoengineering (or Solar Radiation Management), (2) Carbon Geoengineering (or Greenhouse Gas Removal).

The first category is focused on the energy received from the Sun and retained by the Earth. A part of this energy is transmitted back into the space, depending on the properties of the atmosphere layers and reflectivity of the planet's surface. Three techniques are mentioned in [71]: (1) albedo enhancement, (2) space reflectors, (3) stratospheric aerosols. The first one is based on the increasing of the reflectiveness of clouds (or land surfaces). During the history the human civilization impacted the albedo factor mainly by agriculture (replacing large natural surfaces with croplands), deforestation and desertification. The second technique is focused on blocking of a fraction of solar radiation to enter the Earth system by using solid reflectors. The third one is similar with the second, but it is using reflective particles inserted into the upper atmosphere.

The second category is based on the removing techniques of CO2 and other GHGs form the atmosphere or oceans. The following techniques are mentioned [71]: (1) ocean fertilization (adding nutrients to increase the absorption of CO2 from atmosphere), (2) enhancement of ocean alkalinity (introduce substances able to increase the retention of Carbon), (3) afforestation, (4) biochar (biomass is buried to sequestrate the carbon in the soil), (5) bio-energy with CCS (cultivate biomass, burning it for energy, and use the carbon capture and sequestration method), (6) ambient air capture (removing CO2 from the air and storing it), (7) enhancing carbon retention (exposing large quantities of minerals able to absorb CO2 from atmosphere).

There are many controversial issues and a lot of drawbacks for the geoengineering techniques. In [72] the solar geoengineering (SG) is discussed. It consists of adding annually several megatons of aerosols (sulphate species) in the lower stratosphere to increase the albedo coefficient. The intervention is seen difficult, but necessary since the conventional approaches to reduce CO2 in the atmosphere have failed [72]. As global impact, it is expected SG will counteract around 50% of global warming [73].

A more feasible intervention consists of the painting of the surfaces (roofs and pavements) of the urban agglomeration with high albedo materials. This approach may reduce a lot the energy consumption for the cooling during summer, but will possibly increase the consumption for heating during winters. Also, the painting and re-painting (estimated at 10 years) must be considered in the carbon emissions.

From a general perspective, the Ge methods may reduce the implementation of free carbon technologies enabling the business as usual of the fossil-fuel economy. This will be a major impact on the possible evolutions of the energy sector reducing the speed of decarbonization by increasing the share of RES in the total energy production.

It is important to note that Ge is a complex and controversial topic, and its potential impacts on energy systems would need to be carefully assessed and considered in the context of broader environmental, social, and ethical implications. Many geoengineering methods are still theoretical or experimental, and implementing them on a large scale could have unforeseen consequences. In Fig. 4.11.1 the main impacts of Geoengineering, on the energy demand and energy system, are presented.

Energy Demand

- many geoengineering methods require significant energy inputs for their implementation. For example, stratospheric aerosol injection may require the deployment of aircraft or specialized equipment, which will increase energy demand.
- the energy needed for manufacturing and operating these systems could be substantial

Energy Source Shift

- involves the deployment of reflective materials in space or the atmosphere to reduce incoming solar with impact on the reducing of the warming effect; it may temperate the implementation of clean energies

Renewable Energy Integration

- some geoengineering approaches, such as afforestation or bioenergy with carbon capture and storage, can be integrated with energy systems. Such integration may drive the development and utilization of bioenergy technologies, which can impact the overall energy mix.

Existing Energy Infrastructure

- certain geoengineering methods may pose risks to existing energy infrastructure. For example, if solar radiation management techniques lead to reduced solar irradiance, it could affect the efficiency of solar power generation.

Energy Policy and Regulation

- the deployment of geoengineering methods is likely to prompt discussions on energy policy and regulation. Governments and international bodies would need to address the potential energy implications of geoengineering initiatives and set guidelines for responsible implementation.

Fig. 4.11.1 Main impacts of Ge on the energy demand and energy system

5.12 Concluding remarks on the impact of disruptive technologies

The 11 technologies discussed above have a disruptive character both in terms of the development of society and in the evolution of the energy sector (consumption requirements, balancing methods, energy mix).

While the factors discussed in Section 3 can be considered through a classical approach, based on predictive models of economic and social development, disruptive technologies are not part of these models. These technologies not only introduce great uncertainties in the evolution of society, they have a major potential to profoundly change the development patterns.

How can we take them into account in the formulation of the development scenarios? Although the answer to this question is difficult to formulate now, what is crucial is not to neglect these technologies in our predictions or projections of possible futures. These technologies diversify the spectrum of development scenarios and implicitly the set of future energy scenarios. A separate deliverable (D8.3) will be dedicated to identifying these scenarios.

Some of the disruptive technologies will act toward a better energy efficiency in energy generation, transport, distribution, and consumption. In the current medium-term vision (decarbonization based on a massive increase of RES) the Es (energy storage) seems to be the key technology. With increased energy storage capacity, excess electricity generated during off-peak times can be stored and used during peak demand periods, reducing the need for additional power generation. Without Es the most of the advantages of iRES becomes questionable from the point of view of the sustainability. Therefore, if enough investment in RDI for Es will be injected and will be followed by successful innovations, a performant and practical energy storage system will be developed and the world will have the chance to rely on a large share of RES.

A group of technologies (AR, 3Dp, Ms, D, and Bt) may create a new paradigm in the production of goods with a great decrease of classical manufacturing (based on machineries and humans), a more distributed/localized production, performant materials, and a new level in using the biological techniques. Most of the influences will act towards a reduction of the energy consumption by energy efficiency, optimization of the production, reduction of the transport, replacing the needed human comfort from the factories with a more neutral environment appropriate for robots.

Another group (AI, Bd, and IoT) will determine an increase of electricity consumption on the short-term, until the reaching of a mature phase when these technologies will be able to develop the best algorithms to construct the optimal solutions. In the mature phase a great contribution to the decreasing of the energy consumption is expected.

Blockchain remains a energy intensive technology and its contribution to the general future demand is dependent only on Bch market penetration, for example a shift from classical currency to a crypto system.

Geoengineering introduces a lot of controversies due to the technical difficulties for implementation and due to the great uncertainties in the economics and environmental impacts. However, due to the urgency of climate change actions such technology should not be eliminated from the discussion since its implementation can greatly affect the vision in the energy sector, more exactly the speed of implementation of clean energy.

Es, AI, Ms, 3DP, Dr, and AR will improve the efficiency in the energy sector, will decrease the costs and can enable consumers to generate electricity locally, reducing the overall demand on centralized power plants and changing the dynamics of electricity demand. A transformation of the grids will occur towards decentralized and Distributed Energy Resources (DERs). Photovoltaics, wind turbines, and small-scale energy storage systems are likely to become more prevalent.

A better grid management will be possible by AI and IoT, such as smart meters and advanced demand response systems, working to optimize the electricity usage. Smart homes and buildings with IoT-enabled appliances can optimize electricity usage based on real-time data, potentially reducing overall electricity demand.

The digitalization of energy systems and the use of blockchain technology for energy transactions could streamline electricity markets, enabling more efficient and transparent energy trading. This could influence electricity demand patterns and pricing structures.

6 Impact of different crisis

The societies have faced, globally or regionally, periodic crises. These include: the Great Recession of 1929-1939, the energy crisis of the 1970s, the financial crisis of 2007-2009, as well as the Covid 19 (2020-2022). With the effects of globalization, the crises lost more and more of their local character, becoming germs for world economy and global society crises. Financial, economic, or social crises cause decreases in the economic activity as well as in the energy demand.

6.1 Pandemic

The COVID-19 pandemic started in Wuhan (China) in December 2019. The coronavirus (SARS-CoV-2) quickly spreads globally, leading to an unprecedented public health crisis. The World Health Organization (WHO) declared COVID-19 a pandemic on March 11, 2020.

The pandemic had profound social, economic, and health impacts. It strained healthcare systems, disrupted economies, and led to widespread social restrictions. To mitigate the spread of the virus, various public health measures were implemented, including lockdowns, social distancing, mask-wearing, travel restrictions, and widespread testing. Vaccination campaigns were initiated to protect people from the virus and reduce the severity of the disease. A huge effort was dedicated to implement measures to reduce the transmission of the disease sometimes without enough medical basis due to the very low knowledge of the virus and due its high flexibility to produce new variants.

The Covid 19 crisis caused the largest global recession in history, by blocking the activity, in March 2020, of more than a third of the global population [74]. As the virus spreads globally, concerns have shifted from problems caused by reduced production to drastic declines in business in the services sector.

The goods market suffered a major impact due to panic-induced buying, rising demand for pandemic goods, and a disruption of predominantly placed production in China. Global stock markets suffered massive declines in February 2020, reaching a global collapse in March 2020.

In the initial phase of the pandemic, electricity demand fell to the weekend consumption levels, with dramatic reductions in services and industry, only partially offset by higher residential use [75].

After the quarantine measures were lifted, electricity demand began to return to pre-crisis levels. However, for most countries, except India, where the recovery was more pronounced, electricity demand in June-July remained 5-10% below the 2019 level [75]. In August 2020, EU countries reached a consumption close to that of 2019, and in the following months the trend was to place consumption at the levels of the previous year.

In addition to the decrease in electricity demand, an important effect on the EU energy market was induced by the increase in the share of renewable energy production (in the period February-June the RES production was constantly higher than the whole contribution of fossil fuels) leading to lower energy prices and economic losses for conventional sources.

Due to the high variability (generated mainly by wind generation), the demands for peak load balancing have increased by stimulating natural gas production, which is, for the first half of 2020, the second largest resource after renewables [75].

By August 2020, globally, the nuclear power generation has been declining due to reduced demand, with production levels rising to the monthly average of 2019 [75]. In September-October, the increase in wind production and the maintenance of the level of nuclear production led to a decrease in the share of gas, which returned to the level of the quarantine period of March 2020.

In France, due to diminished economic activity, a substantial reduction in the total nuclear power supplied to the national system was needed, from a nuclear maximum of 52.3 GW to a minimum of 24.6 GW (April 5), then to 23.2 GW (June 6) and, subsequently, at the lowest production in March-October of 19.9 GW (July 5) [76], ie at 38% of the maximum power of the nuclear system.

During pandemics, many industries experienced slowdowns or temporary closures to prevent the spread of the disease. This reduction in industrial activity leads to lower energy consumption in manufacturing processes and decreased demand for electricity and fuel. Due to the mobility restrictions a reduced travel and transportation occurred with a decline in energy consumption in the transportation sector, which includes gasoline and diesel consumption. In the building sector, many commercial buildings (especial offices) were closed or working partially (restaurants, shops) leading to a drastically reduced demand for lighting, heating, cooling. The residential energy use increased due to the remote working and mobility restrictions.

Some patterns produced by the pandemics continued to be effective after 2022, for example work-from-home arrangements, altered consumer behaviour, investment in certain sectors, etc. It may affect the energy consumption on medium-term.

6.2 Economic/financial crisis

Economic or financial crises produce economic declines with direct effect on energy demand. Depending on the severity of the crisis, it can decrease by values between a few percent and tens of percent. This level of impact cannot be neglected in long-term projections. The difficulty lies in predicting periods when seizures are more likely to occur. Even the economic/financial crises are challenging to predict precisely, historical data reveals that they tend to follow certain patterns and occur periodically. However, the specific causes and severity of each crisis can vary widely.

Some key points [77], [78] regarding the periodicity of economic/financial crises are the following: (1) business cycles (referring to economic natural fluctuations with periods of expansion and contraction), (2) triggers (various factors, such as excessive debt levels, speculative bubbles, financial market instability, geopolitical tensions, natural disasters, technological shocks, structural imbalances may trigger the crisis), (3) frequency (historically the observed frequency varied from a few years to several decades influenced by the global economic conditions, financial imbalances, regulatory policies, and geopolitical events), (4) contagion (spreading of crisis from a region to other, sometime with a domino effect), (5) response to crisis (measures are usually introduced by Governments and central banks such as monetary stimulus, fiscal stimulus, bank bailouts, and regulatory reforms), (6) learning (often the policymakers and institutions benefits from lessons learnt, from past mistakes, and can influence the likelihood and severity of future crises).

The last big pure economic crisis in the EU was started in 2008. It was a severe and far-reaching financial downturn that originated in the United States with the subprime mortgage crisis [79]. Its impact on the EU was significant, leading to a prolonged period of economic stagnation and financial instability. The crisis began with the bursting of the US housing bubble in 2007-2008. The collapse led to a global financial contagion, affecting European financial institutions that held toxic assets tied to US subprime mortgages. Liquidity problems occurred disrupting the normal functioning of credit markets and led to a credit crunch. The initial financial crisis soon evolved into a sovereign debt crisis in some EU member states (like Greece, Ireland, Portugal, Spain, and Italy). The financial turmoil had severe consequences for the real economy. The EU experienced a deep recession, characterized by negative economic growth, rising unemployment, and declining consumer and business confidence. In response to the sovereign debt crisis, several EU countries implemented austerity measures to reduce budget deficits and stabilize their economies. These measures included spending cuts, tax increases, and structural reforms, but they also contributed to economic contraction and social tensions. The European Central Bank implemented monetary policy measures, including lowering interest rates and providing liquidity to banks. The EU's recovery from the 2008 crisis was slow and uneven across member states. Some countries faced a prolonged period of economic stagnation, while others experienced a more robust recovery.

In terms of general economic impact, the crisis of 2007-2008 produced a decrease of 4% (2009 compared to 2007) [81] of the gross domestic product in the EU. In 2011 the fall of GDP was recovered, and subsequently the GDP increasing slightly later, by 1.5% (2014 compared to 2009). Consequently, the energy consumption decreased by 11% (2014 compared to 2007) [81], and CO2 emissions were reduced by 18% (2014 compared to 2007). Although part of the reduction in consumption is due to measures such as increasing energy efficiency, the significant reduction in energy consumption can be attributed almost entirely to the decline in industrial production [81]. Therefore a -10% effect in the energy consumption was experienced in this economic crisis.

The decrease is strongly dependent on the context of the economy, especially for the cases where there is a deep correlation between economic growth and electricity consumption, such the China case. In [81] the situation of the economic crisis in North China (producing 25% of the country's GDP) is analysed. In 2008, compared to 2007, a decrease in GDP of 2.83%, generated by the economic and financial crisis, led to a decrease in electricity consumption by 14.31% [81], the total energy impact was not specified.

6.3 Geopolitical crisis

Geopolitical crises can have significant impacts on energy demand and the energy market. Conflicts or political instability in major energy-producing regions, can disrupt the supply of energy resources. On the other hand, geopolitical crises can create uncertainty in the energy market, leading to price volatility. Sudden changes in political landscapes, trade policies, or sanctions can affect energy prices and market dynamics. Investors and market participants may respond to geopolitical tensions by adjusting their expectations and investments, which can influence energy prices and create instability in the market.

On the other hand, geopolitical crises can raise concerns about energy security for both importing and exporting countries. Importing countries heavily dependent on energy imports may worry about supply disruptions and seek to diversify their sources or increase domestic production. Exporting countries may face challenges in maintaining stable markets and securing long-term contracts if geopolitical tensions affect their credibility as reliable energy suppliers. Geopolitical crises can affect regional energy interdependencies and cooperation. Countries in a region may face challenges in maintaining energy trade agreements or infrastructure projects due to political tensions. Disruptions in regional energy cooperation can lead to increased energy costs, reduced access to resources, and a less reliable energy supply.

Geopolitical crises can also have implications for the ongoing global energy transition. In some cases, geopolitical tensions may hinder international cooperation on renewable energy projects or impede the flow of technology and investments needed for clean energy development. Additionally, countries with energy resources may prioritize short-term stability over long-term sustainability, which could slow down the adoption of renewable energy sources.

The most recent geopolitical crisis, the Ukraine war, produced a serious impact on the EU both in terms of energy market and energy policies. On 24 February 2022, Russia invaded Ukraine in an escalation of the

Russo-Ukrainian War which began in 2014. Until the summer of 2023, around six million Ukrainian refugees were registered across Europe and 6.3 million worldwide [82]. As a consequence of the war, the GDP of Ukraine fall by 35 percent in 2022, whereas for Russia the decrease was estimated at 4.5% [82].

The territory of Ukraine has become the target of intense bombardment with effects on infrastructure, economy, but also civilian targets. Energy infrastructure including production facilities and transmission lines was periodically damaged. This culminates in 2023 (June 6) with the destruction of the Dnieper River dam at Nova Kakhovka and the discharge of one of Europe's largest reservoirs, producing an ecological catastrophe, estimated as the second largest after the Chernobyl disaster. Even more serious remains the situation of the Zaporizhzhia nuclear power plant under Russian military occupation, operating under the order of the army, mined, and used as an element of pressure in the conduct of the battle. The destroying of the infrastructure was extended outside Ukraine at Nord Stream 1 and 2 gas pipelines, in the Baltic Sea.

The war already accumulated a huge impact on the emission by direct effects such as fossil-fuel used by soldiers, munitions, refugees, explosion of oil depots and power plants, replacing the electricity from the grid by Diesel generators, etc.). According with [83] at the end of the first year of war, the carbon footprint was around “155 million metric tons, roughly the annual emissions of the Netherlands”. On the other hand, the war has broken the existing balance in terms of oil and gas trade, with Russia's exports to the EU dropping dramatically. Under these circumstances, there was a major fear the emissions would increase by resuming coal-fired power generation. Due to the increase of the gas prices, a better coordinated management of the gas trading at EU level, and an unexpected gentle winter the gas consumption significantly decreased, for example “non-electricity natural gas consumption has fallen 17% year-over-year since the start of the war—which translates to 117 metric tons of avoided carbon emissions” [83].

In terms of the policy the war determines the EU to accelerate the energy transition and to re-prioritization of the objectives with security of supply and reducing on the dependence on the imports on the first place. Moreover, there is a clear orientation of the consumers to become less dependent on the oil and gas imports. In 2022 the solar new installed capacity in the EU increased with 47% (vs 2021), the heating pumps with 37%, and the electric vehicles with 31% [83].

Russia's military aggression against Ukraine has a direct impact on food security and the affordability of global food prices. The export of cereals from Ukraine was strongly disturbed, mainly by the naval blocking of the Black Sea ports in summer of 2023. Other affected goods such as the steel and derivatives created large disturbances on the market.

The continuation of war is a powerful source of instability in the region with effects on the economies, demographics, energy balance, and is affecting the development at least on the short-term, the cost of the reconstruction and recovery of Ukraine being estimated at more than $411bn after a year of war [84].

In summary, even in a case of a quite localized geopolitical crisis such as the Ukraine war, the effect on the energy system may be considerable, impacting the level of consumption, the energy mix, and the medium- and long-term policies.

Even there are many opinions supporting the decrease of frequency of the wars, mainly due to the economic aspects (reduction of benefits in comparison with the costs), in a projection on a horizon of three decades the geopolitics crisis cannot be neglected.

6.4 Energy crisis

Energy crisis consists of a significant disruption in the supply of energy resources for a country or region. The energy crisis may be triggered by: (1) market manipulation, (2) resource shortages, (3) geopolitical tensions, (4) natural disasters, (5) sudden changes in demand, (6) supply chain disruptions. An energy crisis may damage the economy especially when the rising of the prices is high and no other energy alternatives are found in a short time.

During an energy crisis, countries may experience fuel shortages, high inflation, and an overall slowdown in economic growth. People may face difficulties in affording energy resources, and industries may struggle to maintain operations. Governments often intervene with energy conservation measures, price controls, and attempts to secure alternative energy sources.

During the history energy crisis impacted the regional and even global evolution, for example oil shortage (1973), oil price shock (Persian Gulf war, 1990), central Asia energy crisis (2008).

The last energy crisis seems to be triggered by the war in Ukraine, due to the blockage of the natural gas export from Russia to Europe, particularly due to the conflict in the eastern region near key gas infrastructure raising concerns about the stability and reliability of gas supplies to EU countries. The energy security of EU was affected, with a powerful effect during the winter months. Some elements of the war, including the impact on the energy sector were discussed in the previous section.

On the other hand, there are opinions the crisis, at least the increase of the energy prices appeared at least 6 months before the starting of the war in Ukraine (February 2022). The energy crisis is in this case connected with the post-pandemic situation with a recovery of the economy in condition of a slower recovery of the energy sector.

However, looking to the evolution of the energy sector during pandemics (see Section 5.1) the depression of the economic activity introduced a lower energy demand. Consequently, the dispatchable fraction was reduced, based on the existing intermittent production in EU (solar and wind). The impact was not only in the level of the prices, but also at the level of patterns for the price formation. The long-term contracts were progressively reduced, and the traders understood a new context, more speculative and more profitable was created, shifting most transactions to day-ahead-market and spot-market. Even the dispatchable capacities come back in the production at the end of 2021, the situation of the long-term contract remained unchanged due to the new orientation of the traders.

Therefore, the recent energy crisis is a combination of post-pandemic situation (with a more speculative energy market) and the war in Ukraine. It is affecting mainly the stability of the economy, prices, and consumption.

The crisis created a prompt response from the authorities and consumers. The increase of the energy prices determined more actions to reduce any wasted energy, to improve energy efficiency, to diversify the resources, and to act to less dependent on external energy resources. As an effect the number of prosumers is in an amazing increasing (see Section 3.6). At the same time, there is more chances, in some EU countries to build a synergy between RES and nuclear.

Energy crises can serve as a catalyst for the development and adoption of alternative energy sources. As traditional energy supplies become scarce or unreliable, there may be a push towards renewable energy, such as solar, wind, or geothermal, as well as investments in energy storage technologies and nuclear. While this transition may help diversify the energy mix in the long term, the initial investment costs and infrastructure changes can create short-term challenges.

Overall, an energy crisis can significantly impact energy demand and the energy market, leading to higher prices, rationing, blackouts, economic repercussions, and disruptions in critical services. These consequences can collectively affect the quality of life by increasing costs, limiting access to essential services, and disrupting daily routines. However, energy crises can also serve as a wake-up call to accelerate the transition towards sustainable and resilient energy systems.

6.5 Migration crisis

Migration can change the consumption of electricity at local, national, or regional level, for the areas where the process has demographic relevance. The arrival of many migrants in a particular region or country can lead to an increased demand for energy. Additional energy is needed to provide heating, cooling, and lighting in temporary shelters, refugee camps, or housing facilities. This increased demand can put a strain on the local energy infrastructure and resources. Accommodating a sudden influx of migrants may require the construction of new infrastructure such as housing, schools, hospitals, and transportation networks. Building and operating this infrastructure will increase energy consumption and may require the expansion of existing energy networks, such as electricity grids and gas pipelines.

The migration crisis can have broader economic consequences that can indirectly impact the energy market. Economic strain caused by the crisis can result in reduced purchasing power, lower investments in energy infrastructure, or delayed projects. These factors can influence energy market dynamics, including prices, supply, and demand.

Migration can be internal (predominantly from rural to urban areas) or international (generated by economic discrepancies, local political / military crises, etc.). A first effect of migration is the demographic change, the urban / rural structure. Most of the times, both national and international migration takes place predominantly from rural to urban. In addition to geographical changes with an effect on local consumption, there is also an effect of increasing energy consumption, given the urban tendency to consume more [85].

In countries with low urbanization, the phenomenon of rural-urban migration is intense. Thus, in China, in 1995, the rural population was 850 million, decreasing in 2017 to 577 million, while the urban population increased, in the same period, from 352 million to 813 million, an average annual increase of 3.9 %. Developed countries have a small rural population (17% in the US, UK). In China, per capita energy consumption has increased at an average annual rate of over 4% since the launch of the reform (1978), part of this increase being generated by migration.

Migration can be triggered by conflicts, economic situation, natural disaster, climate changes. Global warming can have significant effects on migration patterns and human populations worldwide. These effects arise due to various environmental, economic, and social factors that are influenced by changes in temperature, precipitation patterns, extreme weather events, sea-level rise, and other climate-related impacts. EU is a possible destination of migrants on medium- and long-term due to the attractivity in terms of economic and social situations.

On the other hand, as climate change intensifies, some regions of EU may experience more frequent and severe natural disasters such as hurricanes, floods, droughts, and wildfires creating the condition for a EU internal migration of the population.

As people migrate away from climate-affected rural areas, they often move to urban centres in search of better opportunities and resources. This trend can lead to the growth of mega-cities and put immense pressure on urban infrastructure and services.

Crisis induces by refugees after localized crisis influences both the origin and the destination countries/regions by relevant changings in the consumption and in the demographics. For example, the Syrian crisis beginning in 2011 has increased the “pressures on public services and already strained water and energy resources of Jordan” [86]. On the other hand, significant influence on some of the countries from the region was produces, for example Lebanon suffered economic losses by a dramatically fall of the government revenues due to the interrupted trade, the loss of business, and loss of the consumer confidence [87].

But the Syrian crisis impacted not only the region, but also many of the EU countries, generating an unprecedented influx of refugees commonly described as the "European refugee crisis". In 2015-2016 more than 1.3 million refugees crossed the Mediterranean and Aegean Seas trying to reach Europe, especially Germany [88] due to the adoption, in 2015, of the famously "pen border" policy. In 2015, 890,000 refugees entered in Germany, with 476,649 formal applications for political asylum [88]. After 2018 the new asylum applications in Germany has dropped nearly to the level before 2015, but the situation remains complicated (total cumulated asylum applications reaching 1.7 million). A high financial impact was produced and the hopes are to obtain future benefits from the integration of the migrants. However due to the socio-political impacts, the 2015 experience 2015 "cannot, should not and must not be repeated." (Chancellor Angela Merkel). As a consequence of the migration the greatest increase of the total population of Germany for the last several decades was produced. Some locally great impacts were produced, for example the population growth in Berlin, driven almost by citizens of other countries. At the same time there is a influence in the demographics structure since the most coming refugees are young men (84% of new asylum seekers in 2017), were under the age of 35, and 60% were male [89]. The important impact in the consumption may be illustrated by the total expenditures allotted to the asylum seekers: €20.5 billion (2016), €21.2 billion (2017), at €20.8 billion (2018, more than 6% of the entire federal budget in 2018) [89]. More than 65% of the allocations go to housing, social security benefits, and integration initiatives [89].

The case of flooding may be discussed in terms of global tendencies of the climate changes to produce the sea level rise and extreme weather phenomena involving flooding. The seasonal flooding in limited have io be treated by preventive measures by the local/national authorities and are not the subject of the present analysis. A serious increase of the number of communities (both coastal and inland) affected by the flooding (or by the sea level rise) is expected in the next years. These phenomena will impact on the internal migration and also on the needs for the reconstruction affecting directly the distribution of the energy consumption and, also, the production and transport of the electricity. The impact is difficult to be quantified due to the dispersion and elements derived from natural hazard characteristics.

The global food shortages become more stringent in the conditions of the climate changes. The complexity of the interdependences among water, energy, and food and essential resources are analysed in [90]. A sustainable, integrated and intelligent management is compulsory needed to reduce the global risks (driven by extreme weather, large migrations, hazards inside vulnerable communities). Although a great impact in the energy may occur (for example the efforts to transport the food to affected areas, or the consumption of energy to produce food in difficult weather conditions) the estimation is very difficult.

6.6 Complexity of superposition

The superposition effect of different crises refers to the combined and interconnected impacts that multiple crises can have on various aspects of society and the global order. When multiple crises occur simultaneously or overlap in their effects, their interactions can lead to complex and often unpredictable outcomes.

For example, geopolitical crisis is often accompanied by another crisis, the migration. It is not only induced by the intention to save life during bloody conflicts in which civil structures are also attacked, it can be amplified by the consequences of the war in peacetime, for example by the economic difficulties and a low level of quality of life.

Economic crises, characterized by a downturn in economic activity and declining GDP, can be exacerbated by financial crises, which involve issues with the stability of financial institutions and markets. The superposition of these two crises can lead to a downward spiral in economic growth, rising unemployment, and increased financial instability. Economic downturns may also strain financial systems and exacerbate debt burdens, leading to potential banking collapses and exacerbating the overall economic situation.

Migration crises are characterized by large-scale movements of people fleeing conflicts, economic hardships, or environmental challenges. Pandemic crises, as seen with outbreaks of infectious diseases like COVID-19, can lead to severe health and economic impacts. The superposition of these crises can further strain health systems, impact migration patterns, and lead to socio-economic disruptions. Border controls and restrictions may be tightened, affecting the movement of both refugees and travelers, while refugee camps and migrant shelters may become potential hotspots for disease spread.

Geopolitical crises encompass tensions, conflicts, or diplomatic disputes between nations. When combined with other crises, such as economic or energy crises, they can escalate existing conflicts or create new ones. Geopolitical tensions can impact trade relationships, disrupt supply chains, and worsen global instability, potentially affecting cooperation in addressing other crises.

Climatic crises involve extreme weather events, rising sea levels, and disruptions to ecosystems due to climate change. Energy crises occur when there are significant shortages or disruptions in energy supply or high energy prices. The superposition of these crises can lead to heightened vulnerabilities, as climate change impacts may affect energy production, transportation, and distribution systems. Extreme weather events, like hurricanes or heatwaves, can cause damage to energy infrastructure, exacerbating energy shortages and triggering higher energy costs.

The interplay between pandemic and economic crises is evident in events like the COVID-19 pandemic. Pandemic-induced lockdowns and restrictions can lead to severe economic contractions, unemployment, and business closures. Additionally, overwhelmed healthcare systems can exacerbate the economic impact by affecting productivity and healthcare costs. Conversely, economic struggles may hinder the ability of governments to respond effectively to public health challenges and implement necessary containment measures.

Generally, the superposition effect of different crises results in a complex web of interactions that can amplify each other's consequences. The interconnectivity and magnitude of these crises will produce great impacts on the energy demand and functionality of the energy system. Therefore, a simple view of the effects of different crisis is not sufficient to understand the complexity of future scenarios. By considering the superposition of different crisis it is possible to define the scenarios beyond the desired and accepted ones.

7 Conclusions

(C1) Predicting energy demand on a medium and long-term basis can be challenging due to several complex factors and uncertainties involved such as the economic growth and development, demographic evolutions, consumer behavior, technological advancements, policy changes, climate variability, geopolitical factors. Unexpected events like natural disasters, economic crises, or pandemics (like the COVID-19 pandemic) can significantly disrupt energy demand projections and make them less reliable. A set of the difficulties are generated by the interconnectedness, the energy sector being intricately connected with other industries, like transportation and manufacturing. Changes in one sector can have ripple effects on energy demand across the entire economy, making it difficult to isolate and predict specific energy consumption patterns. On the other hand, predicting energy demand requires access to accurate and comprehensive historical data.

(C2) The present deliverable is a basis for the development of the future energy scenario in order to understand the role of nuclear power at the horizon of 2050. Therefore, the required accuracy in the energy demand is a moderate one, a simple projection on the possible developments is relevant for the existing objective. To address the above-mentioned difficulties the investigation was started by the selection of the most appropriate assumptions for the evolution of demographics, GDP, quality of life, and of the impacts produced by the implementation of energy efficiency measures, electrification and decarbonization policies. The assumptions indicate a very probable increase of the electricity demand, despite the large efforts to implement energy efficiency measures. A doubling of the electricity demand in 2050 vs 2020 is very probable, influencing a lot the generation of energy. The economic growth and the tendency to increase the standard of life increase of quality of life will be the second, respectively the third factor influencing the increase of the electricity demand. The demographics will not impact significantly the energy demand. The decarbonization of the economy will create a market dominated by renewables with difficulties in the balancing the generation and the demand. In such conditions the development of the storage together with the presence of a significant share of very stable energy is crucial for the security of supply.

(C3) The possible impacts of a set of eleven disruptive technologies (Artificial intelligence, Big data, Internet of Things, Advanced Robotics, Material science, Energy storage, Additive manufacturing, Drones, Biotechnology, Blockchain, Geoengineering) were analyzed. Due to their potential to disrupt the expected evolutions of the economy and society, it is crucial to discuss these technologies in relation with the predictions or projections of possible futures. These technologies diversify the spectrum of development scenarios and implicitly the set of future energy scenarios. The energy storage seems to be the key technology. With increased energy storage capacity, excess electricity generated during off-peak times can be stored and used during peak demand periods, reducing the need for additional power generation. Without it the most of the advantages of iRES becomes questionable from the point of view of the sustainability. A group of technologies (Advanced Robots, Additive manufacturing, Material sciences, Biotechnologies) may create a new paradigm in the production of goods with a great decrease of classical manufacturing (based on machineries and humans), a more distributed/localized production, performant materials, and a new level in using the biological techniques. Most of the influences will act towards a reduction of the energy consumption by energy efficiency, optimization of the production, reduction of the transport, replacing the needed human comfort from the factories with a more neutral environment appropriate for robots. Another group (Artificial Intelligence, Big data, and Internet of Things) will determine an increase of electricity consumption on the short-term, until the reaching of a mature phase when these technologies will be able to develop the best algorithms to construct the optimal solutions. In the mature phase a great contribution to the decreasing of the energy consumption is expected. The Blockchain remain a energy intensive technology and its contribution to the general future demand is dependent only to the Bch penetration of the market, for example the shifting from classical currency to crypto system. The

Geoengineering introduce a lot of controversies due to the technical difficulties for implementation and due to the great uncertainties in the economics and environmental impacts. However, due to the urgency of climate change actions such technology should not be eliminated from the discussion since its implementation can affect a lot the vision in the energy sector, more exactly the speed of the implementation of clean energy.

(C4) Moreover, the analysis takes into consideration unexpected events such as the economic/financial crisis, pandemics, geopolitical conflicts and war, energy crisis and possible migration crisis. In the current context due to the globalization and high interdependencies the crises lost more and more of their local character, becoming the germs of crisis for the world economy and global society. For example, the Covid 19 crisis caused the largest global recession in history, by blocking the activity as of March 2020 of more than a third of the global population, and creating drastic decline in economies. In the initial phase of the pandemic (March-April 2020), dramatic reductions in services and industry led to around -25% in European average electricity demand, which thus fell to weekend consumption levels. Past economic or financial crisis experienced in different historical contexts has seen energy demand decrease from few percent (in the case of the early 1990s recession) to 10-20% (in the case of economic crisis started in 2008). Geopolitical crisis affects not only regional economies, but also supply chains including energy resource transactions, as seen for example in the context of the Russian aggression on Ukraine. Such conflict has a strong impact redefining energy measure, such as the acceleration of transition in the EU and measures to reduce dependence on the import of energy and energy resources. Energy crisis can significantly impact energy demand and the energy market, leading to higher prices, rationing, blackouts, economic repercussions, and disruptions in critical services. These consequences can together affect the quality of life by increasing costs, limiting access to essential services, and disrupting daily routines. The current energy crisis was triggered by the war perpetrated on Ukraine, concomitant with the post-pandemic effect of a more speculative market. The impact on prices was important and creates difficulties especially for the segments of population already affected by energy poverty. Various administrative measures have been introduced, but their effects are temporary and limited, and do not solve the underlying issues. Migration may be a real concern depending on the evolution of climate changes and of the attractivity of the EU. The arrival of many migrants in a particular region or country can lead to an increased demand for energy, creating pressures on the local energy infrastructure and resources.

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