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What is the future of nuclear power in Ukraine? The role of war, techno-economic drivers, and safety considerations

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ABSTRACT

The TIMES-Ukraine energy system model is used to explore the future of nuclear power plants (NPPs) under an ambitious climate policy scenario, achieving net zero greenhouse gas emissions in 2050. Varying techno-economic (construction costs and capacity factors for NPPs, capital costs for solar and wind), policy (ban on construction or extension of NPPs), and macroeconomic (alternative economic recovery trajectories) factors are considered. The difference in the techno-economic assumptions for nuclear power generation has a very moderate impact on the total system costs (TSC) of the energy transition, as their variation (positive or negative change) does not exceed 0.1%–0.2% relative to the default case. Policy decisions on restricting nuclear power generation could have a more substantial impact, as TSC increase by 4–5 billion USD (0.6%–0.9%) over the 2020–2050 period under the most restrictive case. In terms of the economic viability of various NPPs, we find small modular reactors to be more competitive than large NPPs due to the higher availability factor. Overall, in terms of developing new NPP capacities, policymakers can consider alternative futures for this technology without major implications for the energy transition costs, as retired NPPs can be substituted by alternative generation technologies in a cost-competitive manner.

1. Introduction

Providing a cost-competitive and carbon-free alternative to other sources of electricity generation, nuclear power remains a major source of energy supply in Ukraine. As the share of electricity coming from nuclear power plants (NPPs) increased from 25% in 1990 to over 52% in 2020,[1] Ukraine has been among the top nuclear power producers in the world (IEA, 2021).

At the same time, the lifetime of most NPPs in the country expires between 2025 and 2030 (World Nuclear Association, 2021), and long-term decisions regarding possible extensions of the lifespan or construction of the new NPPs need to be made. In light of Ukraine's recent efforts to reduce greenhouse gas (GHG) emissions – supported both by national legislation (Government of Ukraine, 2017) and international commitments (EBRD, 2020), such decisions could have a major impact on the cost of climate mitigation.

Decisions regarding the future of nuclear energy are impacted not only by climate mitigation ambitions and economic viability but are also driven by concerns regarding potential safety issues and environmental implications of nuclear waste treatment (Prăvălie and Bandoc, 2018; Dai et al., 2019).

While over 30 countries around the world are considering, planning, or starting nuclear power programs (World Nuclear Association, 2020), other countries, like Belgium (Hoti et al., 2021), Germany (de Menezes and Houllier, 2015), Spain (IAEA, 2018) and Switzerland (Eser et al., 2018), are in the process or already have phased out NPPs due to environmental or safety concerns. In the case of Ukraine, additional safety concerns regarding future of the nuclear energy have been raised following the Russian invasion and attacks on nuclear power facilities (Sawano et al., 2022).

Most studies show that if unconstrained with political and social choices, nuclear power would continue to play an important role in the long-term climate mitigation pathways (Riahi et al., 2017; IPCC, 2018; Zhang et al., 2021). Studies also show that nuclear power has one of the

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[1] Share of the nuclear power generation in the total electricity production. Partly an increase in the corresponding share of nuclear has been driven by a reduction in the overall electricity generation.

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lowest life-cycle GHG emissions compared to renewable technologies (Siddiqui and Dincer, 2017) and that a hybrid renewable-nuclear energy system could be a viable solution for the future mitigation strategies (Siddharth, 2018; Wang et al., 2020). At the same time, considering uncertainties regarding the role of nuclear power generation in future climate policy decisions, several recent studies have explored the issue of the economic and environmental viability of nuclear energy in national and global mitigation strategies.

Lehtveer and Hedenus (2015) rely on the global energy system model to analyze the role and economics of nuclear power in meeting the global 2°C temperature target by 2100. Authors estimate that an expansion of the currently commercially available nuclear technologies results in 10% savings in climate mitigation costs (compared to the scenario where such expansion is not allowed). If advanced nuclear technologies such as Fast Breeder Reactors (FBRs) and alternative uranium extraction methods are also available, the savings reach 20%. Though it should be noted that a more recent data on the techno-economic characteristics of generation technologies might have an impact on the overall conclusions of this study.

Kan et al. (2020) explore the cost of a future low-carbon electricity system for the case of Sweden. Authors find that overall there is rather moderate economic rationale for the country to reinvest in nuclear power. For the case of optimal transmission expansion, the cost difference between nuclear and non-nuclear scenarios ranges from 0% to 8%. Roth and Jaramillo (2017) explore the cost-effectiveness of preserving existing nuclear power plants in the United States. Their results suggest that the cost of preserving multi-reactor plants through 2040 is lower than the social cost of carbon, under any of the considered natural gas price pathways. Authors also show that even wind generation, which has the lowest cost of avoided CO_2 among the considered options, is more expensive than preserving the least financially viable nuclear plant currently in operation under the lowest gas price scenario.

Carrara (2020) estimates that the additional policy costs induced by the global nuclear phase-out are in the range of 0.4% of GDP (over the 2015–2100 period), while an immediate global shutdown of the nuclear power plants results in a doubling of these losses. The study also suggests that the phase-out costs are largely compensated by the innovation benefits in renewable generation and the energy efficiency areas stimulated by the nuclear phase-out.

Overall, most studies find that an extension of the NPPs' operational lifetime, upon availability, is an economically feasible solution, especially under stringent abatement pathways, while early retirement of the NPPs could bring a moderate to substantial increase in mitigation costs. Research also suggests that the construction of the new NPPs is associated with larger uncertainties in terms of economic and environmental benefits, when compared to alternative technologies, such as wind or solar.

Several studies have explored the current state and future of nuclear energy in Ukraine. Babenko et al. (2007) provide a technical overview of the nuclear power plants and discuss alternative nuclear technologies that can be adopted in Ukraine. Kasperski (2015) discusses the potential benefits and risks of Ukraine's reliance on nuclear power, including considerations of energy independence, economic and social benefits, safety concerns, and radioactive waste treatment. Bellona (2017) provides an overview of the historical trends and current state of nuclear power in Ukraine.

Model-based assessments of the ambitious mitigation pathways for Ukraine reported by Child et al. (2017) and Diachuk et al. (2017) assume a gradual phase-out of the NPPs and their substitution mostly by wind and solar power generation so that by 2050 the share of the nuclear power generation is negligible. Chepeliev et al. (2018) show that under a somewhat less ambitious climate mitigation scenario (relative to the two studies discussed above) – consistent with Ukraine's low-emission development strategy (Government of Ukraine, 2017) – nuclear power generation could still be a part of the electricity generation mix, though its share would decrease significantly by 2050.

Providing useful insights regarding the role of nuclear power generation in Ukraine under specific policy assumptions, existing literature though does not explicitly address the point of the costs and benefits of potential nuclear power extension or constraint. In addition, earlier studies did not consider the impact of the variation in cost characteristics in the alternative generation technologies on the future of nuclear power generation, as well as varying post-war economic recovery pathways in the country.

This study aims to fill this gap. We rely on the TIMES-Ukraine energy system model and explore an ambitious climate policy scenario, which achieves net zero GHG emissions from industrial processes by 2050. Under the mitigation scenario, we explore several alternative futures of nuclear power generation, including the extension of the existing NPPs' lifetime, construction of the new NPPs, as well as scenarios that assume no new large NPPs or do not allow for the lifetime extensions. We also perform sensitivity analysis of the selected scenarios concerning the techno-economic parameters – load factors and capital expenditure (CAPEX). The latter is being varied both for nuclear and selected renewable generation technologies. Finally, we consider two alternative post-war recovery pathways for the economy of Ukraine in an attempt to capture the uncertainty in the energy demand drivers. Our analysis provides valuable insights for the policymakers in Ukraine and other countries that face similar decision-making choices regarding the future development of nuclear power generation.

The rest of the paper is organized as follows. Section 2 provides an overview of the state of nuclear power generation in Ukraine. Section 3 outlines the methodological framework of the study. Section 4 describes the baseline and climate mitigation scenarios considered in the paper. Section 5 provides an economic and environmental assessment of the role of nuclear energy in Ukraine's future climate mitigation policies under varying techno-economic drivers, safety considerations, and economic recovery pathways. Finally, Section 6 concludes.

2. Nuclear power in Ukraine

Dominating the electricity generation mix in Ukraine since the mid-90s, after surpassing coal power generation, nuclear energy has been constantly expanding its share in the power mix. This has been driven primarily by the reduction in total electricity generation volumes following the economic recession of the 1990s (World Bank, 2022). As of 2018, the share of electricity coming from NPPs has reached 52%, with generation volumes exceeding 85 billion kWh per year, making Ukraine one of the top nuclear power producers in the world (IEA, 2021). State company NNEGC "Energoatom" is responsible for the operation of all four NPPs in Ukraine (Zaporizhzhya, Rivne, Khmelnytsky, and South Ukraine). There are 15 power units at the operating NPPs: 13 with the

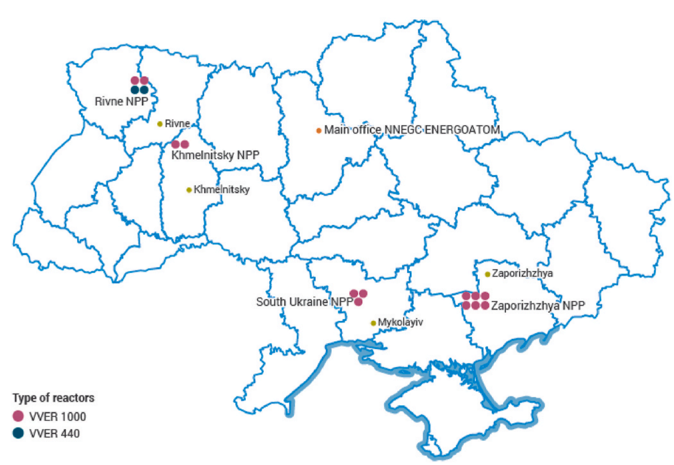

Fig. 1. Geographical distribution of the NPPs in Ukraine.
Source: WNA (2021).

VVER-1,000 reactor type and two with the VVER-440 reactor type (Fig. 1).

Construction of the two power units (No. 3 and 4) at the Khmelnitsky NPP started in the 1980s but has not been completed. The process has been suspended by the moratorium on the construction of new nuclear units in 1990. As of 2022, there is no approved decision on the completion of the construction process of these power units. The lifetime of many of the power units under operation has been extended, while the extension of the lifetime of other units, is at the planning stage (Table 1). All units are also available for further potential lifetime extension for an additional 5–30 years (Table 1).

Further development of the nuclear industry has been publicly supported by the Ukrainian government (Bellona, 2020). At the same time, several concerns regarding the potential extension of the NPP's lifetime, as well as the development of the nuclear sector in general, have been raised by civil society, activists, and experts. In particular, previous reports have discussed risks of the nuclear reactors' aging and the issue of their runtime extension without the implementation of additional safety improvements (e.g. Bellona, 2020; Bellona, 2017). Many Ukrainians still have fresh in mind the dire consequences of the Chornobyl nuclear accident, showcasing the possible risks of this source of energy (Bromet, 2012; Adams et al., 2011).

Another widely discussed concern is the treatment of radioactive waste. The latter is coupled with the fact that Ukraine does not have its own facilities for reprocessing the spent nuclear fuel and relies for this on other countries (Kasperski, 2015), which poses both political and energy security issues for Ukraine. In terms of nuclear fuel sourcing, after the Russian invasion, Ukraine stopped importing Russian nuclear fuel while continuing imports of the fuel supplied by the Westinghouse company (Forbes Ukraine, 2022). In the next two years, the Westinghouse company is planning to further increase the supply of nuclear fuel to Ukraine, while Ukraine is planning to attract additional (non-Russian) fuel suppliers to diversify import sources. Ukraine is also working on the development of nuclear fuel domestically, while the current stock of nuclear fuel in Ukraine can sustain the operation of domestic NPPs for 5–6 years (Forbes Ukraine, 2022).

Ukrainian environmental activists have launched several campaigns over the recent years stressing the potential risks of nuclear energy. And while the government continues to support the development of Ukrainian NPPs, with a further shift in public opinion and continuing reduction in generation costs of alternative generation technologies (IEA/NEA, 2020), the situation might change in the future. Therefore, it is important to understand the tradeoffs of the potential NPPs closure, extension, or new development in light of the economic, social, and environmental outcomes.

In addition, Russia's invasion of Ukraine accompanied by shelling of Europe's largest nuclear power station – the Zaporizhzhia plant – has added another important factor to the decision-making process, as an attack on the nuclear power plant carries a risk of radiation contamination, as well as other major health risks among residents (Sawano et al., 2022).

3. Methodological framework

To explore the role of nuclear energy in the future of Ukraine's climate mitigation, we rely on the TIMES-Ukraine energy system model (Diachuk et al., 2017; EBRD, 2020). TIMES-Ukraine is a linear programming optimization model of the energy flows that represent Ukraine as a single region. The model includes seven sectors: energy supply sector (production, imports, exports, international bunkers, stock changes, and the production of secondary energy resources – petroleum products, briquettes, etc.); electricity and heat production; industry; transport; residential users (household); trade and services; and agriculture (including fishing) (Fig. 2). The model has a separate technology for the new distribution lines, which covers network development costs.

The first step of the modeling approach includes the development of the baseline scenario. The latter is based on the future trends of the energy demand, technological, macroeconomic, and demographic assumptions. A model finds the least cost trajectory of the system to meet the required energy demand, providing estimates of the associated energy supply mix, energy system costs, emissions, etc. In the second step, additional targets/constraints are introduced to the model, corresponding to the policy scenario and the model finds the least cost solution under the imposed constraints (the sum of the discounted costs over years is minimized). Finally, two scenarios (baseline and policy) are compared toward each other to identify the impact of selected policies. Specific assumptions behind the baseline and policy scenarios are discussed in Section 4. Additional details regarding the TIMES-Ukraine modeling framework can be found in Diachuk et al. (2017) and Chepeliev et al. (2023).

While the TIMES-Ukraine model includes a detailed representation of various energy supply technologies, for the current study additional refinements were made for the case of nuclear power generation. In particular, to estimate the cost of the potential lifetime extension of the NPPs, we relied on the reported costs of the lifetime extension for power units No. 1 and 2 of the Rivne NPP. According to Energoatom (2013), corresponding costs amounted to 358 USD per 1 kW, taking into account implemented reconstruction and renovation measures. These costs though do not take into account expenditures for the implementation of a Comprehensive (consolidated) program for increasing the level of safety of NPPs, approved by the Regulation of the Cabinet of Ministers of Ukraine (CMU, 2011). Corresponding costs are 1.31 billion USD per 9

Table 1
Key characteristics of the NPPs in Ukraine.

NPP name	Unit No.	Reactor type	Capacity (MW)	Start of construction	Connection to the grid	Extension of lifetime	Potential max lifetime
Zaporizhzhya	1	VVER-1000/320	1,000	04/1980	10/12/1984	23/12/2025	2045
	2	VVER-1000/320	1,000	04/1981	22/07/1985	19/02/2026	2046
	3	VVER-1000/320	1,000	04/1982	10/12/1986	05/03/2027	2037
	4	VVER-1000/320	1,000	01/1984	18/12/1987	04/04/2028	2048
	5	VVER-1000/320	1,000	07/1985	14/08/1989	27/05/2030	2040
	6	VVER-1000/320	1,000	06/1986	19/10/1995	Planned in 2026	2056
South Ukraine	1	VVER-1000/302	1,000	03/1977	31/12/1982	20/12/2023	2043
	2	VVER-1000/338	1,000	10/1979	06/01/1985	31/12/2025	2035
	3	VVER-1000/320	1,000	02/1985	20/09/1989	10/02/2030	2050
Rivne	1	VVER-440/213	415	08/1976	22/12/1980	22/12/2030	2035
	2	VVER-440/213	420	10/1977	22/12/1981	22/12/2031	2036
	3	VVER-1000/320	1,000	02/1981	21/12/1986	11/12/2037	2047
	4	VVER-1000/320	1,000	1986	10/10/2004	Planned in 2035	2065
Khmelnitsky	1	VVER-1000/320	1,000	11/1981	22/12/1987	13/12/2028	2038
	2	VVER-1000/320	1,000	1983	07/08/2004	Planned in 2035	2065
	3	VVER-1000		09/1985	Construction not completed		
	4	VVER-1000		06/1986			

Source: developed by authors based on Diachuk et al. (2017) and EBRD (2020).

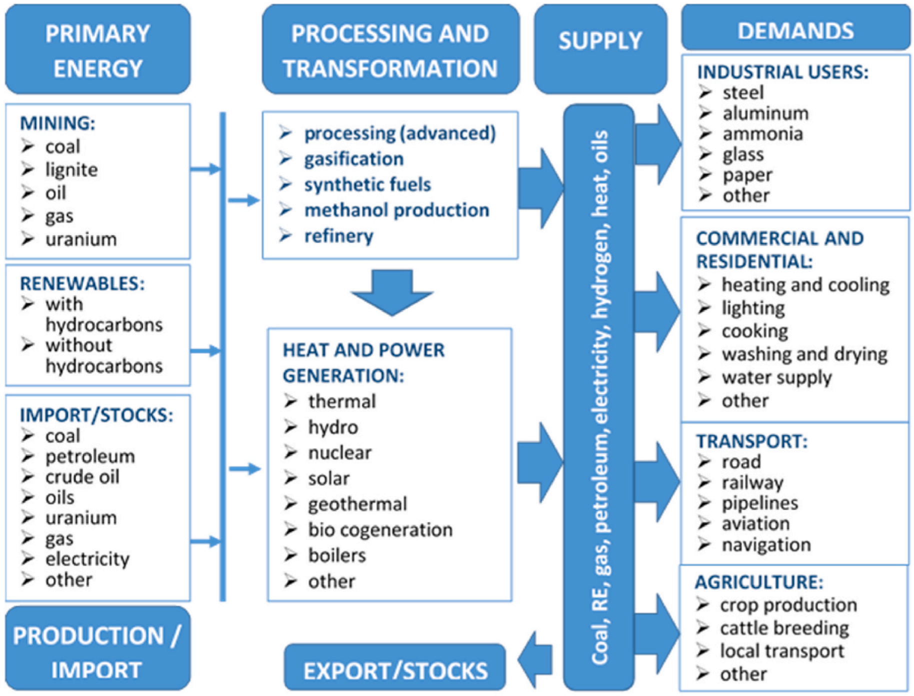

Fig. 2. Representation of the energy system in the TIMES-Ukraine model.
Source: developed by authors.

NPP units or around 146 USD per kW. Therefore, we assume that the total cost of the lifetime extension of operating NPP units for 20 years is 504 USD per kW of installed capacity.

In terms of the cost of the power units' construction on a new site, during recent years NNEGC Energoatom has reported estimates between 5,000 USD (Energoatom, 2021) and 7,000 USD per kW (Energoatom, 2016). The construction cost of the new NPP power units of the European Pressurized Reactor (EPR) type with a capacity of 1,600 MW in Flamanville (France) is estimated at 8,250 EUR (8,900 USD) per kW, and in Olkiluoto (Finland) the cost of construction of new NPP power units of 1,600 MW is estimated at 11 billion EUR for the entire power unit or 6, 900 EUR (7,400 USD) per kW (IEEFA, 2023). An earlier joint study of the International Energy Agency and the Nuclear Energy Agency indicates that the cost of construction of new NPP power units in European countries is varying from 4,986 USD (4,640 EUR) per kW in Slovakia to 7,535 USD (7,012 EUR) per kW in Hungary (International Energy Agency /Nuclear Energy Agency, 2015). Considering this range of estimates, for the case of Ukraine, we assume that the cost of constructing a new NPP is USD 5,900 per kW, which is consistent with an average CAPEX reported by the International Energy Agency /Nuclear Energy Agency (2015). Selected cost and technological assumptions across technologies most relevant for the current analysis are provided in Appendix B. Cost and technological assumptions for other generation technologies can be found in Chepeliev et al. (2023). An overview of potentials across various renewable energy sources is provided in Appendix C.

4. Baseline and climate mitigation scenarios

4.1. Baseline scenario

We start our assessment from the construction of the business as usual (BaU) scenario, which is developed in a way to achieve the targeted energy demand in a least-cost manner. The energy demand is driven by the aggregate GDP, sectoral value-added, and population growth forecasts. The Reference scenario assumes that Ukraine's GDP declines by 30.3% in 2022 following a forecast by the National Bank of Ukraine (National Bank of Ukraine, 2023) and that the active phase of the war in Ukraine would finish by the end of 2023. It is projected that the GDP would grow by 0.3% in 2023, 5.1% in 2024, and 6.4% in 2025 (National Bank of Ukraine, 2023). GDP is assumed to grow 5% per year during the 2026–2030 period. Starting from 2031 the growth rate is gradually reducing over time reaching 2.5% in 2035 and stabilizing in a range of 2.3%–2.5% by 2050. In the long run, no radical structural transformations in the economy were assumed, though a higher growth rate for the construction sector is anticipated driven by the infrastructure rebuilding activities.

In terms of structural transformations, the Reference scenario sees a moderate increase in the share of services over time – from 58.5% in 2020 to 63.6% in 2050 (Appendix A). A share of construction activity, which is a key producer of capital goods more than doubles over this period (Appendix A). It is also assumed that the agricultural sector sustains its substantial role in the Ukrainian economy, while the share of manufacturing activities moderately declines. The largest reductions in relative terms are observed in the mining sector, as the reliance on fossil fuels reduces over time.

The demographic forecast takes into account the projected movements of refugees. As of May 2022, 6.4 million refugees fled Ukraine (UNHCR, 2022), although 79% of them intend to return (Razumkov Center, 2022). For the post-2022 period, the population growth rate follows the medium scenario from PIDSS (2020).

While aggregate GDP increases by over 70% during the 2021–2050 period, accompanied by growth in incomes and industrial output, availability of the new more efficient technologies more than compensates for the growth in energy demand. As a result, by the mid-century, the total primary energy supply (TPES)[2] declines by almost 25% compared to the 2020 level (Fig. 3).

On the supply side, with no mitigation policies, the share of fossil fuels in the energy mix in 2050 is still substantial, with coal, oil, and gas

[2] In this paper, TPES is estimated based on the energy balance accounting framework, i.e. no conversion rates for noncombustible renewable energy sources are applied.

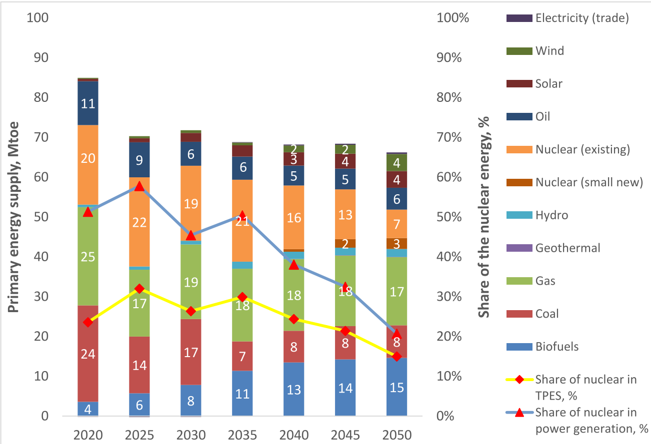

Fig. 3. TPES and the share of nuclear energy in the BaU scenario. *Notes:* Each reported year (except 2015 and 2020) represents an average over a 5-year period. For instance, the year 2030 represents an average over the 2028–2032 period. 2015 and 2020 data years correspond to the actual data points. The "Other" category includes geothermal generation and electricity trade.
Source: developed by authors using the TIMES-Ukraine model.

together accounting for 46% of the total supply. The share of modern renewables[3] increases substantially – from 6% in 2020 to 38% in 2050. Solar and wind generations show the largest growth rates during the modeled period, as their installed capacity increases at a pace of 11%–14% per year (Fig. 3).

Nuclear power significantly loses its share in TPES in a post-2035 period (Fig. 3). As the potential maximum lifetime extension of existing NPPs is at least till 2035 (Table 1), an extension option is being selected by the model as an economically feasible solution and thus the share of nuclear energy in TPES remains high in 2035 (around 25%). In the post-2035 period, existing NPPs are being decommissioned and partially substituted by new small and big NPPs (Fig. 3). At the same time, newly added nuclear capacities are not enough to fully substitute the decommissioned ones and the share of nuclear power in TPES drops to under 16% in 2050 (Fig. 3). The contribution of nuclear power to the electricity mix also reduces substantially – from over 51% in 2020 to 21% in 2050 (Fig. 3). By the end of the period, 71% of nuclear generation is being supplied by existing NPPs and 29% by new small power plants. No new big NPPs are being constructed under the BaU scenario by 2050 as they are not cost-competitive compared to other types of electricity generation options. Appendix Bprovides an overview of the default cost and technological assumptions used in the current study.

GHG emissions in the BaU scenario show a declining trend over time. In 2050 emissions are 45% lower relative to the 2020 level (Fig. 4), as the overall decarbonization of the energy mix is observed. While emissions decline over time in all sectors, the most substantial reductions in emissions are observed in the electricity and heat generation activity (Fig. 4). In relative terms, the share of emissions from both residential and supply sectors increases over time (by 8 percentage points each), as these activities prove to be harder to decarbonize. Industrial sectors, such as chemicals, metals, and non-metallic minerals, with relatively limited efficiency improvement opportunities due to the relatively high cost of the alternative technologies, sustain their share in the total GHG emissions (around 33% both in 2020 and 2050).

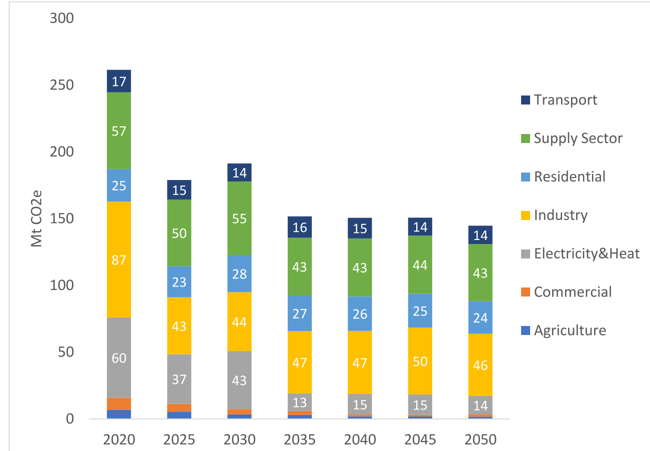

Fig. 4. GHG emissions under the BaU scenario.
Source: developed by authors using the TIMES-Ukraine model.

4.2. Mitigation scenarios

Baseline emission trends suggest that even without any additional climate mitigation measures, Ukraine is capable of achieving absolute decoupling – a development trajectory, where emission volumes decline, while the level of economic activity (GDP) increases (Wiedmann et al., 2015). At the same time, such an emission trajectory is not consistent with Ukraine's efforts to limit global warming well below 2 °C.

To explore more stringent mitigation pathways, we develop a GHG emission reduction scenario that is consistent with Ukraine's reaching net zero GHG emissions by 2050. This scenario is supported by Ukraine's recent signing of the Decision of the Ministerial Council of the Energy Community No 2022/02/MC-EnC regarding the ratification of the Regulation (EU) 2018/1999 (Energy Community, 2022). The considered mitigation scenario is consistent with a 1.5 °C mitigation effort for Ukraine estimated in the Climate Action Tracker study (CAT, 2020) (Fig. 5). Depending on the choice of approach, more or less stringent targets can be derived for Ukraine, though in general, the CAT (2020) approach reported in Fig. 5 results in a more ambitious mitigation target for Ukraine than the average over five IPCC equity categories derived in Robiou du Pont et al. (2017), as discussed in Chepeliev et al. (2021).

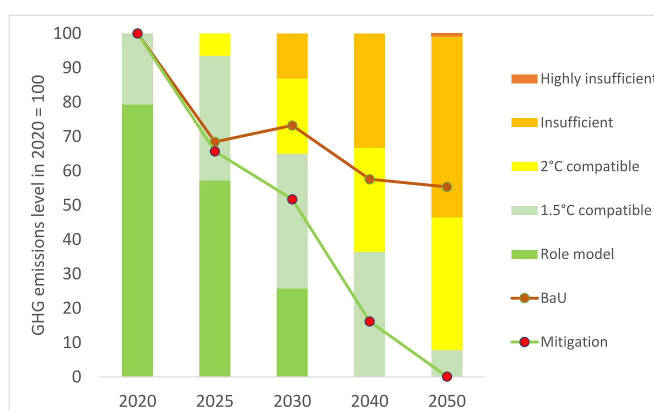

Fig. 5. GHG emission trajectories under considered scenarios and Ukraine's fair contribution to mitigating global warming. *Notes:* quantification of the mitigation targets for Ukraine are based on the CAT (2020) estimates that include the impact of COVID-19. The emissions level in 2020 is indexed to 100. Since CAT (2020) reports 2030 and 2050 emissions, 2040 levels are estimated using linear approximation between 2030 and 2050.
Source: developed by authors based on CAT (2020) and TIMES-Ukraine model.

[3] These include solar, wind, hydro, geothermal and biofuels (excluding traditional biomass). Currently existing subsidies to renewable energy sources are gradually eliminated by 2030.

The considered mitigation scenario is substantially more ambitious than Ukraine's Second Nationally Determined Contribution (NDC), which is aimed at reducing GHG emissions by 65% of the 1990 level in 2030 (Government of Ukraine, 2021). In our mitigation scenario, GHG emissions in 2030 fall by around 84% relative to the 1990 level. Although it should be noted that the Ukrainian Second NDC was developed both before the COVID-19 pandemic, as well as the Russian invasion of Ukraine, therefore, unlike this study, it does not take into account the impacts of these major events.

Implementation of such ambitious mitigation targets leads to substantial changes in the energy mix (Fig. 6). In the mitigation scenario, the primary supply of coal is almost eliminated by 2040 – a reduction of 94% relative to the 2020 level. By 2050 the primary supply of both coal and gas drops by 98% w.r.t. 2020 level in line with the ambitious decarbonization of the energy system. Wind and solar generations expand substantially, together contributing around 24% of the supply mix, with a larger contribution coming from wind due to more favorable conditions for this type of generation in Ukraine compared to solar (EBRD, 2020). Even more rapid expansion is observed for the case of bioenergy, which by the end of the modeled period constitutes almost 50% of the total primary energy supplying both heat and electricity.[4] This supports earlier findings of the important role of this energy source in Ukraine's mitigation efforts (Chepeliev et al., 2021). The volume of the primary oil supply drops substantially by 2050 (−90% wr.t. 2020 level), as almost the entire road transport sector is being electrified (Fig. 6).

The trend of transport electrification in the mitigation scenario can be also observed by examining the composition of emissions by sectors (Fig. 7). In 2050 only emissions in the industrial and supply sectors are present in the system, as all other activities are fully decarbonized. Key channels of decarbonization in industry include increasing electrification rates (e.g. in metal and steel production), transitioning from natural gas to renewable gases (e.g. in chemical industry), and increasing use of recycled and renewable feedstocks (e.g. in cement production). Space

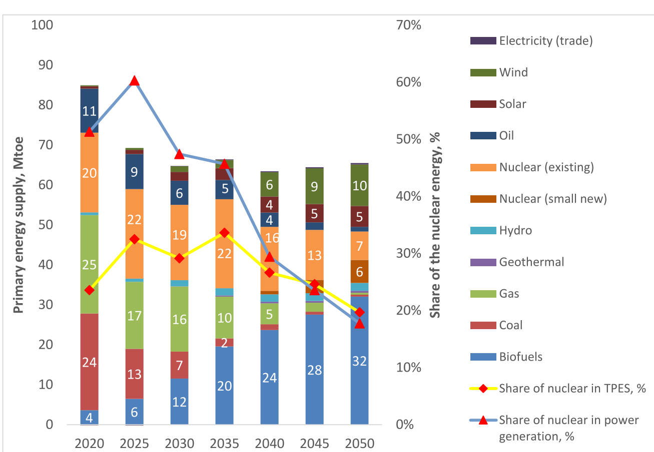

Fig. 6. TPES and the share of nuclear energy under the mitigation scenario.
Notes: TPES is estimated based on the energy balance accounting framework, i. e. no conversion rates for renewable electricity are applied.
Source: developed by authors using the TIMES-Ukraine model.

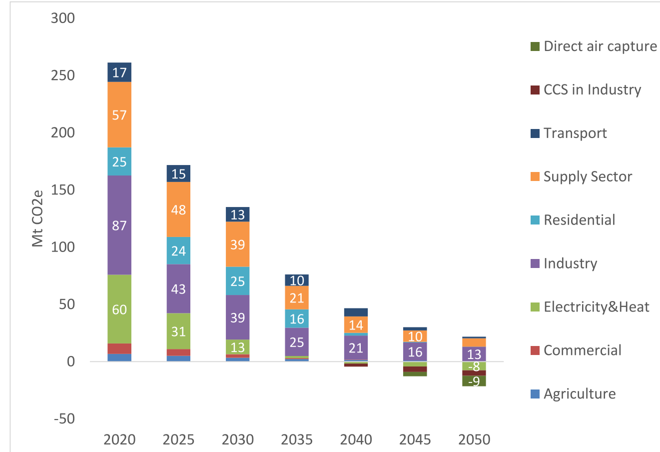

Fig. 7. GHG emissions under the mitigation scenario.
Source: developed by authors using the TIMES-Ukraine model.

and water heating activities see an increasing penetration of heat pumps (both air and ground sources) in combination with solar power technologies. Increasing energy efficiency plays an important role in reducing energy demand both in commercial and residential buildings. The latter is combined with switching toward renewable energy sources, since the electricity and heat generation sector almost fully decarbonizes in 2035, with abatement technologies being relatively cheap for this activity. At the same time, reducing emissions in the industrial sector proves to be the most challenging. This result is in alignment with earlier literature that suggests relatively high abatement costs in such sectors as the cement industry, iron and steel, and chemicals (Paltsev et al., 2021). All these sectors play an important role in the Ukrainian economy, as the country is a leading producer and exporter of these commodities (SSSU, 2022). Under the mitigation scenario, a substantial reduction in emissions in the industrial and supply sectors is achieved via the introduction of carbon capture and storage (CCS) and direct air capture (DAC) technologies that become cost-efficient closer to the end of the period and in 2050 allow capturing around 14 $MtCO_2e$ emissions (Fig. 7). Negative emissions in electricity and heat generation activities are attributed to the application of the bioenergy carbon capture and storage (BECCS) technology.

Total system costs (TSC)[5] under the mitigation scenario increase by around 13% relative to the baseline case, indicating that achievement of the net zero emissions target in 2050 could come at a moderate cost for the economy.[6] However, such aggregate changes hide an important distributional aspect of expenses over time.

Examining the investment pathway, one can see that the investment needs are not uniformly distributed across the years. Under the baseline scenario, larger amounts of investment needs are observed during 2030–2035 period and are associated with the expansion and rebuilding of the national energy system (Fig. 8a). Under the mitigation scenario, in relative terms, investment needs are increasing in the second half of the period – peaking during the 2035–2045 timeframe (Fig. 8b). In the case of the pre-2030 period, additional investments are largely associated with the development of new bioenergy projects, as well as demand-

[4] It should be noted that the bioenergy TPES share reported here is estimated based on the energy balance accounting framework, i.e. no conversion rates for noncombustible renewable energy sources are applied. An equivalency factor of 40% (British Petroleum, 2022), would imply that the input-equivalent primary energy from solar and wind power generation under the mitigation scenario is around 39 Mtoe, which is almost 22% larger than the 32 Mtoe supplied by the biofuels.

[5] Total system costs are used to measure the aggregate costs of the baseline and policy scenarios. Total system costs represent all costs (operational and investment expenditures) of the energy system operation discounted to the 2005 reference year of the model and summed over the corresponding period of time. A discount rate of 5% is used. CAPEX estimates reported in the paper are not annualized.

[6] When considered in the macroeconomic context, these additional TSC represent around 3.5% of the cumulative discounted GDP over the 2020–2050 timeframe.

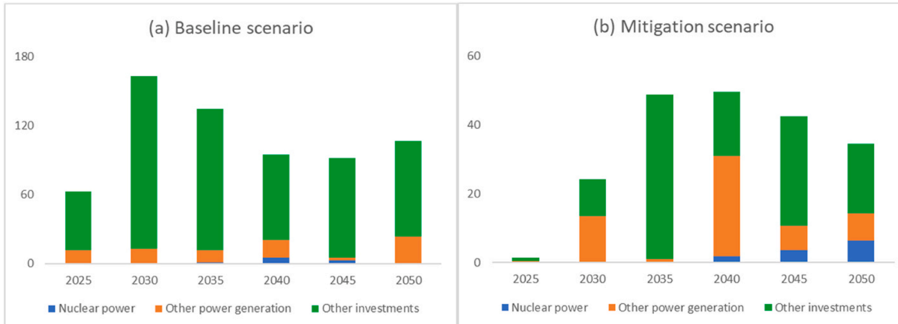

Fig. 8. Distribution of investments across scenarios and years, billion EUR. *Notes:* panel (a) represents investments under the baseline scenario; panel (b) represents investments needed in addition to the baseline scenario investments to achieve the mitigation goals. "Other investments" correspond to all other investment needs outside the electricity and heat generation sector.
Source: developed by authors using the TIMES-Ukraine model.

related measures (energy efficiency, electrification, etc.). In 2050, investment needs are more diversely distributed, covering a larger set of new generation capacities, including new small and large nuclear power plants (Fig. 8b). It should be noted, however, that the actual mitigation-related expenditures within the economy would have different (most likely more uniform) distribution over time, driven by the related loan schedules. As an alternative metric of changing costs across considered scenarios, Appendix Dreports marginal prices of electricity under various scenario options.

In terms of the role of nuclear power generation under the mitigation scenario, its share moderately increases relative to the baseline case, reaching 20% in 2050 (a five percentage points increase compared to the baseline pathway). This expansion is happening due to the construction of the new small nuclear power plants, while the capacity of large NPPs remains the same as in the BaU scenario (Fig. 6). The relative advantage of the small NPPs can be explained by their higher net capacity (availability) factor – while large NPPs have an availability of 93%, the availability factor for the small modular reactors is 98% (Tables B.14, B.15; Appendix B). In additional small NPPs have shorter construction period than large NPPs – 3 years vs 5 years respectively.

5. Potential futures of the nuclear power generation

5.1. Techno-economic factors

The future role of nuclear power generation is shaped by a variety of economic, environmental, technological, social, and policy-induced drivers (Sovacool and Valentine, 2012). In the current analysis, we explore the role of three broad sets of factors. The first group defines the relative competitiveness of this technology and is driven by the underlying techno-economic assumptions. Existing studies suggest a relatively wide range of estimates for the capital cost of the NPPs construction in Europe – ranging between 4,986 USD per kW in Slovakia to 7,535 USD per kW in Hungary (International Energy Agency /Nuclear Energy Agency, 2015). To explore this uncertainty, we use lower and higher estimates of CAPEX equaling 5,000 USD per kW and 7,000 USD per kW respectively following Energoatom. 2016 (2016; 2021) estimates, in addition to our central case value of 5,900 USD per kW.

Apart from capital costs, another important characteristic of the NPPs that define their economic feasibility is the capacity factor. In general, NPPs have the highest capacity factors across all generation technologies in many countries exceeding 80%–85% (IAEA, 2022). In the case of Ukraine, the average capacity factor over 2018–2020 was 70.3%, while in the neighboring countries like Hungary, Romania, and Slovakia the average capacity factor during the same period was over 90%. A higher capacity factor in the case of these Eastern EU member states has been largely driven by the fact that these countries have newer NPPs that required a lower number of days for maintenance and repairs.[7] Additional maintenance measures implemented on Ukrainian NPPs could lead to a lower number of repairs and thus increase load factor. The latter case is explored under an additional sensitivity scenario. Assumptions for the corresponding cases are outlined in Appendix G.

Finally, the third considered driver is a variation in the generation costs of other technologies, in particular, solar and wind power generation. Literature suggests that there is a major uncertainty in terms of the future CAPEX estimates for these technologies, as in the case of photovoltaic (PV) plant system CAPEX ranges between 100 and 500 EUR per kWe, while in the case of onshore wind, a range is between 600 and 1200 EUR per kWe for 2050 (Sens et al., 2022). Under the default assumptions of the TIMES-Ukraine model, CAPEX for these two generation technologies is within the above-reported bounds, but closer to the upper range of the estimates (Tables B.14, B.15; Appendix B). To explore the potential impact of more optimistic assumptions regarding the reduction of the costs of renewable generation technologies over time, we consider a case where the CAPEX of solar and wind generations follows the lower bound assumptions of the IRENA (2019a) and IRENA (2019b) studies respectively. The latter corresponds to the lower bounds of the CAPEX estimates discussed above.

Simulations suggest that across considered techno-economic assumptions for nuclear power generation, variations in CAPEX have the most significant impact on the contribution of nuclear power to the total energy mix (Fig. 9a). CAPEX of $7000 reduces the share of nuclear in the baseline scenario in 2050 by almost 5 percentage points, while the reduction under the mitigation scenario is 0.5 percentage points. Lower CAPEX ($5000) leads to an expansion in the share of nuclear in TPES by 7 percentage points under the baseline scenario and 0.9 percentage points under the mitigation pathway (Fig. 9a). This expansion is happening through the construction of new small nuclear power plants, which have a higher availability factor compared to the large NPPs under the same construction costs (Tables B.14, B.15; Appendix B). Increased load factor leads to more moderate changes in the share of nuclear in TPES. More substantial changes in the nuclear power generation volumes are observed under the reduction in the cost of solar and

[7] It should be noted that higher capacity factor is also driven by other factors, including more efficient transmission and distribution networks. Modernization of the energy networks in Ukraine would require additional investments, which are not considered in the current analysis.

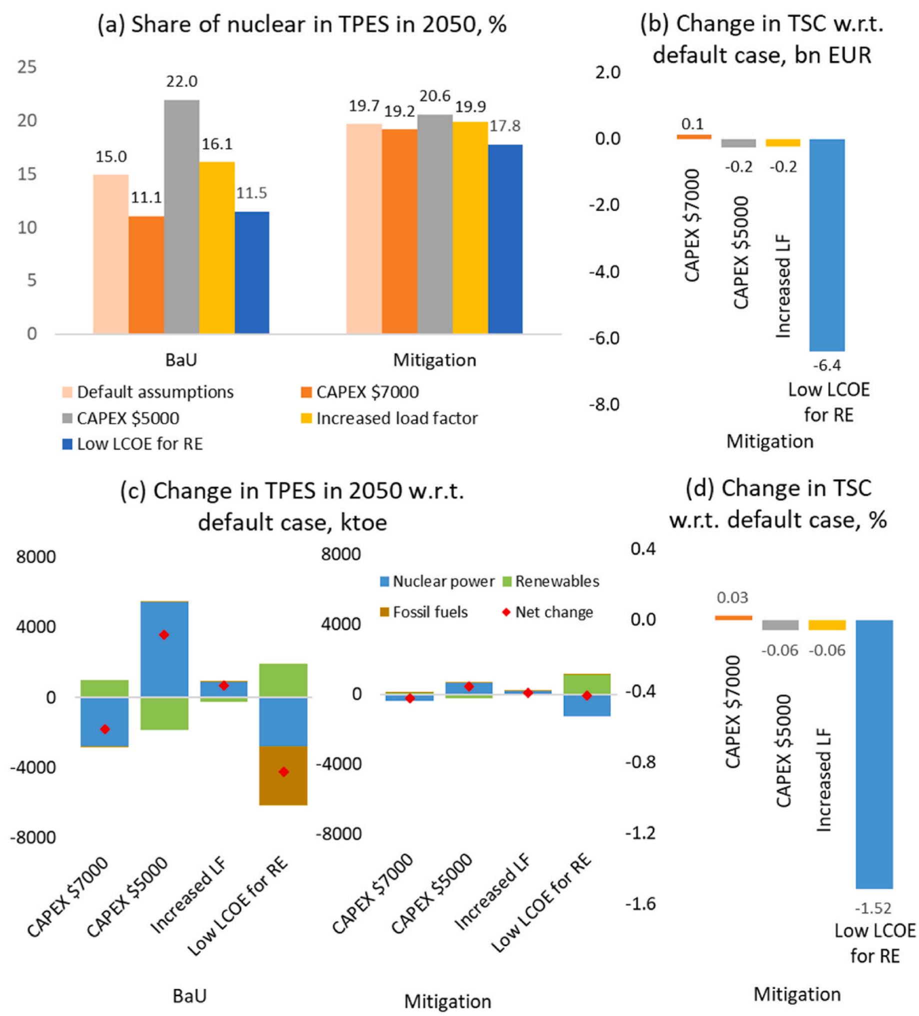

Fig. 9. Selected energy system indicators under alternative techno-economic assumptions for nuclear power plants. *Notes:* changes in TSC are cumulative over the analyzed time horizon. "LF" stands for load factor. "RE" stands for renewable energy and marks the scenario with reduced LCOE for solar and wind generations. *Source:* developed by authors using the TIMES-Ukraine model.

wind generation, as the share of nuclear in the baseline drops by 3.5 percentage points and under the mitigation scenario by almost 2 percentage points. These reductions are happening due to the decline in the construction of new small NPPs.

In almost all considered cases changes in nuclear power generation lead to changes in renewable generation supply, without having a major impact on fossil-fuel-based generation (Fig. 9c). The only exception is the baseline scenario under low LCOE for solar and wind generation, where increasing renewable generation substitutes both nuclear and fossil fuel supply in approximately equal shares (Fig. 9c). Changes in aggregate TPES across scenarios are largely driven by differences in efficiency rates across various technologies, as nuclear power generation has a substantially lower efficiency rate (around 33%) compared to gas/combined-cycle (50%), and solar/wind (100%) power.

While we find a substantial sensitivity of nuclear energy supply under varying techno-economic assumptions for NPPs, these have a very minor impact on TSC (Fig. 9b and d). Variation in the techno-economic assumptions of the nuclear power generation changes TSC within 0.1% across scenarios (Fig. 9d). With higher CAPEX assumptions under the mitigation scenario TSC increase by 0.1 billion EUR (0.03% of the default value). Under more favorable techno-economic assumptions for nuclear (lower CAPEX or higher load factor), positive impacts are somewhat more substantial, but still do not exceed 0.2 billion EUR (0.06%) in terms of cumulative TSC (Fig. 9b and d). In contrast, a reduction in the LCOE for solar and wind generation proves to have substantial benefits for the overall cost of transition, reducing TSC by around 6.4 billion EUR, which is equivalent to 1.5% over the analyzed period (Fig. 9b and d).

5.2. Safety and environmental drivers

Decisions regarding future of the nuclear power generation could be impacted not only by the techno-economic competitiveness of this technology but also by considerations regarding potential safety risks, as well as environmental concerns related to nuclear waste storage (Prăvălie and Bandoc, 2018; Dai et al., 2019). To analyze the impacts of such considerations, we explore a set of scenarios with different levels of restrictions on the future development of nuclear power in Ukraine. In particular, we consider three options: (a) restrictions on the construction of new large NPPs; (b) restrictions on the construction of large and small NPPs, and (c) restrictions on the construction of large and small NPPs, as well as no lifetime extensions.

Results suggest that restrictions on the construction of large NPPs have no impact on either generation mix or transition costs (Fig. 10), since new large nuclear power plants are not being constructed under the default mitigation scenario and thus corresponding constraint is not binding. When in addition to the construction of large NPPs, the ban is also imposed on the development of new small modular reactors, this has a moderate negative impact on the overall cost of transition (measured as a change in cumulative TSC), as the latter increases by 0.8

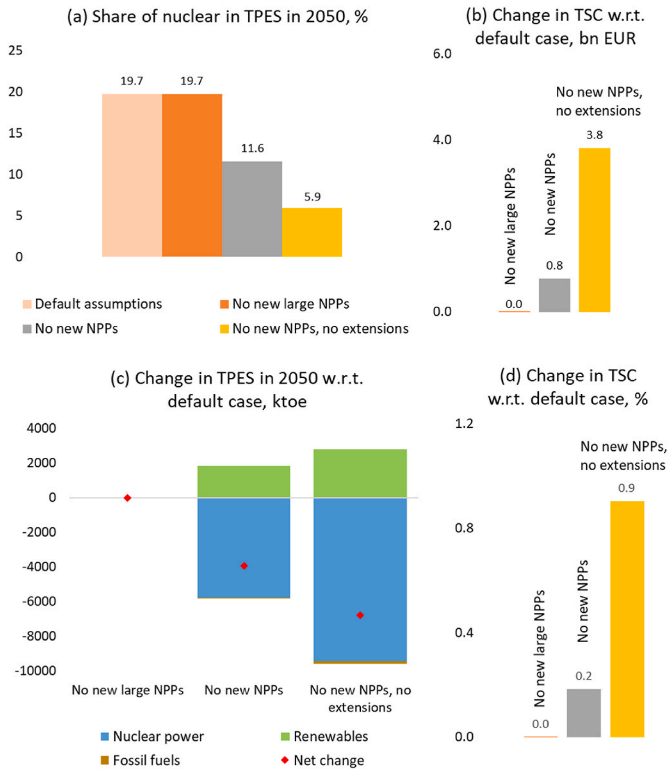

Fig. 10. Selected energy system indicators for the mitigation scenario under varying nuclear power restrictions. *Notes:* Differences are reported relative to the case with no restrictions. Changes in TSC are cumulative over the analyzed time horizon (2020–2050).
Source: developed by authors using the TIMES-Ukraine model.

bn USD or 0.2% (Fig. 10b and d). A more prohibitive case that does not allow for any lifetime extensions increases mitigation costs much more substantially – by 3.8 billion EUR or 0.9% (Fig. 10b and d).

In terms of the impacts on nuclear power generation share, a ban on the construction of new small NPPs leads to a reduction in nuclear generation share by over 8 percentage points in 2050 (Fig. 10a). Under the most restrictive case (no new NPPs and no extensions) even more substantial reductions are observed (almost 14 percentage points), as only two blocks remain in operation. In all considered cases, a reduction in nuclear power generation is being compensated by increasing volumes of renewable generation – primarily solar and wind.

5.3. *Optimistic economic recovery pathway*

Considering a major uncertainty around Ukraine's economic recovery pathway, in this section, we explore the future of nuclear power generation in the country under the alternative growth trajectory of the national economy (Appendix E). In particular, we consider a more optimistic GDP growth rates post-2025 driven by a higher level of gross capital formation, which is assumed to reach 25%–30% in the second half of the analyzed period. In this scenario, it is assumed that at the sectoral level the key drivers of economic growth, in addition to construction and agricultural activities, would include high-tech manufacturing, the chemical industry, information technologies, and professional services. In this scenario, the average GDP growth rate over the 2020–2050 period is 3.7% compared to 1.8% in the default BaU. GDP growth rates over the 2025–2050 period are 5.3% and 3.1% for the optimistic and default scenarios respectively.

The updated economic assumptions are used to construct the refined baseline and mitigation scenarios. In the latter case, the targeted emission trajectory remains the same as discussed in section 4.2. Results suggest that with refined baseline drivers and higher economic growth, the TPES is substantially higher compared to the default BaU case – by around 43% in 2050 (Fig. 11a). As a result, GHG emissions under the optimistic baseline scenario are 42% in 2050 compared to the default baseline level (Appendix F), requiring more substantial mitigation efforts to reach the net-zero targets in 2050. The structure of the energy supply mix remains similar to the default reference scenario: the share of fossil fuels is still substantial (47% in 2050) and nuclear generation contributes 14.5% to the overall supply mix in 2050 (Fig. 11a). Nuclear-based primary energy supply is equally split between existing large and new small power plants (Fig. 11a).

A mitigation scenario under optimistic baseline assumptions sees a substantial expansion of wind power generation (compared to the default BaU) and nuclear power. A moderate expansion in solar and biomass-based generation (compared to the mitigation under default BaU). The share of primary energy supply from nuclear reaches almost 29% in 2050 with over 60% of this being contributed by small modular reactors (Fig. 11b).

To explore the role of nuclear power generation under the optimistic baseline economic growth, we assess three sets of factors among those considered in sections 5.1 and 5.2. To explore the potential more favorable conditions for nuclear power generation we look into the case that combines lower CAPEX and increased load factor. On the downside, we evaluate an impact of the case that does not allow the construction of new NPPs or the extension of the existing ones. Finally, to take into account changes in the cost of other generation technologies, we consider an option with low CAPEX for wind and solar generation (Fig. 12).

Lower CAPEX and increased load factor case have a moderate positive impact on TSC that fall by 2 bn EUR or 0.2% relative to the default case (Fig. 12b and d). The nuclear energy share in TPES increases substantially in this case - by almost 21 percentage points (Fig. 12a), largely substituting solar and wind power generation (Fig. 12c). Expansion in nuclear power generation is happening both via the construction of new small, as well as large NPPs, as in 2050 around 42% of nuclear-based energy is supplied by the new small NPPs, 45% by the new big NPPs and 14% by the existing large NPPs. The fact that a substantial share of energy is being supplied by the new large NPPs in this scenario is driven by the fact that the construction of new modular reactors in this scenario is reaching an allowed upper bound (within each period) and thus the additional demand is covered by new large NPPs. At the same time, as can be seen from the differences in TSC, even these optimistic assumptions regarding NPPs have a relatively low impact on the overall transition costs, indicating that other generation technologies are competitive with NPPs under these favorable conditions for the latter source of energy.

Restrictions on the construction of new NPPs, as well as a ban on extending the existing blocks, lead to a 4.9 bn EUR or 0.6% increase in TSC (Fig. 12b and d). In this case, the share of nuclear energy in TPES drops to 10.9% in 2050 (Fig. 12a), as it is being substituted by renewable energy sources (Fig. 12c). A reduction in the cost of solar and wind generation has the most substantial benefits in terms of reductions in TSC, as the latter decline by 10 bn EUR or 1.2% relative to the default case.

Overall, the results under a more optimistic economic recovery pathway suggest that with higher energy demand, nuclear power has better scope for sustaining (or even expanding under favorable techno-economic assumptions) its share in the primary energy supply, since the renewable energy generation (solar, wind and bioenergy) is closer to their allowed upper bounds (potentials) in this case. At the same time, even in such conditions, renewable generation sources remain highly competitive and any restrictions on nuclear power expansions in the future would not be associated with substantial economic costs. In addition, if the reductions in the cost of renewable power generation, in particular, solar and wind, would follow the optimistic forecasts (IRENA, 2019a; 2019b), associated economic benefits would be much

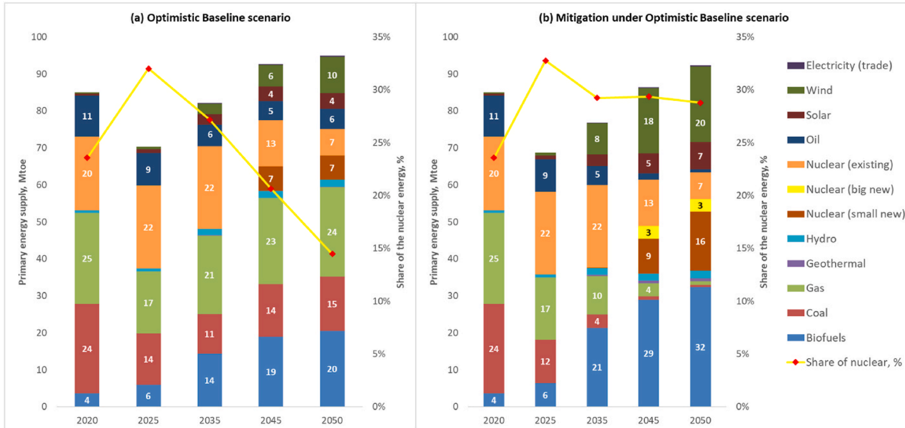

Fig. 11. Optimistic Baseline and corresponding mitigation scenarios. *Notes:* Panel (a) reports the primary energy supply and the share of nuclear energy under an optimistic baseline scenario. Panel (b) reports the primary energy supply for the mitigation scenario implemented under optimistic baseline assumptions. *Source:* developed by authors using the TIMES-Ukraine model.

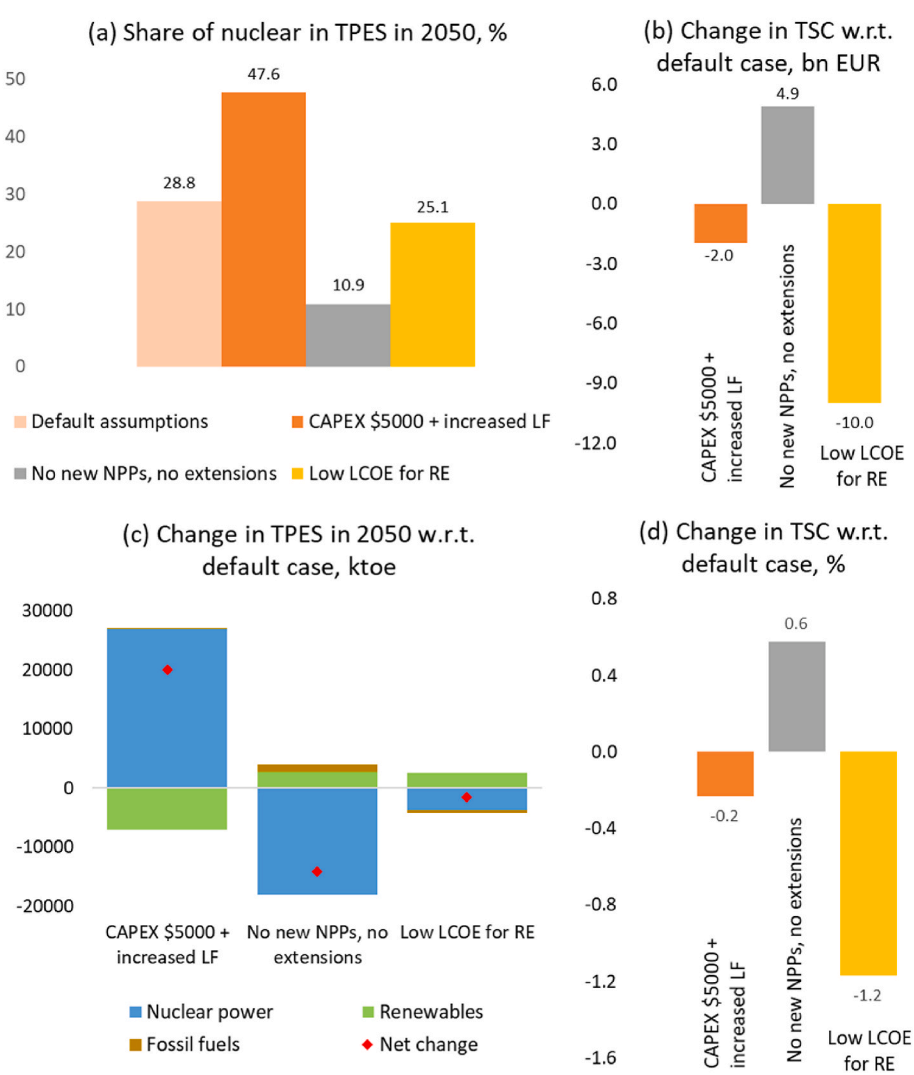

Fig. 12. Selected energy system indicators for the mitigation scenario under the optimistic economic recovery pathway *Notes:* changes in TSC are cumulative over the analyzed time horizon. "LF" stands for load factor. "RE" stands for renewable energy and marks the scenario with reduced LCOE for solar and wind generations. *Source:* developed by authors using the TIMES-Ukraine model.

more substantial than (the costs or benefits) from the variation in the techno-economic assumptions for nuclear power generation.

6. Conclusion and policy implications

With over 52% of electricity coming from nuclear power plants as of 2020, Ukraine had one of the highest shares of nuclear power generation in the world. At the same time, the lifetime of most NPPs in the country expires between 2025 and 2030, and long-term decisions regarding a possible extension of the lifespan or construction of the new NPPs need to be made, considering social, economic, and environmental aspects. Decisions regarding the future of nuclear energy are impacted both by economic viability and competitiveness (techno-economic factors), as well as driven by concerns regarding potential safety issues and environmental implications of nuclear waste treatment. Additional safety considerations have been raised following the Russian invasion of Ukraine and attacks on nuclear power facilities (Sawano et al., 2022).

In this paper, we relied on the TIMES-Ukraine energy system model and analyzed an ambitious climate policy scenario (consistent with reaching net-zero GHG emissions by 2050) under alternative futures of nuclear power generation. We considered varying techno-economic (NPPs' construction costs and capacity factors, varying LCOE for solar and wind generation), policy (ban on constructing new large or small NPPs, and restrictions on the NPPs' lifespan extension), and demand (optimistic economic recovery pathway) factors.

Under the default techno-economic assumptions and demand drivers, the share of nuclear power in the total primary energy supply moderately reduces over time reaching around 20% in 2050 in the mitigation scenario. Existing large nuclear reactors are being extended, where technically possible, but no new large NPPs are being constructed, as they are less competitive than the alternative renewable generation sources, such as solar and wind, and even to a larger extent bioenergy. The mitigation scenario, however, sees an expansion in the construction of small modular nuclear reactors, which have CAPEX comparable with large NPPs but are characterized by higher availability factor and thus are overall more economically attractive. As a result, in 2050 small modular reactors supply around half of all nuclear-based power.

Changes in techno-economic drivers of the nuclear power generation has a very moderate impact on the total cost of the energy transition, as variation in TSC (positive or negative change) does not exceed 0.1%–0.2% relative to the default case even under optimist economic growth trajectory with high energy demand. Policy decisions on restricting nuclear power generation could have a more substantial impact on the overall system costs. Under the most restrictive case – ban on the lifetime extensions or construction of new NPPs – TSC increase by 4–5 bn USD (0.6%–0.9%) depending on the assumed baseline. Restrictions on the construction of new large nuclear power plants have no impact under the default economic growth assumptions since only new small modular reactors are being developed in the corresponding mitigation scenario. Restrictions on the construction of new modular reactors increase the cost of mitigation by around 0.2%

Variation in both techno-economic and safety drivers though has a major impact on the share of nuclear power generation in the total energy mix, as the latter varies between 6% and 21% in 2050 under climate mitigation scenario and default economic growth assumptions. The share of nuclear in TPES reaches 48% in the mitigation scenario under optimistic economic growth assumptions and favorable techno-economic conditions for the nuclear power development (low CAPEX and high load factor). Since the supply of renewable energy sources is closer to their allowed potential in the case of high economic growth, nuclear power generation serves as an economically feasible solution for meeting the additional energy demand. At the same time, even in such conditions, renewable generation sources remain highly competitive and any restrictions on nuclear power are being compensated by an expansion in a renewable generation without major implications for the overall mitigation costs. In the case when reductions in the cost of solar and wind generation follow the optimistic forecast, TSC decline by up to 1.2%–1.5%, which is much more substantial than the costs or benefits from changing assumptions underlying nuclear power generation.

It should be noted that policy decisions regarding future technological solutions should also take into account additional considerations not explicitly analyzed in the paper. First, the timing of the decision-making process is critical in the case of NPPs. Considering that the global median construction time of large NPPs is around 7.7 years (Harris et al., 2013) and taking into account decommissioning schedule, decisions regarding nuclear power generation should be made well in advance and at a pre-defined timeline. Second, it is important to take into account the broad economic impacts of the alternative generation options, in particular, whether associated fuel and technological supply chains could be developed and scaled up domestically or would they be primarily of import origin. Having supply chains with a high share of domestic inputs (equipment, fuel, energy services, etc.) would be preferable both from the economic, as well as energy security points of view. In this context, small modular reactors have a shorter construction period and with potentially less complex supply chains could be characterized by a better opportunity for the domestic sourcing of inputs (Mignacca and Locatelli, 2020). In addition, considering that the overall scale of the infrastructural project when constructing a small NPP is substantially lower compared to the development of a large nuclear plant, the former also bares a much lower risk (of failure). Combined with the higher availability factors under the same construction costs, small modular reactors could be considered preferable to large NPPs.

At the same time, it should be noted that while model-based results suggest several benefits of small modular reactors over large NPPs, the former generation technology is still relatively new and has a low level of market penetration, as only three reactors were in operation as of 2022 (IEA, 2022). This creates uncertainty in terms of the actual costs and timeframes for implementing this technology (Bartak et al., 2021), which should be taken into consideration within the decision-making process. As more small modular reactors would be coming into operation over the next years, a more reliable parametrization of the techno-economic characteristics of this technology would be possible, enhancing the modeling and analytical capacity for the assessment of future energy transition pathways.

Though to a less extent than for the case of small modular reactors, projects implemented in countries around the world suggest that the construction of large NPPs has been subject to increasing duration and construction costs comparedto the initial estimates in a number of cases (Eash-Gates et al., 2020). In this regard, a corresponding uncertainty should be factored into the decision-making process of the construction of the new large NPPs. It should also be noted that notwithstanding the size of the nuclear power plants constructed in Ukraine, they would be dependent on imported nuclear fuel. Considering a limited number of potential suppliers, the security of the fuel supply should be factored in as one of the key decision criteria when deciding on the potential development of the new NPPs in the country.

Overall, our results suggest that except for the case of not allowing an extension of existing nuclear power plants, civil society, and policy-makers can decide on the future of nuclear power generation in Ukraine without major implications for the cost of energy even under ambitious mitigation pathways. With a range of available renewable generation technologies, such as wind, solar, and bioenergy, retired nuclear power plants can be substituted by these alternatives in a cost-competitive manner.

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CRediT authorship contribution statement

Maksym Chepeliev: Conceptualization, Writing – original draft, Writing – review & editing, Visualization, Supervision. **Oleksandr Diachuk:** Methodology, Software, Formal analysis, Investigation, Supervision. **Roman Podolets:** Methodology, Software. **Andrii Semeniuk:** Methodology, Software, Formal analysis, Investigation, Visualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Appendix A. Macro assumptions of the Reference scenario

	2020	2025	2030	2035	2040	2045	2050
GDP structure, %							
Agriculture	9.8	12.0	12.5	12.9	13.0	12.9	12.7
Mining	6.6	5.1	4.6	3.4	3.0	2.7	2.4
Manufacturing	10.4	7.6	7.5	7.5	7.5	7.5	7.6
Electricity and heat supply	3.4s	4.3	3.6	3.0	2.8	2.6	2.5
Construction	2.7	1.7	2.1	2.5	2.7	2.8	2.8
Trade	14.1	15.1	15.3	15.3	15.0	14.7	14.5
Transportation	5.4	4.4	4.4	4.3	4.3	4.2	4.1
Other services	32.9	36.5	36.7	37.4	38.0	38.9	39.7
Taxes and subsidies	14.8	13.4	13.4	13.6	13.6	13.6	13.7
Aggregate GDP in billion 2021 USD GDP	193	155	197	235	265	297	332

Notes: Totals over GDP sectoral shares might not exactly add up to 100% due to rounding error.

Appendix B. Cost and technological assumptions for selected technologies

B.1 Nuclear power plants (NPPs)

Table B.11
Unit №3 on Khmelnytska NPP

Technical and economic parameters	2025–2050
CAPEX, USD/kWe	5900
Fixed Operation and Maintenance Expenses, USD/kWe	73.35
Variable Operation and Maintenance Expenses, USD/MWh	1.65
Decommission Cost, % of CAPEX	10
Efficiency, %	33
Net Capacity Factor (Availability factor), %	83
Heat Rate, MWh•of heat/MWh of electricity, %	0.03
Lifetime, years	60
Period of construction, years	4
Potential year of the start of the operation, year	2025
Self-consumption of electricity, %	5

Table B.12
Unit №4 on Khmelnytska NPP

Technical and economic parameters	2030–2050
CAPEX, USD/kWe	5900
Fixed Operation and Maintenance Expenses, USD/kWe	73.35
Variable Operation and Maintenance Expenses, USD/MWh	1.65
Decommission Cost, % of CAPEX	10
Efficiency, %	33
Net Capacity Factor (Availability factor), %	83
Heat Rate, MWh•of heat production/MWh of electricity production, %	0,03
Lifetime, years	60
Period of construction, years	5
Potential year of the start of the operation, year	2030
Self-consumption of electricity, %	5

Table B.13
Extension of the operational life of existing units of NPPs

Technical and economic parameters	2015–2050
The cost of Extension of the operational life for 20 (30) years, USD/kWe	300 (400)
Fixed Operation and Maintenance Expenses, USD/kWe	73.35
Variable Operation and Maintenance Expenses, USD/MWh	1,65
Efficiency, %	33
Net Capacity Factor (Availability factor), %	80
Heat Rate, MWh•of heat production/MWh of electricity production, %	0,03

Table B.14
New big units of NPPs (1000 MW)

Technical and economic parameters	2025–2100
CAPEX, USD/kWe	5250
Fixed Operation and Maintenance Expenses, USD/kWe	73.35
Variable Operation and Maintenance Expenses, USD/MWh	1,65
Decommission Cost, % of CAPEX	400
Efficiency, %	33,8
Net Capacity Factor (Availability factor), %	93
Heat Rate, MWh•of heat production/MWh of electricity production, %	0,04
Lifetime, years	80
Period of construction, years	5
Potential year of the start of the operation, year	2031
Self-consumption of electricity, %	5

Table B.15
New small nuclear reactors (160 MW)

Parameters	Value
Overnight Capital Cost, USD/kWe	5250
Fixed Operation and Maintenance Expenses, USD/kWe.	73.35
Variable Operation and Maintenance Expenses, USD/MWh	1.65
Decommission Cost, USD/kW	400
Efficiency, %	32
Net Capacity Factor (Availability factor), %	98
Lifetime, years	80
Period of construction, years	3
Potential year of the start of the operation, year	2025
Self-consumption of electricity, %	5

B.2 Thermal Power Plants (TPPs)

Table B.21
Gas TPPs

Indicator\year	2015–2050			
	Combined Cycle	Combustion Turbine	Steam Turbine	Fast Start Internal Combustion Engine
CAPEX, EUR/kWe	1000	600	920	1000
Fixed Operation and Maintenance Expenses, EUR/kWe	20	11.9	16.6	20
Variable Operation and Maintenance Expenses, EUR/MWh	2	4.1	2.1	0.555
Decommission Cost, % of CAPEX	2	2	2	2
Efficiency, %	60	40	42	50
Net Capacity Factor (Availability factor), %	50	50	50	50 (as balancing ~1.5%)
Lifetime, years	35	30	30	35
Heat Rate, %	0.05	0.05	0.05	

Table B.22
Bioenergy TPPs.

Indicator\year	2015	2020	2025	2030	2035	2040	2045	2050
Wood biomass								
CAPEX, EUR/kWe	2800	2800	2800	2700	2650	2600	2550	2500
Wood biomass + CCS								

(*continued on next page*)

Table B.22 (*continued*)

Indicator\year	2015	2020	2025	2030	2035	2040	2045	2050
CAPEX, EUR/kWe	4000	3650	3550	3450	3350	3250	3200	3140
Fixed Operation and Maintenance Expenses, EUR/kWe	30							
Variable Operation and Maintenance Expenses, EUR/MWh	6.12							
Decommission Cost, % of CAPEX	1.5%							
Efficiency, %	24							
Net Capacity Factor (Availability factor), %	50							
Lifetime, years	30							
Biomass from the waste of agri-food complex, etc.								
CAPEX, EUR/kWe	3500	2900	2850	2800	2750	2700	2650	2600
Fixed Operation and Maintenance Expenses, EUR/kWe	30							
Variable Operation and Maintenance Expenses, EUR/MWh	6.12							
Decommission Cost, % of CAPEX	1.5%							
Efficiency, %	23							
Net Capacity Factor (Availability factor), %	50							
Lifetime, years	30							
Biogas								
CAPEX, EUR/kWe	4500	3200	3200	3200	3200	3200	3200	3200
Biogas + CCS								
CAPEX, EUR/kWe	5500	5350	5250	5150	5050	4950	4900	4850
Fixed Operation and Maintenance Expenses, EUR/kWe	30							
Variable Operation and Maintenance Expenses, EUR/MWh	6.12							
Decommission Cost, % of CAPEX	1.5%							
Efficiency, %	42							
Net Capacity Factor (Availability factor), %	50							
Lifetime, years	30							
Energy crops								
CAPEX, EUR/kWe	3300	2900	2850	2800	2750	2700	2650	2600
Energy crops + CCS								
CAPEX, EUR/kWe	3900	3750	3650	3550	3450	3350	3300	3250
Fixed Operation and Maintenance Expenses, EUR/kWe	30							
Variable Operation and Maintenance Expenses, EUR/MWh	6.12							
Decommission Cost, % of CAPEX	1.5%							
Efficiency, %	24							
Net Capacity Factor (Availability factor), %	50							
Lifetime, years	30							
Industrial Waste								
CAPEX, EUR/kWe	3500	2900	2850	2800	2750	2700	2650	2600
Fixed Operation and Maintenance Expenses, EUR/kWe	30							
Variable Operation and Maintenance Expenses, EUR/MWh	6.12							
Decommission Cost, % of CAPEX	1.5							
Efficiency, %	23							
Net Capacity Factor (Availability factor), %	50							
Lifetime, years	30							
Heat Rate, %	0.05							

Table B.23
Gas TPPs with CCS

Indicator\year	2015–2050	
	Combined Cycle + CCS	Combustion Turbine + CCS
Overnight Capital Cost, EUR/kW	2450	2050
Fixed O&M Expenses, USD/kWe	24	14.3
Variable O&M Expenses, USD/MWh	2	4.1
Efficiency, %	51	34
Availability factor, %	50	50
Lifetime, years	35	30
Heat Rate, %	0.05	0.05

Table B.24
Coal TPPs

Indicator\year	2015–2050			
	IGCC	Supercritical parameters	Subcritical parameters	Circulating Fluidized Bed
CAPEX, EUR/kWe	1800	1300	1600	1700
Fixed Operation and Maintenance Expenses, EUR/kWe	63	43	30	27
Variable Operation and Maintenance Expenses, EUR/MWh	5.8	6	6	6
Decommission Cost, % of CAPEX	5	5	5	5
Efficiency, %	46	43	39	43

(*continued on next page*)

Table B.24 (*continued*)

Indicator\year	2015–2050			
	IGCC	Supercritical parameters	Subcritical parameters	Circulating Fluidized Bed
Net Capacity Factor (Availability factor), %	50	50	50	50
Lifetime, years	35	40	35	35
Heat Rate, %	0.15	0.15	0.15	0.15

Table B.25
Extension of the operational life of existing Coal TPPs

Indicator\year	2015–2050
CAPEX, EUR/kWe	950
Fixed Operation and Maintenance Expenses, EUR/kWe	33
Variable Operation and Maintenance Expenses, EUR/MWh	18
Decommission Cost, % of CAPEX	5
Efficiency, %	33–40
Net Capacity Factor (Availability factor), %	34–62
Lifetime, years	30
Heat Rate, %	0.04

Table B.26
Coal TPPs with CCS

Indicator\year	2015–2050			
	IGCC	Supercritical parameters	Subcritical parameters	Circulating Fluidized Bed
CAPEX, EUR/kWe	4400	3900	4650	4300
Fixed Operation and Maintenance Expenses, EUR/kWe	75	52	36	34
Variable Operation and Maintenance Expenses, EUR/MWh	5.8	6	6	6
Decommission Cost, % of CAPEX	5	5	5	5
Efficiency, %	39	37	33	36
Net Capacity Factor (Availability factor), %	50	50	50	50
Lifetime, years	35	35	35	35
Heat Rate, %	0.15	0.15	0.15	0.15

B.3 Cogeneration or combined heat and power (CHP)

Table B.31
Bioenergy CHPs

Indicator\year	2015	2020	2025	2030	2035	2040	2045	2050
Wood biomass								
CAPEX, EUR/kWe	3500	3500	3300	2850	2750	2700	2650	2600
Wood biomass + CCS								
CAPEX, EUR/kWe	4600	4450	4350	4250	4150	4050	4000	3950
Fixed Operation and Maintenance Expenses, EUR/kWe	50							
Variable Operation and Maintenance Expenses, EUR/MWh	6							
Decommission Cost, % of CAPEX	1.5							
Efficiency, %	20							
Net Capacity Factor (Availability factor), %	50							
Lifetime, years	35							
Biomass from the waste of agri-food complex								
CAPEX, EUR/kWe	3500	3400	3200	3100	2900	2900	2800	2800
Fixed Operation and Maintenance Expenses, EUR/kWe	56							
Variable Operation and Maintenance Expenses, EUR/MWh	6.6							
Decommission Cost, % of CAPEX	1.5							
Efficiency, %	19							
Net Capacity Factor (Availability factor), %	50							
Lifetime, years	35							
Municipal waste								
CAPEX, EUR/kWe	5500	5500	5200	2950	2850	2800	2750	2700
Fixed Operation and Maintenance Expenses, EUR/kWe	56							
Variable Operation and Maintenance Expenses, EUR/MWh	3.4							
Decommission Cost, % of CAPEX	1.5							
Efficiency, %	25							
Net Capacity Factor (Availability factor), %	50							
Lifetime, years	35							
Energy crops								
CAPEX, EUR/kWe	3500	3500	3300	3150	3050	3000	2950	2900

(*continued on next page*)

Table B.31 (*continued*)

Indicator\year	2015	2020	2025	2030	2035	2040	2045	2050
Energy crops + CCS								
CAPEX, EUR/kWe	4600	4450	4350	4250	4150	4050	4000	3950
Fixed Operation and Maintenance Expenses, EUR/kWe	50							
Variable Operation and Maintenance Expenses, EUR/MWh	6							
Decommission Cost, % of CAPEX	1.5							
Efficiency, %	20							
Net Capacity Factor (Availability factor), %	50							
Lifetime, years	35							

Table B.32
Gas CHPs

Indicator\year	2015–2050	
	Combined Cycle	Steam Turbine
CAPEX, EUR/kWe	800	920
Fixed Operation and Maintenance Expenses, EUR/kWe	42	42
Variable Operation and Maintenance Expenses, EUR/MWh	1.55	1.55
Decommission Cost, % of CAPEX	2.0	2.0
Efficiency, %	50	45
*Net Capacity Factor (Availability factor)**, %*	50	50
Lifetime, years	35	30
Heat Rate, %	1.5	1.5

* Availability factor is in the range of 46%–90%.

Table B.33
Gas CHPs with CCS

Indicator\year	2015–2050	
	Combined Cycle + CCS	Combustion Turbine + CCS
Overnight Capital Cost, EUR/kW	2450	2050
Fixed O&M Expenses, USD/kWe	24	14.3
Variable O&M Expenses, USD/MWh	2	4.1
Efficiency, %	51	34
Availability factor, %	50	50
Lifetime, years	35	30
Heat Rate, %	0.05	0.05

Table B.34
Coal CHPs

Indicator\year	2015–2050	
	Combined Cycle	Steam Turbine
CAPEX, EUR/kWe	1200	1100
Fixed Operation and Maintenance Expenses, EUR/kWe	52	52
Variable Operation and Maintenance Expenses, EUR/MWh	5.76	5.76
Decommission Cost, % of CAPEX	5.0	5.0
Efficiency, %	36	33
Net Capacity Factor (Availability factor), %	50	50
Lifetime, years	35	35
Heat Rate, %	1.5	1.5

Table B.35
Extension of the operational life of existing CHPs

Indicator\year	2015–2050	
	Gas	Coal
CAPEX, EUR/kWe	280–650	880–1300
Fixed Operation and Maintenance Expenses, EUR/kWe	41–51	51
Variable Operation and Maintenance Expenses, EUR/MWh	0.3	1.0
Decommission Cost, % of CAPEX	2.0	5.0
Efficiency, %	25–34	16–26

(*continued on next page*)

Table B.35 (*continued*)

Indicator\year	2015–2050	
	Gas	Coal
Net Capacity Factor (Availability factor), %*	50	50
Lifetime, years	15	15
Heat Rate, %	1.55	1.1

* Availability factor is in the range of 46%–90%.

Table B.36
Fuel Cells Power Plants (FCPPs)

Indicator\year	2025–2050	
	TPPs	CHPs
Overnight Capital Cost, EUR/kW	2530–844	2530–844
Fixed O&M Expenses, USD/kWe	62	62
Variable O&M Expenses, USD/MWh	14	14
Efficiency, %	50	50
Availability factor, %	85	60
Lifetime, years	10	10
Heat Rate, %	–	0.64

B.4 Other power plants

Table B.41
Solar Power Plants

Indicator\year	2015	2020	2025	2030	2035	2040	2045	2050
PV Plant size (without tracker)								
CAPEX, EUR/kWe	1300	750	725	700	630	560	510	475
Fixed Operation and Maintenance Expenses, EUR/kWe	15							
Net Capacity Factor (Availability factor), %	12.5							
Lifetime, years	25							
Decommission Cost, % of CAPEX	1%							
Construction time, years	1							
PV Plant size (with a tracker)								
CAPEX, EUR/kWe	1450	920	850	800	720	645	590	540
Fixed Operation and Maintenance Expenses, EUR/kWe	17.3							
Net Capacity Factor (Availability factor), %	14.5							
Lifetime, years	25							
Decommission Cost, % of CAPEX	1%							
Construction time, years	1							
PV Roof panel								
CAPEX, EUR/kWe	1100	900	875	850	800	750	700	600
Fixed Operation and Maintenance Expenses, EUR/kWe	12							
Net Capacity Factor (Availability factor), %	13.0							
Lifetime, years	25							
Decommission Cost, % of CAPEX	1%							
Construction time, years	1							

Table B.42
Wind Power Plants

Indicator\year	2015	2020	2025	2030	2035	2040	2045	2050
Onshore								
CAPEX, EUR/kWe	1600	1100	1075	1050	1000	975	950	900
Fixed Operation and Maintenance Expenses, EUR/kWe	25	25	26	28	37	40	40	40
Net Capacity Factor (Availability factor), %	36							
Lifetime, years	20							
Decommission Cost, % of CAPEX	1%							
Construction time, years	1.5							

Table B.43
Hydro Power Plants (HPPs)

Indicator\year	2015–2050		
	Large	Pump Storage	Small
CAPEX, EUR/kWe	3300–3080	610	3150–3000
Fixed Operation and Maintenance Expenses, EUR/kWe	45	45	59
Decommission Cost, % of CAPEX	3.0	3.0	3.0
Net Capacity Factor (Availability factor), %	33–36	26	30
Lifetime, years	60	60	40

Table B.44
Geothermal Power Plants (GPPs)

Indicator\year	2015–2050
CAPEX, EUR/kWe	5000–3400
Fixed Operation and Maintenance Expenses, EUR/kWe	143.5
Decommission Cost, % of CAPEX	1.0
Net Capacity Factor (Availability factor), %	35–55
Lifetime, years	25

Table B.45
Storage electricity technologies

Indicator\year	2020	2025	2030	2035	2040	2045	2050
CAPEX, EUR/kWe	600	570	542	514	489	464	441
Fixed Operation and Maintenance Expenses, EUR/kWe	8.6	8.1	7.6	7.0	6.5	6.5	6.5
Variable Operation and Maintenance Expenses, EUR/MWh	2.50	2.20	1.91	1.61	1.32	1.32	1.32
Efficiency, %	92%						
Availability factor (8 h per day), %	33.3						
Construction time, years	3						
Lifetime, years	10						

B.5 Supply Sector

Table B.51
Hydrogen technologies

Technology Description	Input	Starting year	Fuel input level	AFA	Lifetime	Capex	Fixed O&M Cost	Variable O&M Cost
	Commodities			*%*	*years*	*Million EUR/(PJ/year)*	*Million EUR/PJ*	*Million EUR/PJ*
H2 Electrolyser Centralised	Electricity	2030	1.43	90	10	21.9	0.44	
H2 HT Steam Electrolyser Centralised	Electricity	2030	1.07	90	10	40.3	0.81	
	Heat		0.20					
H2 SMR Centralised	Natural Gas	2030	1.35	90	10	10.6	0.53	0.51
H2 Electrolyser De-centralised	Electricity	2030	1.43	90	10	27.3	0.55	
H2 SMR De-centralised	Natural Gas	2030	1.50	90	10	21.9	1.09	0.51
H2 Liquefaction	Hydrogen Gas	2035	1.00	75	10	9.5	0.57	
	Electricity		0.21					

B.6 Transport

Table B.61
Main characteristics of hydrogen transport used in the TIMES-Ukraine model

Mode of transport	Cost, thousand EUR		Lifetime, years	Efficiency, km/GJ		Annual mileage, thousand km
	2015	2050		2015	2050	
Intercity buses	320	280	20	277	332	27.5
City buses	320	280	20	270	324	27.5
Cars, long-distance (gas)	61	41	20	900	1200	17.5
Cars, short-distance (gas)	61	41	20	765	792	17.5
Cars, long-distance (liquid)	59	38	20	900	1200	17.5
Cars, short-distance (liquid)	59	38	20	765	792	17.5
Trucks	350	200	20	285	340	22.0

B.7 Industry

Table B.71
CCS technologies

Technology Description	Efficiency	AFA	Lifetime	Capex	Starting
	%	%	years	USD/tCO_2eq.	year
Iron and Steel Production	80	90	10	65–70	2031
Cement production	90	90	10	110	2031
Ammonia production	100	90	10	100	2031
Ethylene production	100	90	10	190	2031

Appendix C. Potential of renewable energy sources

C.1 Wind potential

The potential of the on-shore wind energy assumed in the current study is presented in Table C1. Under the process of building the least-cost energy generation system to satisfy the energy consumption needs, the model chooses the level of wind energy generation constrained by the figures in the table below and taking into account other data inputs and assumptions.

Table C.1
Wind Energy Potential, GW

	2030	2035	2050
On-shore wind	12	24	43

C.2 Solar energy potential

Table C.2 provides an overview of the solar energy potential assumed in the study. The reported roof-top solar potential covers private households, commercial real estate, industry, and agricultural sectors.

Table C.2
Solar Energy Potential, GW

	2030	2035	2050
Ground-mounted solar panels	10	20	60
Roof-top solar panels	6	12	24

C.3 Bioenergy potential

In Ukraine, biomass use has significant potential for heat, electricity, and liquid biofuel production due to the abundant residues in agriculture, untreated solid waste landfills, favorable climate conditions, agricultural land availability, and affordable labor supply. As of 2020, 40% of agricultural waste could potentially substitute up to 10 billion cubic meters (bcm) of natural gas per year (SAEE, 2020). Dedicated energy crops that could be planted on 4 million hectares of marginalized lands could substitute up to 20 bcm of natural gas, whereas biogas/biomethane could substitute up to 7.8 bcm of natural gas (SAEE, 2020). The overall potential of natural gas substitution with biomass is almost 38 bcm, whereas total natural gas consumption in Ukraine in 2019 was 30 bcm (SAEE, 2020).

According to the State Statistics Service of Ukraine, only 11% of the economically feasible bioenergy potential was used in 2015 (Table C.3). Over half of the economically feasible potential is associated with agricultural waste and woody biomass, while the rest includes energy derived from energy crops and biogas (Table C.3). By 2050, an economically feasible potential of biomass is projected to reach 42 million tonnes of oil equivalent (Mtoe), mainly due to the increased cultivation and supply of energy crops, as well as the supply of biogas from by-products of the agri-food industry (Table C.3).

Table C.3
Actual supply and potential of the bioenergy in Ukraine

Biomass type	2015				2050
	Actual production, Mtoe	Theoretical potential, M t (or as specified)	Share available for energy sector, %	Economic potential, Mtoe	Economic potential, Mtoe
Cereals' straw	–	35.14	30	3.65	5.48
Rape straw	–	3.10	40	0.43	0.65
Corn grain production waste (stems, cores)	–	30.3	40	2.32	3.48
Sunflower seed production waste	–	21.2	40	1.22	1.22
Secondary agricultural waste (sunflower husks)	–	1.9	41	0.27	0.27
Total agricultural potential	**0.65**	**91.64**	**-**	**7.90**	**11.10**

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Table C.3 (*continued*)

Biomass type	2015				2050
	Actual production, Mtoe	Theoretical potential, M t (or as specified)	Share available for energy sector, %	Economic potential, Mtoe	Economic potential, Mtoe
Wood biomass (firewood, logging waste and residues, splinters)		8.8	41	1.03	2.08
Wood biomass (maintenance logging of forest bands, dead-wood)		11.0	58	1.80	1.03
Total wood	**0.79**	**14.80**	-	**2.41**	**3.11**
Biodiesel	–	-	-	0.19	0.19
Bioethanol	–	-	-	0.54	0.54
Total biofuel	**0.00**	–	–	**0.73**	**0.73**
Biogas from by-products of the agri-food sector (manure + food industry)	0.01	1.6 B m^3 CH_4	50	0.68	2.38
Biogas from solid waste landfills	–	0.6 B m^3 CH_4	34	0.18	0.59
Biogas from waste water	–	1.0 B m^3 CH_4	23	0.19	0.39
Total biogas	**0.01**	**3.2 B m^3 CH_4**		**1.05**	**3.37**
Poplar, miscanthus, acacia, alder, willow, rapeseed	–	11.5	90	4.40	13.19
Corn (biogas)	–	3.3 B m^3 CH_4	90	2.58	10.30
Total energy crops	-	-	-	**6.97**	**23.49**
Peat	–	-	-	0.28	0.28
Grand total, Mtoe	**1.45**	-	-	**19.34**	**42.07**
Share of biomass in TPES, %	**1.7**	-	-	-	-

Source: Based on Chepeliev et al. (2021).

C.4 Hydro energy potential

Large hydropower development is limited in the considered scenarios, as this type of generation is recognized as an unsustainable renewable energy source. Thus, only the completion of the Kakhovka hydropower plant (HPP)-2 using the existing dam is considered in the study as a potential extension. Based on these assumptions, the capacity of large hydropower will be 6033 Megawatt (MW) (existing HPPs) and 250 MW (Kakhovka HPP-2), amounting to 6283 MW in total.

According to environmental non-governmental organizations, there are no small HPPs in Ukraine that meet stringent environmental requirements (EBRD, 2020). At the same time, there are examples of HPPs in Austria and Norway that are considered environmental-friendly. In the current study, 50% of the available potential of small HPPs is assumed, provided that the most stringent environmental criteria are met. As of 2016, the installed capacity of small HPPs was 90 MW (MCTDU, 2017).

According to the estimates by the Institute of Renewable Energy, the maximum capacity of small HPPs, which could be achieved by 2030 is 250 MW (MCTDU, 2017). This implies that the additional potential to existing capacities will be 180 MW. Assuming that 50% of the new small HPPs meet stringent environmental criteria, the additional increase will be 90 MW. It is assumed that a significant part of this potential should be implemented as a result of modernization and efficiency improvements of the existing small HPPs.

C.5 Geothermal potential

Based on the available assessments, economically feasible geothermal energy potential is assumed at the level of up to 8.4 million toe per year (MCTDU, 2017).

Appendix D. Marginal electricity prices across scenarios (EUR per MWh)

Scenario characteristics						Years						
Scenario type	Economic recovery assumptions	CAPEX for nuclear, USD per kW	Load factor	Constraints on nuclear	LCOE for renewable generation	2020	2025	2030	2035	2040	2045	2050
Baseline	Default	7000	Default	No constraints	Default	82.5	13.2	15.7	39.6	50.5	51.2	48.1
Baseline	Default	7000	Increased	No constraints	Default	82.5	13.2	27.5	36.1	50.5	51.3	48.2
Baseline	Default	5000	Default	No constraints	Low	82.5	13.2	22.1	33.4	20.6	30.3	40.8
Baseline	Optimistic	5000	Default	No constraints	Default	82.5	12.9	23.5	40.5	57.9	40.9	48.7
Baseline	Default	5000	Default	No constraints	Default	82.5	13.2	15.7	35.9	50.5	51.2	48.1
Baseline	Default	5000	Increased	No constraints	Default	82.5	13.2	27.5	36.1	50.5	51.2	48.2
Baseline	Optimistic	5900	Default	No constraints	Low	82.5	12.9	13.0	32.8	35.4	41.8	44.0
Baseline	Optimistic	5900	Default	No constraints	Default	82.5	12.9	23.5	41.8	51.3	51.4	49.5
Baseline	Default	5900	Default	No constraints	Default	82.5	13.2	15.7	39.6	52.2	51.2	48.2
Baseline	Default	5900	Increased	No constraints	Default	82.5	13.2	27.5	36.1	53.1	51.3	48.2
Mitigation	Default	7000	Default	No constraints	Default	82.5	11.1	31.9	68.7	75.1	52.0	59.2
Mitigation	Default	7000	Increased	No constraints	Default	82.5	11.1	31.9	68.7	75.3	50.5	59.2
Mitigation	Default	5000	Default	No constraints	Low	82.5	11.1	31.9	57.3	47.7	50.0	43.6
Mitigation	Default	5000	Default	No constraints	Default	82.5	11.1	31.9	64.0	80.5	53.9	59.0
Mitigation	Optimistic	5000	Increased	No constraints	Default	82.5	11.1	35.5	81.4	59.1	61.2	59.0
Mitigation	Default	5000	Increased	No constraints	Default	82.5	11.1	31.9	65.9	54.3	53.1	50.2
Mitigation	Default	5000	Default	No new large NPPs	Default	82.5	11.1	31.9	64.0	80.5	53.9	59.0

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(*continued*)

Scenario characteristics						Years						
Scenario type	Economic recovery assumptions	CAPEX for nuclear, USD per kW	Load factor	Constraints on nuclear	LCOE for renewable generation	2020	2025	2030	2035	2040	2045	2050
Mitigation	Default	5000	Increased	No new large NPPs	Default	82.5	11.1	31.9	63.6	78.6	50.2	59.2
Mitigation	Optimistic	5900	Default	No constraints	Low	82.5	11.1	27.5	81.1	55.9	68.9	64.9
Mitigation	Optimistic	5900	Default	No constraints	Default	82.5	11.1	32.5	80.8	70.7	72.9	65.9
Mitigation	Default	5900	Default	No constraints	Default	82.5	11.1	31.9	68.8	80.5	53.9	59.2
Mitigation	Default	5900	Increased	No constraints	Default	82.5	11.1	31.9	68.9	80.5	52.1	59.2
Mitigation	Default	5900	Default	No new NPPs, no extensions	Default	82.5	11.1	31.6	62.5	84.1	80.6	61.7
Mitigation	Optimistic	5900	Increased	No new NPPs, no extensions	Default	82.5	11.1	31.7	71.7	95.4	90.5	83.8
Mitigation	Default	5900	Increased	No new NPPs, no extensions	Default	82.5	11.1	31.9	63.2	84.9	80.4	61.7
Mitigation	Default	5900	Default	No new NPPs	Default	82.5	11.1	31.9	64.6	73.0	66.8	61.9
Mitigation	Default	5900	Increased	No new NPPs	Default	82.5	11.1	31.9	68.0	73.0	66.6	62.5
Mitigation	Default	5900	Default	No new large NPPs	Default	82.5	11.1	31.9	68.8	80.5	53.9	59.2
Mitigation	Default	5900	Increased	No new large NPPs	Default	82.5	11.1	31.9	68.9	80.5	52.1	59.2

Appendix E. Load factor assumptions for the nuclear power plants

NPP type\years	Load factors							
	Default assumptions				Increased load factor			
	2020	2030	2040	2050	2020	2030	2040	2050
Existing units	63%	76%	76%	76%	63%	76%	76%	76%
Extended		76%	76%	76%		80%	80%	80%
New units on existing NPPs		76%	76%	76%		85%	85%	85%
New units on new NPPs		76%	76%	76%		93%	93%	93%
Small nuclear units		98%	98%	98%		98%	98%	98%

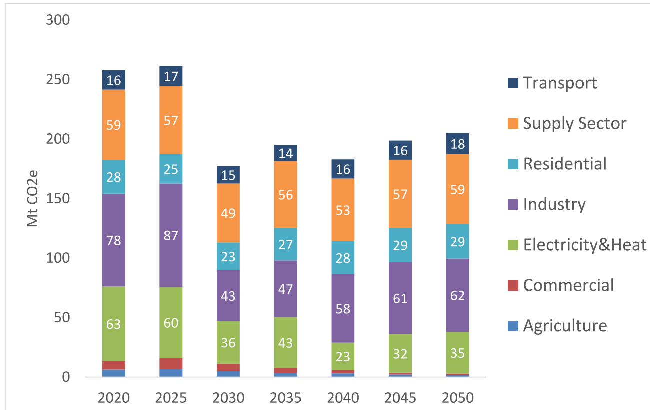
Source: developed by authors.

Appendix F. Macro assumptions of the alternative Reference scenario

	2020	2025	2030	2035	2040	2045	2050
GDP structure, %							
Agriculture	9.8	11.9	13.8	14.9	15.0	14.7	14.5
Mining	6.6	5.2	4.0	2.9	2.6	2.3	1.9
Manufacturing	10.4	7.6	7.3	7.2	7.1	7.2	7.2
Electricity and heat supply	3.4	4.3	3.5	2.8	2.6	2.4	2.3
Construction	2.7	1.7	2.7	4.0	5.0	5.7	6.4
Trade	14.1	15.1	15.5	16.0	15.6	15.3	15.0
Transportation	5.4	4.4	5.0	5.2	5.2	5.2	5.2
Other services	32.9	36.5	34.6	33.3	32.8	32.8	32.8
Taxes and subsidies	14.8	13.4	13.6	13.9	14.1	14.3	14.6
Aggregate GDP in billion 2021 USD							
GDP	193	155	229	329	401	476	565

Notes: Totals over GDP sectoral shares might not exactly add up to 100% due to rounding error.

Appendix G. GHG emissions under the optimistic baseline scenario



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