LONG-TERM DECARBONISATION PATHWAYS FOR THE UKRAINE POWER SECTOR

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INTRODUCTION

Due to the destructions of the war, the Ukrainian power sector faces multiple challenges: reconstruction of the damaged network and generation assets and at the same time meeting the present and expectedly increasing power needs with the reconstruction of the country. At the same time, Ukraine plans to decarbonize its power sector by no later than 2050, and the whole economy by 2060, thus decarbonization considerations are layered over the already mentioned war and recovery related challenges. This report aims to help this transition planning as it analyses long-term decarbonisation scenarios for Ukraine's power system with quantitative models.[1] It assesses the feasibility of reaching a net zero power system by 2050 with the adjacent costs in two net zero scenarios with different technology portfolios. Questions the report aims to answer:

- What are the implications of integrating Ukraine into the EU power market?
- How power generation mix needs to evolve to decarbonize the power sector of Ukraine by 2050, based on the overall decarbonization goal of Ukraine by 2060? More specifically:
  - What is the future role of nuclear power? Does Ukraine need new nuclear capacity?
  - How much coal-fired generation is needed to securely satisfy electricity demand in the coming winters? Can coal-fired power plants be closed down by 2035?
  - What is the optimal portfolio of renewable energy technologies and geographical distribution?
- How to provide the necessary system flexibility and what is the role of fossil gas-based power plants?
- What is the impact of introducing EU Emission Trading Scheme - ETS (or equivalent) for power generation and trade in Ukraine? And of the application of carbon border adjustment mechanism (CBAM)?

Decarbonising the power sector of Ukraine has multiple benefits. The falling cost of wind and solar generation makes the transition affordable. The benefits of resilience and enhanced security of supply thanks to distributed energy sources have been made starkly visible by the war. And the prospect of European integration makes tackling the problem of fossil power plants emissions even more urgent.

Results of the modelling assessment

The study develops two net zero scenarios, in addition to the Reference scenario which reflects the frozen policy and, to a wide extent – frozen technology pathway. The Net Zero–Open Technology scenario (NZ-OT) is a technology-neutral trajectory, based on an optimistic cost assumption for nuclear technologies (both for large and small modular reactors (SMR)) that is identical to the one used in the Ukraine Energy Strategy. The Net Zero–Renewable energy (NZ - RES) scenario

1 The model descriptions and earlier applications could be accessed here: TIMES-Ukraine, EPMM and Green-X

assumes higher nuclear investment cost, corresponding to the latest trends observed in Europe. Consequently, this scenario places a primary emphasis on renewables as the dominant technology of the energy transition.

Table 1: Key assumption of the scenarios

	Reference	Sub-scenario Reference + CBAM*	Net Zero Open Technology	Net Zero Renewable
Population, GDP	same for all scenarios			
Carbon pricing	no	CBAM	EU ETS prices	
RES potential	low		high	
Nuclear	SMR not available; large scale available (5250 €/kW)		Both technologies are available (5250 €/kW)	Both technologies are available (7000 €/kW)

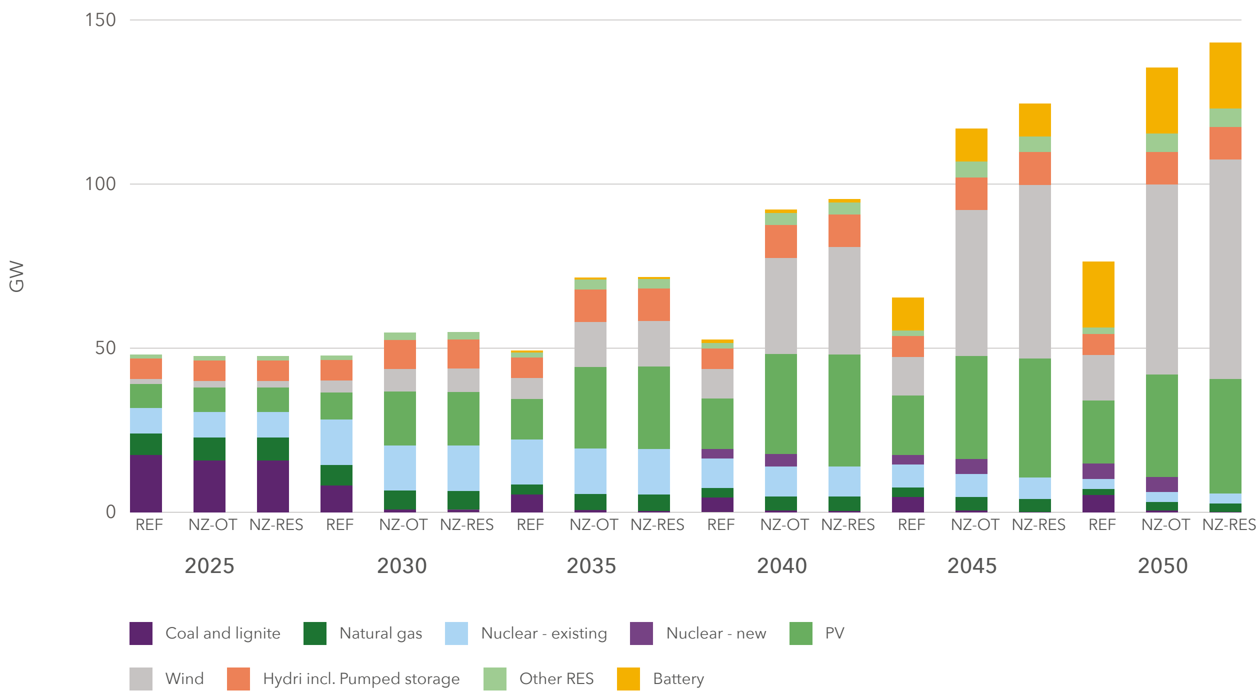
The **assessment shows that decarbonising the Ukrainian power sector before 2050 is feasible, both technically and economically**. Power demand is met in both scenarios in all modelled years. There is sufficient flexible generation to provide adequate reserve capacities, even in the face of demand that, driven by the strong electrification and sector coupling, is anticipated to reach almost three times its current level.

Box1:

Capacity mix in the modelled scenarios

While in the Reference coal and lignite play important role in all years with 5 GW remaining capacities even in 2050, in the Net Zero scenarios coal virtually gets phased out by 2030. Nuclear capacities remain in the capacity mix with approximately 8 GW in 2050 in the reference and Net Zero - OT scenarios - roughly at similar level as today (considering occupation of Zaporizhzhia NPP) - but only with 3 GW in the Net Zero-RES scenario. In this later scenario no new nuclear capacity is built according to the TIMES modelling results. driven by the higher investment cost level of nuclear presently observed in the EU markets. Large renewable investments take place in both. The significant increase in hydro capacities in the Net-Zero scenario between 2025-2035 are the plans of UKRENERGO. Such huge developments warrant environmental and social assessment. Battery capacity is exogenous in the model and the same in all 3 scenarios.

Figure 1. Power generation capacity per technology, GW



The Net Zero scenarios foresee **90-100 GW new PV and wind capacities by 2050**, with small scale PV systems reaching 14-24 GW depending on the scenario. After 2035, massive wind development is anticipated to take place, driven by the carbon pricing introduced in these scenarios. Solar development is very dynamic until 2040, when offshore wind grows dynamically. **Reaching net zero is feasible without new nuclear reactors,** meaning that nuclear at the current investment cost level in the European Union (EU) is more expensive than renewables. Ukraine has to follow nuclear investment developments closely to minimise the risk of stranded costs of new reactors. The results also confirm that **rapid coal phase out is possible.** The Net Zero scenarios demonstrate that coal-based production could be phased out from the generation mix by 2030, if EU-equivalent carbon pricing was introduced, sufficient renewable capacities were added and the Zaporizhzhya power plant returned to operation in full capacity. Natural gas plants play a bridging role in the energy transition, slightly increasing their contribution to the electricity mix up until 2040 in all scenarios and later serving as reserve units.

The **net trading position** of Ukraine changes from exporter to importer in the modelled period. Ukraine has substantial exports in all scenarios until 2030 driven by the cost advantage of domestic generation in the absence of CO_2 pricing.

In the Net Zero scenarios, post-2030, exports to the EU declines due to the implementation of the ETS in Ukraine. Nevertheless, a net export position is maintained until 2040. Towards the end of the period, Ukraine is likely to become importer of electricity. Although the results also indicate that Net Zero scenarios require lower level of import as the Reference one in 2050, in spite of the increasing demand resulting from widespread electrification efforts.

The **total system cost of meeting the increasing energy demand while eliminating emissions is nearly identical to pursuing business-as-usual development** (as in the Reference scenario), despite adding a price to carbon and investing substantial resources in low carbon technologies. The higher capital investments in both Net Zero scenarios are reasoned by the fact that they serve not only power sector development (as in the Reference scenario) but ensure decarbonization of other coupled sectors of economy.

BOX 2:

System cost comparison of scenario

The minimization of discounted total energy system costs (the objective function of the TIMES-Ukraine model) is the main criterion upon which the trajectory of the energy system development is evaluated. It serves as the important metrics when comparing different scenarios. Total energy system cost has a wide coverage: it includes the CAPEX and OPEX of all assets associated with the energy system, including generation, energy transport and energy use equipment. Therefore, capital investments, considered in TIMES-Ukraine, are not just investments in the energy sector but are «energy related investments» accounting for about 60-70% of total investments in the economy. Thus, investments in the power generation sector make just 15-25% of investments assessed by the model, while the rest capital expenditures should be directed to other sectors such as Industry, Transport and Buildings.

Total capital costs in the Net Zero scenarios are roughly 51% higher than in the Reference scenario and ranges between 30 and 40 billion Euro/year. Major investments include electric and other clean-fuelled vehicles, upgrades to buildings, installation of clean heating systems, and new renewable and nuclear power plants. Investments for clean heating, power, and CHP plants double in Net Zero scenarios comparing to the Reference case and costs about 6.5 billion Euro/year.

Although upfront investment need in the Net Zero scenarios is higher than in the Reference, total system costs are only 3% higher as fuel cost savings over equipment lifetimes substantially offset the greater upfront capital costs. An additional benefit of fuel savings in the Net Zero scenarios would be improved energy security in Ukraine as a considerable part of fuels relates to imports.

Table 2. System cost estimates by the TIMES-Ukraine model

	Reference Scenario	NZ-OT Scenario		NZ-RES Scenario	
	Bln Euro	Bln Euro	Difference (%)	Bln Euro	Difference (%)
Total energy system costs (discounted)	1 733.1	1 784.0	2.9%	1 785.8	3.0%
Total capital costs for 2025-2050 (non discounted)	623.2	940.4	50.9%	942.2	51.2%
Capital costs in power generation sector for 2025-2050 (non discounted)	96.1	201.5	109.7%	191.0	98.8%
Total O&M Costs for 2025-2050 (non discounted)	431.8	481.9	11.6%	485.9	12.5%
Total Fuel Costs, incl. revenues from exogenous export for 2025-2050 (non discounted)	368.4	213.6	-42.0%	210.9	-42.8%

Source: TIMES-Ukraine Model

The strong increase in capital investment costs in the Net Zero scenarios, mainly driven by the PV and wind investments, is counterbalanced by the reduction in fuel and CO2 costs. The increase in capital investments underlines the **importance of good regulation that can reduce overall financing costs** and foster greater international financing. Good regulation includes long-term planning, predictable regulation of carbon emissions, and renewable and infrastructure development.

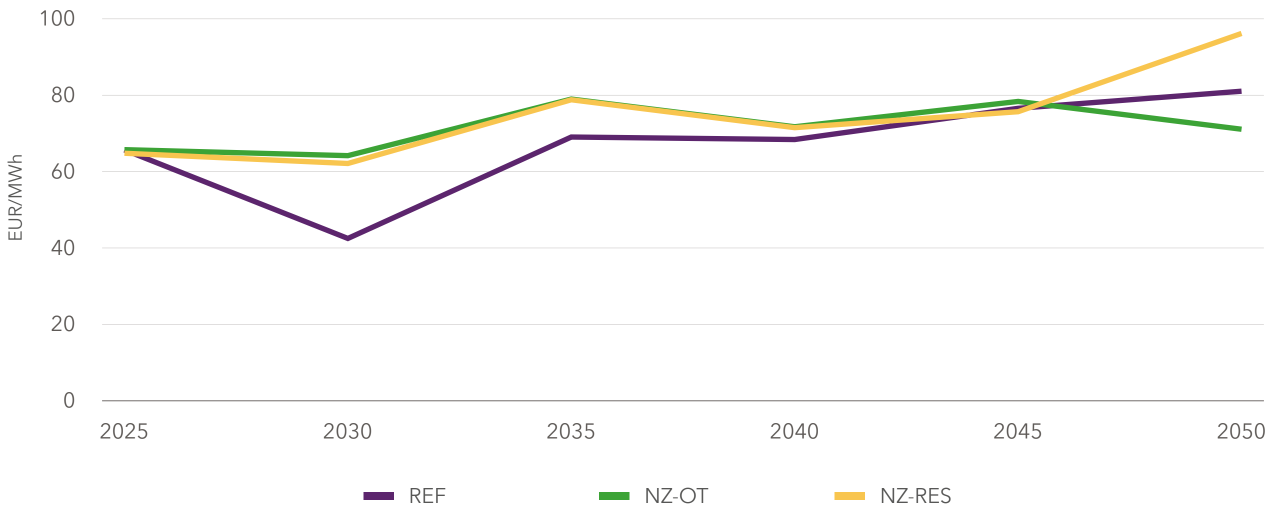
Wholesale electricity prices from 2035 onwards are in the same range in all three scenarios. Before 2035, the lack of carbon pricing makes the electricity price in the Reference scenario 20 €/MWh cheaper, when compared to the Net Zero scenarios. In the wind-dominated Net Zero-RES scenario, the price increase after 2045 demonstrates the risk of an unbalanced technology portfolio alongside various flexibility options (interconnectors and peak load reduction) than can mitigate this potential price increase.

BOX 3:

Wholesale electricity prices in the scenarios

In 2025 wholesale electricity price in Ukraine is similar in all three scenarios. The approximately 65 €/MWh is significantly lower than in neighbouring countries as there is no carbon pricing in Ukraine, while it has high share of nuclear capacities with comparatively low marginal costs due to wear and tear. Between 2025 and 2030 the price is much lower in the Reference scenario because this is the only scenario without carbon pricing, and domestic capacities combined with import are sufficient to avoid high prices in most of the hours. The estimated drop in this period is a result of shrinking gas price. Consequently, in 2030, the prices in the Net Zero scenarios are approximately 20 €/MWh higher than in the Reference.

Figure 3.: Evolution of baseload electricity price in three scenarios



Source: EPMM

Price convergence across the scenarios toward 2040 is due to contrasting trends in capacity dynamics. In the reference scenario, available – predominantly - coal/lignite-based capacities diminish due to retirement. This decline in domestic electricity production results in higher prices during certain hours. In the net zero scenarios, on the other hand, a substantial increase in the share of renewable generation in total supply push average price down. As a result, by 2045, prices across all three scenarios converge at approximately 75 €/MWh.

By 2050 prices diverge again. The Net Zero – OT scenario produces the lowest price (~70 €/MWh) as nuclear and renewable capacities can meet the increasing demand in most hours, preventing the occurrence of high prices. The reference scenario results in higher prices (~80 €/MWh) due to the lower share of renewable generation. The high price in the net zero-RES (~95 €/MWh) is due to the dominance of wind in the electricity mix. In low wind hours, domestic supply falls short, leading to exceptionally high prices and elevating the yearly average.

There are several policy options to mitigate this increasing price at the end of the period in the Net Zero-RES scenario. The installation of an additional 9 GW solar capacity in 2050 would results in the same price as in the Net Zero-OT scenario. Increasing cross-border capacities by 1.5 GW or a 3.3% reduction in consumption would bring prices to the level of the Net Zero-OT scenario.

Until 2035, the higher wholesale electricity prices in the net zero scenarios will translate into increasing consumer prices. This will require **well-designed support schemes targeting vulnerable consumers:** too-wide coverage would be expensive to maintain for a longer period and would undermine price responsiveness of consumers. Simultaneously, **energy efficiency improvements** should be promoted during the reconstruction phase, as cost-reflective pricing is the most efficient and long-term tool to curtail energy consumption and address energy poverty.

The price spreads between Ukraine and the EU in the initial period results **in high utilization of interconnectors for exporting**. Utilization deteriorates after 2030 as price spread gets smaller. Towards the end of the modelled period, both utilization rate and congestion bounce back in the Net Zero scenarios in both trading directions. The high utilisation rates of the interconnectors indicate that **cross-border capacity expansion is key aspect for the future sector development** of Ukraine.

Table 3. Average hourly trade flows as a % of NTC (upper row) and the share of congested hours (lower row) for UA interconnectors

		REF				NZ-OT				NZ-RES			
Utilization, %													
		2025	2030	2040	2050	2025	2030	2040	2050	2025	2030	2040	2050
Export	HU	94,4%	97,8%	64,5%	45,9%	94,6%	85,6%	60,9%	52,0%	94,8%	85,7%	57,4%	50,2%
	MD	12,7%	90,1%	4,8%	33,2%	11,4%	81,3%	47,8%	46,3%	11,4%	82,0%	43,1%	43,9%
	PL	99,8%	100,0%	48,7%	20,2%	99,8%	87,9%	30,7%	30,8%	99,8%	88,2%	29,3%	33,6%
	RO	92,7%	97,0%	61,1%	46,1%	92,9%	82,9%	64,4%	53,2%	93,5%	83,6%	60,9%	51,3%
	SK	94,2%	97,2%	31,8%	20,3%	94,3%	76,5%	19,5%	30,6%	94,5%	76,7%	20,0%	33,1%
Import	HU	4,2%	1,8%	7,8%	47,0%	4,0%	7,3%	8,0%	44,0%	3,9%	6,9%	10,2%	44,9%
	MD	48,7%	3,9%	77,7%	43,9%	49,8%	8,8%	10,8%	37,5%	49,4%	8,8%	13,5%	38,3%
	PL	0,0%	0,0%	35,7%	71,5%	0,0%	7,0%	56,7%	57,1%	0,0%	6,9%	60,6%	57,6%
	RO	5,0%	1,6%	14,2%	41,1%	4,8%	7,9%	11,8%	38,6%	4,5%	7,5%	14,7%	39,1%
	SK	4,2%	1,9%	36,2%	66,4%	4,1%	13,0%	56,6%	55,2%	3,9%	12,6%	60,2%	54,7%

The **Carbon Border Adjustment Mechanism (CBAM)** was modelled on the Ukrainian electricity sector as a variation of the Reference scenario, as in the Net Zero scenarios Ukraine is assumed to have an EU ETS or equivalent and hence the CBAM is not applicable. CBAM is a carbon border tax introduced by the EU to create a level playing field for products created in the EU or imported from countries with no or less carbon tax. The CBAM is applicable for high emitting industrial sectors and electricity and will be fully implemented from 2026. This means that electricity exports from Ukraine to the EU will be taxed at the border. This effectively reduces exports, as in those hours, when the tax is higher than the price spread, no exports will take place to EU countries. Once

CBAM is implemented, the relatively cheap electricity will get consumed domestically instead of being exported to the EU. This substitution lowers domestic wholesale electricity price in Ukraine while increasing price spread between Ukraine and the EU. CBAM has serious negative impacts on **power generators and traders** as **they lose export revenues**. It, however, does not impact the merit order and hence does not trigger the decarbonisation of the power sector like ETS (or an equivalent carbon tax) does. The Reference+CBAM scenario foresees **significant change in the net export position of Ukraine, reducing it by approximately 7-13 TWh** compared to the Reference scenario.

POLICY RECOMMENDATIONS

Long-term vision

A comprehensive and forward-looking long-term vision embedded in a national policy is the cornerstone of successful decarbonisation. Ukraine should develop a clear roadmap that aligns with EU climate goals, outlining explicit targets and milestones. This includes a phased transition plan that takes into account technological advancements, market dynamics, and evolving regulatory landscapes. By providing a long-term perspective, the government can enable a stable and predictable environment for investors, fostering confidence and commitment to the decarbonisation journey.

The 2030 implementation of the EU carbon pricing scheme, as assumed in the net zero scenarios, serves as a key catalyst of energy transition. This would provide a credible framework for decarbonisation, leading to the accelerated adoption of renewables and the phase-out of coal-based generation. In order to take part in the EU carbon pricing scheme, Ukraine needs to speed up the preparation of institutions and processes. A smooth transition could involve the gradual increase of the current national carbon tax. The introduction of ETS would make the Carbon Border Adjustment Mechanism (CBAM) – to be implemented on all third countries to the EU from 2026 – irrelevant for Ukraine. Whereas ETS revenues would be retained within Ukraine, the revenues from the border tax are, by default, kept by the EU. This would reduce Ukraine's competitive position, as the country would be able to export 30-50% less electricity compared to the reference case. CBAM does not trigger decarbonisation until there is enough domestic demand to consume the generation previously exported.

Principles of energy transition

Transparency is vital in building public trust and attracting private investment. Establishing clear mechanisms for policy formulation, decision-making, and implementation helps stakeholders understand the rationale behind regulations. Therefore, the Ukrainian government should prioritize transparent communication channels and mechanisms to maintain a strong connection with the public and investors alike. **Public participation** and robust **communication** strategies should be embedded in the regulatory framework to foster a sense of ownership and shared responsibility for the energy transition.

Ensuring **equity** in the distribution of costs and benefits and burdens is a fundamental consideration in the decarbonisation process. Policymakers must prioritise policies that prevent vulnerable populations from disproportionately bearing the costs of the transition. Neglecting equity considerations may result in social unrest, resistance to policy implementation, and a fractured societal approach to decarbonisation.

The development and strengthening of **robust institutions** – competition watchdog, energy regulatory office, consumer protection office – are critical to reducing the country risk premium and attracting private investment. Establishing agencies with the capacity to oversee and enforce regulations ensures a level playing field for all market participants.

Infrastructure and international opening

Power sector transition means, on the one hand, the large-scale buildout of new, carbon-free generation assets, and transmission and distribution grids on the other. These assets are characterised by large upfront and low variable costs. The sheer volume of the required investment means that public resources must be accompanied by private money. Therefore, lowering the currently high cost of capital in Ukraine is a key factor to reduce the overall investment cost. **Substituting fossils with carbon-free generation is achievable before 2050 by the scaling up of renewables, even without new nuclear facilities (Net Zero-RES scenario).** With the reintegration of the Zaporizhzhya NPP, the existing nuclear fleet, however, helps to decarbonise the sector. For new nuclear to be built, strong investment cost reduction (5250 €/kW in the Net Zero-OT scenario) would be needed when compared to current levels.

Ukraine has vast solar and wind potential. This study forecasts particularly strong uptake of wind. Integrating wind in the vast territory of Ukraine would reduce generation volatility due the portfolio effect. The optimal renewable technology portfolio, however, is sensitive to cost developments and network availability.

To accelerate large-scale renewable energy projects, Ukraine should streamline permitting processes, reducing bureaucratic hurdles regarding network connection. Additionally, investing in grid infrastructure and storage facilities is crucial to handling the intermittent nature of renewable sources.

One specific recommendation is to implement a cost-efficient and market-driven support mechanism such as a two-sided Contract for Difference (CfD) system. This would provide investors with a predictable revenue stream and enhance competition while protecting consumers from unnecessary costs. Careful consideration will need to be given to auction and contract design as well as setting correct ceiling prices and providing long-term visibility over auction schedules.

Coal can be phased out completely by 2035 without endangering resource adequacy of the power system. According to the modelling, only 850 MW coal power plants remain in the system by 2030 in both net zero scenarios.

To be able to benefit from the integration of Ukraine to ENTSO-E and trade and balance renewable electricity in a wider geographical market, there is a need for considerable cross border capacities (CBCs). The utilisation rates of CBCs are high throughout the modelling period, indicating that CBCs are important elements of the Ukraine power system. They help the system in peak demand hours and increase system flexibility. One option to mitigate the high electricity price of the Net Zero-RES scenario at the end of the period is to build capacities additional to the ones already planned and reported in the TYNDP; the modelling results indicate that an additional 1.5 GW of CBC capacity would have a price reducing effect of 25 €/MWh. The buildout of planned cross-border capacities should get priority in the future transformation of Ukraine's power system. Higher CBC capacities enable higher and quicker deployment of variable RES resources, provide higher system security and allows achieving higher revenues for Ukraine up to 2040, till Ukraine power system has some price advantage compared to the neighbouring EU countries.

Flexibility

An electricity system based on large amounts of renewables requires a lot of flexibility. It is important to recognize all possible contributors (supply side, demand side, storage, interconnectors) and prioritize those with speediest implementation times and best cost-benefit ratio. Enhancing system flexibility also requires significant investments in smart grid technologies and demand response systems. Additionally, incentivizing the adoption of energy storage technologies, such as batteries, will contribute to system flexibility.

The power system remains balanced in all scenarios throughout all years, meeting reserve requirements even when dispatchable generation is substituted with variable technologies. In all cases, the modelling assumes the increase of mobilisable flexible load capacity, from 8% (of average weekly load) in 2020 to 25% in 2050. Flexibility in the upward direction is supplied through hydro and battery storage and with demand-side resources. In the downward direction, coal is substituted by gas and, to a much larger extent, by renewables from 2030 onwards in the Net Zero scenarios. The role of gas in the Net Zero scenarios is even more limited, accounting for less than 8% in 2030 and only 2% of production in 2050. This underscores a gradual shift towards cleaner and more sustainable energy sources, minimising reliance on gas as the transition progresses.

Demand

Decarbonisation of the economy requires massive electrification and sector coupling. Despite power demand more than doubling between 2025 and 2050 in the Net Zero scenarios, the modelled systems effectively satisfy the increased need. This demonstrates the adaptability and robustness of the decarbonization approach.

Prosumers are key actors in the transition. They reduce the volume of electricity supply from the grid and, hence, the need for power transport infrastructure. In combination with PV and small-scale batteries, prosumers could provide flexibility, especially when organized by aggregators. Encouraging prosumer participation requires simplifying bureaucratic procedures and introducing financial incentives (also by efficient price discovery on the wholesale and retail markets) while not putting a strain on the functioning of the system. A robust regulatory framework might include net billing or buy-all, sell-all schemes that address concerns related to flexible demand.

Moreover, fostering community-based energy projects through cooperative models can empower local communities. The government can incentivise such projects through targeted subsidies or tax breaks, fostering a sense of ownership and sustainability.

Improving energy efficiency is still one of the main drivers of emissions reductions, in addition to shifting generation to renewables. Rebuilding Ukraine should incorporate the optimal mix of these main decarbonisation options. Ukraine should consider adopting and enforcing updated building codes that prioritize energy efficiency. A concrete recommendation is to implement financial incentives, such as tax credits or subsidies, for businesses and households adopting energy-efficient technologies. Reconstruction should keep in mind that investment into fossil infrastructure, including gas transmission and distribution grids, but also gas boilers, runs the risk of creating stranded assets.

Furthermore, the government should invest in public awareness campaigns to educate citizens on the importance of energy conservation. Building a culture of energy efficiency requires a coordinated effort involving educational institutions, media, and local communities.

Cost of transition

The total energy system cost in the Net Zero scenarios, including of all energy generation, transport and use assets, is similar to the Reference scenario. **This means that the energy transition is not significantly more expensive for the society on the long run.** The energy transition requires a high amount of capital investment, especially in the beginning of the modelled period. The modelled investments include not only large-scale assets but electric vehicles (EVs), heat pumps and more efficient domestic appliances purchased by households. The power sector investments to double in the Net-Zero scenarios compared to the Reference to serve the twofold increase in demand due to electrification. The large investment cost is balanced by the relatively modest running cost of a decarbonised energy system, with all the associated benefits such as improved security of supply, trade balance and environmental gains.

The need to mobilise private capital is a recurring theme in both planning the transition and implementing the necessary regulatory environment. Private investors, both foreign and domestic, will need to be assured that their investment is protected, and the prospective returns are proportionate to the risks involved. Therefore, the biggest regulatory priority would be to lower investor risk and provide a stable and predictable investment climate, firmly showing the pathway to full implementation of EU law. Due to the war, the so-called country risk will remain elevated for some time, at least until Ukraine becomes a full member of the EU. It is all the more important, therefore, to strive to reduce the risk that remains under full government control, which is the regulatory risk.

While wholesale prices are initially 15-20 €/MWh higher (until 2035) in the Net Zero scenarios, they later stabilize and converge with the Reference scenario prices due to the price reducing effect of renewables (merit order effect). This suggests that any temporary price increase during the early stages of decarbonisation is mitigated over time, resulting in a cost-effective and sustainable energy transition.

Final consumers make their choice based on retail prices, which should reflect scarcity or price at the wholesale market. The majority of final consumers, however, cannot be exposed to the price risk prevalent at the wholesale level. Consumers should have a choice of tariff offers which suit his or her risk appetite, level of consumption and flexibility potential.

Ensuring equity in the distribution of costs and benefits and burdens is a fundamental consideration in the decarbonisation process. Policymakers must prioritize policies that prevent vulnerable populations from disproportionately bearing the costs of the transition. This could involve targeted subsidies for low-income households, job transition programs for workers in declining industries, and inclusive financing mechanisms. By conducting thorough impact assessments, the government can identify potential disparities and proactively address them in the policy design phase. Conversely, neglecting equity considerations may result in social unrest, resistance to policy implementation, and a fractured societal approach to decarbonisation.

The full report can be accessed HERE.