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INFORMING UKRAINIAN RECONSTRUCTION THROUGH BUILDING RETROFITS AND DECARBONIZATION MODELING

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ACRONYMS AND ABBREVIATIONS

BECCS	Bioenergy carbon capture and storage
CHP	Combined heat and power
CO_2	Carbon dioxide
DH	District heating
EU	European Union
GCAM	Global Change Analysis Model
GDP	Gross Domestic Product
GHG	Greenhouse gas
GWh	Gigawatt hour
IEA	International Energy Agency
IEF	Institute for Economics and Forecasting of the National Academy of Sciences of Ukraine
Ktoe	Thousand tons of oil equivalent
MinInfrastructure	Ministry of Communities, Territories and Infrastructure Development of Ukraine
$MtCO_2$	Metric tons of carbon dioxide
Mtoe	Million tons of oil equivalent
NASU	National Academy of Sciences of Ukraine
NDC	Nationally Determined Contribution
NRC	National Council for the Recovery of Ukraine
PNNL	Pacific Northwest National Laboratory
RES	Renewable Energy Source
TFC	Total Final Consumption
TPES	Total Primary Energy Supply
UAH	Ukrainian Hryvnia
Ukrstat	State Statistics Service of Ukraine
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States Dollar

EXECUTIVE SUMMARY

Ukraine has developed a comprehensive plan to reduce energy consumption in buildings for heating and cooling by two-thirds by 2050 while moving to net-zero greenhouse gas (GHG) emissions and increasing country-level energy security. To accomplish these goals, Ukraine has put forth strategies to retrofit residential, commercial and public building shells with highly efficient materials to reduce losses, improve newly constructed buildings, and transition building-scale heating systems that will aid in reducing energy consumption.

Russia began its full-scale invasion of Ukraine on February 24, 2022, resulting in significant loss of buildings and energy-providing infrastructure, while also causing significant population migration out of Ukraine and a sharp decline in the economy. As a result of the invasion, the retrofit and decarbonization strategies have transitioned to one of reconstruction. The Government of Ukraine has developed the Ukraine Reconstruction Plan, which prioritizes rebuilding the Ukrainian energy system using clean, sustainable, and resilient energy systems.

Through a collaborative effort between the Pacific Northwest National Laboratory (PNNL) and the Institute for Economics and Forecasting of the National Academy of Science of Ukraine (IEF), we use an energy system model and an integrated assessment model to develop and analyze a set of three future scenarios that focus on the effects of war, reconstruction, and energy system-wide net-zero CO_2 pathway for building and energy systems in Ukraine. We seek to answer two main questions:

1. To increase energy resiliency within Ukraine, what measures are necessary to achieve a two-thirds reduction in building energy consumption for heating and cooling by 2050?

2. How does the compounding effect of decarbonizing Ukraine impact building and energy systems by 2050?

Using GCAM-Ukraine and TIMES-Ukraine models (see Annex 1 and 2), we perform a model comparison of how war-related socioeconomic stressors and infrastructure loss throughout Ukraine may impact future energy resiliency and the ability for clean and sustainable reconstruction within Ukraine. This collaborative work has resulted in the following key findings which are outlined in detail throughout the Report:

> 1. Ukraine's goal to reduce building energy consumption for heating and cooling by two-thirds by 2050 can be met under a strategic, and comprehensive, building stock retrofit strategy and economy wide decarbonization thus enhancing Ukraine's energy resiliency.
>
> 2. District heat remains an important heating source in Ukraine with decarbonization, provided that low-carbon alternatives are used, such as heat pumps and low carbon synthetic fuels (biomethane, synthetic methane, and hydrogen).
>
> 3. The decarbonization of buildings will require overall electrification with renewable electricity and/or fuel-switching.

This Report is designed to inform the Ministry of Communities, Territories and Infrastructure Development, Ministry of Energy, Ministry of Environmental Protection and Natural Resources and other interested parties of the potential for Ukraine to rebuild Ukraine's infrastructure in line with increased resiliency and European integration goals. Further, through stakeholder engagement and iterative interactions between IEF and PNNL, this Report lays the groundwork for future modeling exercises of reconstruction and decarbonization with Ukrainian partners.

1. INTRODUCTION

Ukraine has significant needs for reconstruction of its buildings and energy infrastructure. This presents an important opportunity to plan for a future that includes European integration, modernization, and decarbonization. Understanding the most cost-effective and viable paths forward for reconstruction is important in shaping the decisions that Ukraine and its partners are making in an ongoing way. This report is designed to help inform those decisions.

1.1 Energy Usage in Buildings – Ukraine's Plan to Lower Energy Consumption

The Ministry of Communities, Territories and Infrastructure Development of Ukraine has developed a draft strategy to retrofit buildings in Ukraine with the goal of reducing energy consumption for heating and cooling to two-thirds that of 2012 by 2050. Through this planned reduction in energy consumption, Ukraine aims to become increasing resilient to energy supply disruptions. To accomplish this, Ukraine plans to retrofit existing buildings with increasingly efficient materials for windows, doors, and insulation, new construction will make use of state-of-the-art building shell components, and technological shifts to higher efficiency fuel sources and heating systems will combine to lower consumption. Three potential retrofit pathways have been established by the Ministry of Communities, Territories and Infrastructure Development of Ukraine (Annex 2, Table 5). However, the new construction rate and the penetration of new technologies remain undetermined; thus, reaching such a reduction by 2050 requires scenario analysis to explore pathways towards energy reduction goals which can inform the potentials of such a policy.

In combination with the above practices, Ukraine has also embarked on district heating (DH) reforms to ensure more efficient and effective local district heating markets. DH reform can increase efficiency in Ukraine's local heat markets, while ensuring these systems contribute to Ukraine's long-term energy security. However, the current DH infrastructure in Ukraine is outdated and dominated by fossil fuel technologies (Kuznetsov et al., 2020). Thus, there is potential to reform the DH systems in Ukraine by shifting fuel sources to higher efficiency renewable inputs and heat pumps which can significantly reduce energy consumption. Concurrently approaching DH reform and building scale retrofits in Ukraine may provide the best opportunity to increase energy resiliency and security while improving building-scale infrastructure around the country.

1.2 Increasing Energy Resiliency in Ukraine – Co-benefits of Decarbonization

Ukraine updated its Nationally Determined Contribution (NDC) on climate change in 2021 by announcing a goal of reaching economy-wide net-zero GHG emissions by 2060 (GoU, 2021). With Ukraine's ambitions to join the European Union (EU), Ukraine would need to shift to the EU's agreed upon NDC which is a more ambitious target of net-zero GHG emissions by 2050 (European Commission, 2021). Regardless of emissions reduction strategy, the shift towards low-carbon technologies to reach specific targets in the future introduces an increased reliance on renewable energy sources, such as wind, solar, and biofuels. This shift to distributed energy sources has the potential to decrease energy dependencies in the future by allowing for increased domestic production (Petrovic et al, 2021). Distributed energy sources will also increase the resiliency of the power sector. By analyzing future decarbonization scenarios in Ukraine, we seek to understand the degree to which these renewable technologies may be required to reach defined emissions targets in the future.

A by-product of such energy and technology shifts is an overall electrification of end-use sectors which are often more efficient than fossil fuel powered energy systems. This Report seeks to understand the co-benefits of decarbonizing and retrofitting concurrently, the impacts that decarbonization may have on reaching the two-thirds energy consumption reduction goal set in the retrofit draft strategy, and the implications for the future energy dependencies in Ukraine.

1.3 Effects of the War with Russia – A Shift to Reconstruction

Russia began a full-scale invasion of Ukraine on February 24, 2022, resulting in significant loss of building and energy infrastructure. The invasion also resulted in significant migration out of Ukraine and a sharp decline in the economy. Since October 2022, Russian forces have targeted the power grid and district heating systems, causing massive power outages. The Russian army has destroyed, damaged, or occupied over 50% of power generation capacity, including 40% of solar and 90% of wind facilities in Ukraine (NCR, 2022).

In response to the war, the retrofit and decarbonization strategies have transitioned to one of building and energy system reconstruction. The Government of Ukraine has developed the Ukraine Reconstruction Plan, which prioritizes rebuilding and modernizing the Ukrainian energy system using clean, sustainable, and resilient energy systems. Additionally, close attention is paid towards the development of distributed generation, which can increase the resiliency of the power system.

1.4 Considerations for Modeling

This Report acts as the first modeling study to consider the effects of Russia's invasion of Ukraine and potential post-war reconstruction pathways. Here, we focus on building retrofits, energy system reconstruction, and economy-wide decarbonization. We consider comprehensive, multi-sector impacts of socioeconomic stressors, infrastructure loss, and territorial shifts brought upon by the war. We construct three distinct scenarios (Section 2) which analyze the implications of the war's effects, a dedicated residential, commercial and public building retrofit strategy, and an economy-wide decarbonization pathway which seeks to reach net-zero CO_2 emissions by 2050. To model such scenarios, several assumptions needed to be made about the future evolution of Ukraine, of which some currently exists as goals of various Ukrainian organizations, others remain uncertain.

In line with the Government of Ukraine's official domestic and foreign policy, we assume that all occupied territories of Ukraine, including the Autonomous Republic of Crimea, Sebastopol city and part of the temporarily occupied territories in Donetsk and Luhansk regions, will be returned to Ukrainian control no later than 2025. This assumption in reflected in population and GDP assumptions (Annex 2) and has been prepared, in part, by the Institute for Demography and Social Studies of the National Academy of Sciences of Ukraine (NASU) and IEF. We note that this assumption brings about a large uncertainty in our scenario analysis as we do not investigate varying levels of immigration and economic recovery which will alter energy demand and decarbonization pathways. Additionally, we assume that through the process of territorial recovery and war-related reconstruction, building floorspace will gradually increase through 2050 (Annex 2). Finally, we assume that technological change and fuel switching will allow for the economically viable development and future deployment of electric air-source heat pumps for DH, and air-to-water heat pumps for buildings.

2. METHODOLOGY

2.1. Research questions

Pacific Northwest National Laboratory (PNNL) and the Institute for Economics and Forecasting of the National Academy of Science of Ukraine (IEF) used two distinct energy models to understand the post-war effects of reconstruction and decarbonization in Ukraine. Together, the teams seek to answer two main research questions:

1. To increase energy resiliency within Ukraine, what measures are necessary to achieve a two-thirds reduction in building energy consumption for heating and cooling by 2050?

2. How does the compounding effect of decarbonizing Ukraine impact building and energy systems by 2050?

Below, we describe each model, the three distinct scenarios which are analyzed in the inter-model comparison of reconstruction and decarbonization, and methodological areas of uncertainty. Further model documentation can be found in Annex I at the end of this Report.

2.2. Models

The **Global Change Analysis Model (GCAM)** is an integrated assessment model that links five major systems – energy, water, land, climate, and the economy, through an integrated assessment modeling framework. Composed of 32 energy-economy regions, 384 land regions, and 235 water basins, the model simulates the complex interactions, synergies, and tradeoffs between these systems at global and regional scale at 5-year time steps through 2100 (Calvin et al., 2019). The energy component of GCAM captures both the supply and demand for energy across end-use sectors. Within each sector, competition for differing fuel types and energy sources occurs based upon the combined price for extraction, refinement, and generation, as well as the capital and overnight costs for energy supply systems. For this Report, PNNL developed the GCAM-Ukraine model, in which Ukraine is added as a 33rd energy-economy region, allowing for increased country-level representation of Ukraine in GCAM. All references to GCAM in the remainder of this report refer to GCAM-Ukraine.

TIMES-Ukraine is a linear optimization energy system model of the MARKAL/TIMES model family which provides a technology-rich representation of the energy system (bottom-up framework) for long-term estimations of energy dynamics (Loulou et al., 2016; Podolets and Diachuk, 2011). While GCAM models global interactions, the TIMES-Ukraine model represents a bottom-up representation of only Ukraine with detailed representation of energy technologies, floorspace, and other parameters. For example, the model mimics the district heating technologies in use across Ukraine. The TIMES-Ukraine model, developed by IEF, was used for preparation of several energy and climate strategic documents, which were adopted by the Government of Ukraine in 2016-2021. All references to TIMES in the remainder of this report refer to TIMES-Ukraine model developed by IEF. Annex 1 shows a comparison of the two models in select areas.

2.3. Scenarios

The teams modeled three scenarios: a reference scenario, a building retrofit scenario, and decarbonization scenario. All scenarios include post-war assumptions on population, GDP growth rates, floorspace of residential, commercial and public buildings, and territorial recovery (Annex 2). Each scenario is outlined below:

Reference. The Reference scenario assumes that no fundamental changes occur throughout Ukraine, often referred to as a "business-as-usual" scenario. Specifically, this includes no additional emission reduction measures, and implementation of energy efficiency improvements, deployment of renewable energy sources, penetration of new technologies, and implementation of environmental and climate commitments happen with rates observed over the past years.

Retrofit. The Retrofit scenario builds upon the Reference by adopting a dedicated building-scale retrofit strategy, in line with that of the Ministry of Communities, Territories and Infrastructure Development of Ukraine from 2022. This scenario shows the pathway to reduce energy consumption for covering energy demand and services in residential, commercial and public buildings according to the Building Retrofit Strategy through 2050. We adopt a retrofit pathway which closely follows a combination of policy approaches provided by the Building Retrofit Strategy (Annex 2). First, we apply a retrofit rate which reaches the Strategy's "Middle Way" scenario through 2040, then we increase the rate of retrofits to reach the Strategy's "Ambitious" scenario of 100% fully retrofitted buildings by 2050. The key goal of the Building Retrofit Strategy is to reduce energy consumption for heating and cooling in residential, commercial and public buildings by two-thirds between 2012 and 2050. This scenario introduces the potential for deployment of electric air-source heat pumps for DH, and air-to-water heat pumps for buildings which are three to four times more efficient than current fossil fuel heating systems (IEA, 2022a).

Decarbonization. The Decarbonization scenario for both models further builds on the assumptions made in the Retrofit scenario by including all technological change capabilities outlined above, and the same retrofitting rate for buildings. Additionally, the Decarbonization scenario assumes that Ukraine reaches zero emissions from buildings and net-zero CO_2 emissions economy-wide by 2050, with reductions beginning in 2025.

2.4. Post-War Uncertainty

For the purposes of this work, there are several areas of uncertainty surrounding the implications of the war and post-war reconstruction that must be noted. As stated above, the modeling teams assume, in line with the Government of Ukraine, that all occupied territories of Ukraine (Donbas, Crimea, and currently occupied regions within the Government Controlled Areas (GCA)) will be returned to Ukrainian control. With that assumption, comes uncertainty surrounding the extent of building and energy system infrastructure destruction and usability, population return, and economic rebound. Each of these components act as significant drivers of change in both models used for this Report, and deviations from the currently defined pathway have the potential to cause cascading result changes across scenarios and models.

3. RESULTS COMPARISON

As we show below, while GCAM and TIMES are consistent in their shift to low-carbon fuels, the models diverge in the fuel mix over time. Shown throughout the results, in the Retrofit and Decarbonization scenarios, GCAM shows electrification to a decarbonized grid, while TIMES favors modest electrification and a switch to low-carbon fuels such as biofuels and synthetic fuels (synthetic methane produced through a reaction of captured CO_2 and renewable hydrogen). The differences in fuel mix and deployment are a complex function of not only what technologies are available in each model, but also differences in cost, resource availability, model structure, and solution approach.

3.1. Building Energy Consumption

Figure 1 and Figure 2 show final total consumption by buildings for all energy services. In the Retrofit scenario, final total consumption by buildings decreases by 28% in TIMES, however, remains stable in GCAM from 2020 to 2050. Likewise, in the Decarbonization scenario, final consumption for buildings decreases by 36% in TIMES and only 4% in GCAM, respectively, during this period. GCAM's lack of energy reduction can be attributed to increased electricity use for other household appliances and electronics. As this increase includes the 35% reduction from 2012 to 2020, the modeling suggests that Ukraine's retrofit strategy target can be exceeded. Reductions in energy consumption can bolster energy security by increasing the likelihood that Ukraine can meet its energy demands from domestic sources and provide resilience to external supply shocks. In turn, cost savings from energy efficiency gains can offset in part the costs of rebuilding.

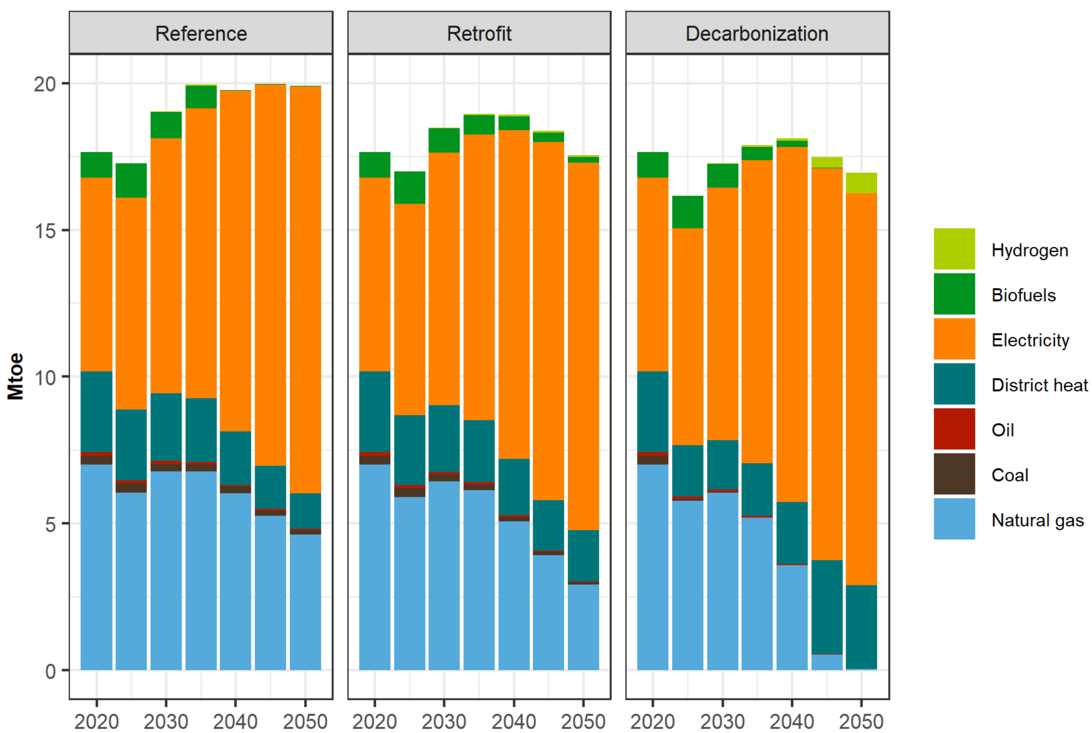


Figure 1. Final consumption for all buildings by fuel, GCAM-Ukraine.

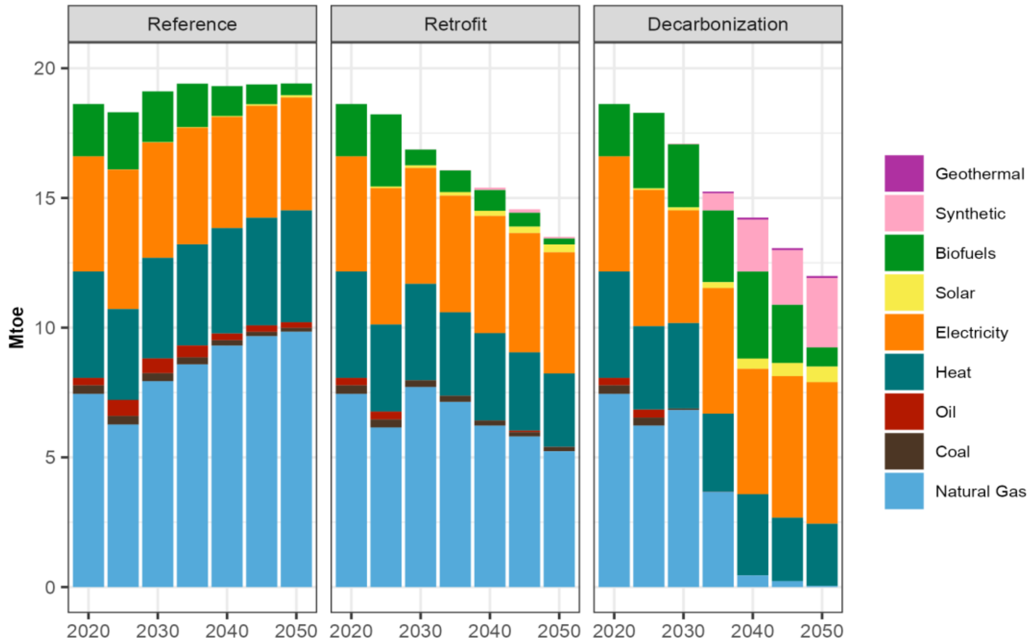


Figure 2. Final consumption for all buildings by fuel, TIMES-Ukraine.

Note: Synthetic fuels include bio- and synthetic methane and hydrogen.

While GCAM and TIMES are consistent in their shift to low-carbon energy sources, the models diverge in the fuel mix over time. GCAM meets the net zero CO_2 emissions constraint relying more on widespread electrification, while TIMES uses a suite of technologies, including synthetic fuels, biomass, and electricity. In 2050, under the Decarbonization scenario in GCAM, 82% of building final energy is supplied by electricity, and 99% including the contribution from district heat (DH), which is almost entirely supplied by DH-scale heat pumps (see next section). For TIMES, 94% of the building final energy is supplied by low-carbon sources (synthetic fuels, biomass, and electricity), including the contribution from DH. Natural gas no longer supplies any building energy in 2050 in this scenario in either model.

The difference in the use of renewables (see below on electricity generation) and biofuels to supply building energy is notable, and at least partially reflects model structure and solution approach. Moreover, GCAM, unlike TIMES, is a global model with trade for various resources, including biofuels. There is competition for land between food and energy production, for example, that does not exist in TIMES. One should also be cautious about the inclusion of biomass, in general, as a low-carbon fuel. The climate impacts of biofuels compared to fossil fuels is highly situational, depending on feedstock, production methods, and whether land use change is incorporated (Jeswani et al., 2020).

As such, the possible energy and food security implications of a reliance on biofuels should be treated cautiously and would need to be explored further. In TIMES in the Decarbonization scenario, the use of biomass to meet final energy increases 188% from 2020 to 2050.

Figure 3 and Figure 4 show building energy consumption just for heating. In the Decarbonization scenario, heating energy consumption declines 44% in GCAM from 2020 to 2050. In TIMES, the reduction is 57% from 2020 to 2050 in the Decarbonization scenario. The modeling results for building heating energy consumption indicate that Ukraine can reach its goal of reducing energy consumption for heating and cooling by two thirds by 2050 from 2012 levels, bolstering its energy security needs. Significant reductions in building heating and cooling energy use can be achieved with an aggressive retrofit strategy. Coupling retrofits with an economy-wide CO_2 emissions constraint results in further reductions.

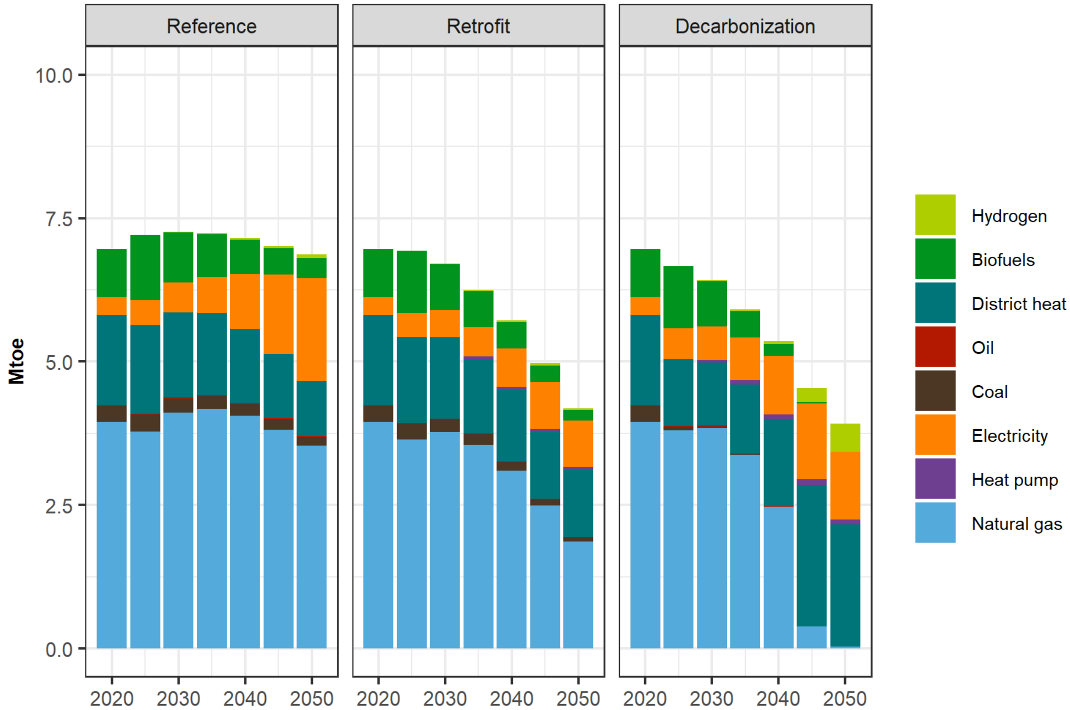


Figure 3. Energy consumption for heating by buildings, GCAM-Ukraine.

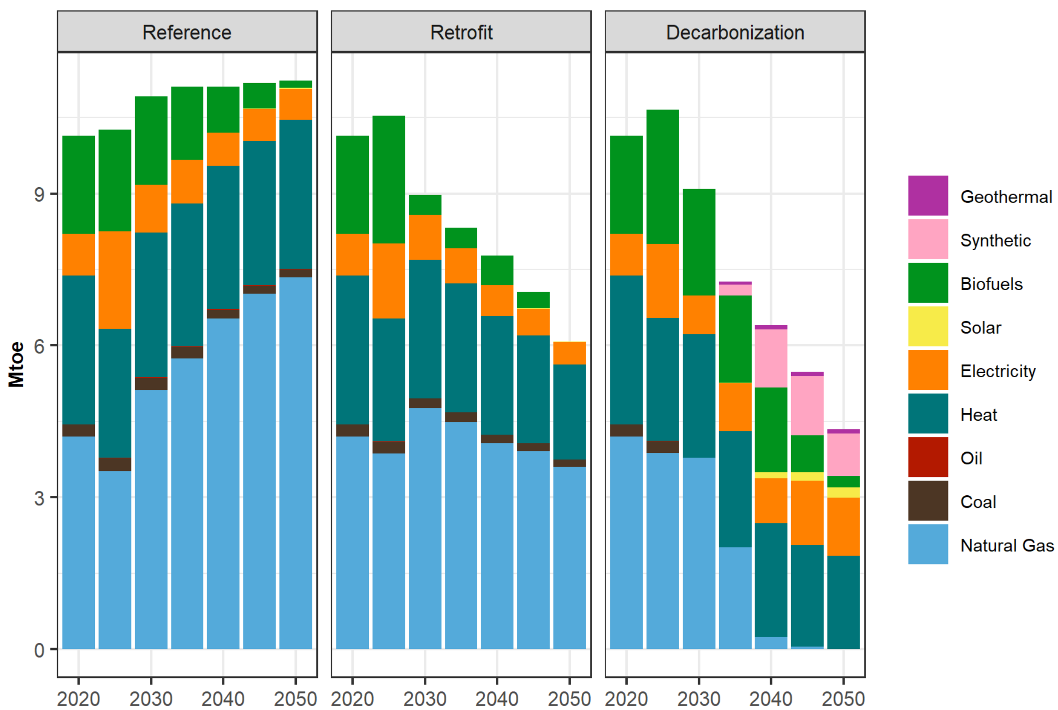


Figure 4. Energy consumption for heating by buildings, TIMES-Ukraine.

In GCAM, heat is supplied by conventional electric heating, air-to-water heat pumps, hydrogen, and DH. Considering that 99% of DH is supplied by air source heat pumps in 2050 in the Decarbonization scenario (next section), this means building-scale and DH-scale heat pumps supply 57% of heating demand in 2050. Like GCAM, all the building heat demand in TIMES is supplied by low-carbon sources.

Heat consumption by buildings decreased by 35% between 2012 and 2020. Recognizing this reduction, the modeling suggests that Ukraine's retrofit strategy target can be exceeded. Reductions in energy consumption can bolster energy security by increasing the likelihood that Ukraine can meet its energy demands from domestic sources and provide resilience to external supply shocks. In turn, cost savings from energy efficiency gains can offset in part the costs of rebuilding.

3.2. District Heat

The results for DH indicate that DH can remain an important heating source in a resilient, decarbonized future in Ukraine. If DH makes a low-carbon transition, then it will likely persist, given the existing distribution network and the generally lower costs compared to building-level heat technologies. Figure 5 shows the fuel source for district heat for buildings by scenario from GCAM. In the Decarbonization scenario, electricity supplies 99% of the heat in 2050, and all of this is generated by DH-scale electric air source heat pumps. The large drop in energy consumption for heating is in part explained by the high efficiency of heat pumps, which, on average are 3-5 times more efficient than fossil fuel boilers (IEA, 2022a).

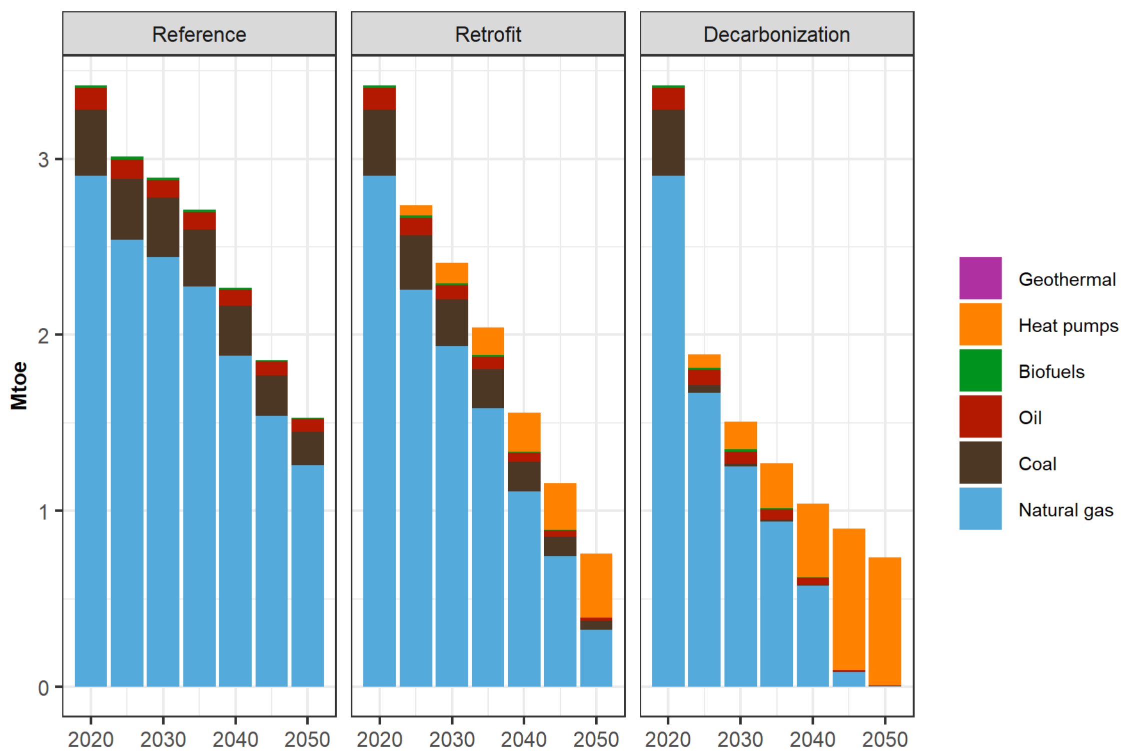


Figure 5. Fuel sources of DH for buildings only, GCAM-Ukraine.

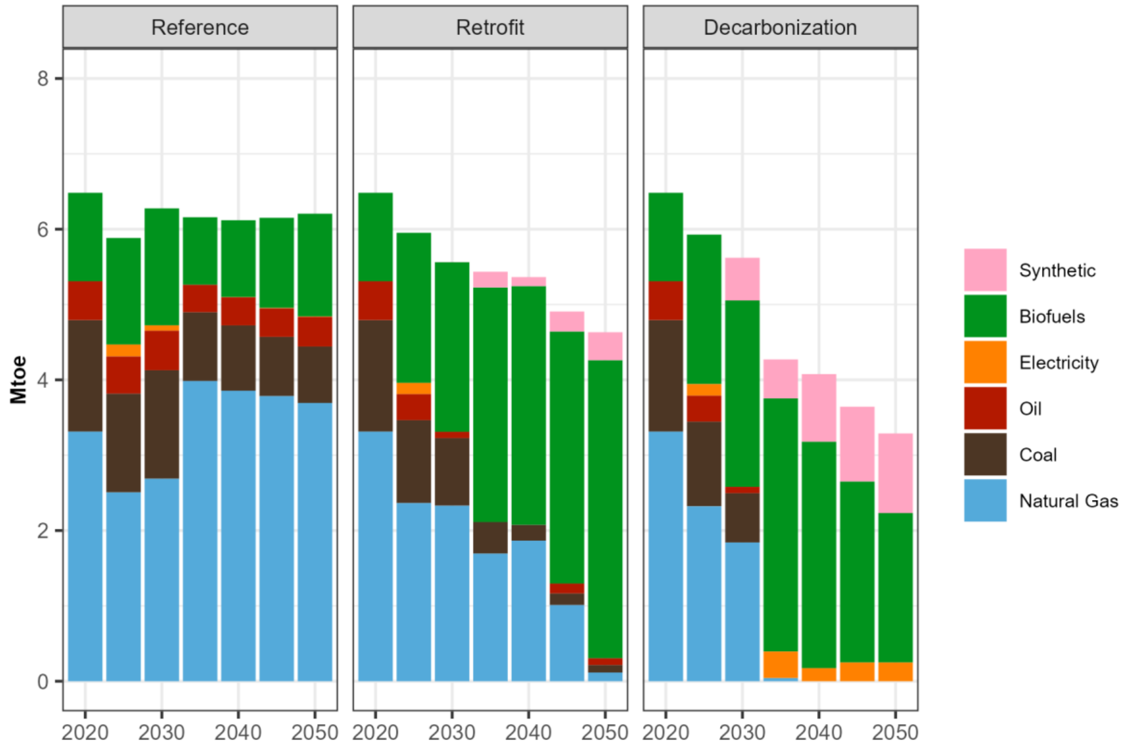


Figure 6. Fuel sources of district heat plants and industrial boilers, TIMES-Ukraine.

TIMES models DH somewhat differently than GCAM, separating DH plants from industrial boilers (Figure 6). In 2050 under the Decarbonization scenario in TIMES, DH is produced by low-carbon fuels, including biofuels (60%), synthetic fuels (32%), and electricity (8%). All the electricity is used by DH-scale electric air source heat pumps. TIMES relies less heavily on electric heat pumps to produce heat than GCAM in the Decarbonization scenario, in part due to its selection of bioenergy.

3.3. Economy Wide Energy Supply, Consumption and Emissions

Final Energy Consumption

Reconstructing Ukraine in a resilient way leads to the use of electricity from renewable sources and low-carbon fuels. This aligns with Ukraine's plans to integrate with the European Union, including EU decarbonization targets. Figures 7 and 8 show final energy consumption by fuels, which largely mirror those on building energy consumption. Fossil fuel use declines in the Decarbonization scenario from 45% of final energy consumption to 14% in GCAM from 2020 to 2050. For TIMES, fossil fuel use declines from 59% to 5% in the Decarbonization scenario over the same period. GCAM meets the net zero CO_2 emissions constraint relying more on widespread electrification (i.e., shift from fossil fuel combusting devices to electrical ones), using electricity produced with wind and solar.

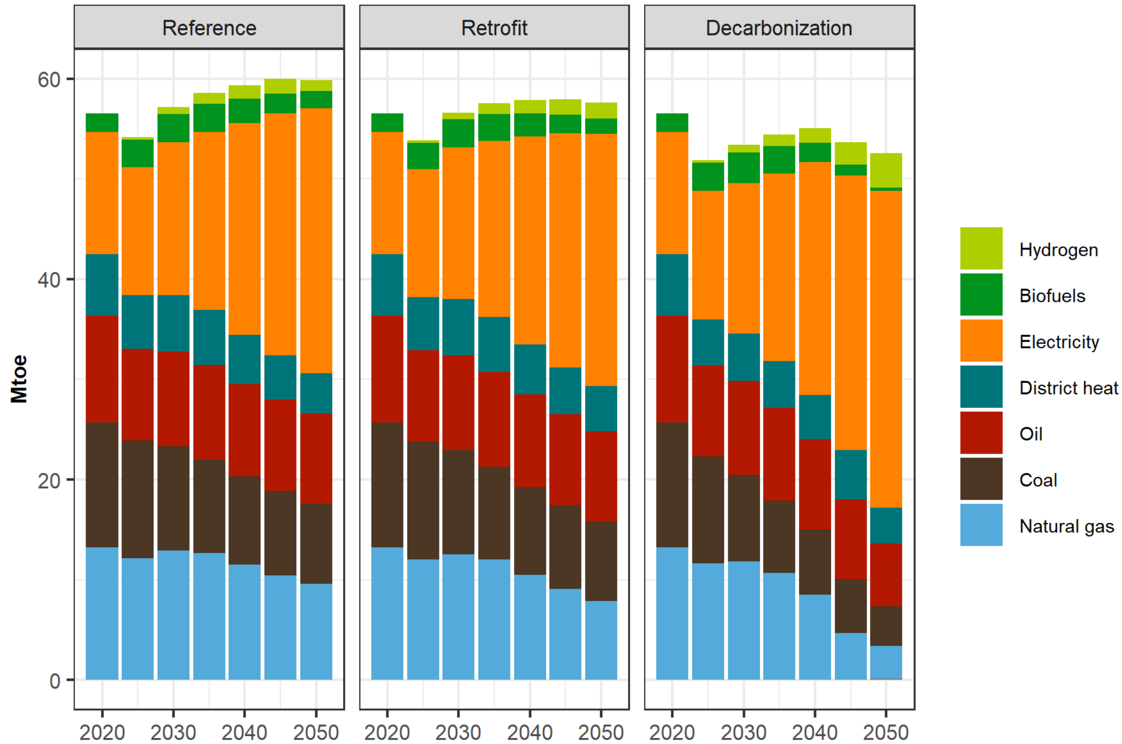


Figure 7. Total final consumption by fuels, GCAM-Ukraine.

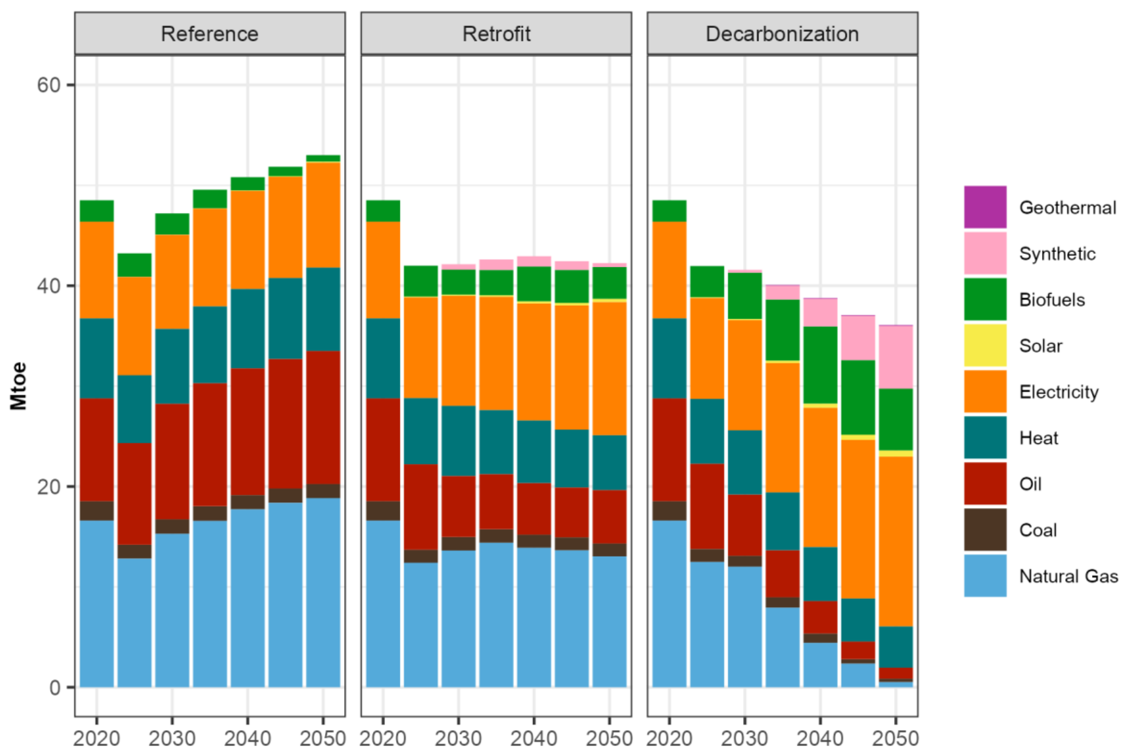


Figure 8. Total final consumption by fuel, TIMES-Ukraine.

In 2050, 60% of final energy is supplied by electricity under GCAM's Decarbonization scenario. In contrast, TIMES meets the net-zero target using multiple technologies, including electrification (47%), but also biofuels (17%) and synthetic fuels (17%) (includes both hydrogen and methane). (Of these, only hydrogen is explicitly included in the technology mix in GCAM). In aggregate, both models illustrate the importance of fuel switching / electrification, as one pillar of decarbonization. Electric devices, for example, not only reduce CO_2 emissions when the grid is powered by renewable electricity, but they are many times more efficient than conventional fossil fuel devices (IEA, 2021).

We note that differences in final consumption between TIMES and GCAM in 2020 arise as GCAM's harmonization of the industrial sector for Ukraine was outside the scope of this Report and therefore warrant future vetting. Annex 3 has additional results on total primary energy and final energy consumption by sector.

Electricity Generation

The results for electricity generation indicate that the scaling up of more renewable energy, such as solar and wind, is essential for building decarbonization. This shift from more centralized electricity generation to distributed renewables can enhance energy security and resilience. While both models show this transition, there are some differences in the electricity generation mix between GCAM and TIMES (Figures 9 and 10). In 2050, in the Retrofit scenario, TIMES projects that 61% of electricity generation to be wind and solar, with wind dominating (39%). Likewise, in 2050, under the Decarbonization scenario, TIMES projects 64% of electricity generation to be wind (46%) and solar (18%). For GCAM, the corresponding electricity mix in 2050 in the Retrofit (Decarbonization) scenario is 43% (57%) for solar, and 19% for wind.

There are many reasons why the results differ. Cost is not the only driver of technology selection in the models. For example, while both models have lower capital costs for utility-scale solar photovoltaics than wind, the TIMES model selects more wind than solar in the Decarbonization scenario in 2050 as significantly more cost-competitive wind generation potential is prescribed in TIMES by 2050 (IRENA, 2017). The deployment of technologies in both GCAM and TIMES is a complex function of resource availability, cost, and the degree to which non-cost factors impact technology selection. GCAM and TIMES differ in model structure (global vs. Ukraine-only), and solution approach (e.g., least cost solution in each period vs. optimization across all time periods) (Annex 1).

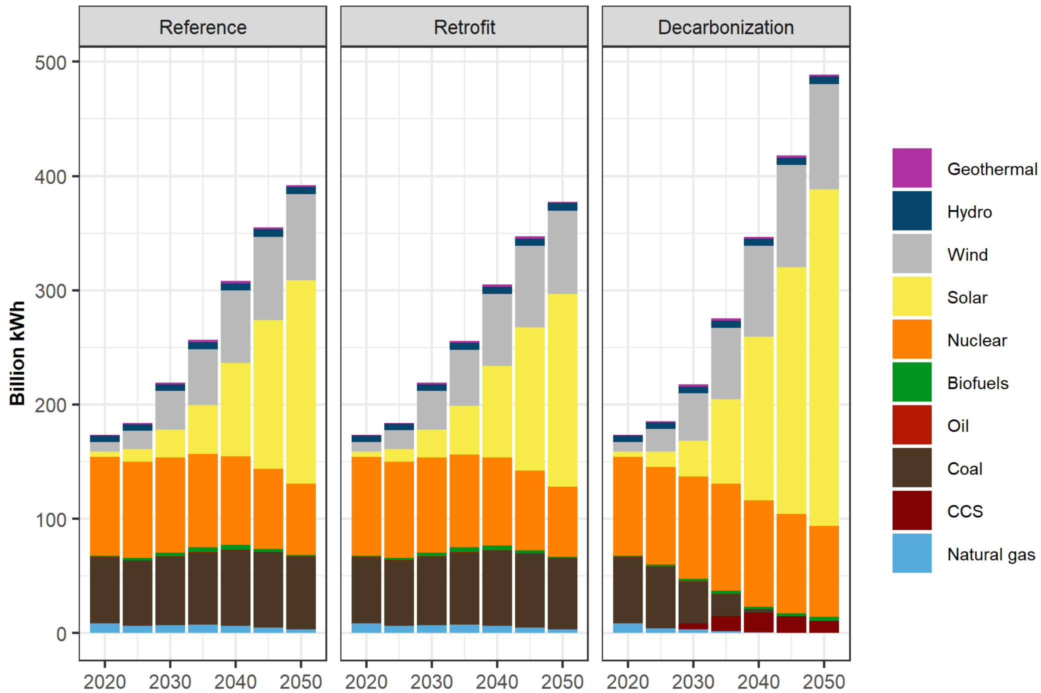


Figure 9. Electricity generation, GCAM-Ukraine.

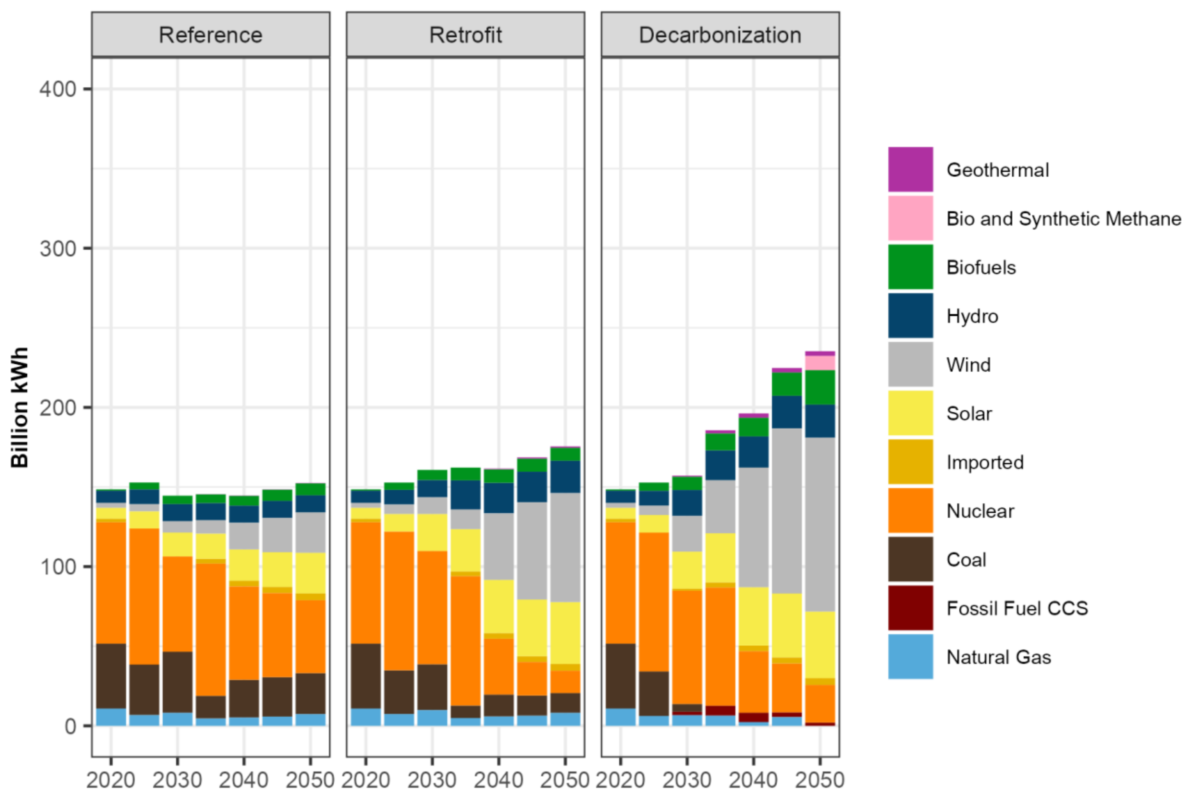


Figure 10. Electricity generation, TIMES-Ukraine.

Note: CCS refers to carbon capture and storage.

The increase in the electrification of end uses, such as electric heat pumps and vehicles, necessitates an increase in electricity demand. This particularly true for GCAM, which relies more heavily on electrification through the mid-century in all scenarios. As noted, TIMES relies on more modest electrification and fuel switching to non-electricity fuels like biomethane, synthetic methane, and hydrogen. Additionally, TIMES has embedded grid-balancing requirements that demand baseload generating technologies, whereas GCAM currently does not model variable load requirements and grid-balancing specifications. GCAM results, while high on electricity, are in line with plans and practice in most heating-dominant countries that plan to rely on a range of balancing technologies, such as smart meters, grid-integrated electric vehicles, and grid-scale storage. Further, TIMES assumes an 8-9-fold increase in bioenergy potential between 2020 and 2050 (Diachuk et al., 2017; Ukrenergo), allowing for significantly higher shares of biofuel-derived generation than GCAM. This is reflected in smaller increases in electricity generation in the Retrofit (35%) and Decarbonization (58%) scenarios in TIMES from 2020 to 2050 and much larger increase, mainly from intermittent technologies, in total electricity generation in GCAM from 2020 to 2050 in the Retrofit (118%) and Decarbonization (181%) scenarios.

CO_2 Emissions

Not surprisingly, CO_2 emissions vary significantly across scenarios, highlighting the importance of careful planning to reach EU integration and decarbonization goals. Reaching economy-wide net-zero emissions in 2050 in Ukraine will require almost a complete elimination of direct emissions in the buildings sector. In both models, the electricity and buildings sectors experience the steepest emissions reductions. (While all sectors will need to reduce emissions to reach net-zero emissions, industrial decarbonization falls outside our analysis and is subject for further research).

Both models can reach the net-zero CO_2 emissions constraint in the Decarbonization scenario in 2050 only with negative emissions technologies, namely direct air capture (DAC) and bio-energy carbon capture and storage (BECCS). (TIMES accounts for emissions slightly differently, but the negative 'wedge' for power and industry is all BECCS). Both GCAM and TIMES rely on about 20 Mt of CO_2 removal in 2050, although they differ in how much of that total is BECCS (91% for GCAM, 37% for TIMES) versus DAC. GCAM also allows for carbon removal in the land sector, but land use, land use change, and forestry emissions are not shown here and are not considered in the emissions constraint prescribed in the Decarbonization scenario.

The full energy security implications of the net-zero transition are outside the scope of this report but need to be explored more fully. However, the overarching conclusion is that the reduction in fossil fuel use will reduce import reliance, for example, on crude oil and petroleum products imports. According to the IEA Energy Balances (IEA, 2022b), Ukraine imported 85% of its crude oil in 2020. The net-zero transition will significantly improve energy security and resiliency of the national economy.

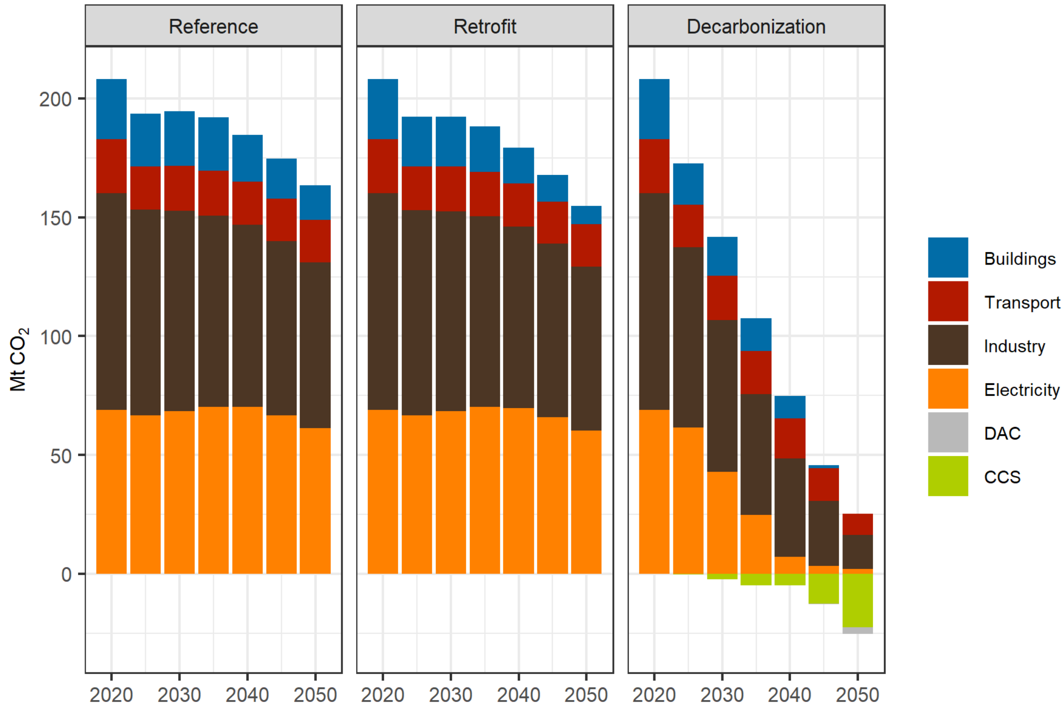


Figure 11. Total CO_2 emissions by sector, GCAM-Ukraine.

Note: CCS is bio-energy carbon capture and storage

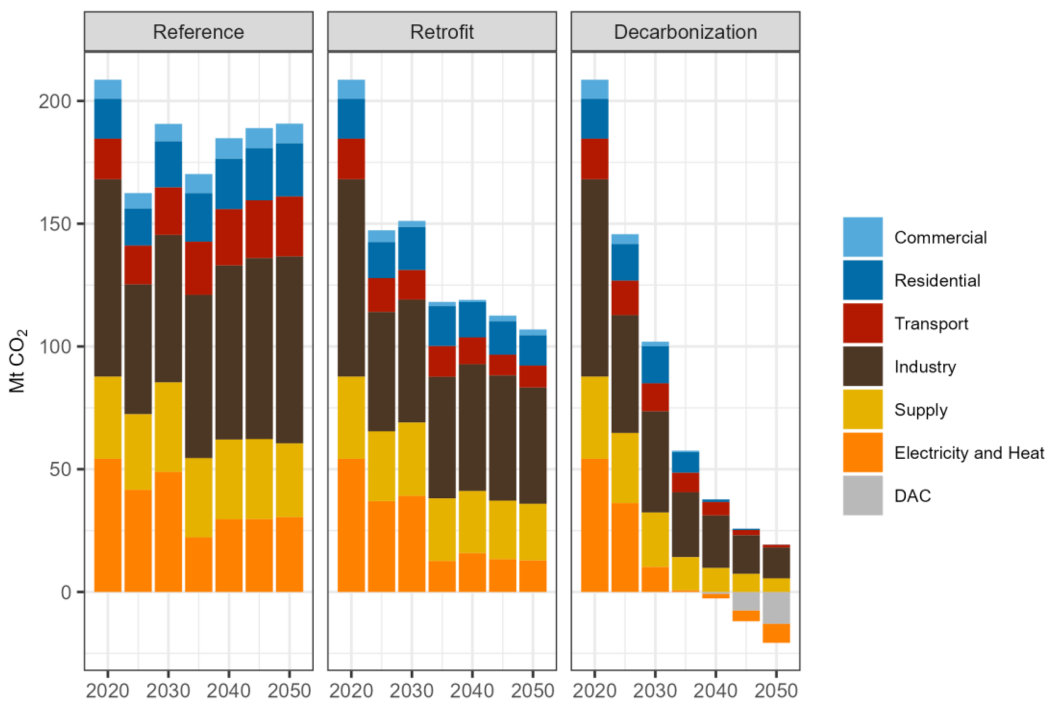


Figure 12. Total CO_2 emissions by sector, TIMES-Ukraine.

Note: Electricity and heat sector includes bioenergy carbon capture and storage (BECCS), which "emits" negative emissions. Supply includes mining, oil and gas extraction and distribution, and refining. These are included under Industry in GCAM.

4. LIMITATIONS AND UNCERTAINTY

There is significant uncertainty associated with affects from the war with Russia that affect many assumptions in this Report. One area of uncertainty is how Ukraine socioeconomically rebounds after the war; for example, the rate and location of population return, the rate of GDP recovery, population growth through mid-century, among others (Annex 2). Each of these uncertainties affect Ukraine's energy future and transition to a low carbon economy. There are countless possible scenarios which describe this rebound, and this Report does not attempt address this uncertainty.

Significant uncertainty exists due to the loss of energy infrastructure and destruction of buildings caused by the war. This study models building destruction with a decrease then rebound in floorspace after 2025, representing rebuilding and territorial recovery. However, neither GCAM and TIMES have limited means represent the destruction or loss of energy infrastructure, like destroyed power plants, transmission, etc. However, the models do represent vintaging in power plants that allows old power plants to age out and be replaced by new ones.

These uncertainties will be magnified in occupied areas where population loss and the destruction of energy infrastructure is more significant. However, the uncertainties with modeling occupied territories stem from the same uncertainties present in the modeling of other parts of Ukraine and GCAM and TIMES are unable to robustly address this uncertainty. Further, the data accessibility within non-Government Controlled Areas currently institutes a level of uncertainty as reporting for this area is not currently well understood and the transition of building and energy infrastructure from 2014's annexation to present is currently unknown. Developing mechanisms within GCAM and TIMES that could explore this uncertainty warrants further exploration in a future study.

Despite the above uncertainties surrounding the effects of the war and territorial reclamation, scenario analysis of this type can provide useful information for stakeholders and policymakers alike. GCAM and TIMES are well positioned to investigate future energy trends, driven by socioeconomics and policy through their integrated frameworks. While uncertainty exists, this Report lays the groundwork for our initial understanding of how the future will evolve, and can be altered, in time, with changing realizations.

Additional uncertainty exists in the modeling of new and emerging technologies, specifically the cost of such technologies and the extent to which they may be deployed. For this study we have implemented several new heat pump technologies at the building and DH scale which may emerge as competitive, highly efficient, and low carbon options in the future. However, we have implemented cost assumptions based upon existing data in other regions around the world (DEA, 2016b) and may not reflect the exact capital costs which Ukraine may face to adopt such technologies. As such, uncertainty exists in the potential adoption and deployment of these based upon Ukraine-specific costs which arise in the future.

Finally, there exist inherent differences between GCAM and TIMES. As shown, the two models depict very different pathways forward for Ukraine, under net zero goals and without decarbonization goals. No model can perfectly depict the interactions in an economy that decide how energy technologies are deployed, but the varying results of GCAM and TIMES show that a range of decarbonization strategies can be deployed in Ukraine to achieve a low carbon economy. GCAM shows that mass electrification through the availability of solar and wind can be deployed to replace fossil fuels, while TIMES shows that fuel switching to other non-electricity low carbon fuels like biofuels and synthetic fuels can be harnessed to replace declining fossil fuels. These differing pathways towards decarbonization highlight modeling differences between GCAM and TIMES. Specifically, GCAM considers globalized markets which allow for the trading of agricultural commodities, such as food and bioenergy crops between regions, whereas TIMES utilizes detailed representations of Ukraine and the resource availability within Ukraine.

5. CONCLUSIONS AND DISCUSSION

The goal of our analysis is to inform the policy process as the Ministry of Communities, Territories and Infrastructure Development of Ukraine and other Ukrainian ministries begin to plan for reconstruction in an era of decarbonization. The scenarios presented can provide guidance on how to become increasingly energy-resilient and shine light on the energy transition that Ukraine will need to embark upon as they seek accession to the European Union.

There are some key messages that can be gleaned from this analysis.

Ukraine's goal to reduce building energy consumption for heating and cooling by two-thirds by 2050 from 2012 can be met, enhancing Ukraine's ability to meet some of its energy security needs. Meeting the goal will require an ambitious retrofit strategy and an economy-wide, net-zero CO_2 emission target. Both models project that buildings final energy consumption for heating and cooling could decrease 44% to 57% in 2050 compared to 2020 under the Decarbonization scenario, on top of the 35% decrease in energy consumption from 2012 to 2020. Similarly, total final energy consumption under the Decarbonization scenario is projected to decline by about 8% (GCAM) to 28% (TIMES) from 2020 to 2050 in both models. Reduction in energy consumption can help foster energy security by increasing the likelihood that Ukraine can meet its energy demands from domestic source and helping to buffer external supply shocks. Cost savings through energy efficiency gains and fuel switching can in turn help to offset the costs of rebuilding.

District heat can remain an important heating source in Ukraine in a resilient, decarbonized future and could help bolster energy security. However, district heat will only be consistent with a transition to net-zero CO_2 emissions if low-carbon alternatives are used to supply heat. Both models show that a future, resilient, and EU-oriented Ukraine will significantly shift the fuels used in district heating. For example, in the Decarbonization scenario, the models find that about 100% of district heating in 2050 will come from a mix of low-carbon domestic resources, including electric heat pumps (powered by local renewables), industrial waste heat, synthetic fuels (hydrogen and methane, and biofuels. The models differ in how much bioenergy district heating will need, which reflects differences in whether the models incorporate competing food and export demands. Depending on future sources and feedstocks, however, biomass may have higher lifecycle CO_2 emissions than fossil fuels. If district heat makes a low-carbon transition, then it will likely persist, given the existing distribution network and the generally lower costs compared to building-level heat technologies.

Rebuilding Ukraine requires helping buildings shift to modern, low-carbon options, such as electrification with domestic renewable energy and fuel-switching. In the Decarbonization scenario as Ukraine rebuilds and modernizes its infrastructure almost all of building heat will be supplied by low-carbon alternatives in 2050, including both district heat and building-level technologies. Natural gas consumption declines steeply, transitioning from the predominant fuel for district heat in 2020, to virtually zero in 2050 in the Decarbonization scenario. Electric heat pumps are a particularly important technology, given that they are 3-4 times more efficient than traditional fossil fuel combustion boilers and furnaces. In both models, building- and district heat-scale electric heat pumps provide about half the building heat demand in 2050. The scaling up of more distributed renewable energy needed for building decarbonization, such as solar and wind, can also enhance energy security and resilience. In the Decarbonization scenario, solar and wind go from constituting close to 5% of electricity generation in 2020 to 64% and 76% in 2050.

Reaching economy-wide net-zero emissions in 2050 in Ukraine will require almost a complete elimination of direct emissions in the buildings sector. In the Decarbonization scenario across both models, the electricity and buildings sectors are projected to experience the steepest emissions reductions. While all sectors will need to reduce emissions to reach net-zero emissions, in particular, industry, this is outside our analysis. The use of negative emissions technologies, such as direct air capture or bioenergy carbon capture and storage will likely be needed to balance any emissions from hard-to-abate sectors of the economy 2050.

Our analysis in this report has been focused resilient reconstruction options for district heat and buildings. Future modeling efforts can consider policy scenarios in industry and transport and examine net-zero emissions pathways across all greenhouse gases, in accord with the EU targets. The complete energy security implications of the net-zero transition need to be more fully explored. While crude oil imports are expected to decline dramatically, there may be an increase in imports in other fuels, such as biomass.

The scenarios presented here are not predictions, but rather quantifications of possible pathways for net-zero emission futures. Indeed, the differences in the technology mix employed by the two models in some areas emphasize that there is more than one pathway to net-zero. Our results illustrate how Ukraine can combine an ambitious retrofit strategy with decarbonization to rebuild and modernize its building sector, supplying its energy needs through domestic sources, such electrification with renewable energy and low-carbon fuels. District heat can remain a viable heating source as Ukraine embarks on this energy transition. Ukraine will likely need new and enhanced fiscal and regulatory policies, building codes and standards, and an enabling environment that facilitates private sector investment, in order to reach its targets and 'builds forward' a more energy-secure, resilient, and decarbonized country.

ANNEXES

Annex 1. Models Used in This Study

Global Change Analysis Model (GCAM)

Global Change Analysis Model (GCAM) is a market-equilibrium model that links five major systems – energy, water, land, climate, and the economy, through an integrated assessment modeling framework (Figure 13). The model simulates the complex interactions, synergies, and tradeoffs between these systems at global and regional scales at 5-year time steps through 2100 (Calvin et al., 2019). This allows insights that are not possible in single-sector models.

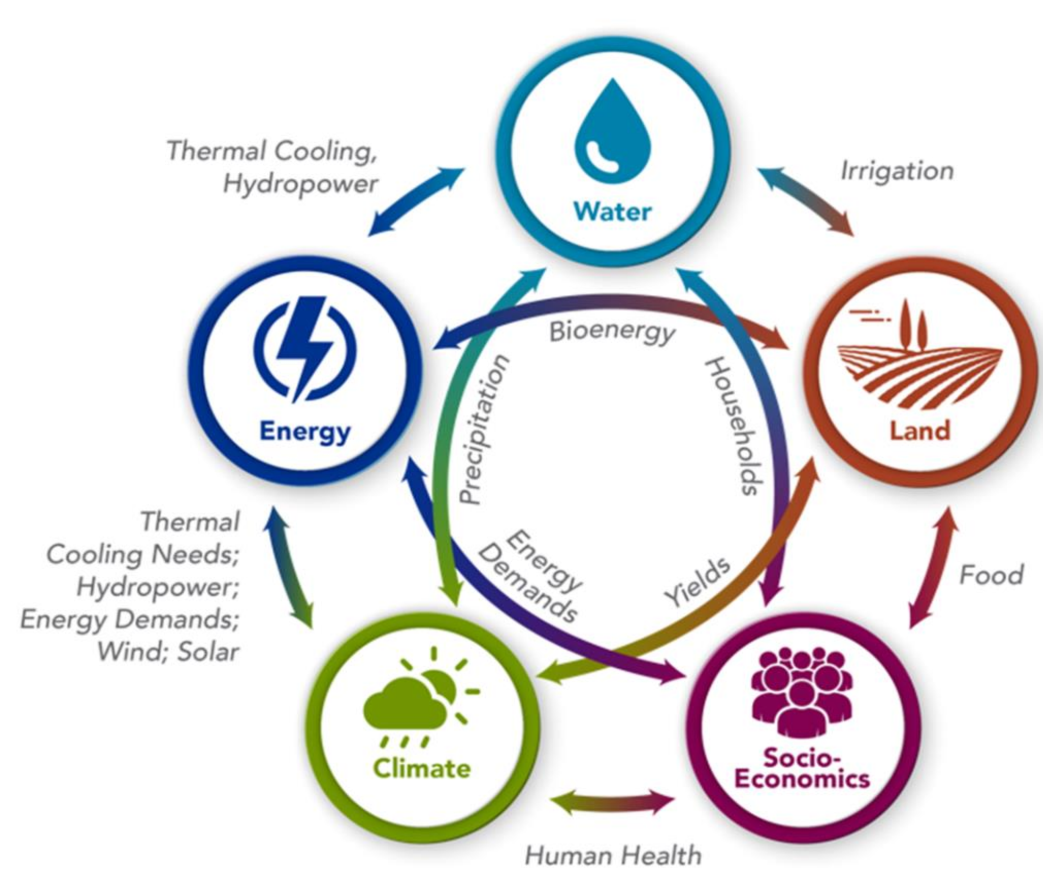


Figure 13. System map of GCAM.

Economic competition is used to determine the share of competing technologies in each model period. The model uses a partial-equilibrium approach to resolve global markets each period and ensure that supply is not exceeded by demand. The model also uses historical data to calibrate with future trends and assumptions. To model supply data, GCAM uses information on production, prices, technology cost and performance in the historical period to calibrate model parameters (Figures 14 and 15). In addition, GCAM's supply modeling requires information on future technology cost and performance and emissions factors for future periods. GCAM requires that supply data is globally consistent with demand data for each of its historical model periods as it solves for market equilibrium in these years as it does for future years. These inputs are required for each region and historical year.

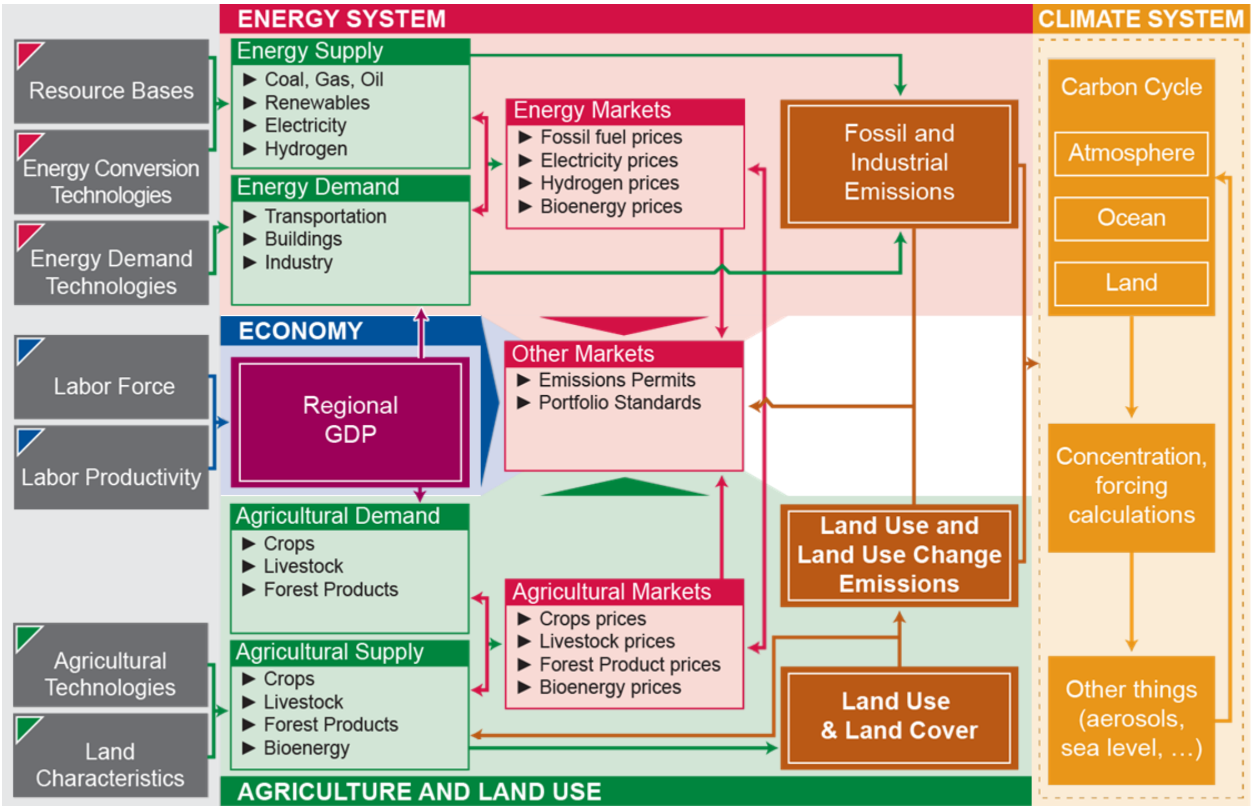


Figure 14. Basic GCAM structure (excludes water).

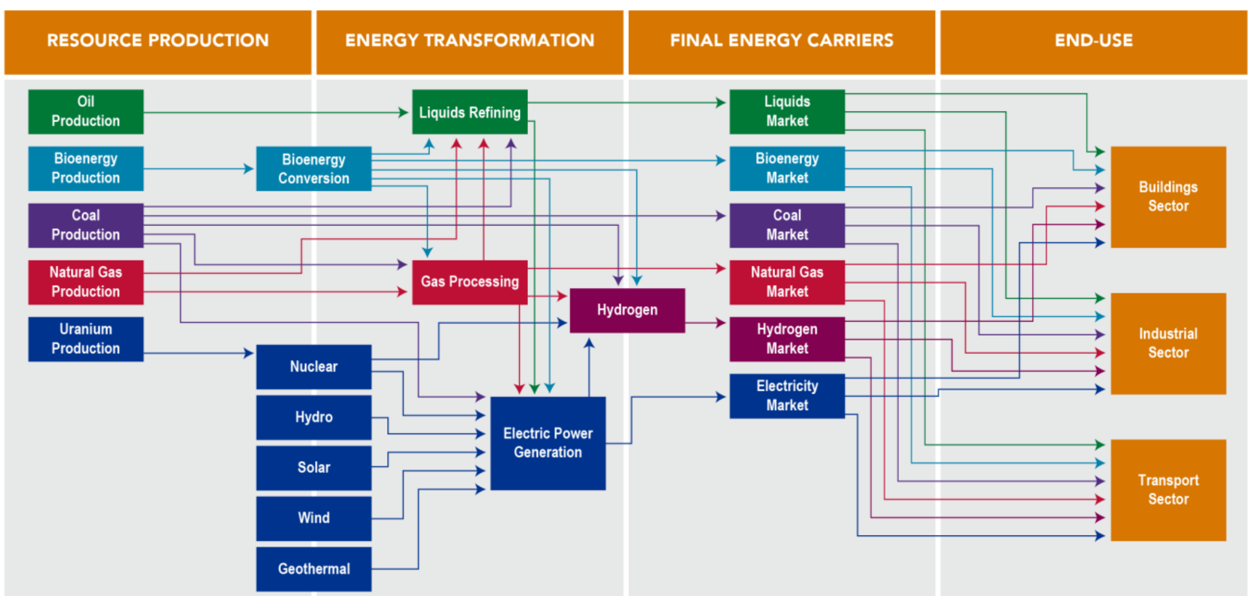


Figure 15. Energy system in GCAM.

GCAM has been used for numerous modeling activities in a variety of projects and studies, including all IPCC Assessment reports, the U.S. Long-term Strategy on net-zero GHG emissions by 2050 (White House, 2021), national decarbonization strategies in other countries, and sector-specific studies focusing on long-term interactions between the energy, water, land, and climate systems.

The standard GCAM model composed of 32 energy-economy regions, 384 land regions, and 235 water basins. However, PNNL has developed a number of country-specific model to analyze country-specific research questions.

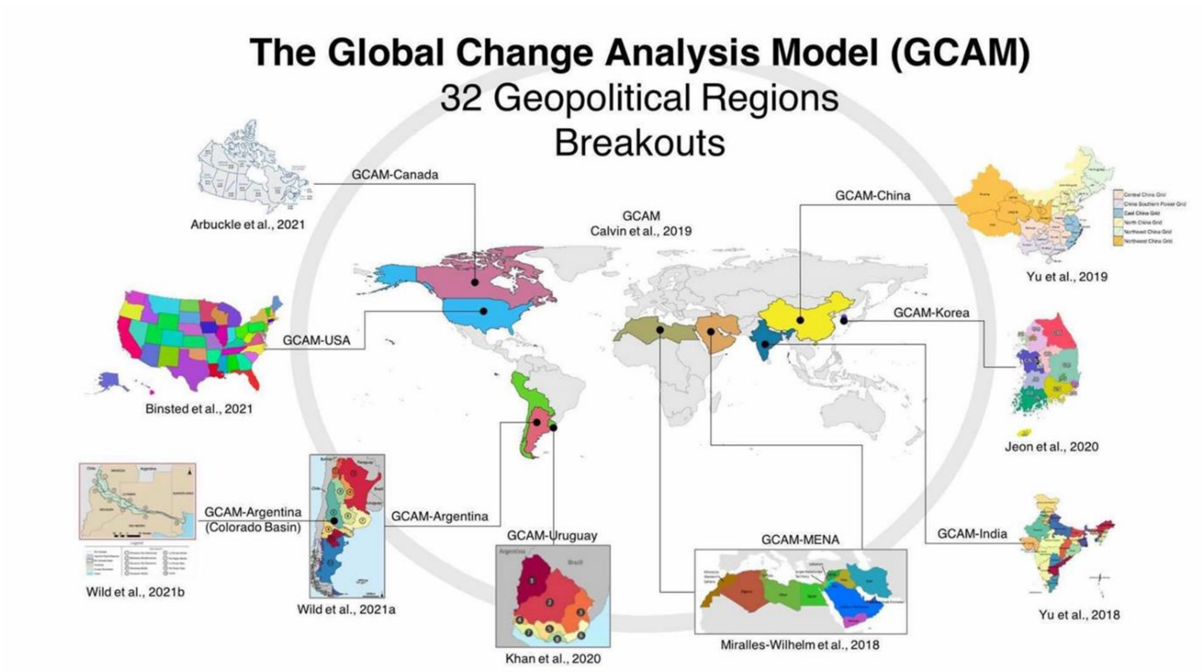
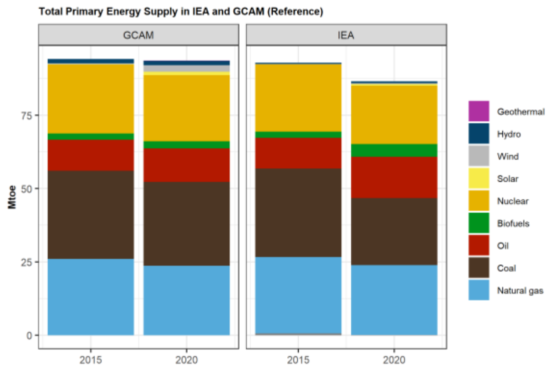


Figure 16. Break-out of standard GCAM.

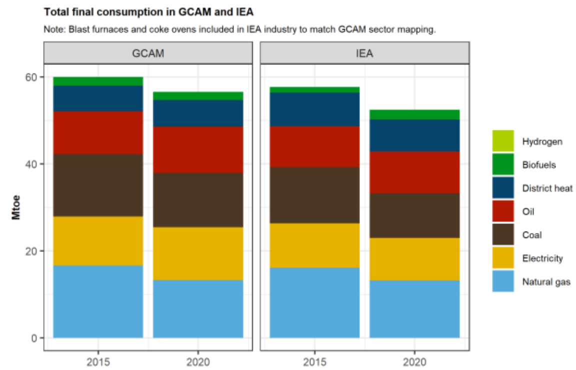
GCAM-Ukraine is used with the intent of modeling the long-term evolution of building energy demand globally and within the country of Ukraine, including the fuel mix and share of renewables. This assists in exploring the implications of end-use efficiency improvements in buildings at different stages of development and climate conditions. The building sector is divided into two building types: commercial and residential, with energy demand covering heating, cooling, and other services which includes all non-heating and cooling energy demands. The service-based model represents the changes in building energy consumption, building floorspace, and various energy services delivered to the floorspace over time.

GCAM-Ukraine includes two new technologies that are not part of the latest release version of GCAM: electric air-source heat pumps for district heat, and air-to-water heat pumps for buildings, based on data from the Danish Ministry of Environment (DEA, 2016a, b). The size of the district-heat-scale heat pump was assumed to be 10 MW with an efficiency of 3.8 (ratio of output energy to input energy). The corresponding values for building-scale heat pumps included 5 MW for residential buildings (efficiency 3.1) and 140 MW for commercial buildings (efficiency 2.5). Overall, heat pumps are 3-4 times more efficient than competing fossil fuel heating technologies. The capital and operations and maintenance costs were used to calculate non-energy levelized costs for the building and district heat technologies. The GCAM-Ukraine model development also included the separation of district heat for buildings and industry, so heat consumption for buildings could be analyzed separately.

GCAM-Ukraine was compared with IEA to ensure that modeling results are close to historical data in 2015 and first GCAM modeling period of 2020. The difference between IEA and GCAM-Ukraine in 2015 is about 1%. GCAM values are slightly different from IEA values in the first modeling period (year 2020) – the difference is 4% for TPES and 4.8% for TFC (Figure 17a and Figure 17b, respectively).



a) Total Primary Energy Supply



b) Final Energy Consumption

Figure 17. Comparison of GCAM-Ukraine and IEA results in 2015 and 2020.

TIMES-Ukraine Model

TIMES-Ukraine is a linear optimization energy system model of the MARKAL/TIMES model family (IEA-ETSAP) that provides a technology-rich representation of the energy system (bottom-up framework) of Ukraine for the long-term estimation of the energy dynamics (Loulou et al., 2016; Podolets and Diachuk, 2011).

The structure of the model is harmonized with Eurostat and IEA methodology with approximately 2000 technologies. The runs till 2060 and every year comprises 64 non-sequential time slices, representing 4 seasons, 2 weekly and 8 daily levels. The model database is filled with economic and energy data for 2005-2020 and fully calibrated for the years 2005, 2009, 2012, and 2015 (any of the listed years could be set as a base year for calculations). The Ukrainian energy system is divided into seven sectors in the model: supply sector, power and heat, industry, transport, residential, commercial and agriculture (including fishing). The database of the TIMES-Ukraine model includes data from several sources, including, the State Statistics Service of Ukraine, the Ministry of Energy, Ministry of Economy, Ministry of Environment and Natural Resources, Ministry of Internal Affairs, Ministry of Communities, Territories and Infrastructure Development, and many others. Energy data is gathered from the IEA, OECD, IAEA, and others. Long-term macroeconomic development indicators are based on data from the IEF NASU, IMF, World Bank, National Bank of Ukraine and Ministry of Economy.

The Ukrainian energy system is divided into seven sectors in the model (Figure 18). Therefore, the structure of the TIMES-Ukraine model complies with the methodological approach of the State Statistics Service of Ukraine (in turn, harmonized with Eurostat and IEA methodology) on energy statistics.

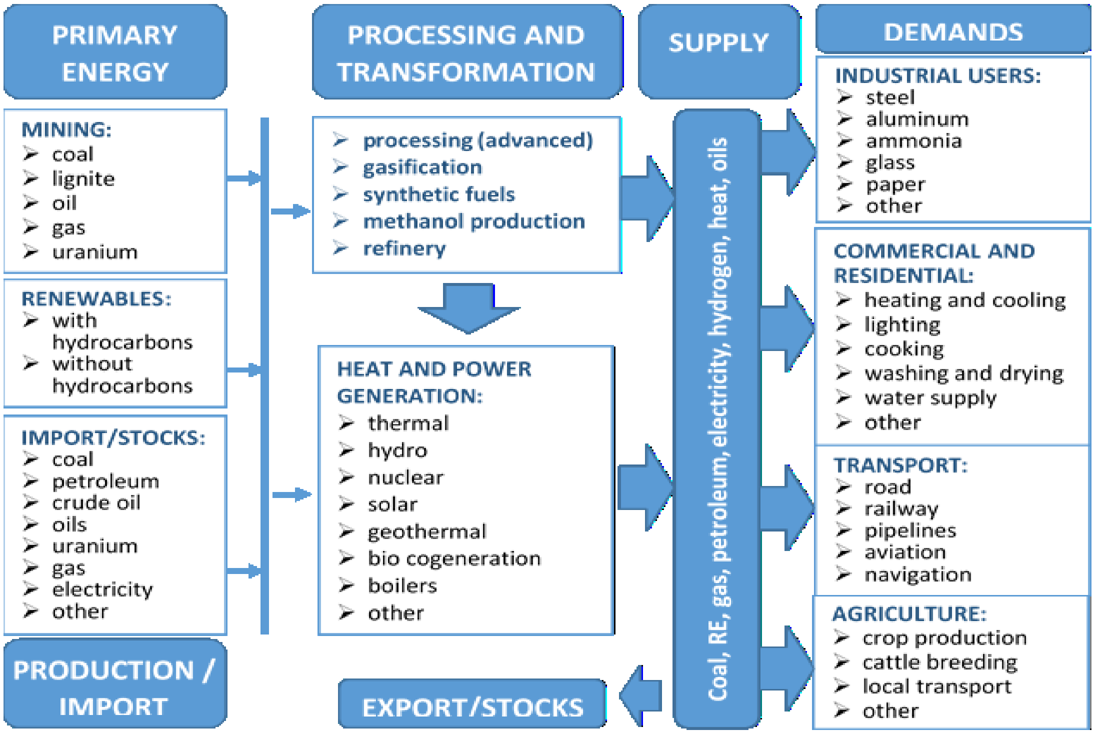


Figure 18. Representation of the energy system in the TIMES-Ukraine model.

The existing structure of the heat sector in TIMES-Ukraine model is shown in Figure 19 below.

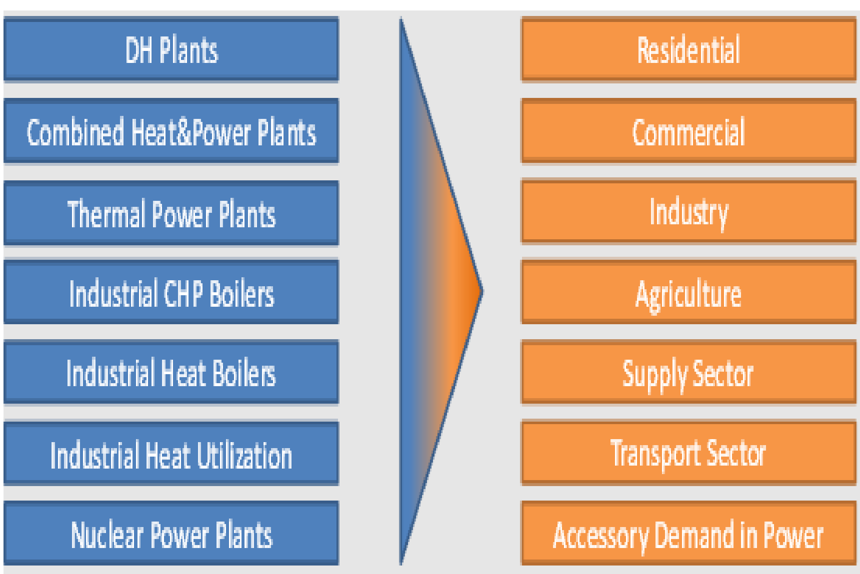


Figure 19. Representation of the heat sector in the TIMES-Ukraine model.

Table 1. shows a comparison of GCAM and TIMES models.

Table 1 Comparison of GCAM and TIMES

Topic	GCAM	TIMES
Solution method	*Recursive dynamic* (i.e., solves each period sequentially) Least cost model, but the logit choice formulation means that the technologies with the lowest cost are not exclusively selected.	*Inter-temporal mixed integer programming optimization* (i.e., finds least cost pathway over entire time horizon)
Model type	Integrated assessment model	Energy system model
Spatial scale	32 world regions and Ukraine	Ukraine only
Time horizon and time-slices	1990 – 2100, annual	Horizon 2005-2060, 64 time-slices per year
Time step	User-defined, usually 5 years	User-defined, usually 5 years
Sectors	Energy, land, water	Energy (including agricultural energy use and waste as energy sources), industrial processes and product use
Competition between food and bioenergy	Yes	No
International trade	Yes, global trade of energy commodities and agricultural commodities.	Only as exogenous inputs: import/export of energy carriers from/to the EU, Russia, and the Rest of the World
Treatment of district heat	District heat includes heat from Combined Heat and Power plants (historical period only) and heat-only plants. Industrial heat is not included.	District heat is heat from all centralized heat producers (power plants (incl. nuclear), Combined Heat and Power plants, heat-only plants). This is treated separately from industrial heat (incl. waste heat). Both used in the buildings sector.
Final energy consumption (fuels)	Fossil fuels (coal, oil, natural gas), renewables, hydrogen	Fossil fuels (coal, oil, natural gas), renewables, synthetic fuels (hydrogen, biomethane, and synthetic methane)
Building demands	Cooling, heating, other	Clothes Drying, clothes washing, cooking, cooling, dishwashing, heating, lighting, refrigeration, water heating, other
Heat pumps	Electric air-source heat pumps for district heat and air-to-water heat pumps for buildings	Electric air-source heat pumps for district heat and electric air-source and geothermal heat pumps for buildings

Electricity generation technology cost	US National Renewable Energy Lab (Annual Technology Baseline)	Various international (International Energy Agency, Lazard, EU Joint Research Centre) and Ukraine-specific sources (Bioenergy Association of Ukraine, Ukraine Wind Energy Association, Energoatom)
CO_2 emissions	Combustion from energy use, industrial process emissions, land use change	Combustion from energy use, industrial processes and product use emissions, fugitive emissions, and CO_2 storage
Negative emissions technologies	BECCS (Bioenergy carbon capture and storage), direct air capture, land use change (land sink)	BECCS (bioenergy carbon capture and storage), DAC (direct air capture)

Additionally, we note that GCAM-Ukraine and TIMES-Ukraine are calibrated to the year 2015 and that 2020 acts as the first future modeling time period. As a result, each model may not exactly match recorded data from any reporting agency for 2020, rather they have individually been tuned to align with 2020 data more closely.

Annex 2. Key Assumptions

GCAM-Ukraine and TIMES-Ukraine models used harmonized assumptions for key socioeconomic and building variables.

Population and GDP were assigned exogenously, using data from the Ptoukha Institute for Demography and Social Studies of the National Academy of Science of Ukraine, and GDP assumptions from the World Bank, IMF and the Institute for Economics and Forecasting of the National Academy of Science of Ukraine.

Future building floorspace has been estimated by IEF and assigned exogenously in each model. Additionally, retrofit and new construction rates have been estimated by IEF and applied in each model, although GCAM and TIMES model building age and turnover differently.

Table 2. Estimates of population, 2020-2050 (millions of people)

	2020	2025	2030	2035	2040	2045	2050
Population (all territories)	44.1	40.8	39.3	37.9	36.5	35.2	33.7
Population (without Crimea and part of Donbas)	38.0	35.0	33.8	32.6	31.5	30.3	29.2
Share of the rural population	30.6	30.7	30.9	31.0	31.2	30.6	30.7
Number of households	14.8	13.6	13.1	12.7	12.2	11.8	11.4

Source: Institute of Demography and Social Studies, IEF.

Table 3. Estimates of GDP with Crimea and Donbas after 2025 (billion USD 2015)

	2020	2025	2030	2035	2040	2045	2050
GDP of Ukraine, billion USD 2015	98.1	82.5	105.3	124.6	140.9	156.8	175.2
GDP growth rate, %, average for the 5-year period		-4.4	5.0	3.5	2.5	2.3	2.3

Source: IEF estimates based on consultations with IMF and World Bank.

Table 4. Projection of total areas of residential and public buildings (million m^2)

	2020	2025	2030	2035	2040	2045	2050
Residential buildings (with Crimea and Donbas)	1011.4	1070.7	1096.0	1115.6	1131.5	1140.0	1141.7
Commercial and public buildings	324.3	340.0	358.0	376.0	395.0	415.0	437.0

Source: IEF estimates for future years, State Statistics Services of Ukraine data for 2020.

Table 5. Projection of retrofitting rate for residential and public buildings

	2030	2040	2050
Reference scenario			
Public	17%	38%	59%
Residential	17%	33%	40%
Average	17%	34%	44%
Ambitious scenario			
Public	39%	64%	100%
Residential	44%	82%	100%
Average	43%	78%	100%
Middle way scenario			
Public	28%	51%	80%
Residential	30%	57%	70%
Average	30%	56%	72%

Source: Draft Building Retrofit Strategy, v. Dec. 28, 2022.

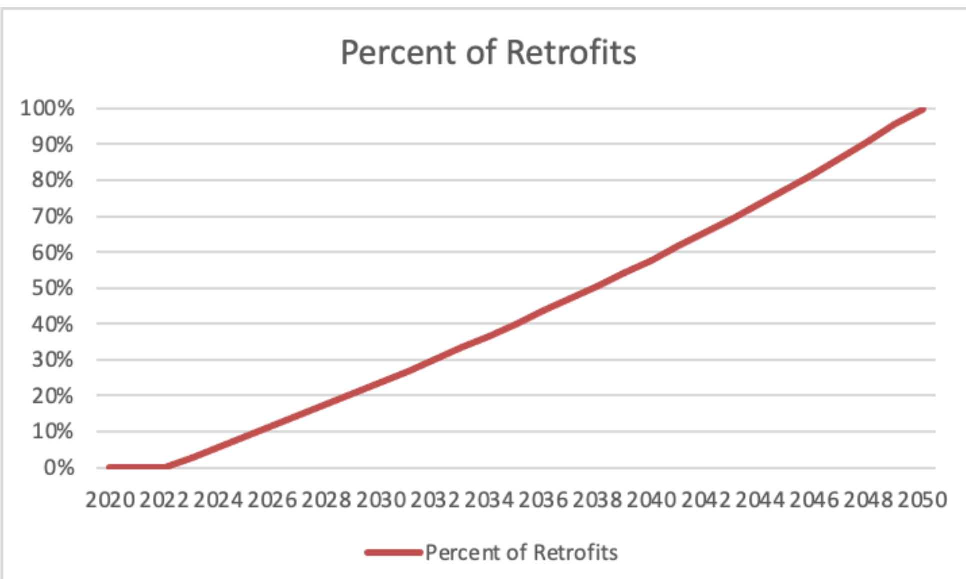


Figure 20. Commercial and residential building retrofits (percent of 2022 building stock).

Annex 3. Additional Results

Total Primary Energy Supply

Total primary energy supply (TPES) (i.e. the sum of energy production minus exports plus imports) for GCAM and TIMES are shown in Figure 21 and Figure 22. In the reference case for both GCAM and TIMES modeling, total primary energy supply stays relatively stable through 2050 after decreasing from 2020 to 2025 due to the war and resulting loss of GDP, population, and floor space. In the Decarbonization scenario, TPES declines 33% from 2020 to 2050 in TIMES, and 15% over that period in GCAM.

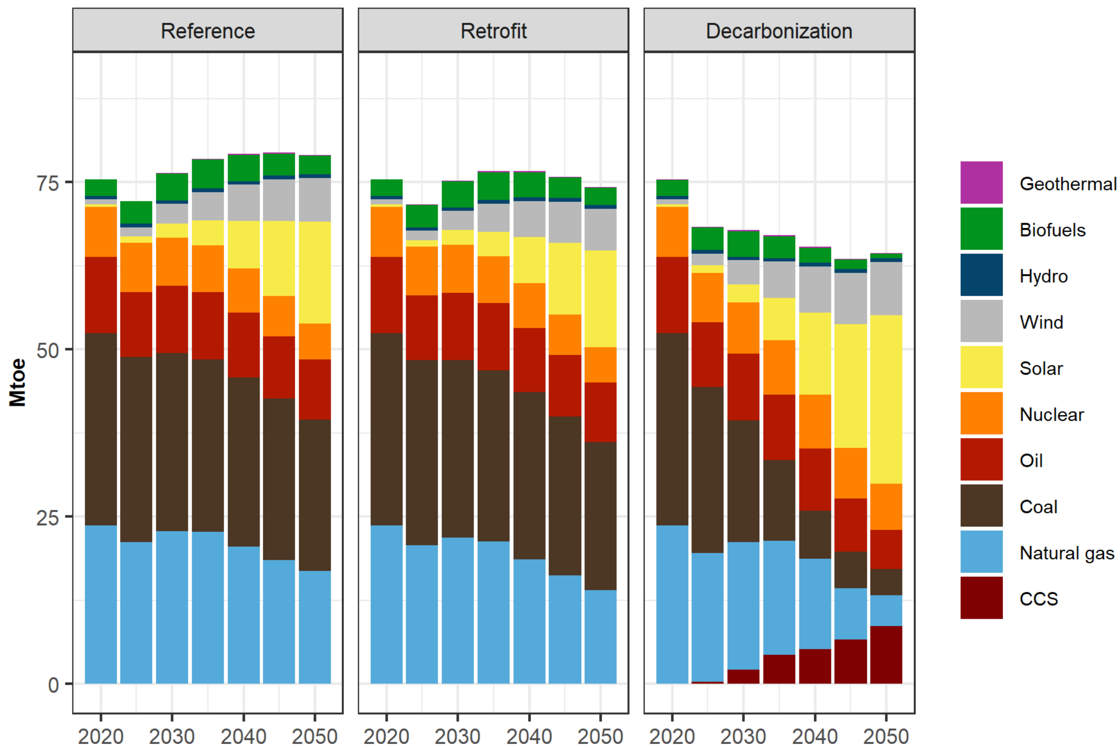


Figure 21. Total primary energy supply, GCAM-Ukraine.

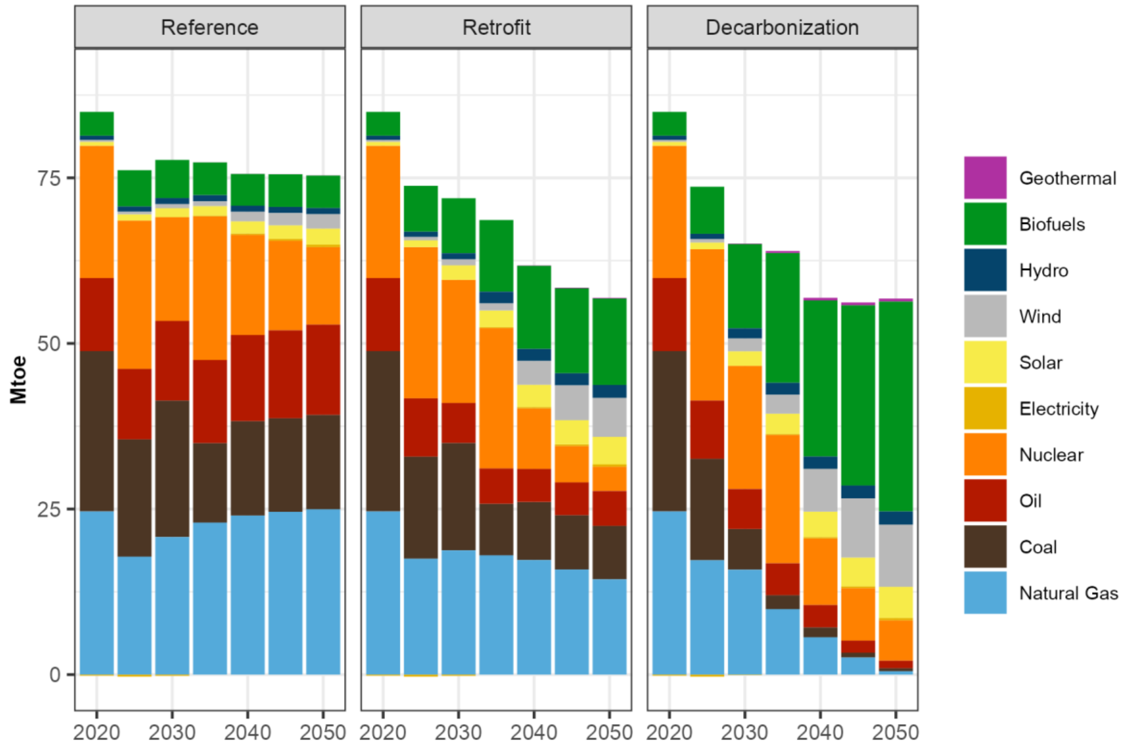


Figure 22. Total primary energy supply, TIMES-Ukraine.

Both GCAM and TIMES modeling show similar final energy consumption by sectors across scenarios (shown in Figure 23 and Figure 24): slowly increasing final energy consumption after rebounding from the war in the Reference scenario, relatively flat to slightly decreasing final energy consumption in the Retrofit scenario, and slowly decreasing final energy consumption in the Decarbonization scenario. Final energy consumption decreases 26% from 2020 to 2050 in the Decarbonization scenario in TIMES and 7% across the time period in GCAM. This reduction in final energy has implications for energy security. Lower energy demand increases the likelihood that Ukraine can meet its energy demands from domestic sources and can help buffer against external energy supply shocks.

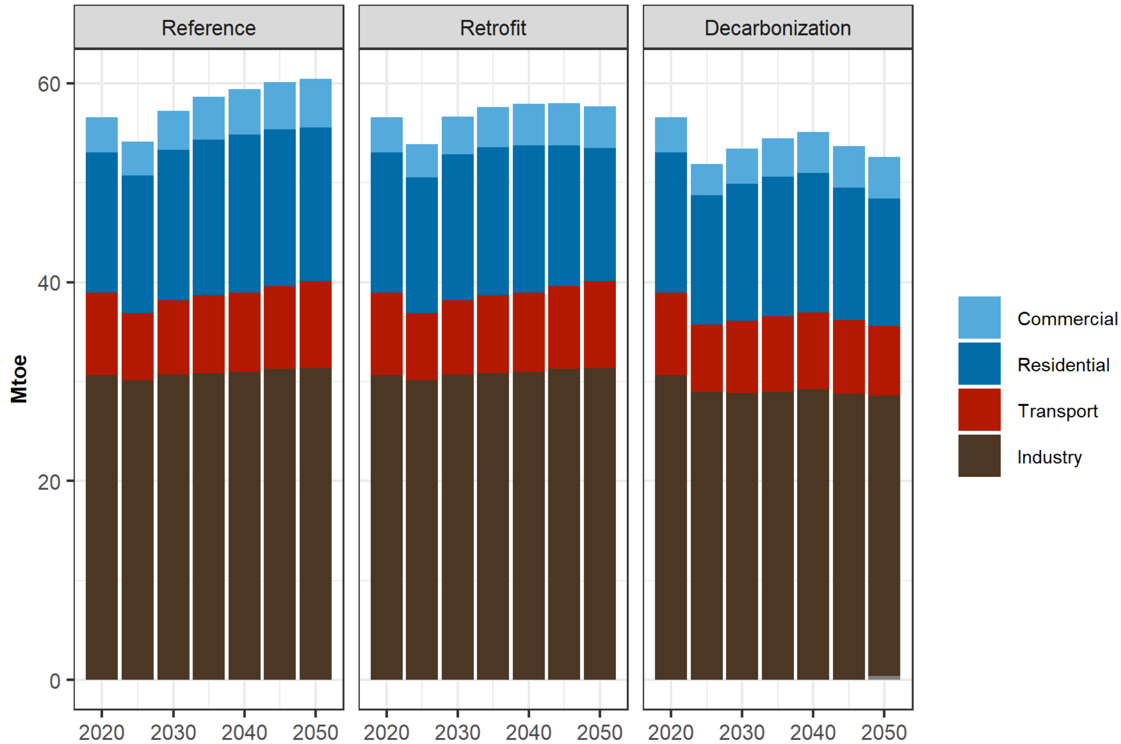


Figure 23. Total final consumption by sector, GCAM-Ukraine.

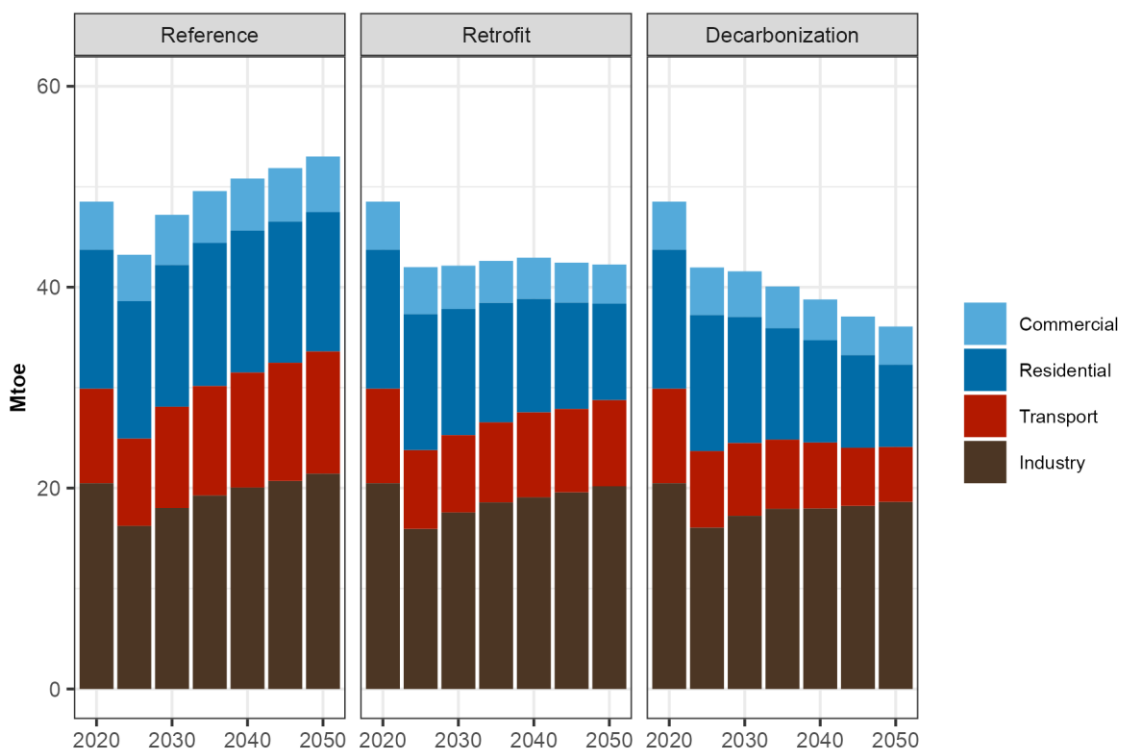


Figure 24. Total final consumption by sector, TIMES-Ukraine.

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