



Photo Credit: Anastasiia Zagoruichyk

BIOENERGY AND CLIMATE CHANGE IN UKRAINE: HOW CLIMATE CAN IMPACT THE SUSTAINABILITY OF BIOENERGY PRODUCTION

Pacific Northwest National Laboratory

May 2024

PNNL-36076

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor Battelle Memorial Institute, nor any of their employees, makes **any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.** Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or Battelle Memorial Institute. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from
the Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062

www.osti.gov

ph: (865) 576-8401

fox: (865) 576-5728

email: reports@osti.gov

Available to the public from the National Technical Information Service
5301 Shawnee Rd., Alexandria, VA 22312

ph: (800) 553-NTIS (6847)

or (703) 605-6000

email: info@ntis.gov

Online ordering: <http://www.ntis.gov>

Bioenergy and Climate Change in Ukraine: How Climate Can Impact the Sustainability of Bioenergy Production

May 2024

Kelly Casper
Meredydd Evans
Nazar Kholod
Anastasiia Zagoruichyk

CONTENTS

LIST OF FIGURES AND TABLES.....	v
ACRONYMS AND ABBREVIATIONS.....	v
EXECUTIVE SUMMARY.....	vi
1. INTRODUCTION.....	1
1.1 GOAL AND STRUCTURE OF REPORT.....	1
1.2 OVERVIEW OF UKRAINE'S BIOENERGY SECTOR.....	1
2. METHODOLOGY.....	4
3. RESULTS.....	6
3.1 EXISTING PROJECTIONS OF BIOENERGY POTENTIAL.....	6
3.2 ANALYSIS OF CLIMATE CHANGE IMPACTS ON BIOENERGY PRODUCTION COMPONENTS.....	9
3.2.1 WATER AVAILABILITY.....	9
3.2.2 AGRICULTURAL YIELDS AND FORESTRY.....	10
3.2.3 SOIL QUALITY.....	11
3.2.4 LAND AVAILABILITY AND FOOD PRICES.....	11
4. DISCUSSION AND RECOMMENDATIONS.....	13
5. CONCLUSIONS.....	15
7. REFERENCES.....	16

LIST OF FIGURES AND TABLES

Figure 1. The overall biomass potential in Ukraine (left circle) and the share of each type of agricultural residue within the biomass potential (right circle) in 2019, presented in Mtoe and percentages.	2
Figure 2. Change in Ukraine harvested area, 2023/24 versus 2021/22.	3
Figure 3. Illustration of the three phases undergone during the research.....	4
Table 1. Range of projections for total bioenergy, solid biomass, bioliquids, and biogas potential in Ukraine for 2020, 2030, and 2050 across different scenarios (units are presented in Mtoe).	8

ACRONYMS AND ABBREVIATIONS

BAU	Business as usual
CO₂	Carbon dioxide
EU	European Union
GCAM	Global Change Analysis Model
GHG	Greenhouse gases
IAM	Integrated assessment models
LULUCF	Land use, land use change and forestry
NECP	National Energy and Climate Plan
TIMES	The Integrated MARKAL EFOM System
TPES	Total primary energy supply
USDA	U.S. Department of Agriculture

EXECUTIVE SUMMARY

The Russian invasion has exacerbated Ukraine's energy security issues, prompting a shift toward diversifying energy supply sources. Additionally, strategic documents aim to align Ukraine's energy system with EU climate requirements, focusing on reducing reliance on fossil fuels and advancing decarbonization efforts. This report focuses on the expansion of bioenergy as an alternative source of energy in Ukraine. Current assessments suggest that Ukraine has substantial bioenergy potential, primarily from agricultural residues and energy crops. However, the challenges posed by climate change and the ongoing war might impact the outcome of these projections.

This report highlights the importance of integrating climate factors into energy modeling using tools like the integrated assessment models to provide a comprehensive understanding of Ukraine's bioenergy potential under various climate scenarios. It also emphasizes the need for climate-smart agriculture and forestry practices to mitigate risks, enhance energy efficiency, and support resilient crop supplies. Recommendations for stakeholders include diversification of the energy supply sources, developing adaptation strategies, diversifying bioenergy feedstocks, and ensuring robust decision-making to navigate the impacts of climate change on Ukraine's energy system.

I. INTRODUCTION

I.1 GOAL AND STRUCTURE OF REPORT

The central goal of this report is to assess how climate change might impact future bioenergy production in Ukraine and how researchers and policymakers can best take climate change implications into account. Section 2 of the paper outlines the methodology used to explore this issue. Section 3 provides an overview of existing bioenergy potential estimates for Ukraine and identifies how and if these estimates account for climate impacts on the bioenergy supply chain. In addition, it provides the results of the literature review on climate change impacts on resources needed to produce bioenergy, linking these findings to Ukraine's bioenergy potential. Finally, Section 4 discusses the findings and offers recommendations for future research and policymaking.

I.2 OVERVIEW OF UKRAINE'S BIOENERGY SECTOR

The Russian invasion has exacerbated energy security issues in Ukraine, prompting a push from the Ukrainian government to move away from a reliance on fossil fuels. The Government of Ukraine has developed strategic documents to guide the decarbonization and diversification of its energy system. These plans aim to reduce reliance on fossil fuels, enhance energy security, and align Ukraine with the European Union's (EU) climate requirements, which is crucial as the country seeks EU membership. The first steps were taken with the adoption of the law, aimed at replacing natural gas with alternative energy sources (Verkhovna Rada of Ukraine, 2017). With most coal-fired combined heat and power (CHP) plants now destroyed, Ukraine plans to replace them with small-scale gas- and biomass-fired generation capacities. Key documents on energy system decarbonization also include the Energy Strategy of Ukraine through 2050 (Ministry of Energy of Ukraine, 2023), the Draft National Energy and Climate Plan 2030 (NECP) (Ministry of Economy of Ukraine, 2024), and the Draft National Action Plan on the Development of Renewables through 2030 (SAEE, 2022). The expansion of bioenergy is a particular focus of the energy transition, given its potential and substitutability for natural gas (Chepeliev et al., 2021; UNECE, 2023).

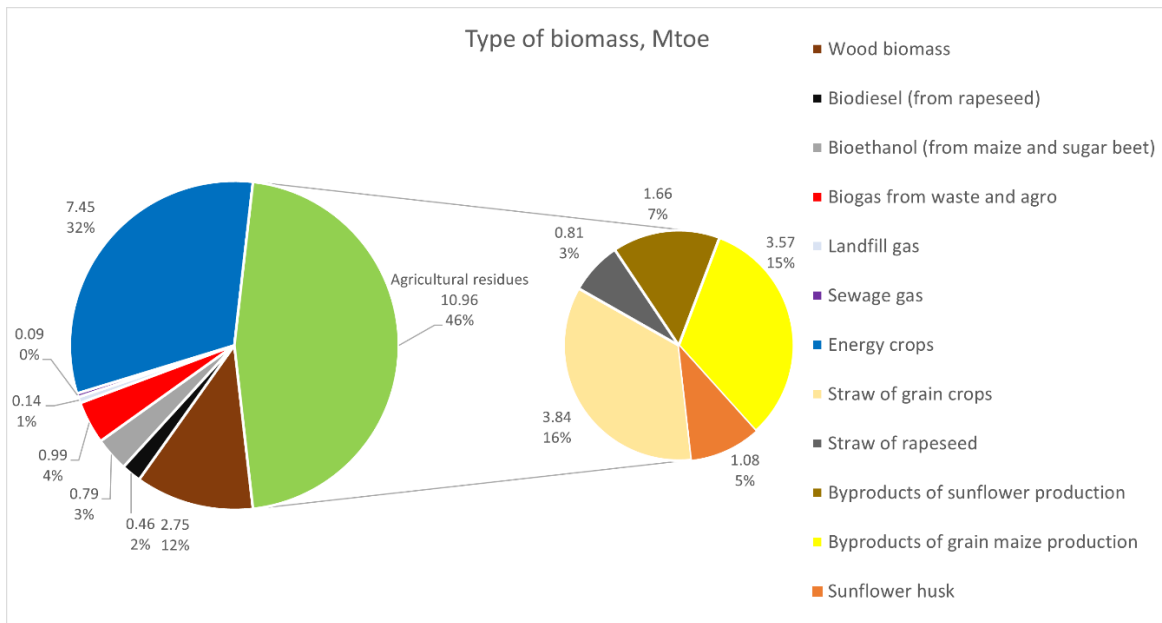
Several assessments conclude that Ukraine can feasibly expand bioenergy production, aligning with the target specified in various strategic documents to expand the share of renewables in gross final energy consumption to 27% (Chepeliev et al., 2021; Diachuk et al., 2020; Diachuk et al., 2017; Ministry of Economy of Ukraine, 2024; Petrović et al., 2021; SAEE, 2022; UNECE, 2023). Ukraine's goal is to significantly boost electricity generation from solid biomass, biogas, and biomethane installations. This increase is planned to be nearly ninefold, rising from 755 gigawatt hours (GWh) in 2020 to 6,530 GWh by 2030, as outlined in the draft of NECP (Ministry of Economy of Ukraine, 2024).

Several studies have quantified bioenergy potential in Ukraine at different geographical and bioenergy feedstock levels. Most studies are primarily concerned with the economic and technological feasibility of bioenergy production (Geletukha et al., 2019; Larina et al., 2021; Trypolska, 2023; Yakubiv et al., 2019), although most of these studies are based on the same

underlying analysis with just small variations. Other studies focus on the cost and technology barriers that could hinder bioenergy development and recommend solutions, such as the creation of bioenergy markets (Geletukha and Zheliezna, 2017; Geletukha et al., 2019; Kucher and Prokopchuk, 2020; Reznik et al., 2024).

The literature finds that most significant bioenergy potential in Ukraine includes agricultural residues, energy crops and woody biomass used for producing solid biofuels and biogas (Geletukha and Zheliezna, 2021). In 2019, 78% of Ukraine’s economically feasible bioenergy potential was from agricultural sources, with 46% of the total potential from agricultural residues and 32% of the total potential coming from energy crops (Fig. 1) (Geletukha and Zheliezna, 2021). A significant proportion of agricultural residues is attributed to the grain crops straw (35%) and the by-products of grain maize production (33%). Moreover, there are expectations that yields and technologies will improve over time to further increase the overall energy potential of biomass in Ukraine (Geletukha et al., 2023; Waş et al., 2022). Ukrainian researchers acknowledge ecological constraints of bioenergy production, especially in terms of agricultural residues availability (Geletukha et al., 2019). They also consider constraints of the biophysical availability of wood in forests (Vasylyshyn et al., 2022). However, the existing estimates and literature seem to overlook the potential impact of climate change on bioenergy production. This oversight represents a significant gap that needs to be addressed in research and discussions.

Figure 1. The overall biomass potential in Ukraine (left circle) and the share of each type of agricultural residue within the biomass potential (right circle) in 2019, presented in Mtoe and percentages.



Source: Adapted from Geletukha and Zheliezna (2021).

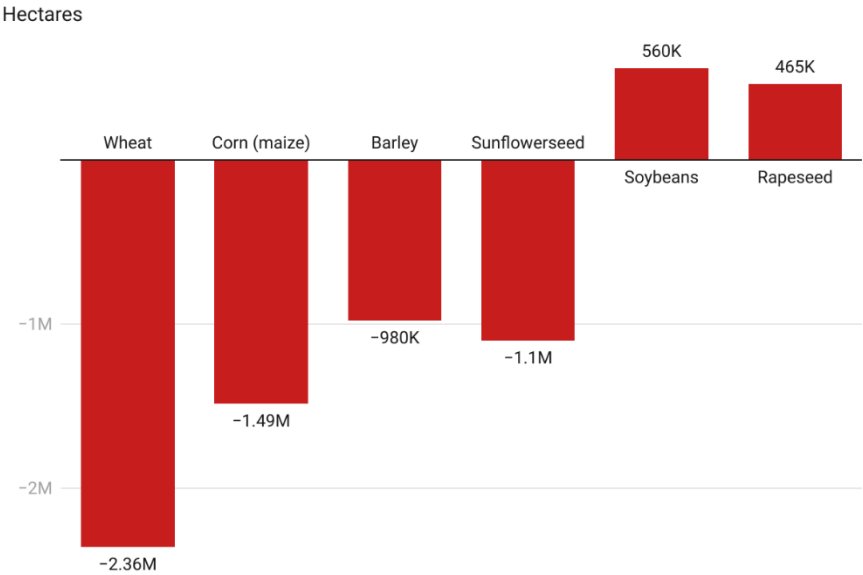
Agriculture is one of the most susceptible sectors to climate impacts and it is expected that rising temperatures, changes in precipitation, extreme weather events, and increases in atmospheric CO₂ concentrations will, to some extent, affect the crop configuration, agricultural yield, and

food prices (Akram et al., 2022). Ukraine is already experiencing the effects of changing climate. For example, in 2019-2020, droughts caused the southern regions of Ukraine to lose 3% of their winter crops. The Odesa region was hit particularly hard, with 10% of its winter wheat lost (Ukrinform, 2020).

In addition, the hurdles for Ukraine’s agricultural activity are created by the fact that approximately 30% of land is mined. In the spring season of 2023, a considerable portion of Ukrainian land remained uncultivated due to contamination by explosive objects (Suspilne, 2023). According to the U.S. Department of Agriculture estimates (USDA, 2024b), the Ukraine’s harvested areas for wheat, corn (maize), and barley in 2023/24 have decreased by 32%, 27%, and 37%, respectively, compared to 2021/22 levels (Fig.2). The area for sunflowers has also decreased by 15%.

Figure 2. Change in Ukraine harvested area, 2023/24 versus 2021/22.

Change in Ukraine harvested area, 2023/24 versus 2021/22



USDA production estimates for 2023/24 exclude statistical data concerning the Donetsk, Luhansk, Kherson and Zaporizhzhia regions
 Chart: Joseph Glauber · Source: USDA/FAS PSD database

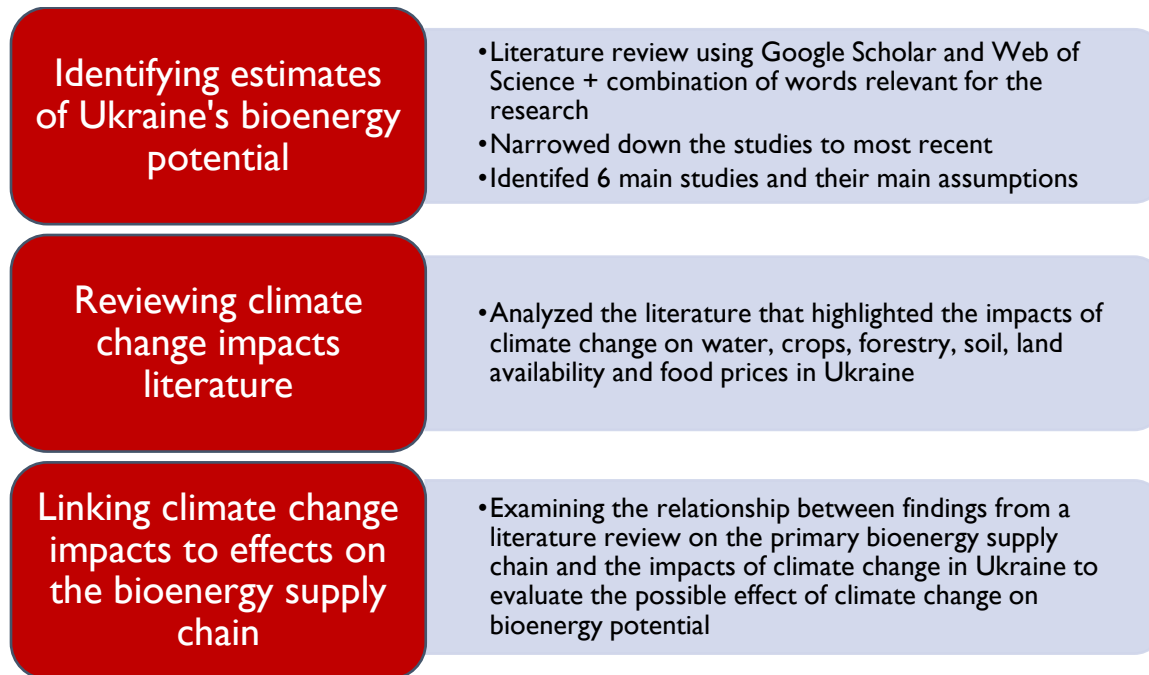
Source: Joseph Glauber, International Food Policy Research Institute with initial data extracted from USDA (Glauber, 2024; USDA, 2024b).

Quantifying the impacts of climate change on bioenergy potential remains complex due to a series of uncertainties, particularly the absence and irregularity of meteorological observation data in Ukraine, partially caused by military actions. However, there is a growing amount of research that can inform strategic decision-making in Ukraine on how climate change affects water and land availability, forest health, soil quality, crop yields and food prices.

2. METHODOLOGY

The research for this report was conducted in three phases i) identifying Ukraine’s bioenergy potential estimates, ii) identifying literature on climate change impacts on components of bioenergy potential, and iii) exploring research that links climate impacts to effects on the bioenergy supply chain (**Fig.3**).

Figure 3. Illustration of the three phases undergone during the research.



Source: Authors.

During the initial phase, the literature review was conducted using Google Scholar to identify existing projections of bioenergy potential in Ukraine. Google Scholar was selected as the primary search source due to its inclusion of grey literature, specifically reports, which are of particular interest for this study. This distinguishes Google Scholar from other search engines like Scopus, which do not comprehensively cover such sources. The following combination of words were employed during the Google Scholar search through a trial-and-error process to find the most relevant and comprehensive results: “bioenergy potential in Ukraine”, “biomass in Ukraine energy potential”, “Ukraine + biomass + projections”, “Ukraine + modeling + bioenergy”, “biomethane potential Ukraine”. We then further narrowed down the studies to those that were published in the last five years to obtain the most updated results. The focus was on the studies that provided a *total* energy potential for bioenergy in Ukraine, rather than the energy potential of only one or several biomass feedstocks. We also reviewed the citations of the studies identified through the initial search, and this yielded several more sources for a total of **six examined studies**. An overview of the key assumptions, methodology, and estimated bioenergy potentials outlined in the aforementioned studies is provided. These studies were used to identify potential primary

biomass feedstocks in Ukraine: agricultural crop residues (grain crops straw, corn residues, sunflower husks), forestry residues, and dedicated energy crops.

The next step involved analysis of the literature that highlighted the impacts of climate change on water, crops, forestry, soil, land availability and food prices. Again, utilizing Google Scholar, the terms “climate impacts on biomass production”, “impact of climate change on bioenergy supply chain”, “climate impacts on agriculture”, “climate impacts on land availability”, “climate impacts on forests”, “climate impacts on soil”, and “impact of climate change on biomass production EU”, “climate change and food prices” were used to identify literature. We also translated these terms into Ukrainian and searched again to further broaden the scope of analysis. To find key studies on the impacts of climate change on the bioenergy supply chain, we used the Web of Science platform and chose the sorting parameter “Highly Cited Papers”.

Finally, we looked at our literature results from the previous round of searches to see how climate change impacts have been modeled to estimate bioenergy potential and what pathways have been explored. Using the results of the literature review, this paper explores how climate change may impact the bioenergy potential in Ukraine.

3. RESULTS

3.1 EXISTING PROJECTIONS OF BIOENERGY POTENTIAL

We evaluated existing projections of bioenergy in Ukraine to determine if the impacts of climate change on bioenergy supply are considered and if projections are feasible in the context of these limitations. This paper provides a brief overview of each set of projections, main assumptions, identified limitations, and any climate impacts that they consider. Table I provides a summary of these projections.

I. According to the latest calculations employed for developing NECP (Ministry of Economy of Ukraine, 2024), the projections were modeled according to two scenarios using TIMES-Ukraine¹ model: “with existing measures” (WEM) and “with additional measures” (WAM), where WEM is the pathway where no new policies and measures are introduced in Ukraine. In the WAM scenario, policies such as “opening export of biomethane to the EU” and “launching the biomass market” are assumed to be implemented in the future. Projections in NECP show the highest bioenergy potential among all other studies in the WAM scenario, with a total of 31.3 Mtoe of estimated production in 2050. However, the impacts of climate change are not considered.

II. Diachuk et al. (2024) model three scenarios using TIMES-Ukraine model and Global Change Assessment Model (GCAM)² model to look at how Ukraine can achieve net zero by 2050 in the buildings sector, assuming post-war conditions with Ukraine regaining control of occupied territories by 2025. Reference scenario implies that no major changes or new emission reduction measures. Retrofit scenario follows the 2050 thermal modernization strategy (Government of Ukraine, 2024), targeting a threefold reduction in building energy consumption, and phasing out coal by 2040 and gas by 2050. Decarbonization scenario aims for net zero GHG emissions by 2050, applying emissions caps starting in 2025.

III. Chepeliev et al. (2021) utilize the TIMES-Ukraine energy system model to project biomass production and consumption under different scenarios. The total bioenergy potential for Ukraine in the baseline scenario is estimated at 6.3 million tonnes of oil equivalent (Mtoe) in 2050. The baseline scenario is based on current policies with no future intervention to encourage uptake of biofuels. Under this scenario, agricultural and industrial waste (industrial waste-sludge in the TIMES model) are projected to account for the bulk of bioenergy production, 61% of total primary energy supply (TPES) in 2050. The authors identify some limitations in their analysis such as the lack of consideration for other sectors besides energy at the macro level. They also note that interactions with agriculture and resulting impacts to food markets are not considered.

IV. Geletukha and Zheliezna (2021) provide an overview of potential development pathways for bioenergy production in Ukraine. The total bioenergy potential for Ukraine in 2050 is estimated at 20.3 Mtoe. The potential for different biofuels were estimated using a bottom-up methodology. The potentials presented are based on several assumptions including increases in the yield of

¹ <https://iea-etsap.org/index.php/etsap-tools/model-generators/times>

² <https://github.com/JGCRI/gcam-core>

crops, increases in the economic potential of biogas obtained from different types of feedstocks, increases in the area of energy crops, growth of felling from forestry, and switchover to the production of the advanced biofuels and new types of feedstocks for first-generation biofuels. They assume that agricultural residues will grow substantially to become the bulk of biomass production, while woody biomass stays consistent over time.

V. Petrović et al. (2021) analyze the development of the Ukrainian energy system through 2050 using the TIMES-Ukraine energy system model. Several scenarios are modeled to represent potential pathways for Ukraine. The Frozen Policy (FZP) scenario includes only currently implemented policies, disregarding their enforcement. The Least-Cost Development (LCD) scenario is an unconstrained scenario that is free of targets and additional constraints but includes all decarbonization measure options, such as energy efficiency, renewables, and new technologies. The Stated Policy (STP) scenario incorporates all stated future policies in addition to the currently implemented ones. The STP scenario, wherein all current and future planned policies are implemented, provides the highest bioenergy potential value. Bioenergy production is projected to be 11.3 Mtoe by 2050. Bioenergy is used primarily for district heating. However, the authors project a declining need for district heating and, therefore, a low utilization of biofuels overall due to increased energy efficiency for heating in buildings. No environmental constraints appear to be considered in the study.

VI. Diachuk et al. (2020) provide results of Ukraine's GHG emissions pathways modeling up to 2050 using TIMES-Ukraine model, Ukraine General Equilibrium model and combined modeling approach to waste sector, agriculture and land use, and land use change and forestry (LULUCF) sectors. Several scenarios are modeled as pathways for reducing GHG emissions, with results for bioenergy potential ranging from 6.8 Mtoe to 25 Mtoe in 2050. Specific biofuel production values are not provided. Although the modeling includes emissions from land use change, the linkages between land use change and biomass production are not explored.

Table 1. Range of projections for total bioenergy, solid biomass, bioliquids, and biogas potential in Ukraine for 2020, 2030, and 2050 across different scenarios (units are presented in Mtoe).

	Study	Year	Scenario	Total bioenergy (Mtoe)			Solid biomass (Mtoe)			Bioliquids (Mtoe)			Biogas (Mtoe)		
				2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050
I	Diachuk	2024	Reference	4.1	6	4.9									
	Diachuk	2024	Retrofit	4.1	8.5	13									
	Diachuk	2024	Decarbonization	4.1	12.9	31.3									
II	NECP	2024	WEM	4.1	5.1	8.4							0.08	0.3	0.3
	NECP	2024	WAM	4.1	9.0	25.9							0.08	0.3	0.5
III	Chepeliev	2021	Baseline	1.7	2.8	6.3	0.7	0.8	2.3	0.1	0.1	0.2	0.9	1.9	3.8
	Chepeliev	2021	Scenario I	3.3	9.1	21	1.4	2.1	13.2	0.1	2.6	0.4	1.8	4.4	7.4
	Chepeliev	2021	Scenario2	3.3	9.1	17.2	1.5	1.8	6.4	0.1	2.5	0.2	1.7	4.7	10.7
IV	Geletukha	2021	Roadmap	3.8	8.6	20.3	3.6	7.4	14.7	0.2	0.4	0.9	0	0.8	4.7
V	Petrovic	2021	FZP	2.4	3.0	6.0									
	Petrovic	2021	LCD	2.4	6.0	9.6									
	Petrovic	2021	STP	2.4	9.6	11.3									
VI	Diachuk	2020	S1		3.1	6.8									
	Diachuk	2020	S2		10.8	16.5									
	Diachuk	2020	S3		11.0	25.0									

Source: Diachuk et al. (2024), Ministry of Economy of Ukraine (2024), Chepeliev et al. (2021), Geletukha and Zheliezna (2021), Petrović et al. (2021), Diachuk et al. (2020).

These studies display a variety of pathways and potentials for bioenergy potential, mostly based on different technological development pathways. There are minimal differences between the ranges in the aforementioned projections as many of them use similar data from the Bioenergy Association of Ukraine in setting their baseline potential and do not consider variations in bioenergy potential from changing climatic conditions. Base year data for bioenergy potentials are sourced from the Bioenergy Association of Ukraine for all studies and used as input for all energy system-wide modeling scenarios utilizing the TIMES-Ukraine model, except (Geletukha and Zheliezna, 2021). It is important to note that the modeling results presented using the TIMES-Ukraine model demonstrate approximate values for the utilization of bioenergy resources to meet Ukraine's economic needs under various scenarios. These values are less than or equal to the estimated economic potential of bioenergy as assessed by the Bioenergy Association of Ukraine.

However, the projections explored in six studies are modeled using tools that do not fully account for the impact of climate change on bioenergy expansion in Ukraine, nor do they track changes in agriculture, and LULUCF sectors. This type of modeling is only possible by using Integrated Assessment Models (IAMs).

3.2 ANALYSIS OF CLIMATE CHANGE IMPACTS ON BIOENERGY PRODUCTION COMPONENTS

The changing climate is expected to affect the supply of a broad range of biomass feedstocks (USDA, 2024a). Extreme weather events are becoming more frequent and intense across the globe and include droughts, floods, prolonged periods of high temperatures, heavy snowfalls, heavy rainfalls, high winds, hail, wildfires, and new or increased pressure from pests and diseases. These environmental factors have the potential to create stress on biomass systems, whether they are crop-based, forest-based, related to livestock, or residual. This pressure can result from direct harm or indirect effects such as decreased yield due to limited inputs like water, or economic difficulties that impact biomass availability, such as infrastructure damage (USDA, 2024a).

Water availability, agricultural yields, forestry, soil quality, and land availability are key factors in the bioenergy supply chain that may be impacted by climate change. Additionally, competition for land between energy crops and food crops increases pressure on bioenergy production. Therefore, this paper provides an overview of the literature highlighting the specific impacts of climate change on these parameters in Ukraine.

3.2.1 WATER AVAILABILITY

Abundant irrigation is essential for agriculture. However, Ukraine's agricultural activities are primarily concentrated in the eastern and southeastern regions, where water availability is expected to become more constrained due to climate change. Consequences include decreasing water content in river basins (such as the South Bug, Dnipro, and Dniester), reduced reservoir levels, declining precipitation, and rising temperatures that increase moisture evaporation (Didovets et al., 2020; Karamushka et al., 2022; Moldavan et al., 2023). This will lead to a greater

need for irrigation to replenish soil moisture and support rainfed agricultural crops (Moldavan et al., 2023). Ukraine is experiencing slight increases in humidity and precipitation along with warming, but some regions remain arid. Higher temperatures and increased evaporation are reducing soil moisture, which, combined with projected increases in heatwaves and drought frequency, threaten to shorten growing seasons and reduce crop yields. Winter precipitation is decreasing, while September-October precipitation has increased, indicating a trend towards more ineffective heavy rains (Davis et al., 2019).

In addition, the irrigation and water sectors in southern Ukraine have been severely impacted by the destruction of the Kakhovka dam in June 2023, leaving 600,000 hectares of farmland without access to irrigation water (World Bank, 2024). Limited water for irrigation may result in reduced agricultural yields, affecting bioenergy potential through a limited supply of bioenergy crops and agricultural residues (Cronin et al., 2018; Tarariko et al., 2017).

In the northern parts of Ukraine, the average rate of precipitation varies little, although its efficiency decreases under the influence of higher temperatures (Moldavan et al., 2023). Meanwhile, as competition for potable water increases, the amount available for bioenergy crops becomes limited, with priority given to food crops (Cronin et al., 2018; Zhang et al., 2018). Crops used as biomass feedstocks can require substantial water resources, so choosing less water-demanding bioenergy crops is key.

Additionally, biorefineries require water to produce biofuels, potentially exacerbating existing water stress (Yang et al., 2022). Water availability may limit the capacity of biorefineries to operate during times of extreme water stress.

3.2.2 AGRICULTURAL YIELDS AND FORESTRY

Agricultural yields depend on various climatic conditions, particularly temperature and precipitation, which are subject to uncertainty under climate change. These impacts affect the availability of both bioenergy crops and agricultural residues. The effects of a changing climate are crop and location-dependent, leading to heterogeneous impacts across Ukraine (Fang et al., 2023). In some cases, climate change may even have positive effects for the yields. For instance, Fang et al. (2023) found no evidence of an adverse impacts of high temperatures for warm season crops such as sunflower, soybean, and corn in Ukraine, which serve as biomass feedstocks. However, two cold-season crops, winter wheat and spring barley, respond negatively to temperatures above a threshold of 29/30°C.

Similarly, Tarariko et al. (2017) and Müller et al. (2016) found that increasing temperatures could improve grain yields in Ukraine. This is explained by the fact that higher CO₂ concentrations can increase photosynthesis in a certain type of plants (e.g., wheat, rice, potatoes, barley), potentially boosting crop yields (Ebi and Loladze, 2019).

However, Müller et al. (2016) also found that grain yields could significantly decrease under a high emissions scenario, with the southern part of Ukraine being particularly vulnerable. This highlights

the need to understand potential threats to crops and identify thresholds at which these threats worsen (e.g., tipping points).

More frequent extreme weather events brought on by climate change, such as droughts, floods, and snowstorms, can directly impact agricultural yields in Ukraine (Akram et al., 2022; Fang et al., 2023).

Meanwhile, wood biomass can also be affected by climate change through the increasing number of natural disturbances in Ukrainian forests, with the area affected by wildfires doubling in recent years, forests impacted by pests and diseases rising from under 4% at the end of the 20th century to 8% after 2011, and the area of dead forests surging from approximately 4,000 hectares per year in the 1990s to over 20,000 hectares per year in 2015 due to adverse weather, insects, pathogens, and fires (Shvidenko et al., 2017).

3.2.3 SOIL QUALITY

The quality of soil is vulnerable to climate conditions (Shafiee et al., 2023). The biophysical properties of soil are heavily influenced by temperature and atmospheric CO₂ levels, affecting soil porosity, salinity, compactness, microbial activity, organic carbon content, and nutrient availability (Mondal, 2021). Temperature rise due to climate change can impact the ability of soil to retain water and nutrients, increasing the risks of erosion and potentially impacting crop yields (Mondal, 2021). Additionally, the intensity and frequency of precipitation and other extreme weather events can increase the risk of soil erosion (Malhi et al., 2021; Mondal, 2021). Erosion contributes to the degradation of land through the loss of nutrient-rich topsoil that supports soil fertility and moisture (Shafiee et al., 2023).

Climate change impacts on soil quality can affect the bioenergy supply chain by reducing crop yields and increasing the amount of degraded land. The total area of eroded land in Ukraine increases by 80,000-100,000 hectares annually, with 500 million tons of productive topsoil being washed away (Moldavan et al., 2023). Erosion is the most widespread soil degradation process taking place in Ukraine, with one fourth of lands being affected (Svetlitchnyi, 2009).

3.2.4 LAND AVAILABILITY AND FOOD PRICES

There is a strong nexus between land availability and food prices. When the amount of arable land decreases for various reasons, its value increases, leading to higher food production costs. These negative trends can hinder the expansion of bioenergy, as such a situation creates competition between food and fuel production (Haberl et al., 2014). In addition to the competition for land between bioenergy crops and food crops, a need to preserve land for natural conservation purposes and urbanization further reduces available arable land (Haberl, 2015). These factors are worsened by climate change, causing land degradation and desertification in Ukraine, with the southern oblasts (Kherson, Odesa, Mykolaiv) experiencing a decrease in annual precipitation and temperature rise, leading to reduced agroecosystem productivity (Jiang et al., 2019; Vozhegova et al., 2021). As mentioned in Section 3.2.2, climate change will also impact agricultural productivity directly, putting pressure on food prices (Bandara and Cai, 2014).

Researchers indicate that the expansion of bioenergy production already forces bioenergy crops to compete with food crops for arable land, resulting in increased food prices and impacting food security (Popp et al., 2014; Wise et al., 2009). According to a study by Hasegawa et al. (2020), an increase in global bioenergy demand from 200 to 300 exajoules (EJ) causes food crop prices to fluctuate between a decrease of 11% and an increase of 40%. This demand also reduces daily food consumption by 2 to 45 calories per person, leading to a possible risk of hunger for up to 25 million people compared to a scenario with no bioenergy demand. Meanwhile, the U.S. EPA found that between 2007 to 2009, there was a 20 to 40% increase in corn prices due to biofuels production (EPA, 2013). With over 7 million Ukrainians experiencing acute food insecurity, the potential for food price increases may create pressure to focus on food demand first, which could constrain bioenergy production (Vos, 2024). Additionally, the impacts of climate change on Ukrainian crops could lead to increased global food prices. Hundreds of millions of people worldwide rely on Ukrainian wheat and sunflower oil supplies (Chandrasekhar et al., 2022).

4. DISCUSSION AND RECOMMENDATIONS

Based on the analysis, it is evident that climate change will impact bioenergy production in Ukraine, and it is crucial for all stakeholders to understand and address these implications. Although the precise consequences are currently difficult to estimate, this presents an opportunity for further in-depth research. This paper offers recommendations derived from the research findings for stakeholders in the bioenergy sector summarized below.



For Researchers:

1. **Integrate Climate Factors into Energy Modeling:** Enhance models by integrating climate variables to accurately assess the impact of climate change on energy systems.
2. **Communicate Findings to Policymakers:** Translate research findings into actionable insights for policymakers to inform evidence-based decision-making.



For Policymakers:

1. **Diversify Energy Supply and Bioenergy Sources Beyond Crops:** Promote the use of non-crop sources for bioenergy production and diversify energy sources to enhance resilience and sustainability.
2. **Develop Adaptation Strategies:** Formulate robust adaptation strategies to mitigate climate risks and ensure long-term energy security.
3. **Incentivize Climate-Smart Agriculture and Forestry Practices:** Provide incentives and support for adopting climate-smart practices in agriculture and forestry sectors to promote sustainability and resilience.



For Businesses:

1. **Incorporate Modern Practices to Avoid Land Degradation:** Adopt modern agricultural practices that reduce land degradation, such as precision farming and soil conservation techniques.
2. **Enhance Energy Efficiency:** Implement energy-efficient technologies and practices to reduce carbon footprint and operational costs.
3. **Curbing Excessive Water Usage:** Employ water-saving technologies and practices to minimize water usage and contribute to water conservation efforts.

To support robust decision-making, *integrating climate factors into energy modeling* is needed. This approach helps better estimate future energy balances, crucial when making decisions for post-war reconstruction, shaping the country's future trajectory. Such modeling is possible with the use of integrated assessment models that can account for the impacts of climate change on bioenergy production and consumption. Incorporating factors that affect the bioenergy

supply chain, specifically the agricultural sector, allows for a more comprehensive understanding of the variability in biomass feedstock and the understanding of changes in agricultural sector overall (Calvin and Fisher-Vanden, 2017). Bioenergy pathways have been modeled previously in IAMs, both directly examining bioenergy production and examining agricultural production in general (Calvin et al., 2021; Cronin et al., 2018; Yalew et al., 2020). However, these scenarios have never been explicitly modeled for Ukraine. Results of bioenergy potential under climate change is mixed in IAMs, with some showing increases in potential due to changing climate factors and others showing decreases (Yalew et al., 2020). This points to the need to model Ukraine-specific conditions to better understand potential bioenergy production in Ukraine under various climate conditions.

In parallel with the first recommendation, we suggest that researchers use the results of such modeling to determine Ukraine's bioenergy potential, while policymakers and other key decision-makers consider the impacts of climate change when incorporating bioenergy into planning.

The leading solution to adapt to changing climate is **diversifying the energy supply sources** to ensure energy security. This strategy involves continuing support a range of energy options, which include other types of renewable energy such as solar, wind, and geothermal energy. Another route, particularly focused on bioenergy, is to broaden the range of bioenergy sources beyond crops. This includes tapping into resources like municipal waste or livestock, reducing the overall dependence of the bioenergy mix on climate fluctuations.

Furthermore, as part of Ukraine's Environmental Security and Climate Change Adaptation Strategy through 2030, the assessment of the risks and vulnerabilities of the energy industry to climate change should be done (Government of Ukraine, 2021). We recommend including in this assessment **a detailed examination of the specific impacts of climate change on each region**. It is important to identify which crops would be suitable for cultivation in these regions in the near future, considering the changing climate conditions. Additionally, **strategies must be developed to protect these crops** from direct damage caused by extreme weather events, pests and other natural disturbances.

Our overarching recommendation for all stakeholders is to build capacity for and **implement climate-smart agriculture and forestry practices**. These practices are essential for mitigating the risks associated with land degradation, enhancing energy efficiency, and curbing excessive water usage. Embracing such practices can lead to increased crop yields, reduced soil erosion, and long-term economic advantages. Specifically, we propose that governmental entities offer subsidies to businesses aiming to modernize their operations. Businesses should demonstrate innovative entrepreneurship and a commitment to adopting modern methods. Civil society plays a pivotal role in advocating for incentivizing policies that promote climate-smart practices. Furthermore, international donors are encouraged to invest in and provide grants to support these initiatives.

5. CONCLUSIONS

Overall, this paper emphasizes the necessity of considering the impacts of climate change when modeling projections of bioenergy potential. Without adequately accounting for these effects, especially on agriculturally derived biomass feedstocks, there remains significant uncertainty regarding Ukraine's potential for bioenergy expansion. Given Ukraine's dependence on agriculture for its biomass feedstocks, efforts should prioritize building a resilient agriculture sector. Climate-smart agriculture is one approach to support a resilient crop supply, offering dual benefits of enhancing food security and contributing to energy security through bioenergy. Additionally, it is crucial to model Ukraine's bioenergy potential with IAMs to address climate interactions within the agriculture, LULUCF and energy systems, using tools such as the GCAM or other models. Developing and implementing an adaptation strategy specifically for the bioenergy sector would further help Ukraine diversify its bioenergy feedstocks and mitigate potential negative impacts from climate change on the bioenergy supply chain. Meanwhile, the impacts of climate change will affect not only bioenergy potential and its utilization but also other energy resources (solar, wind, and especially hydro) and their associated technologies. For Ukraine, climate change could bring different effects, such as reduced final energy needs due to warmer winters and increased solar and wind potential, and negative effects, particularly extreme weather events that could disrupt renewable and nuclear energy operations. Therefore, long-term energy system planning will be more robust if it incorporates climate factors into energy systems modeling.

7. REFERENCES

- Akram, R., Jabeen, T., Bukari, M.A., Wajid, S.A., Mubeen, M., Rasul, F., Hussain, S., Aurangzaib, M., Bukhari, M.A., Hammad, H.M., Zamin, M., ur Rahman, M.H., Iqbal, J., Rehmani, M.I.A., Tariq, M., Abbas, G., Mirza, N., Mubarak, H., Mahmood, F., Sajjad, M., Ali, S., Nasim, W., 2022. Research on Climate Change Issues, in: Jatoi, W.N., Mubeen, M., Ahmad, A., Cheema, M.A., Lin, Z., Hashmi, M.Z. (Eds.), Building Climate Resilience in Agriculture: Theory, Practice and Future Perspective. Springer International Publishing, Cham, pp. 255-268.
- BIOPLAT-EU, 2020. Promoting the Sustainable Use of Low Productivity Lands for Bioenergy through a Web Platform for Europe
https://bioplat.eu/assets/content/documents/Ukraine/2nd/Tryboi_SECB_BIOPLAT-EU_IWG_IC_S_08102020.pdf
- Calvin, K., Cowie, A., Berndes, G., Arneeth, A., Cherubini, F., Portugal - Pereira, J., Grassi, G., House, J., Johnson, F.X., Popp, A., Rounsevell, M., Slade, R., Smith, P., 2021. Bioenergy for climate change mitigation: Scale and sustainability. *GCB Bioenergy* 13, 1346-1371.
- Calvin, K., Fisher-Vanden, K., 2017. Quantifying the indirect impacts of climate on agriculture: an inter-method comparison. *Environmental Research Letters* 12, 115004.
- Chandrasekhar, A., Zagoruichyk, A., Prater, T., 2022. Commodity Profile: Wheat. Carbon Brief <https://interactive.carbonbrief.org/commodity-profile-wheat/>
- Chepeliev, M., Diachuk, O., Podolets, R., Trypolska, G., 2021. The role of bioenergy in Ukraine's climate mitigation policy by 2050. *Renewable and Sustainable Energy Reviews* 152, 111714.
- Cronin, J., Anandarajah, G., Dessens, O., 2018. Climate change impacts on the energy system: a review of trends and gaps. *Climatic Change* 151, 79-93.
- Davis, O., Sergiy, S., Trypolska, G., 2019. Ukraine TECHNOLOGY NEEDS ASSESSMENT REPORT ADAPTATION.
- Diachuk, O., Chepeliev, M., Podolets, R., 2020. Support to the Government of Ukraine on Updating its Nationally Determined Contribution (NDC): Report 3/ Modeling Report. Modeling report.
- Diachuk, O., Chepeliev, M., Podolets, R., Trypolska, G., Venger, V., Saprykina, T., Yukhymets, R., 2017. Transition of Ukraine to the Renewable Energy by 2050. Heinrich Boell Foundation Regional Office in Ukraine, Kyiv.
- Diachuk, O., Kholod, N., Podolets, R., Graham, N., Semeniuk, A., Evans, M.M., Westphal, M.I., Stelmach, T., Hoesly, R., Trypolska, G., 2024. Pathways for Decarbonization of the Buildings Sector in Ukraine, Manuscript
- Didovets, I., Krysanova, V., Hattermann, F.F., del Rocío Rivas López, M., Snizhko, S., Müller Schmied, H., 2020. Climate change impact on water availability of main river basins in Ukraine. *Journal of Hydrology: Regional Studies* 32, 100761.
- Ebi, K.L., Loladze, I., 2019. Elevated atmospheric CO₂ concentrations and climate change will affect our food's quality and quantity. *Lancet Planet Health* 3, e283-e284.
- Fang, M., Jin, S., Deininger, K., Gammans, M., 2023. Heterogenous climate impacts on crop yields: evidence from Ukraine. *Environmental Research Communications* 5, 105015.
- Geletukha, G., Zheliezna, T., 2017. Creation of the competitive biofuel market in Ukraine, UABio Position Paper N 18.

- Geletukha, G., Zheliezna, T., 2021. Prospects for Bioenergy Development in Ukraine: Roadmap until 2050. *Ecological Engineering & Environmental Technology* 22, 73-81.
- Geletukha, G., Zheliezna, T., Drahnev, S., 2019. Analysis of barriers to the production of energy from agribiomass in Ukraine, UABio Position Paper N 21.
- Geletukha, G.G., Zheliezna, T. A., Drahnev, S.V., Kucheruk, P.P., 2023. Prospects for the production of advanced biofuels in Ukraine *Energy Technologies & Resource Saving* 76, 71-82.
- Glauber, J., 2024. Ukraine and global agricultural markets two years later. International Food Policy Research Institute, <https://www.ifpri.org/blog/ukraine-and-global-agricultural-markets-two-years-later>.
- Government of Ukraine, 2021. Environmental Security and Climate Change Adaptation Strategy through 2030. Verkhovna Rada of Ukraine, <https://zakon.rada.gov.ua/laws/show/l363-2021-%D1%80#n17>.
- Government of Ukraine, 2024. Strategy for thermal modernisation of buildings in Ukraine until 2050, <https://www.kmu.gov.ua/en/news/zatverdzheno-stratehiu-termomodernizatsii-budivel-ukrainy-do-2050-roku>.
- Jiang, Y., Havrysh, V., Klymchuk, O., Nitsenko, V., Balezentis, T., Streimikiene, D., 2019. Utilization of Crop Residue for Power Generation: The Case of Ukraine, *Sustainability*.
- Karamushka, V., Boychenko, S., Kuchma, T., Zabarna, O., 2022. Trends in the Environmental Conditions, Climate Change and Human Health in the Southern Region of Ukraine, *Sustainability*.
- Kucher, O., Prokopchuk, L., 2020. Economic aspects of biomass market development in Ukraine. *E3S Web Conf.* 154.
- Larina, Y., Galchynska, J., Kucheruk, P., Zghurska, O., Ortina, G., Al-Nadzhaz, F., Marusei, T., Kuboń, M., Dzieniszewski, G., 2021. Estimation of the Domestic Agricultural Sector Potential for the Growth of Energy Cultures for Bioenergy Fuel Production. *Agricultural Engineering* 25, 73-82.
- Liu, T.T., McConkey, B.G., Ma, Z.Y., Liu, Z.G., Li, X., Cheng, L.L., 2011. Strengths, Weaknessness, Opportunities and Threats Analysis of Bioenergy Production on Marginal Land. *Energy Procedia* 5, 2378-2386.
- Malhi, G.S., Kaur, M., Kaushik, P., 2021. Impact of Climate Change on Agriculture and Its Mitigation Strategies: A Review, *Sustainability*.
- Ministry of Economy of Ukraine, 2024. National Energy and Climate Plan of Ukraine 2025-2030, <https://www.me.gov.ua/Documents/Detail?lang=uk-UA&id=f7088035-142e-4912-9aa0-6fe2def80c1b&title=ProektNatsionalnogoPlanuZEnergetikiTaKlimatuUkraini2025-2030>.
- Ministry of Energy of Ukraine, 2023. Energy Strategy of Ukraine through 2050, <https://zakon.rada.gov.ua/laws/show/373-2023-%D1%80#Text>.
- Moldavan, L., Pimenowa, O., Wasilewski, M., Wasilewska, N., 2023. Sustainable Development of Agriculture of Ukraine in the Context of Climate Change, *Sustainability*.
- Mondal, S., 2021. Impact of Climate Change on Soil Fertility, in: Choudhary, D.K., Mishra, A., Varma, A. (Eds.), *Climate Change and the Microbiome: Sustenance of the Ecosphere*. Springer International Publishing, Cham, pp. 551-569.
- Müller, D., Jungandreas, A., Koch, F., Schierhorn, F., 2016. Impact of climate change on wheat production in Ukraine.
- Petrović, S.N., Diachuk, O., Podolets, R., Semeniuk, A., Bühler, F., Grandal, R., Boucenna, M., Balyk, O., 2021. Exploring the Long-Term Development of the Ukrainian Energy System, *Energies*.

- Popp, J., Lakner, Z., Harangi-Rákos, M., Fári, M., 2014. The effect of bioenergy expansion: Food, energy, and environment. *Renewable and Sustainable Energy Reviews* 32, 559-578.
- Pulighe, G., Bonati, G., Colangeli, M., Morese, M.M., Traverso, L., Lupia, F., Khawaja, C., Janssen, R., Fava, F., 2019. Ongoing and emerging issues for sustainable bioenergy production on marginal lands in the Mediterranean regions. *Renewable and Sustainable Energy Reviews* 103, 58-70.
- Reznik, N.P., Havryliuk, Y.G., Yakymovska, A.V., Predun, K.M., Leszczynski, V.P., Shpakov, A.V., 2024. Strategic Priorities for the Safe Development of Bioenergy in Ukraine: Barriers and Prospects, in: Khoury, R.E., Nasrallah, N. (Eds.), *Intelligent Systems, Business, and Innovation Research*. Springer Nature Switzerland, Cham, pp. 837-846.
- SAEE, 2022. National Action Plan on the Development of Renewables through 2030. The State Agency for Energy Efficiency and Energy Saving of Ukraine, https://sae.gov.ua/sites/default/files/DraftNPDVE_2030_SAE_21_09_2022.pdf.
- Shafiee, M., Longworth, Z., Gizaw, Z., Vatanparast, H., 2023. How does climate change affect biomass production and rural poverty? *Biofuel Research Journal* 10, 1948-1965.
- Shvidenko, A., Buksha, I., Krakovska, S., Lakyda, P., 2017. Vulnerability of Ukrainian Forests to Climate Change, *Sustainability*.
- Suspilne, 2023. In Ukraine, 30% of the territory is mined, it will take decades to demine <https://suspilne.media/366982-v-ukraini-zaminovano-30-teritorii-na-rozminuvanna-pidut-desatki-rokiv-dsns/>.
- Svetlitchnyi, A.A., 2009. Soil Erosion Induced Degradation of Agrolandscapes in Ukraine: Modeling, Computation and Prediction in Conditions of the Climate Changes, in: Groisman, P.Y., Ivanov, S.V. (Eds.), *Regional Aspects of Climate-Terrestrial-Hydrologic Interactions in Non-boreal Eastern Europe*. Springer Netherlands, Dordrecht, pp. 191-199.
- Tarariko, O., Iliencko, T., Kuchma, T., Velychko, V., 2017. Long-term prediction of climate change impact on the productivity of grain crops in Ukraine using satellite data. *Agricultural Science and Practice* 4, 3-13.
- Trypolska, G., 2023. Dedicated energy crops: support policies in Europe and in post-war Ukraine. *International Journal of Foresight and Innovation Policy (IJFIP)* Vol. 16, No. 2/3/4, 2023.
- Ukrinform, 2020. According to the Ministry of Economic Development, Trade, and Agriculture, due to drought in the southern regions, Ukraine has lost a total of 234 thousand hectares (2.6%) of winter crops., <https://www.ukrinform.ua/rubric-economy/3021941-ukraina-vtrabila-vid-posuhi-26-posiviv-ozimih-minekonomiki.html>.
- UNECE, 2023. Designing a Carbon Neutral Energy System of Ukraine: Increasing the Uptake of Biofuels and Biomass in Ukraine, United Nations Economic Commission for Europe.
- USDA, 2024a. Building a resilient biomass supply: A Plan to Enable the Bioeconomy in America U.S. Department of Agriculture, <https://www.usda.gov/sites/default/files/documents/biomass-supply-chain-report.pdf>.
- USDA, 2024b. Market and Trade Data. U.S. Department of Agriculture, Foreign Agricultural Service, <https://apps.fas.usda.gov/psdonline/app/index.html#/app/advQuery>.
- Vasylyshyn, R., Lakyda, I., Yurchuk, Y., Lakyda, M., Melnyk, O., Bondarchuk, R., 2022. Energy potential of woody biomass in Ukraine's forests and prospects for its utilization as an alternative energy source. *IOP Conference Series: Earth and Environmental Science* 1042, 012010.

Verkhovna Rada of Ukraine, 2017. Law of Ukraine on Amendments to the Law of Ukraine "On Heat Supply" Regarding the Promotion of Heat Energy Production from Alternative Energy Sources, <https://zakon.rada.gov.ua/laws/show/1959-19#Text>.

Vozhegova, R.A., Netis, I.T., Onufran, L.I., Sakhatsky, G.I., Sharata, N.H., 2021. Climate change and aridization of the Southern Steppe of Ukraine. *Agrarian Innovations* 7.

Wąs, A., Sulewski, P., Gerasymchuk, N., Stepasyuk, L., Krupin, V., Titenko, Z., Pogodzińska, K., 2022. The Potential of Ukrainian Agriculture's Biomass to Generate Renewable Energy in the Context of Climate and Political Challenges - The Case of the Kyiv Region, *Energies*.

Wise, M., Calvin, K., Thomson, A., Clarke, L., Bond-Lamberty, B., Sands, R., Smith, S.J., Janetos, A., Edmonds, J., 2009. Implications of Limiting CO₂ Concentrations for Land Use and Energy. *Science* 324, 1183-1186.

World Bank, 2024. Third Rapid Damage and Needs Assessment (RDNA3) : February 2022 - December 2023 (English). World Bank Group
<http://documents.worldbank.org/curated/en/099021324115085807/P1801741bea12c012189ca16d95d8c2556a>.

Yakubiv, V., Hryhoruk, I., Maksymiv, Y., Popadynets, N., 2019. Strategic analysis of the potential of bioenergy: outlook for Ukraine, Proceedings of the 2019 7th International Conference on Modeling, Development and Strategic Management of Economic System (MDSMES 2019). Atlantis Press, pp. 217-221.

Yalew, S.G., van Vliet, M.T.H., Gernaat, D.E.H.J., Ludwig, F., Miara, A., Park, C., Byers, E., De Cian, E., Piontek, F., Iyer, G., Mouratiadou, I., Glynn, J., Hejazi, M., Dessens, O., Rochedo, P., Pietzcker, R., Schaeffer, R., Fujimori, S., Dasgupta, S., Mima, S., da Silva, S.R.S., Chaturvedi, V., Vautard, R., van Vuuren, D.P., 2020. Impacts of climate change on energy systems in global and regional scenarios. *Nature Energy* 5, 794-802.

Yang, P., Piao, X., Cai, X., 2022. Water Availability for Biorefineries in the Contiguous United States and the Implications for Bioenergy Production Distribution. *Environmental Science & Technology* 56, 3748-3757.

Zhang, C., Chen, X., Li, Y., Ding, W., Fu, G., 2018. Water-energy-food nexus: Concepts, questions and methodologies. *Journal of Cleaner Production* 195, 625-639.

Zhang, X., Cai, X., 2011. Climate change impacts on global agricultural land availability. *Environmental Research Letters* 6, 014014.