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The role and the scale of investments needed for 'green' transformation of Ukraine's electricity sector

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ABSTRACT

In just six months since October 2022, more than 60% of Ukraine's electricity generation infrastructure has been damaged to one extent or another by missile strikes during Russia's full-scale invasion of Ukraine. Given the high carbon intensity as well as the obsolescence of the affected generation capacity, Ukraine has a chance to undertake a green transition of the electricity sector. However, putting it into practice without additional funds may be incredibly difficult. Hence, this thesis assesses the scale as well as indicates the importance of the required investments for a green transformation of Ukraine's electricity sector.

For the purpose of this study, secondary data published by open scientific databases, international agencies and organisations is analysed. Only data dating prior to the start of Russia's full-scale invasion of Ukraine, i.e., early 2022 at the latest, is taken into account. This is due to the lack of accurate data on the destruction in the Ukraine's electricity sector, as well as the unpredictable dynamics of its development.

The first part of this paper analyses the structure of Ukraine's electricity generation sector and assesses its carbon intensity. The same approach is used to analyse its green side. Based on these results, the second part estimates the scale of investment needed to undertake a green transformation of the sector. To do so, the assumptions and limits of the analysis are first set. Two extreme development scenarios are then simulated, defining lower and upper bounds on the scale of investments. Based on the results, the hypothesis is tested next. Finally, conclusions summarising the results of the study are drawn, the importance of such investments is highlighted and possible areas for further research on the topic are outlined.

The main results of this study are the following.

1. Emissions from electricity generation account for a third of all energy sector emissions and a fifth of all emissions in Ukraine. Hardly any change in the carbon intensity of electricity generation in Ukraine has occurred in the last 20+ years.
2. The development of renewables has been stagnant, except for a period since 2015. Solar and wind power have been the main drivers of the corresponding development, which puts them as a priority for further use as well.
3. In order to maintain the current trends in the use of renewables for electricity generation until 2030, USD 19.73 billion would be needed. A total green transformation of the carbon intensive component of the electricity generation sector would require USD 80.77 billion over the same period.
4. Given the major caveats and uncertainties regarding the availability and sufficiency of the necessary investments, the most realistic development scenario would be a partial green transformation. Depending on its scale, the amount of investment would be determined within the scope defined in this study.
5. The role of investment for a full green transformation is identified as cornerstone. Without their availability, preference will rather be given to less costly and more rapid reconstruction of existing facilities.

Keywords

Investment, Green transformation, Carbon, Electricity generation, Ukraine

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I. Introduction

In just two days, on 10 and 11 October 2022, approximately 30% of Ukraine's entire energy infrastructure was hit by Russian missile strikes (Reuters 2022). On 1 November 2022, in a meeting with the European Commissioner for Energy, President of Ukraine Volodymyr Zelenskyy said that Russian attacks *"has already seriously damaged about 40% of the entire energy infrastructure of Ukraine"* (The Presidential Office of Ukraine 2022). In December 2022, reports began to emerge that approximately 50% of Ukraine's energy infrastructure had already been destroyed (Schlein 2022, Carter 2022). According to the latest figures as of April 2023, more than 60% of the infrastructure that ensures generation of electricity in Ukraine has been damaged by missile shellings in the six months since October 2022 (Jayanti 2023). From this one can see a clear trend in military action against Ukraine's energy facilities, leading to its inexorable collapse. The issue with Ukraine's electricity production capacity is reinforced by the fact that most of the power stations were created when Ukraine was part of the USSR (Wikipedia 2022) and is now in dire need of a deep modernisation. Moreover, Ukraine should consider the EU's 2050 goal for full decarbonisation (European Commission, n.d.), which it would have to meet if it were to join the EU.

Consequently, it is promising for Ukraine to develop green energy, as carbon-intensive energy production capacity is either obsolete or has been destroyed in hostilities. This could be seen as a chance for Ukraine to completely transform its current energy sector structure, become climate neutral and take an important step towards European integration. The importance of this, and the need for foreign investment is recognised by European leaders, such as German Chancellor Olaf Scholz, as well as by the President of Ukraine Volodymyr Zelenskyy (Wehrmann 2022).

This thesis therefore set out to assess the scale investments needed for the green transition of the Ukraine's carbon-intensive electricity sector. The assessment is based on the scenario analysis underpinned by several assumptions. Such scenarios help to look at the scale of investment needed from different angles of possible developments to make the analysis more comprehensive. The availability of such investments and the readiness of investors to provide them are also considered in the context of new economic and political realities.

These, in particular, include increased demand for alternative energy sources from the European countries and Ukraine, given the EU sanctions against Russian energy carriers. This approach explains the originality of this study, its relevance and practical significance for Ukrainian and European experts in the nearest future.

The general hypothesis is that such a green transition will require significant investment to lay the groundwork for replacing Ukraine's carbon-intensive energy sector. The EU might be interested in such investment, as it would allow for long-term imports of renewable energy from Ukraine, reducing dependence on both Russian gas and nuclear power, as well as supplementing its existing green energy production capacity.

The null hypothesis of the research is that investment needs of reconstruction and green transition are of such magnitude that it can happen only when all possible external sources of finance are made available. This may include Russian reparations, Ukrainian private investors and public funds, EU official sources assistance, private EU investors, other global investors etc. The alternative hypothesis of the research is that without large scale external finance of the recovery will rather be based on reconstruction of the existing capacities of electricity generation and can only partially provide for green transition.

Throughout this thesis, the term *'green'* will be used to refer to the use of renewable energy sources. For the purposes of this study, renewable energy sources in turn include hydro-, wind, solar and bioenergy production capacity. Nuclear power is seen as a separate energy source from carbon-intensive but also renewable energy sources. Also, given the diversity of the energy sector's productive uses, the paper is focused on the electricity sector only. The green transformation therefore encompasses replacing carbon-intensive electricity generation capacity with renewable energy sources (excluding nuclear power).

The research is based on pre-war data (until February 24, 2022). This is because there is currently no accurate and publicly available data on the degree of destruction of Ukraine's electricity production capacity. The assessment of the role and scale of investment needed is therefore based on the assumption that renewable energy is gradually replacing Ukraine's carbon-intensive electricity generation capacity under normal circumstances. This substitutes the assumption about the extent of destruction and the investments needed to replace war-damaged electricity production capacity with green energy.

Secondary data are used for the analysis, which forms the basis for answering the research question. The main sources of data for the study are open scientific databases, as well as databases of international organisations and agencies (for detailed description see Annex I). The data are processed quantitatively and qualitatively using meta- and content analysis. The conclusions reached from the data analysis are compared with each other and used to test the null hypothesis.

The structure of the thesis is represented by two main chapters, which are divided into subsections. The first part examines the structure of the Ukraine's electricity sector and assesses how carbon-intensive it is, using pre-war data. This is done in order to then have an idea of the scale of investment that will be needed to replace it with green energy. At the same time, the question of how far Ukraine has developed the use of renewables for electricity generation is addressed. The purpose here is to analyse the extent to which green energy is already being used, whether there is a positive trend in its development and what role each of the renewable sources plays in the electricity supply. The second part estimates investment needs. Assumptions on which this assessment is based are first made and limits of the analysis are given. Two extreme scenarios for the future development of the electricity sector are then simulated, the outcomes of which determine the scale of necessary investment. Based on the findings, the null hypothesis is tested next. In conclusions, the results of the study highlight the importance of investment for the green transformation of Ukraine's electricity sector, and also suggest pathways for future research on the topic.

II. Assessment of carbon intensity of Ukraine's electricity sector and the state of art of 'green' energy development

1. Review of Ukraine's electricity sector, its structure and the share of carbon-intensive electricity production

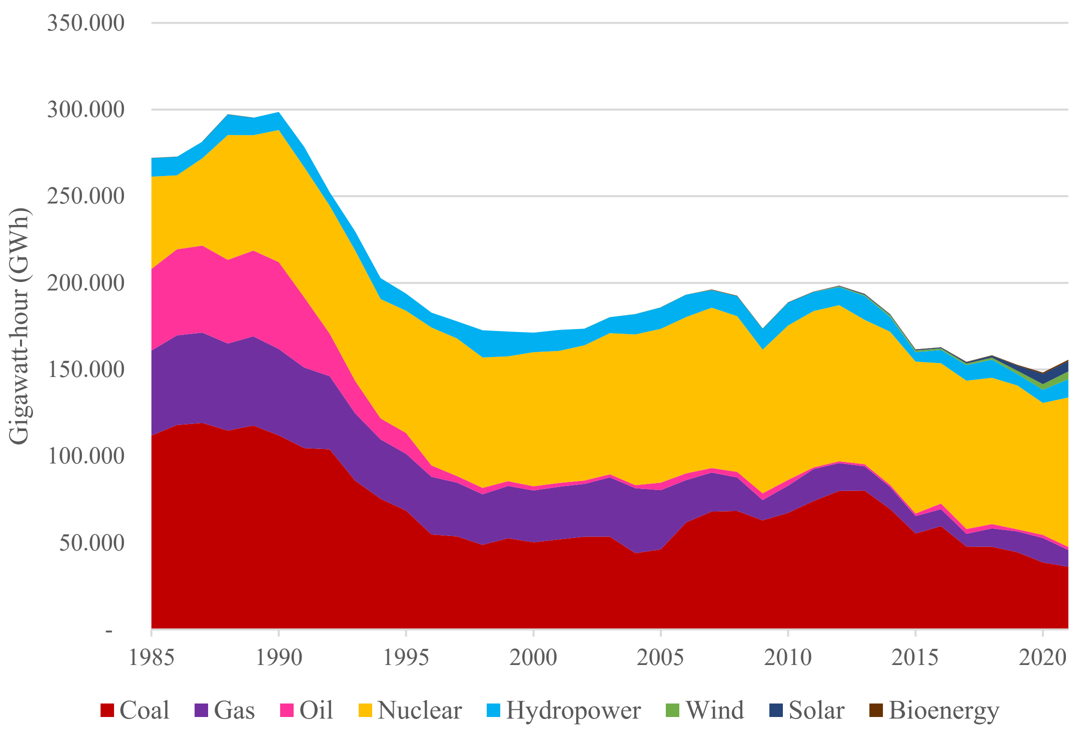
This section describes and analyses the electricity generation capacity of the Ukrainian electricity sector up to 24 February 2022. Particular attention is paid to the structure of electricity generation, i.e., which energy sources it uses. This, in turn, makes it possible to estimate the carbon intensity of electricity production capacity. The results of the assessment are used in the second part of the thesis to estimate the 'green' investments needed.

i) Profile and structure of the electricity generation sector in Ukraine

Electricity generation is one of the components of Ukraine's energy sector. It is essential for the economy as it is used by industry, agriculture, transport, construction, municipal consumers, other non-industrial consumers and the population. In 2020, industry and the population of Ukraine accounted for 42% and 31%, respectively, of total electricity consumption (Probst et al. 2021, 35). On that basis, it is worth examining the structure of electricity production. This will help to determine which sources it is most dependent on and whether they need to be modernised for further efficient use.

Graph 1 below shows the amount of electricity produced in Ukraine from 1985 to 2021 in absolute Gigawatt-hours. It also illustrates how much electricity has been generated using one energy source or another. The data source used for Graph 1 is described in more detail in Annex I. The first point that draws attention is that since Ukraine gained its independence in 1991, electricity production has decreased by a third in the first 5 years of independence (from 278,470 GWh in 1991 to 182,800 GWh in 1996). In terms of distribution of sources, coal and nuclear energy have a large share (together 78% in 2021). In terms of the use of coal for electricity generation, it is noticeable that after 2013 it began to decline sharply by 18%. This is not least due to the temporary occupation by the Russian Federation of parts of the Donetsk and Luhansk regions of Ukraine in 2014. Not only do these areas have some of the richest coal deposits in Ukraine (Task Force 2022, 19), but they also have two thermal power plants, as can be seen in the map in Annex II. Shifting to the nuclear component, it can be seen that Ukraine significantly (by 17%) increased its electricity production capacity using this energy source during the first 5 years of independence. The same level, with minor fluctuations, was maintained throughout the following years. It is also noteworthy that the share of oil in electricity production has almost disappeared since 1991. The share of gas also declined, but at a much lower rate than oil.

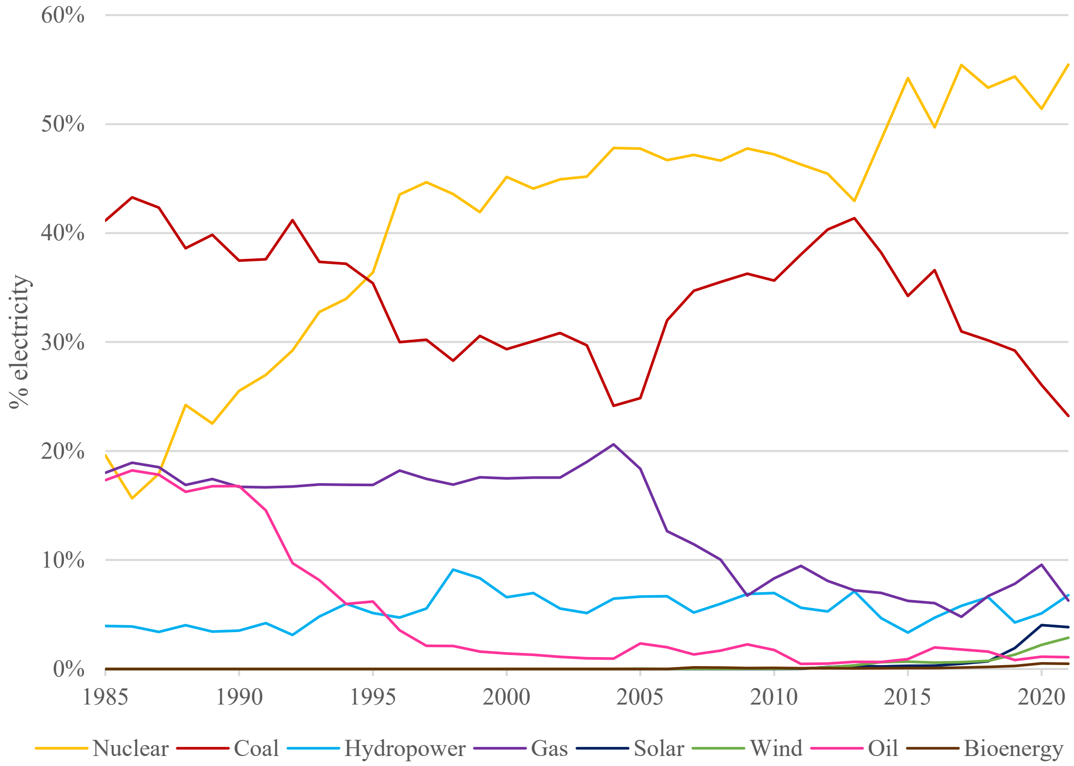
Coming to renewable energy sources, it is worth noting that electricity production using hydropower has remained virtually unchanged over the entire time period for which the data are presented. This suggests that these generation capacities have their roots in the Soviet past and have not been increased during the years of independence. Moving forward, there has been a notable increase in the use of solar and wind energy in recent years. Lastly, bioenergy has hardly changed over the whole time span. Consequently, Ukraine has relatively very little electricity produced from green energy sources.



Graph 1: Electricity production by source, Ukraine (1985-2021)

Data source: Our World in Data, 2022

Graph 2 (for detailed description of data source please see Annex I) below gives an indication of the share of each energy source in electricity generation, i.e., in relative values. As can be seen, the share of the coal component has increased significantly since 2004, replacing the sharp decline in the gas component. At the same time, between 2013 and 2021, a fall of 18% in the coal component was offset by a rise of 12% in nuclear and 6% in the renewable component. In the end, the overall trend points to a steady increase in the share of nuclear in electricity generation, which reaches 55% in 2021. Nevertheless, despite the fall in coal's share, it still has 23% of the total as of 2021.



Graph 2: Share of electricity production by source, Ukraine (1985-2021)

Data source: Our World in Data, 2022

After a brief analysis of the data, it is worth looking at the profile of the main electricity production facilities in Ukraine, namely their infrastructure, which serves to generate electricity using a particular energy source. To begin with, electricity is produced by nuclear power through 4 nuclear power plants (NPPs): Zaporizhzhya, Khmelnytskyi, South Ukraine and Rivne. They comprise 15 reactors, with a total production capacity of 13.8 GW (Task Force 2023, 10). Zaporizhzhia NPP is the largest nuclear power plant in Ukraine and Europe and one of the ten largest NPPs in the world (Power Technology 2019). As of January 2022, the generating capacity of this nuclear power plant was 25% of total electricity generation in Ukraine (Task Force 2023, 10). Accordingly, almost half of all nuclear electricity generation is concentrated in this NPP. The construction of six nuclear reactors has taken place gradually since 1980. It is worth noting that the other three Ukrainian nuclear power plants were also built when Ukraine was part of the Soviet Union. Since then, no new nuclear power plants have been built in Ukraine and the old ones are regularly inspected and repaired (World Nuclear Association 2023). For a more detailed geographical and network overview, please see Annex II.

Coal is quite widely used by almost all thermal power plants (TPPs) in Ukraine to produce electricity as the primary fuel. As of January 2022, 12 TPPs were generating electricity, excluding those in the temporarily occupied territories of Ukraine since 2014 (see Annex 2). The total electricity production capacity is 21.5 GW (Task Force 2023, 10). Almost all of them were built during the Soviet Union era (Wikipedia 2022) and currently require continuous repair and/or modernisation. In addition, coal supply chains from the Donbass region were partially interrupted after 2014, resulting in the reorientation of TPPs to use coal imported by Ukraine (The Global Economy 2020). Accordingly, the use of coal for electricity generation can no longer be called as profitable as it was before 2014. As for the share of gas in electricity production, it is most often a secondary (after coal) fuel source used by the same TPPs.

Thus, Ukraine's electricity generation mix is more than half dependent on nuclear power and almost a quarter on coal from thermal power plants. Since Ukraine became independent, the share of gas and oil has virtually vanished. Hydropower has been used to generate electricity at a more or less stable level of around 7%. The other renewable energy sources have only started to be actively used in the last 2-3 years, showing an upward trend but remaining relatively minor in the overall mix of electricity generation. In terms of infrastructure, both nuclear and thermal power plants were built during the Soviet era, causing an urgent need for modernisation or replacement. The state of green energy infrastructure will be discussed in more detail in the second section of this chapter.

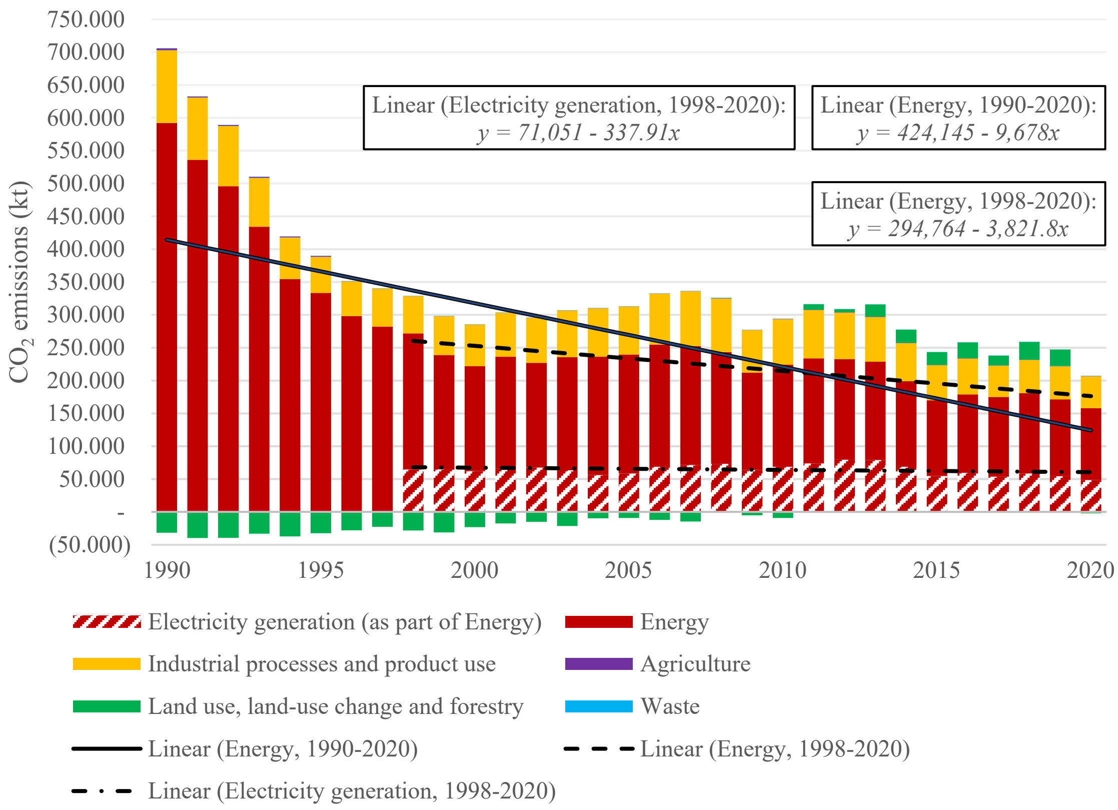
ii) Carbon intensity of electricity generation capacity in Ukraine

First of all, it is worth noting that the entire energy sector is one of the most promising sectors of the Ukrainian economy that has the potential to decarbonise. This can be seen in Graph 3 below (for a description of the data source, please see Annex I). The graph shows the total amount of greenhouse gases, namely CO_2 emissions (without taking into account any other chemical equivalents), which are measured in kilotons. CO_2 equivalents such as methane and nitrous oxide, which are also greenhouse gas components and are present in the database, are not included in the analysis. This is done for two reasons. Firstly, the research question is limited to the carbon intensity of the electricity sector, which implies emissions that contain carbon. Second, from the available data, it is not possible to disaggregate the emissions of CO_2 equivalents specifically for electricity generation, as they add up to a different number of emissions than that reported in the total emissions. Accordingly, for the purpose of equating all emissions to the same 'denominator', only carbon dioxide emissions, i.e., CO_2, are used.

The data cover 5 sectors, namely energy, industrial processes and product use, land use, land-use change and forestry, agriculture and waste. CO_2 emissions caused by the energy sector in turn cover fuel combustion from energy industries (represented by heat production, electricity generation, petroleum refining etc.), manufacturing industries and construction, transport and other sectors as well as fugitive emissions from fuels (solid fuels, oil, natural gas and other emissions from energy production). The graph also illustrates the amount of carbon dioxide emissions from electricity generation, which is included in the total CO_2 emissions from the energy sector. An important note in this regard is that the data for 1990-1997 does not show a split between electricity generation and heat production. These two categories are combined in the fuel combustion section of the database (to access the source of the data, please see Annex I). Consequently, these data are not comparable with those presented for the period 1998-2020 and thus excluded from further analysis.

By analysing the data illustrated in Graph 3, several conclusions can be drawn regarding the energy sector. Firstly, the amount of CO_2 emissions caused by the energy sector averaged 80.85% of the total over the data period. The maximum (93.30%) was reached in 1995 and the minimum (69.30%) in 2019. Consequently, the energy sector is the root cause of CO_2

emissions in Ukraine. Secondly, during the period from 1991 to 2000, Ukraine reduced its total CO_2 emissions by more than half, from 592,717 to 262,115 kilotons. The main sector in which emissions were reduced was the energy sector. This is in line with the fact that electricity production, as shown in Graph 1, was also reduced by more than one-third over the same period, namely from 278,470 to 171,270 Gigawatts-hour. Thirdly, CO_2 emissions from the energy sector are showing a positive downward tendency. The linear trend, which is indicated by a black solid line in Graph 3, shows that each year from 1990 to 2020, carbon dioxide emissions decreased by an average of 9,678 kilotons. In 2020, carbon dioxide emissions from energy activities were 158,054 kilotons, a record low for the entire data period. After all, electricity generation has a slight, almost imperceptible, downward trend in carbon dioxide emissions. Over the period 1998-2020, emissions fell by an average of 337.91 kilotons each year. This observation also overlaps with the fact that nuclear and green energy sources are increasingly being used to generate electricity rather than fossil fuels, as shown in Graph 2.



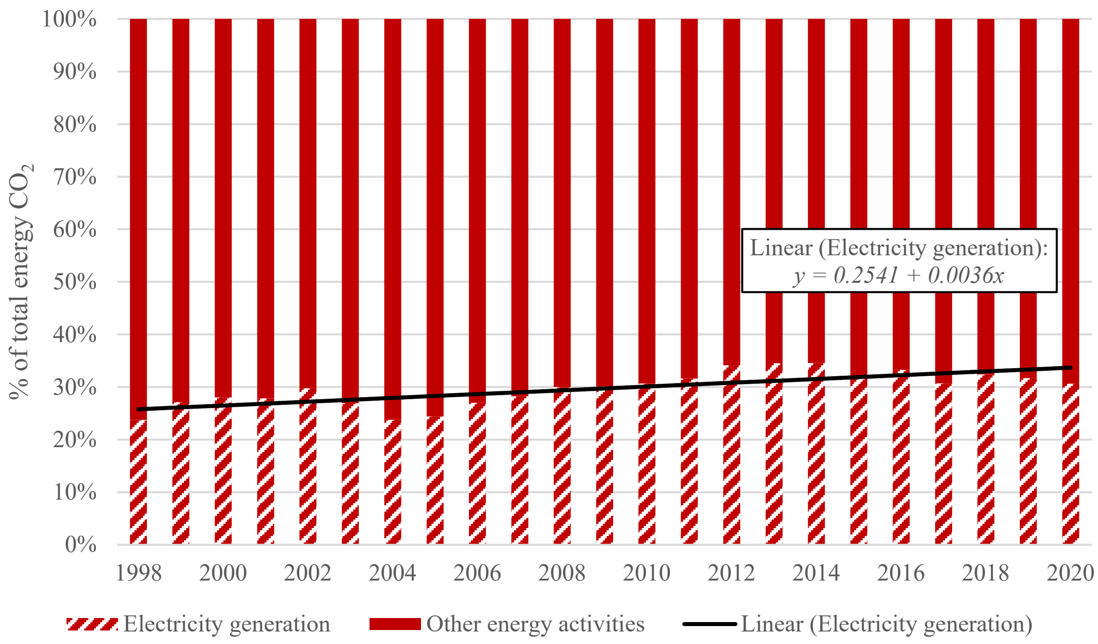
Graph 3: Total CO_2 emissions, Ukraine (1990-2020)

Data source: GHG inventories under the UN Framework Convention on Climate Change, 2022

Since this study focuses specifically on emissions from electricity generation, it is worth taking a closer look at this particular component of the Ukrainian energy sector. It is included in the category of emissions from fuel combustion in the energy industries. Graph 4, which follows slightly below, illustrates the percentage of carbon dioxide emissions from electricity generation as part of the total emissions of the energy sector in Ukraine.

The first thing to note is that there is a weak but positive upward trend in the share of emissions from electricity generation in total CO_2 emissions from energy sector activities. As the linear trend in Graph 4 indicates, on average it is increasing by 0.36% annually between 1998 and 2020. Going back to Graph 3, the linear trend over the same time period, indicated by the black dashed line, indicates that CO_2 emissions caused by the entire energy sector are decreasing by an average of 3,821.80 kilotons each year. If one combines both of these observations, one can make some conjectures. Namely, either polluting energy activities other than electricity generation have been reduced in Ukraine. Or there is less emphasis on decarbonising electricity generation than on reducing emissions from other energy activities. This assumption is discussed in the next section in the light of the use of renewable energy sources for electricity generation. Both of these suggestions may explain why the emission reduction trend in the electricity generation (dash-dotted line) is much smaller than that in the general energy sector (dashed line), which can be seen in Graph 3.

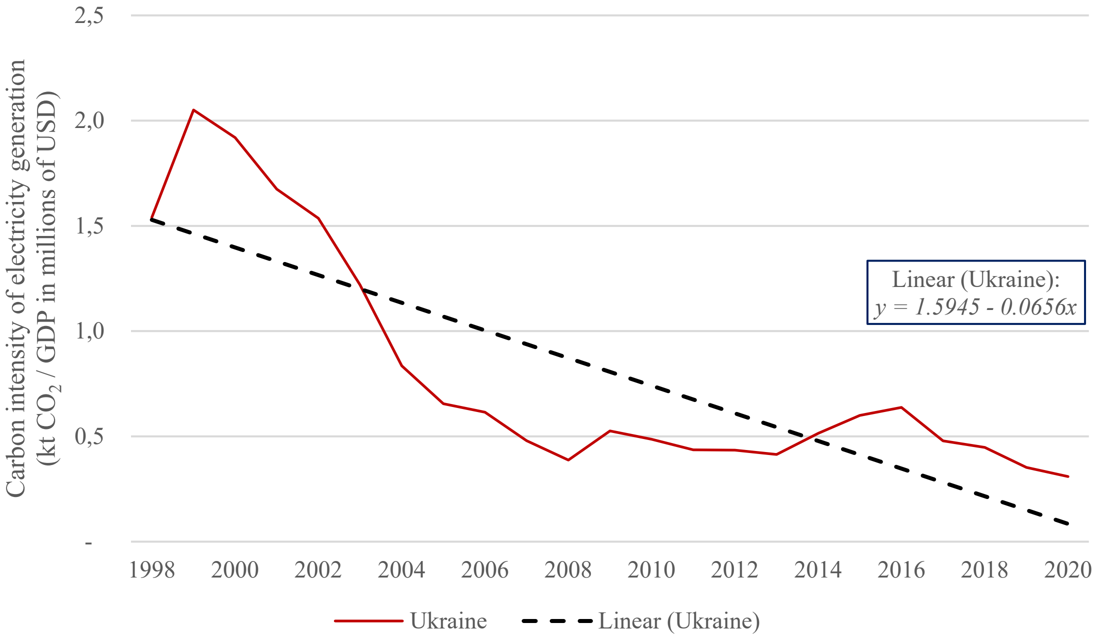
Secondly, CO_2 emissions from the energy sector consist of an average of 29.71% of emissions from electricity generation over the period 1998-2020. In 2020, for example, this figure reached 30.65%. When looking at the aggregate data for Graph 3, carbon dioxide emissions from electricity generation have on average 22.85% of Ukraine's total CO_2 emissions over the same period. In 2020, the figure is 23.65%. Thus, these results provide further evidence of why the electricity generation is a promising sector for decarbonisation in Ukraine.



Graph 4: Share of CO_2 emissions by electricity generation in energy sector, Ukraine (1998-2020)

Data source: GHG inventories under the UN Framework Convention on Climate Change, 2022

An assessment of the carbon intensity of the electricity generation is also worth backing up with an analysis of how much CO_2 emissions (in kilotons) from electricity generation are per million USD of Ukraine's GDP. This is illustrated in Graph 5 below. For a description of the data source, please see Annex I. As can be seen, from 1999 to 2008 this ratio has decreased dramatically from 2.1 to 0.4. After that the trend remains essentially unchanged, with only some spikes. For example, the spike from 2008 to 2009 is due to a 35% drop in GDP (from USD 188,111.14 million to USD 121,552.78 million) and a 13% drop in CO_2 emissions from electricity generation (from 72,991.57 to 63,921.80 kt) due to the global financial crisis. An even bigger leap between 2013 and 2016 was again due to GDP falling by 51% (from USD 190,498.81 million to USD 93,355.99 million) and CO_2 emissions from power generation falling by 25% (from 78,985.11 to 59,527.32 kilotons) because of the temporary annexation of the Crimea and some parts of Donetsk and Luhansk regions. At the same time, as shown in Graph 3, the trend of CO_2 emissions from electricity generation is very weak, averaging a reduction of 337.91 kilotons per year. In Graph 5, the trend shows that the average annual ratio of CO_2 emissions in kilotons per million USD of GDP is decreasing by 6.56%. Consequently, it can be concluded that this indicator of carbon intensity of electricity generation, although showing a strong downward trend, is mainly driven by more rapid growth or decline in GDP and not by changes in the amount of CO_2 emissions.

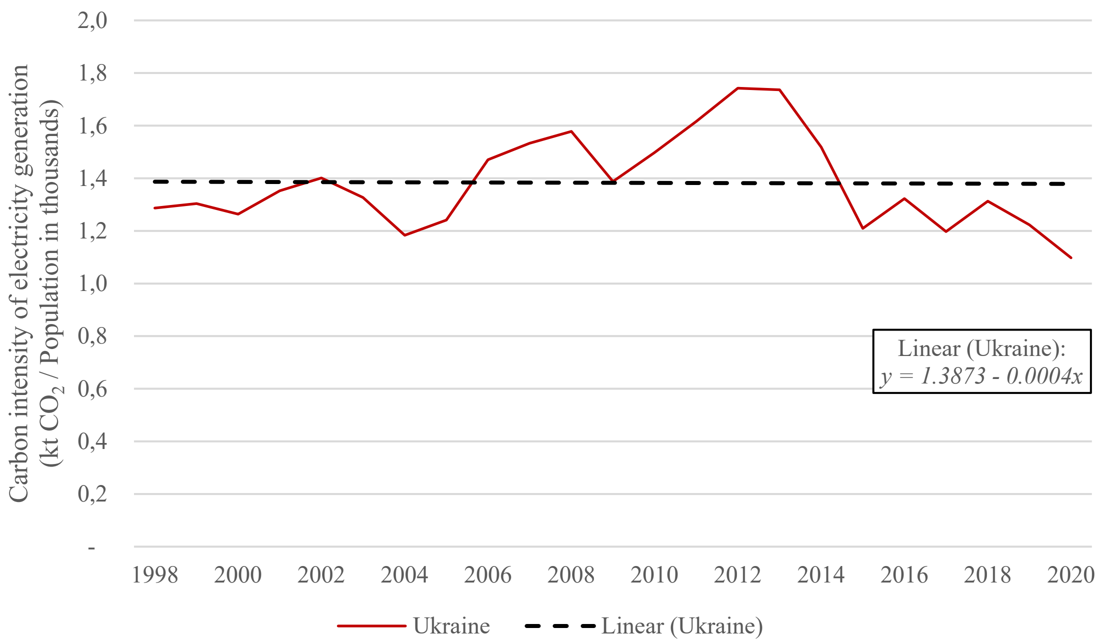


Graph 5: CO_2 emissions per GDP, Ukraine (1998-2020)

Data sources: GHG inventories under the UN Framework Convention on Climate Change, 2022; The World Bank, 2022a

The analysis can also be continued by looking at how many kilotons of CO_2 emissions per capita (in thousands), as shown in Graph 6. For a description of the data source, please see Annex I. In this case the overall trend shows that there has been little change over the period (a reduction of just 0.04% in the ratio of kilotons of CO_2 per thousand population). Consequently, one can suggest that Ukraine's population and CO_2 emissions from electricity generation are decreasing or are increasing in parallel and that the overall trend remains unchanged. But what is interesting is the sharp increase of the coefficient from 2010 to 2012 from 1.4 to 1.7. In this period, the population decreased by 0.6% (from 45,870.74 to 45,593.34 thousand), and CO_2 emissions from electricity generation increased by 15.6% (from 68,714.60 to 79,437.24 kilotons). This is followed by a sharp drop in the ratio between 2013 and 2015, from 1.7 to 1.2. The population decreased by only 0.7% (from 45,489.65 to 45,154.04 thousand), while CO_2 emissions decreased by almost 31% (from 78,985.11 to

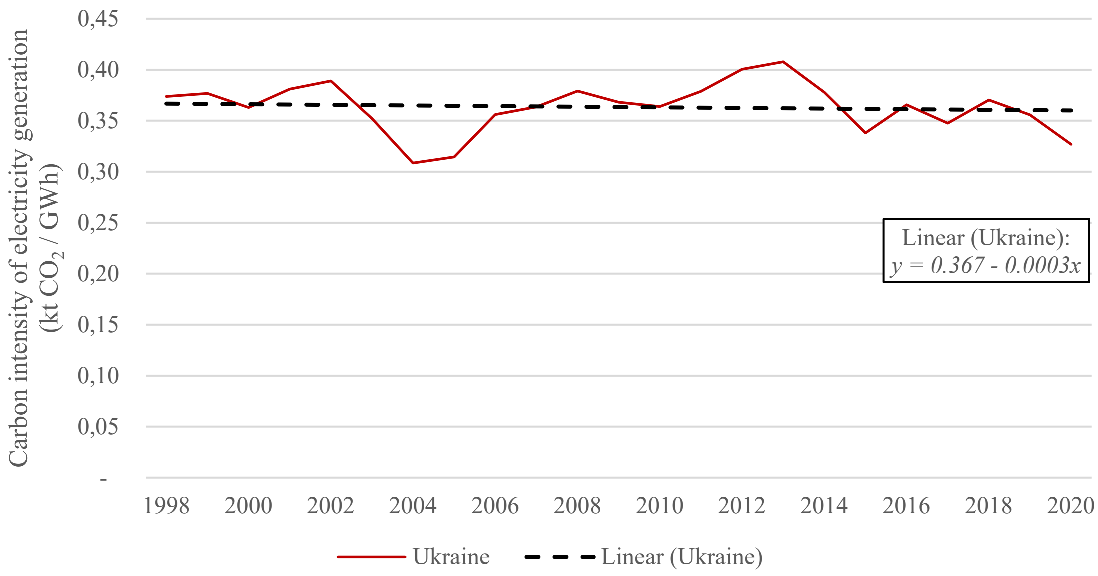
54,620.42 kilotons). These observations indicate that this carbon intensity indicator is more dependent on changes in carbon dioxide emissions than in population.



Graph 6: CO_2 emissions per capita, Ukraine (1998-2020)

Data sources: GHG inventories under the UN Framework Convention on Climate Change, 2022; The World Bank, 2022b

Finally, the carbon intensity of electricity generation can also be measured by the ratio between CO_2 emissions (in kilotons) and the amount of electricity produced (in Gigawatt-hours), as shown in Graph 7. For a description of the data source, please see Annex I. This metric is intended to show the extent to which electricity generation is shifting towards the use of low-carbon energy sources. As the use of, for instance, green energy instead of coal increases, this coefficient should fall steadily. First of all, it is noteworthy that the pattern of Graph 7 repeats almost exactly that of Graph 6. This is explained by the fact that electricity in Ukraine is consumed by the entire population (Our World in Data 2022, see Annex I), which indicates a strong correlation between these variables. Second, over the period 1998-2020, the ratio shows a very slight decrease of 0.0003 kt CO_2 per GWh on average each year. This means that the energy mix for electricity production in Ukraine has remained almost constant over the whole period. This in turn confirms that electricity generation is dependent on fossil fuels accompanied by carbon dioxide emissions.



Graph 7: CO_2 emissions per unit of electricity generated, Ukraine (1998-2020)

Data sources: GHG inventories under the UN Framework Convention on Climate Change, 2022; Our World in Data, 2022

To summarise the analysis of the carbon intensity of electricity generation in Ukraine, several conclusions can be drawn. Firstly, the energy sector is the main cause of the predominant majority of CO_2 emissions in Ukraine, although it is trending downwards. At the same time, emissions from electricity generation are also trending downward, but less so than the whole energy sector. Secondly, emissions from electricity generation are a growing share of all emissions in the energy sector, accounting on average for almost a third. If one looks at all emissions in Ukraine, the electricity generation accounts for more than a fifth of them. Consequently, a green transformation of Ukraine's electricity sector has the potential to reduce these numbers of CO_2 emissions to zero, making a significant contribution to the decarbonisation of the Ukrainian economy. Thirdly, the small reduction in CO_2 emissions from electricity generation is also confirmed in relation to Ukraine's GDP, where the latter is the driving force. In terms of the ratio of emissions to population and the amount of electricity generated, in both cases the trend is downward, but with a negligible reduction.

All of the above in this section makes the Ukrainian electricity sector one of the most promising for decarbonisation. But in order to analyse such potential fully, it is worth looking not only at the carbon-intensive side, but also at the green side, that is, at renewable energy sources. It is precisely this question that the following section explores.

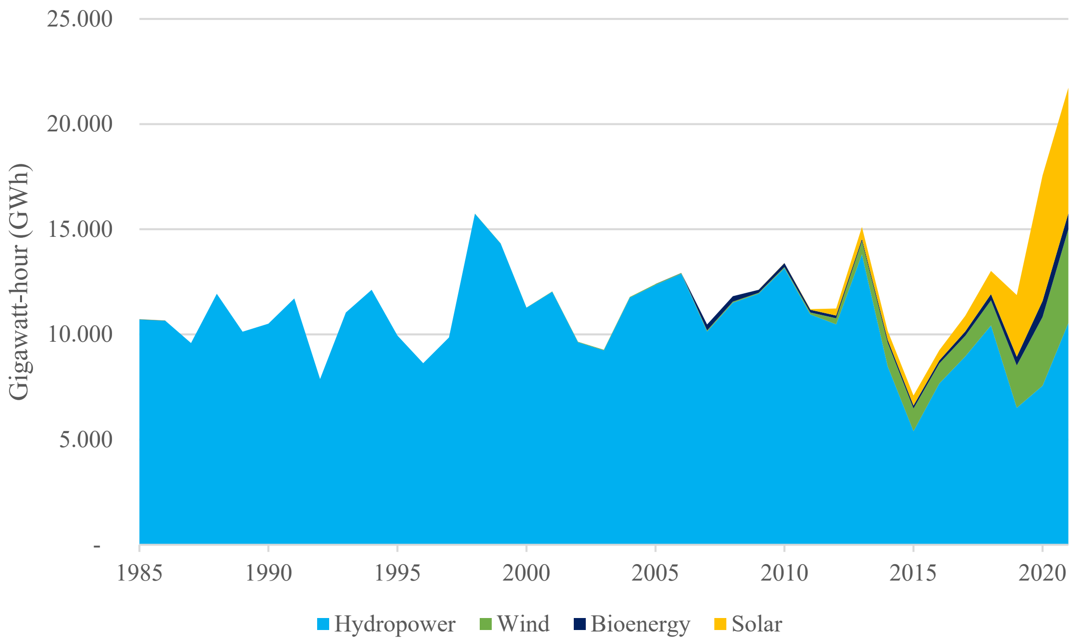
2. The degree of usage and the importance of renewables in Ukraine's electricity sector

This section continues the analysis of the electricity generation sector in Ukraine. Whereas the last section dealt with the carbon intensive side, the focus here is on the intensity and dynamics of the use of renewable energy sources for electricity generation. The section is divided into two sub-sections that describe the use of green energy sources and subsequently analyse the green intensity of electricity generation in Ukraine.

(i) Overview of electricity production capacity from 'green' energy sources

The use of renewable sources for energy production (and in particular for electricity generation) is gaining momentum worldwide. Particularly in the European Union, special attention is being paid to this issue and relevant policies are being developed to stimulate a green transition of the energy sector (Bojek 2022). Ukraine is no exception and also has a share of renewable sources in its electricity mix. In addition, the intensity of their use has been increasing in recent years, as will be shown below, making this an area that is promising for further development and investment.

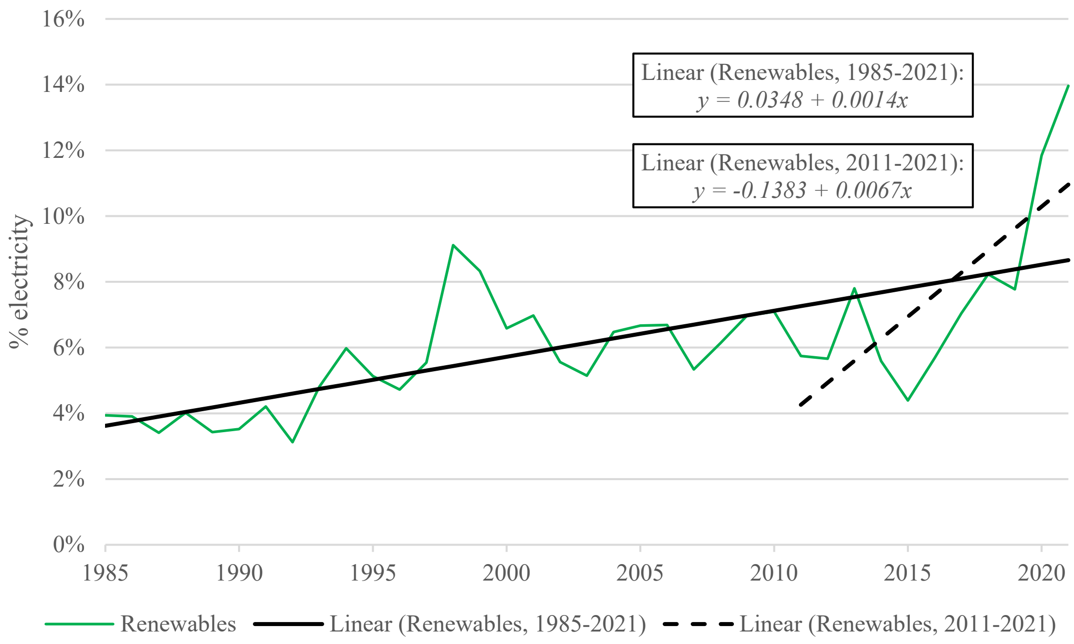
Graph 8, which follows, illustrates the absolute amount of electricity in Gigawatt-hours that has been generated in Ukraine from 1985 to 2021 using renewable energy sources (for a detailed description of the data source, please see Annex I). Green electricity generation in Ukraine covers hydro, wind, solar and bioenergy. The first point that attracts attention is that the bulk of the green sources in electricity generation are hydropower. Hydropower generation has remained at approximately the same average level since Ukraine's independence in 1991. As for other green sources, they were introduced later. For example, wind energy started to be used from 2000, bioenergy from 2007 and solar energy only from 2011. Nevertheless, in the last 5 years, we can see that it is solar and wind energy that are the main drivers in increasing the share of renewable energy sources for electricity generation. The growth dynamics of each of the green sources are discussed in more detail later in this sub-section.



Graph 8: Electricity production from renewables by source, Ukraine (1985-2021)

Data source: Our World in Data, 2022

Moving forward in the analysis of electricity generation capacity from green sources, it is also worth considering their share in the total electricity mix. As can be seen from Graph 9, the use of renewable sources is trending upwards (solid black line). Namely, between 1985 and 2021, their share increased by an average of 0.14% each year. The minimum value was reached in 1992 at 3.12%. In 2021, a value of 13.96% was reached, which was the highest value over the entire data period. It is also possible to trace a sharp jump from 2015 to 2021, which was 9.5%. This is in line with the observation from Graph 8 regarding the increase of electricity generation by wind and solar power.



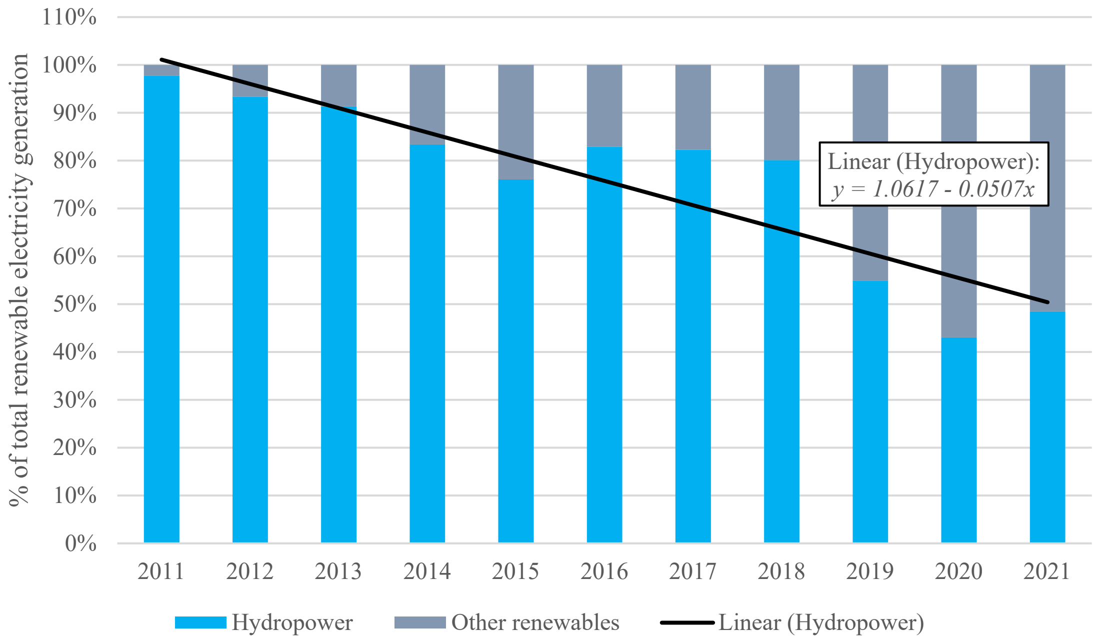
Graph 9: Share of electricity production from renewables, Ukraine (1985-2021)

Data source: Our World in Data, 2022

As has already been seen in the previous 2 graphs, some green sources dominate others. Accordingly, it is worth taking a closer look at the dynamics of each of them, their share in the overall structure of renewable energy sources, and the infrastructure that supports them. It is worth noting that the data for each source are for 2011-2021 only. This is explained by the fact that solar energy has been used to generate electricity in Ukraine only since 2011 and is the newest green source among all others. This will make it possible to compare the development trends of the sources over the period that is common to all of them, both among themselves and with the general trend shown by the dashed line in Graph 9. Ultimately, this will enable preliminary conclusions to be drawn about the development prospects and investment attractiveness of a particular green source, which will be used to further assess the scale of investment required in this study.

(a) Hydropower

Graph 10 below shows the share of electricity generation from hydropower in total green electricity generation over the period 2011-2021. Despite the long-term dominance of this recovering source of electricity in absolute values, as shown in Graph 8, it has shown a significant downward trend over the last 11 years. The black solid line in Graph 10 shows that the share of hydropower decreases by an average of 5.07% each year. Thus, over the given period of 2011-2021, it has halved, from 97.77% to 48.50%.



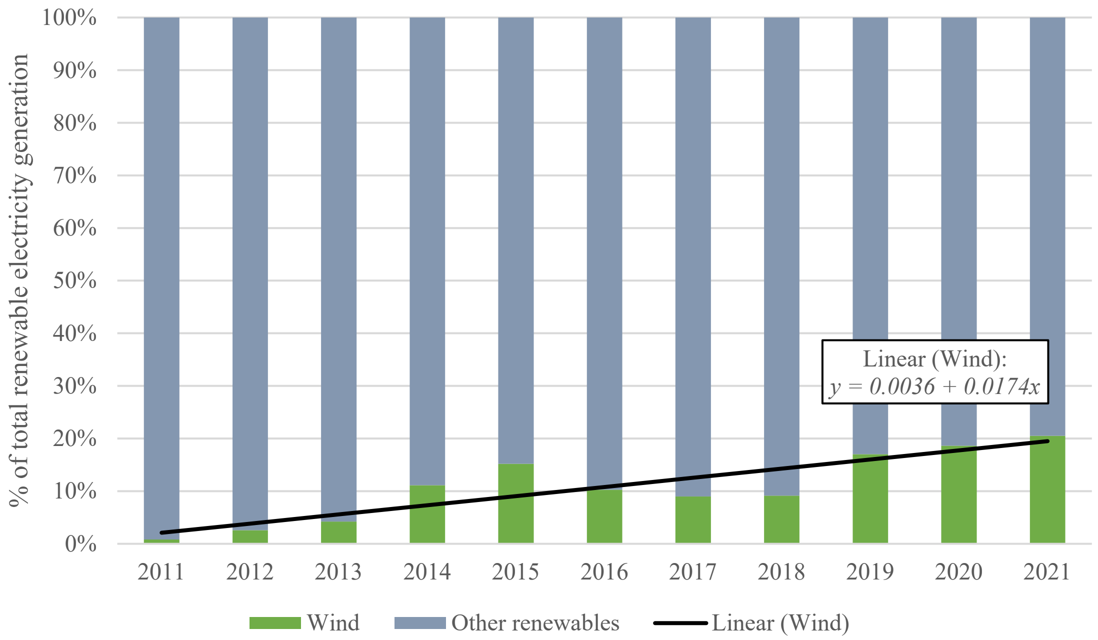
Graph 10: Share of electricity generation from hydropower in all renewables, Ukraine (2011-2021)

Data source: Our World in Data, 2022

As for the infrastructure that provides electricity generation from hydropower, it should be divided into large and small (<10MW) hydropower plants ((S)HPPs). As of 2021, there were 10 large hydropower plants and three pump-storage plants operating in Ukraine, with a total installed generation capacity of 6.7 GW (IRENA 2022a, see Annex I). The problem with large HPPs is that the main infrastructure capacity was built during the Soviet era, which is similar to the situation of nuclear power plants as described above (Wikipedia 2022). Regarding the geography of their location, almost all of them are located on the Dnieper River (see Annex II). On the other hand, small hydro power plants produce only 0.1% of the total electricity generation in Ukraine (installed capacity of 0.12 GW) (Task Force 2023). Most of them were also built during Ukraine's Soviet past but underwent modernisation during Ukraine's independence (Wikipedia 2023).

(b) Wind power (Onshore)

The next source of green electricity in Ukraine is onshore wind power. As it comes from Graph 11, this source of electricity generation tends to grow, namely its share is increasing on average by 1.74% every year. In 2021, the share of wind power peaked at 20.52% of all green electricity produced. This also allows for the assumption that the share of this source will continue to grow.



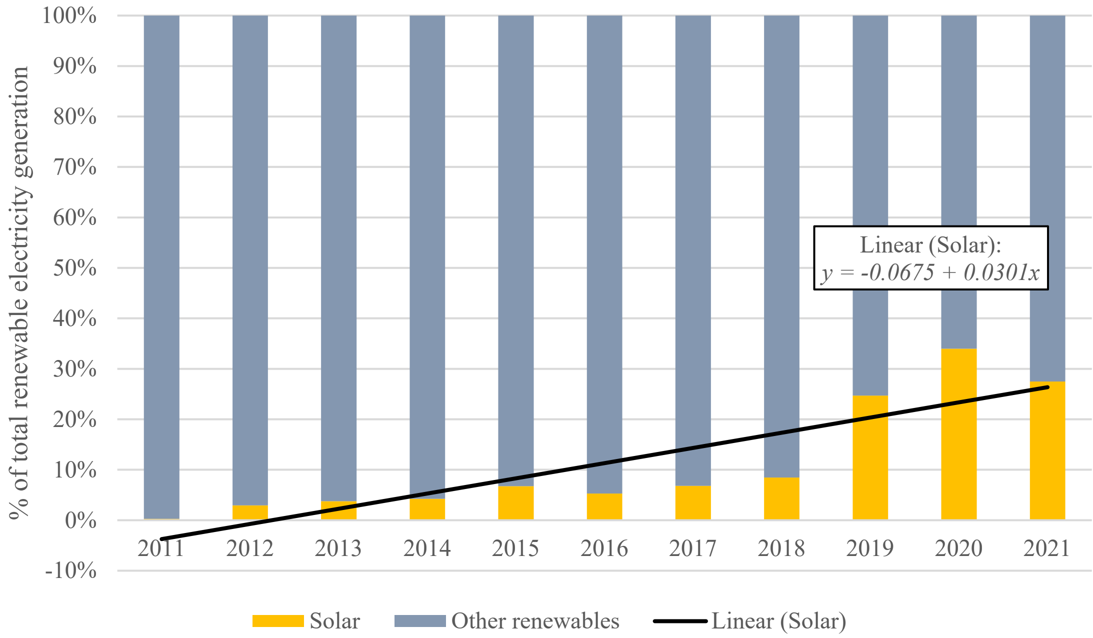
Graph 11: Share of electricity generation from onshore wind in all renewables, Ukraine (2011-2021)

Data source: Our World in Data, 2022

For 2021, the maximum net electricity generation capacity from onshore wind power plants (WPPs) was 1.8 GW (IRENA 2022a, see Annex I). Referring to Annex II, it can be seen that the vast majority of wind power plants in Ukraine are located in the southern regions of Ukraine, the number of which is complemented by those in the western regions. This is due to the favourable landscape which allows the use of wind power. It can also be seen that some WPPs were lost due to Russia's temporary occupation of Crimea and parts of Donetsk and Luhansk regions in 2014. Turning to the data prior to 2011 (Our World in Data 2022, see Annex I), it can be seen that the growth trend has been much smaller than in the last 11 years. This is, not least, due to a certain inflow of investment in wind power development in Ukraine. For example, in 2012 the EBRD invested USD 13.3 million to develop wind power generation in Ukraine (EBRD, n.d.).

(c) Solar power (Photovoltaics)

The evolution of the share of the newest renewable source in Ukraine, namely photovoltaic solar power, is shown in Graph 12 below. As can be seen, the big jump occurred between 2018 and 2020, when the share of solar power increased by 25.55%. The overall trend over the period is positive, namely it shows an increase in the share by an average of 3% each year. The maximum value of 34% was reached in 2020, after which it fell to 27.47% in 2021. Although in absolute terms, the amount of electricity produced from solar power remained the same in 2020 and 2021 and is an 11-year record (see Annex I for access to the data).



Graph 12: Share of electricity generation from photovoltaic solar in all renewables, Ukraine (2011-2021)

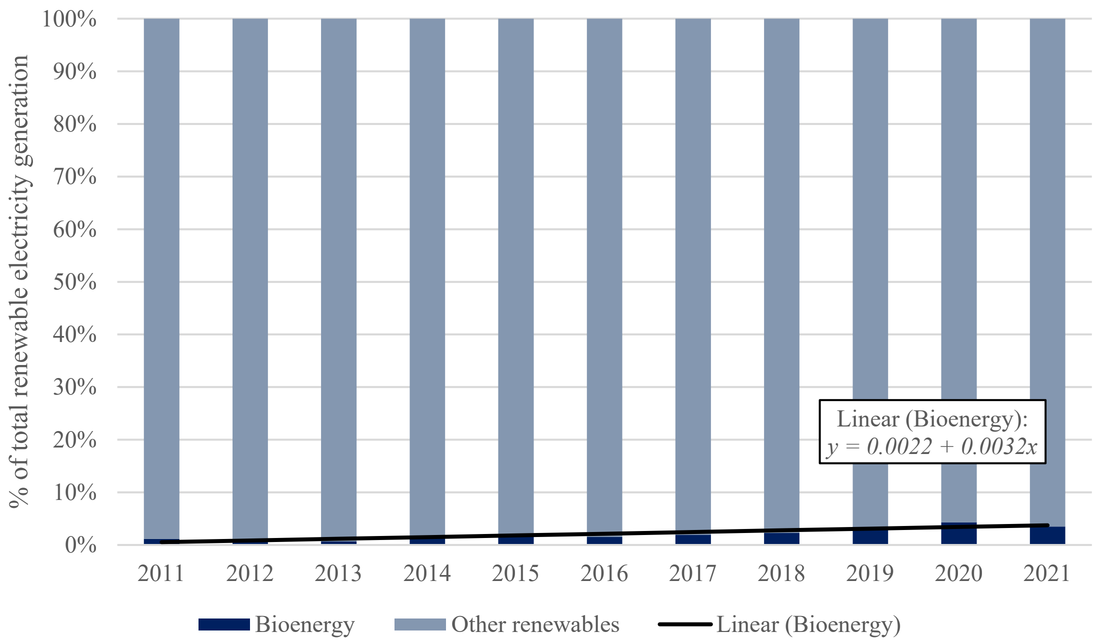
Data source: Our World in Data, 2022

As of 2021, the installed production capacity of photovoltaic solar power plants (SPPs) in Ukraine was 8.1 GW, which is more than, for example, that of hydropower plants (6.7 GW)

(IRENA 2022a, see Annex I). However, this is only the installed maximum net generation capacity, i.e., theoretical under 100% favourable weather conditions, which is not always the case in practice. This is confirmed in Graph 8: In 2021, HPPs generated 10,540 GWh of electricity, which is 1.76 times more than the 5,970 GWh produced by the SPPs. It is also worth noting that Ukraine ranks 7th among European countries in 2020 and 2021, both in terms of installed production capacity (IRENA 2022a, see Annex I) and the actual amount of electricity generation from solar power (Our World in Data 2022, see Annex I).

(d) Bioenergy

As can be seen from Graph 13 below, electricity production in Ukraine from bioenergy is minuscule. The maximum value was reached in 2020 and amounted to only 4.33% of the total green electricity produced. Nevertheless, as can be seen in the graph, the dynamics of bioenergy use in Ukraine is weak but positive. In average, every year the share of this source increases by 0.32%. This low usage of bioenergy is logically explained by the low installed capacity, which was only 0.28 GW as of 2021 (IRENA 2022a, see Annex I).



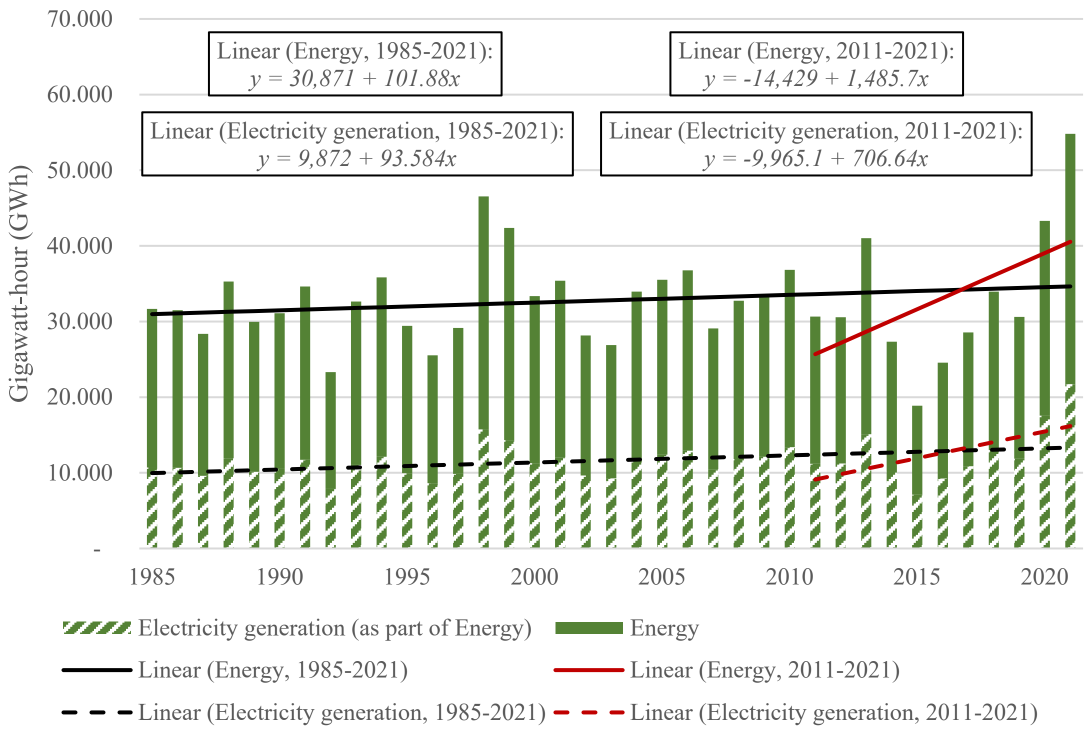
Graph 13: Share of electricity generation from bioenergy in all renewables, Ukraine (2011-2021)

Data source: Our World in Data, 2022

Summarising the above in this section, several conclusions can be drawn. Firstly, the use of renewable energy sources for electricity generation is increasing in Ukraine, especially in the last 5 years. Secondly, green electricity generation has become more diversified over the last 11 years, i.e., coming not only from hydropower but also from the active use of wind and solar energy. As of 2021, hydropower still has the largest share at 48.50%, followed by solar (27.47%), wind (20.52%) and bioenergy (3.50%). Thirdly, the trend in Graph 9 for the period 2011-2021 shows an average growth of renewables' share of 0.67% each year (which is much higher than the trend for 1985-2021, which is 0.14% increase). The largest contribution to this growth has come from the rapid development of solar and wind power generation. In the end, it can be concluded that solar and wind power are the driving forces behind the growth of green electricity generation and have the potential for further development. This, in turn, also increases the investment potential of these sources, which will be taken into account later in this study when assessing the scale of investment needed.

(ii) 'Green' intensity of electricity generation capacity in Ukraine

Having previously examined the carbon intensity of Ukraine's electricity sector, it is now also worth looking at how intensive the use of renewable energy sources is for generating electricity. Graph 14 below illustrates the amount of energy (and electricity as part of it) produced from green sources over the period 1985-2021. As can be seen from the graph, the trends over the period for both the total energy sector (black solid line) and the electricity sector separately (black dashed line) are almost identical. Both are positive, nevertheless the trend for the whole energy sector is growing on average 8.3 GWh faster per year than for the electricity sector. The graph also shows trends for the period 2011-2021 (since the introduction of Ukraine's most recent green source, solar power). They are also positive, but steeper. This is due, as previously shown, to the more intensive use of solar and wind power. While electricity generation from renewable sources has an average growth of 706.64 GWh each year, the growth in the whole energy sector is more than double, at 1,485.7 GWh over the same period. Thus, in absolute terms, green electricity generation is growing slower than in the energy sector. In addition, the increased use of wind and solar power since 2011 has not caused more growth in electricity generation than in the whole energy sector.

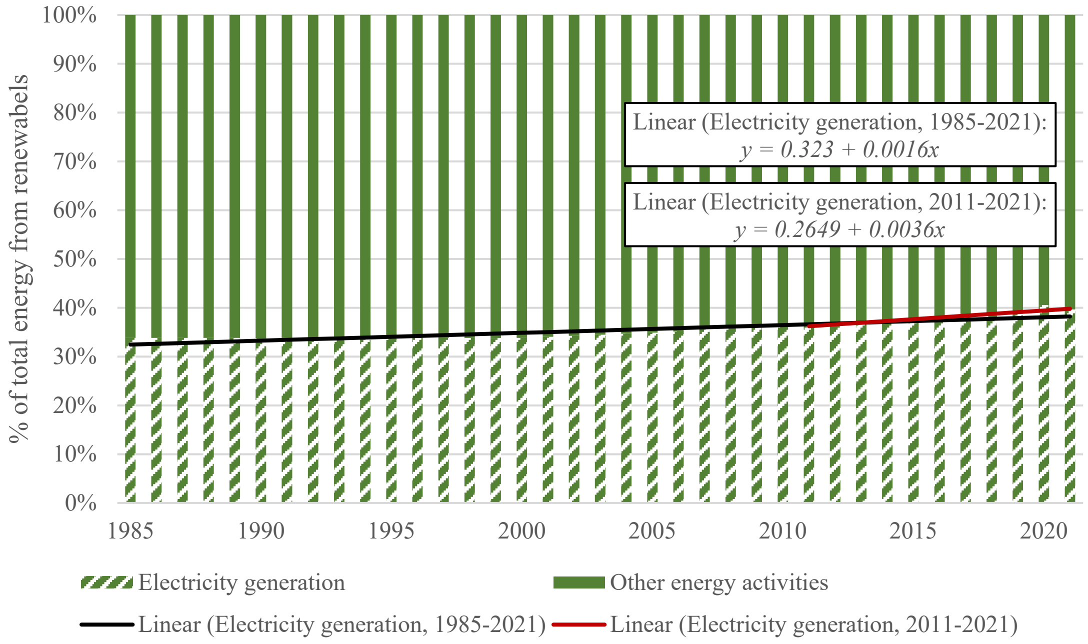


Graph 14: Total energy production from renewables, Ukraine (1985-2021)

Data source: Our World in Data, 2022

The relative values, namely the share of electricity generation in the green energy sector, are shown in Graph 15. The first point to note is that the trend in the share of green electricity in total renewable energy generation, although weak, is positive (black solid line). Over 37 years, from 1985 to 2021, the growth of the share of green electricity averaged just 0.16% per year. The minimum value of 33.80% was reached in 1999 and the maximum of 40.56% in 2020. It is also worth paying attention to the trend from 2011 to 2021. As can be seen from the graph, it is slightly steeper (red solid line), nevertheless only 0.36%. This again confirms the conclusion from the previous paragraph, that despite the greater use of solar and wind power for electricity generation in absolute values, relative to the entire energy sector it has not brought much change.

An interesting observation can also be made when comparing Graph 15 with Graph 4. From the data of the latter, it can be seen that on average over the period 1998-2020, CO_2 emissions from electricity generation were 29.71% of the total Ukraine's energy sector emissions, with an annual average increase of 0.36%. From the data in Graph 15, it can be seen that the share of renewable sources in the electricity sector averaged 36.17% of the total green energy sector over the same period, with an average annual growth rate of 0.26%. Thus, in both cases the electricity sector occupies about one third of the energy sector and has approximately the same growth rate. Accordingly, it can be concluded that the share of CO_2 emissions from electricity generation in the energy sector determines approximately the same share of the distribution of renewable energy for electricity generation.

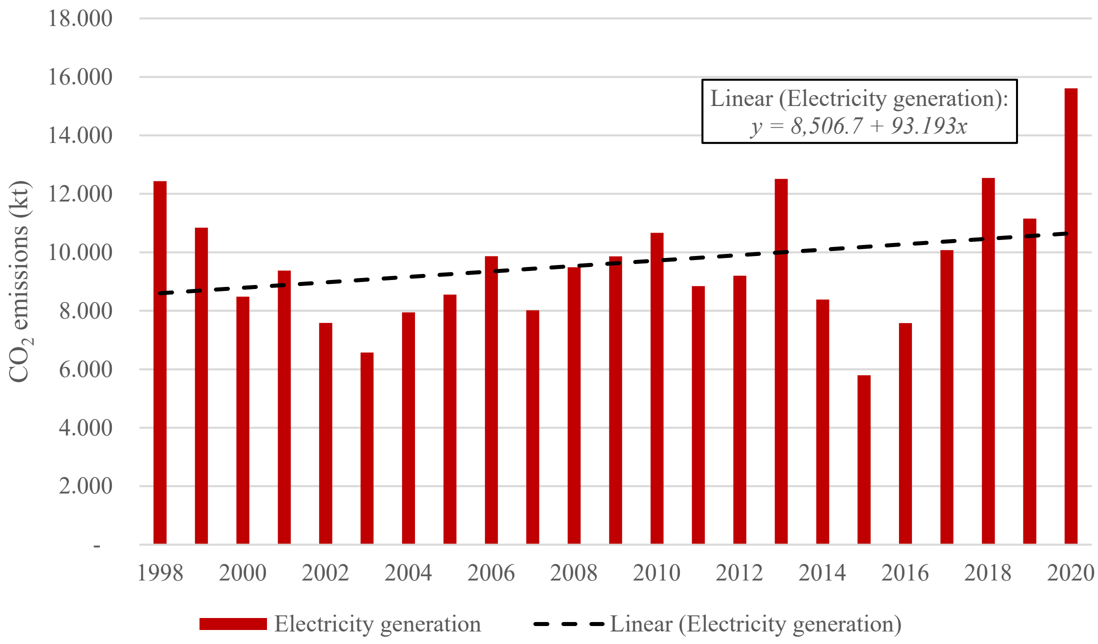


Graph 15: Share of green electricity generation in energy production from renewables, Ukraine (1985-2021)

Data source: Our World in Data, 2022

Moving forward, it is also possible to estimate how much CO_2 emissions (in kilotons) from electricity generation have been avoided in Ukraine using renewable energy sources. This will complement the conclusions about the green intensity of the Ukraine's electricity sector, as the main goal of green energy is precisely to reduce carbon dioxide emissions. The methodology for this assessment is to assume that all CO_2 emissions for electricity generation come from fossil fuels only (i.e., coal, gas and oil). The ratio of all CO_2 emissions from electricity generation to the amount of electricity produced using only fossil fuels is then calculated. This ratio is then multiplied by the amount of green electricity generated.

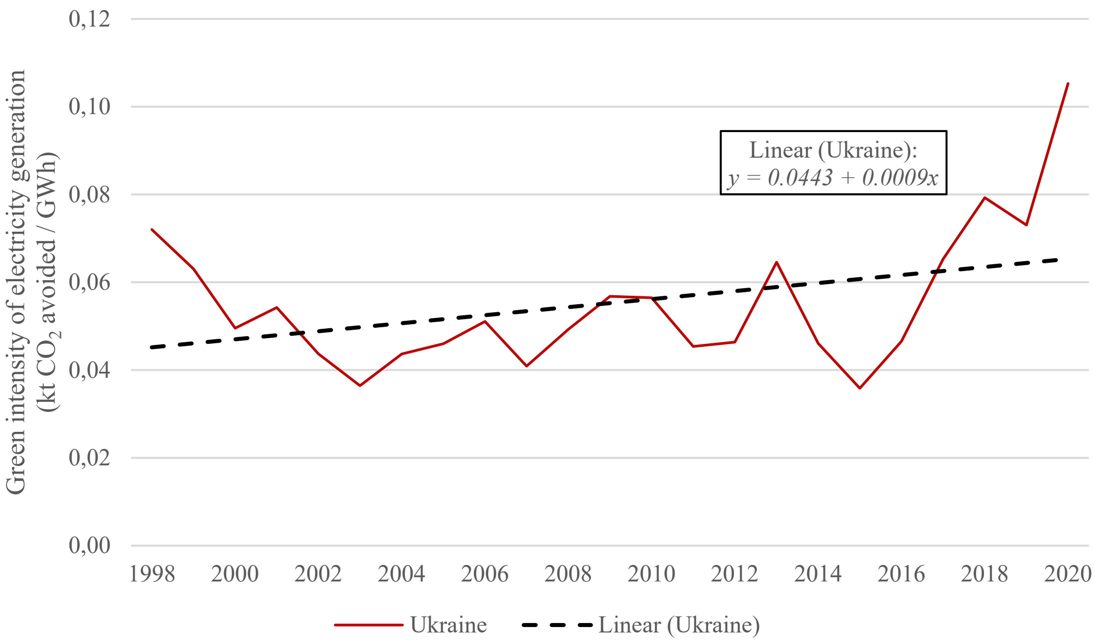
Graph 16 below shows the results of this assessment for the period 1998-2020. Despite the floating dynamic, the overall trend over the whole time period shows that on average each year the avoided amount of CO_2 emissions from electricity generation increases by 93.19 kilotons. The minimum value of 5.796 kilotons can be observed in 2015. In 2020 a maximum of 15,609 kilotons is evident. Altogether, 221,376 kilotons of CO_2 emissions were avoided in those 23 years, which is 15% of all carbon dioxide emissions from electricity generation for the same time period.



Graph 16: Avoided CO_2 emissions in electricity generation, Ukraine (1998-2020)

Data sources: GHG inventories under the UN Framework Convention on Climate Change, 2022; Our World in Data, 2022

Based on the results of the estimation in Graph 16, it is worth examining how much CO_2 emissions avoided are per unit of electricity generated. Graph 17 below illustrates the findings. It is noteworthy that the trend shown in the graph below expectedly mirrors almost exactly the trend in Graph 9, which shows the share of electricity generation from renewable energy sources. The trend below indicates that the ratio has a relatively weak growth in 1998-2020, averaging 0.0009 kt CO_2 per GWh each year. Thus, based on the assumption of avoided CO_2 emissions, the green intensity of electricity generation in Ukraine is gradually increasing (especially noticeable between 2015 and 2020), but it is still relatively weak.



Graph 17: Avoided CO_2 emissions per unit of electricity generated, Ukraine (1998-2020)

Data sources: GHG inventories under the UN Framework Convention on Climate Change, 2022; Our World in Data, 2022

Comparing the results of the assessment of the green intensity of the electricity sector in Ukraine (trending upwards on average by 0.0009 kt CO_2 per GWh each year, see Graph 17) with the results of the assessment of the carbon intensity over the same period (trending downwards on average by 0.0003 kt CO_2 per GWh each year, see Graph 7), the following conclusions can be drawn. Despite a gradual reduction in CO_2 emissions from electricity generation, and an increase in electricity produced from renewable energy sources in absolute values, the corresponding intensity ratios per unit of electricity generated indicate virtually no change in green electricity generation over the last 23 years. Accordingly, the green electricity generation sector in the Ukraine is still at an early stage of development and in some stagnation. Nevertheless, as shown above, the sector has started to develop particularly strongly in the last 5 years due, inter alia, to the inflow of foreign investment.

The importance of developing green energy in Ukraine is also attributed to the security benefits of the national electricity system, an issue that has become particularly acute since October 2022. The use of renewable energy sources implies extensive decentralisation of electricity generation capacity, in particular solar and wind power (Ministry of Energy of

Ukraine 2023). This demonstrates a key difference with the fossil fuel-based, centralised energy infrastructure. Green electricity generation, in contrast, involves a wide network between power plants, which will ensure an uninterrupted supply of electricity to both households and industry. On the other hand, it should not be forgotten that renewable energy sources are directly dependent on weather conditions, which reduces the reliability of the consistency of electricity generation.

Consequently, electricity generation from renewable energy sources is a promising area for further development and investment. In this chapter, the scope of possible green transformation of Ukraine's electricity sector has been assessed, and renewable energy sources have been prioritised for use. In order to achieve this transformation, and to have an idea of its feasibility, it is worth analysing the scale of investment needed. This is the main topic of discussion in the next chapter.

III. Estimation of the scale of investment required to transform Ukraine’s electricity sector from carbon-intensive to ‘green’

1. Assumptions and limits of the analysis

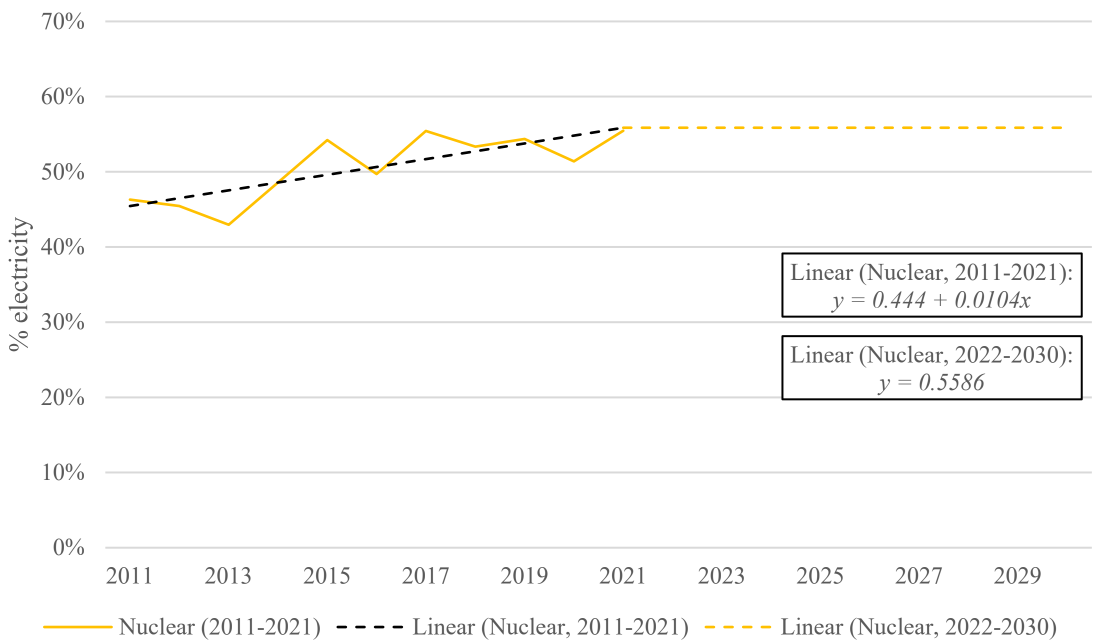
Estimating the scale of investment (including from the European Union) needed for a green transformation of the Ukraine’s electricity sector involves certain assumptions and limitations. First, the assumption is made that the carbon-intensive component of the energy mix of electricity generation is gradually being replaced by green technologies under pre-war circumstances (i.e., before 24 February 2022). This assumption allows the use of the data and conclusions analysed and reached in the previous chapter. Furthermore, it also allows an artificial substitute for the reality of Ukraine's war-ravaged electricity generation capacity, the scale of which was shown in the introduction to the thesis. Nevertheless, the analysis uses current economic and political realities to more adequately calculate investors' willingness to provide funds for the green transformation of Ukraine's electricity sector.

Second, for the purpose of this analysis, a scenario approach is used. The first scenario (the ‘Business As Usual’ scenario) assumes that the electricity generation maintains its previous development trends. The second scenario (the ‘Full Green Transition’ scenario) assumes that the carbon-intensive component of electricity generation in Ukraine is fully replaced by renewable energy sources. Each scenario is described in more detail in the next section. This approach with the two extreme scenarios will allow identifying the scale of investment needed, from which the calculation of required investments depending on the degree of green transition can be derived. It is also worth noting that the investment assessment does not cover any macroeconomic factors but focuses solely on the investment needed for a ‘green’ transformation of electricity generation capacity in Ukraine.

Third, in both scenarios the projection of electricity generation sources development is based on trends (average annual growth/decline) for 2011-2021. This period is taken as a basis for the projection calculation, as the last electricity generation source (solar power) has only started to be used in Ukraine since 2011. Thus, for that period all sources are present in the electricity generation mix and are comparable with each other. Accordingly, trends in the electricity sector assume a projection of the annual average change rather than exact values.

Fourth, the analysis has a planning horizon until 2030. This is because in reality Ukraine, with its destroyed (or obsolete) carbon-intensive electricity generating capacity, is in dire need of deciding how to proceed. Should it be rebuilt with the old energy mix, or should it undergo a full (or partial) green transformation? This mainly depends on the availability of investment and the readiness of relevant investors to provide it, which is also analysed in the third section of this chapter. Furthermore, such a short horizon is more immediate which is essential for Ukraine (given the actual situation) and realistic to plan than, for example, 2050.

The fifth assumption is that the share of nuclear in electricity generation in Ukraine is fixed for the whole projection period at the 2021 trend level (trend period 2011-2021), i.e., 55.86% (see Graph 18 below) for both scenarios. That is, changes only occur in the green and carbon-intensive components. Given relatively big share of its component, and the fact that it is carbon-free (Fusion for Energy 2023), it will help to smooth the green transformation.



Graph 18: Actual and projected share of electricity production from nuclear, Ukraine (2011-2030)

Data sources: Our World in Data, 2022; author's calculations

Furthermore, the analysis assumes that the demand for electricity in Ukraine will grow in the projected period. This is because the post-war reconstruction of Ukraine will require the active involvement of industry, which will need electricity. Accordingly, electricity generation is assumed to increase until 2030. As can be seen from Graph 1, the period 2011-2021 covers one of the peaks of electricity production during Ukraine's independence (namely in 2012). Given the trend approach of the analysis, the maximum trend value for this period is considered as a reference point for the calculation of the 2030 value.

Finally, in terms of investment assessment, it covers only those green sources that have already been used in Ukraine before 2021. These include photovoltaic solar power, onshore wind power, hydropower and bioenergy (IRENA 2022a, see Annex I). The Global weighted average total installed cost (USD/ kWh) and the Levelized cost of electricity (USD/ kWh) (IRENA 2022b, see Annex I) are used for the calculations. Both values are taken for the latest available year, i.e., 2021, for a more realistic investment calculation. It is also worth noting that the total installation cost is based on the average total project cost of deploying green electricity generating capacity in the different countries presented in the report and in the database (IRENA 2022b, see Annex I).

2. Scenario analysis of development of electricity sector in Ukraine and of investments needed

This section analyses the two above-mentioned scenarios for the development of Ukraine's electricity generation capacity and, accordingly, estimates the amount of investment needed to implement one or the other scenario.

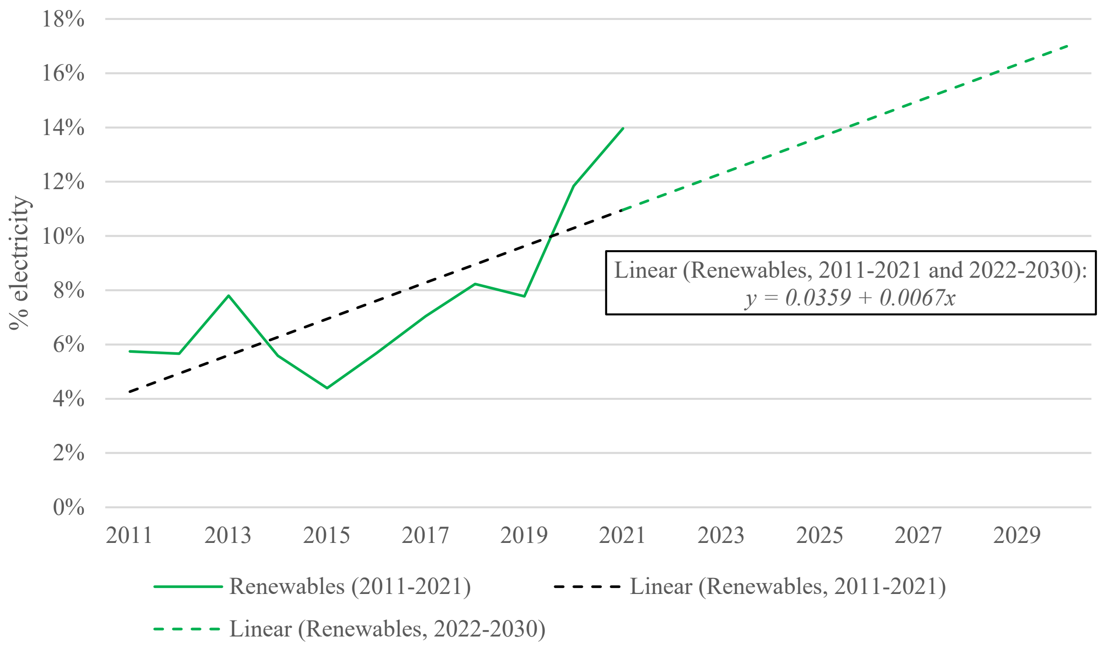
(i) The 'Business As Usual' scenario

This scenario assumes that the green transformation of the electricity generation sector in Ukraine continues to evolve inertially until 2030 following linear trends over the period 2011-2021. For the subsequent calculation of the required investments in this scenario, this means calculating the amount needed to maintain the green transformation trends at the same level until 2030.

It is important to note that the basis for the analysis is to project the shares of each of the energy sources and not the absolute amount of electricity produced from one source or another. This is because the analysis assumes that demand for electricity will increase until 2030, which will consequently require more electricity production (see previous section for assumptions and limits of the analysis). Thus, by projecting the shares of each source, it will be possible to subsequently project the absolute amount of electricity produced, given an increase in total supply.

Turning to the analysis of the share of non-nuclear sources in electricity generation, it is worth noting that the analysis is based on the inertial prolongation of the development trend of the share of renewables, rather than fossil fuels, in the overall energy mix. This is because the study focuses on the green transformation, so in this scenario the inertial trend of green sources determines the trends of the carbon-intensive components of electricity generation.

Graph 19 below shows the actual and projected development of the share of green sources in the total energy mix of electricity generation in Ukraine. As can be observed, the trend over the period 2011-2021 indicates an average annual growth of 0.67% in the share of renewable sources of electricity generation. Accordingly, the scenario assumes the same growth of the share until 2030. Comparing the actual 2021 trend figure (10.96%), and the projected 2030 trend figure (16.99%), it can be seen that on average the share of green sources in the total energy mix of electricity generation will increase by 6.03% over 9 years. It is also worth pointing out that this trend growth of 0.67% forms the reference point for the subsequent analysis in this scenario, as it will determine the development of the share of other sources, as will be shown below.

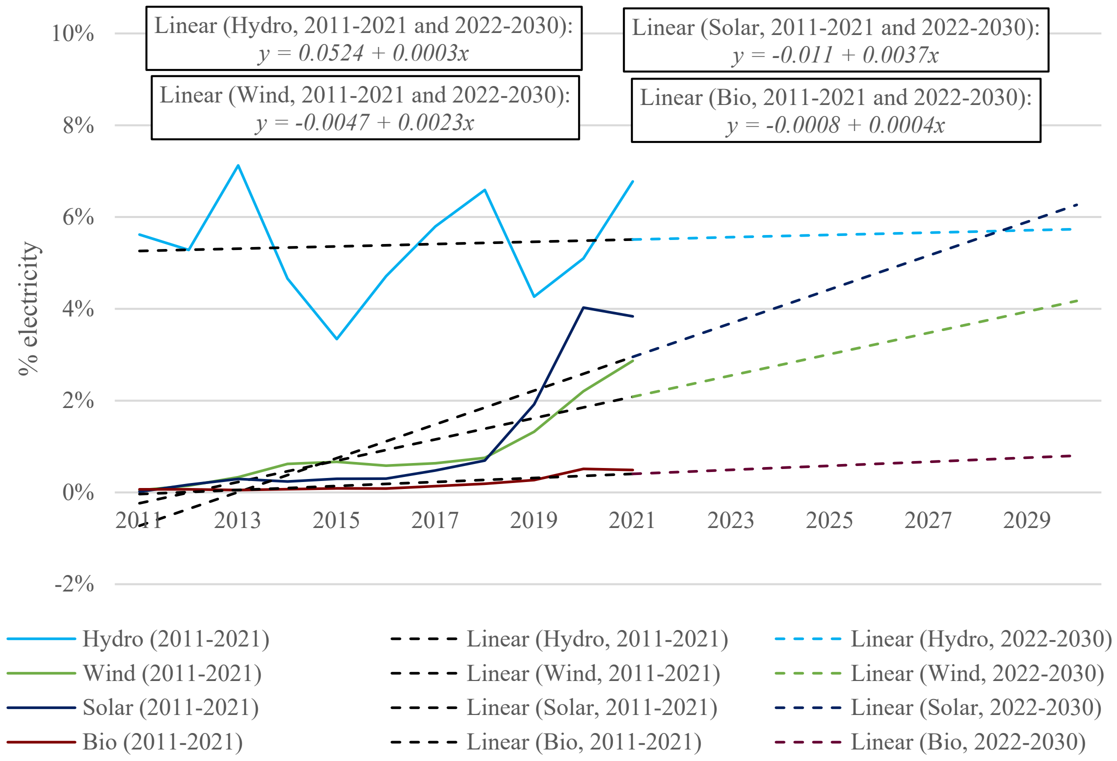


Graph 19: Actual and projected share of electricity production from renewables, the 'Business As Usual' scenario, Ukraine (2011-2030)

Data sources: Our World in Data, 2022; author's calculations

Following the projection of the development trends of the green electricity generation component as a whole, it is also worth looking at the development trends of each of the sources. This will then make it possible to calculate how much electricity each source will produce in absolute terms. This, in turn, will be necessary to calculate the required investments. The actual and projected development trends of each source are shown in Graph 20 below. In this case, the trends of each source for 2011-2021 are extended to 2022-2030 without any change. Also, the sum of all the trends of each source constitutes the total trend of the entire green component (0.67%, see Graph 19).

Hydropower shows the weakest trend of all sources, with an annual average growth of 0.03%. The next source, which shows a slightly steeper annual average growth of 0.04%, is bioenergy. The sources showing the steepest growth are wind and solar power. Wind shows an average annual growth of 0.23%. As for the solar component, its share is growing at the fastest rate, namely by 0.37% on average every year. An observation worth noting is that, in 2029, the projected share of solar power (5.90%) exceeds that of hydropower (5.71%) and becomes the largest source for power generation among all other renewable sources.

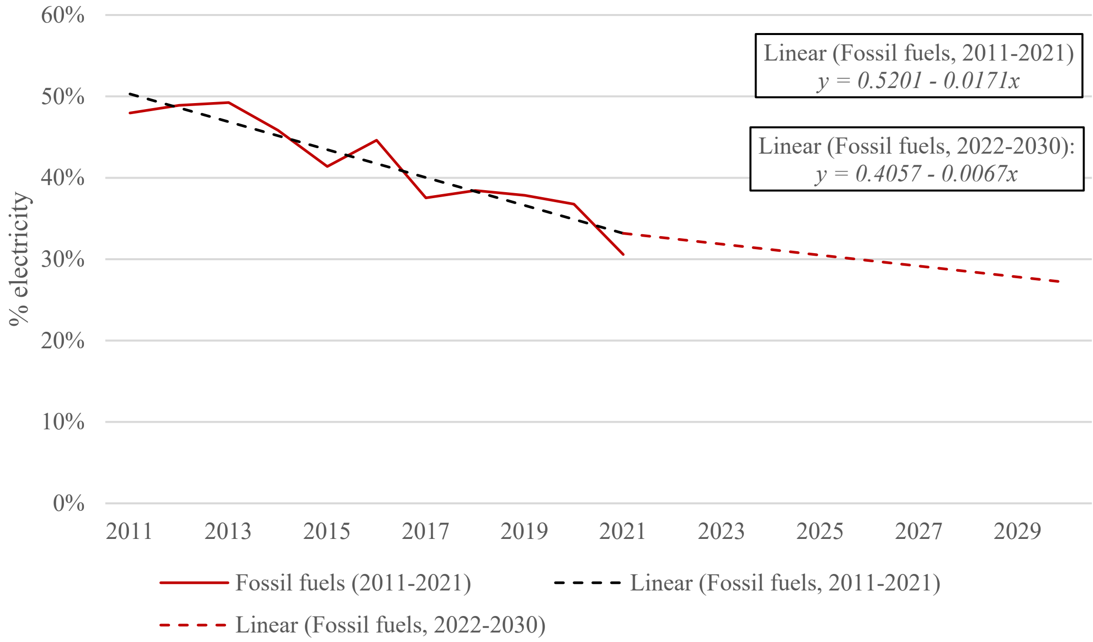


Graph 20: Actual and projected share of electricity production from renewables by source, the 'Business As Usual' scenario, Ukraine (2011-2030)

Data sources: Our World in Data, 2022; author's calculations

Having analysed the trend projections for green sources, both overall and for each of them, it is also worth looking at the evolution of fossil fuel use for electricity generation. Given that the share of nuclear is fixed at the 2021 trend level (i.e., 55.86%), the share of fossil fuels should be gradually replaced by the share of renewable energy sources. It was stated above (see Graph 19) that the projected trend for the period 2022-2030 for renewables is the reference point for calculating the trends for the remaining sources. This means that the projected fossil fuel trend must be adjusted accordingly.

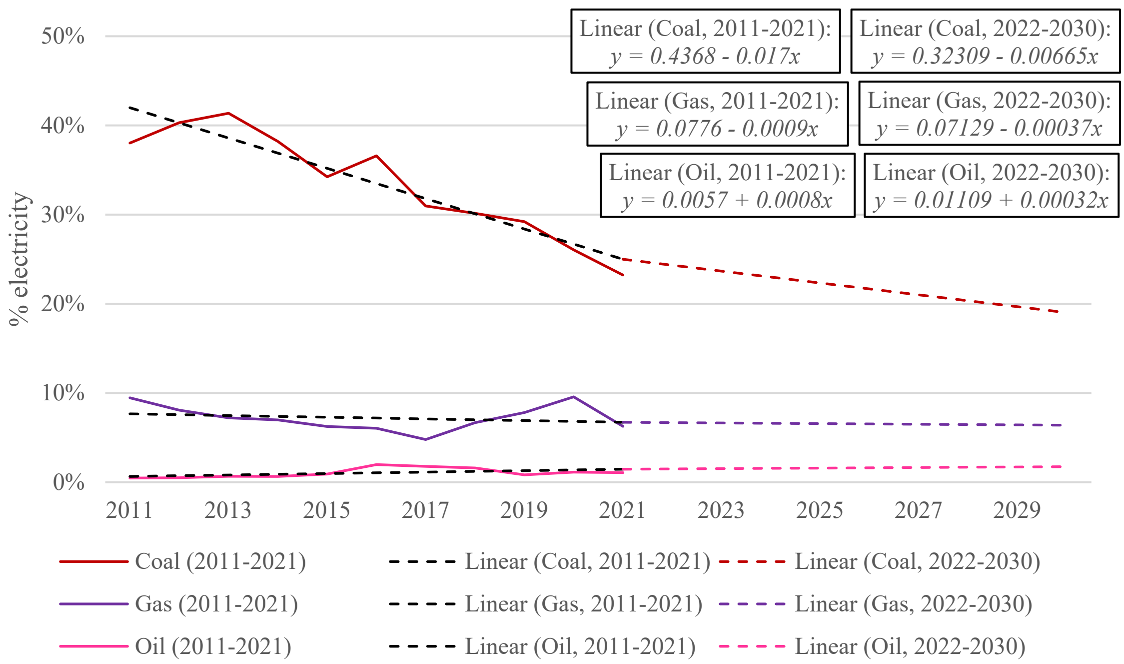
Graph 21 below shows the actual share of fossil fuel generated electricity in the total energy mix as well as the actual trend to 2021 and the projected trend to 2030. As the graph suggests, over the period 2011-2021, the share of carbon-intensive electricity generation has decreased by an average of 1.71% each year. However, for the period 2022-2030, the trend projection does not continue the original trend, but adjusts to the projected trend of green sources. This means that from 2022 the share of fossil fuels decreases at a lower rate, namely by an average of 0.67% each year. This decreasing trend leads to a value of 27.15% for the carbon-intensive component in 2030, which is 6.03% less than the trend value in 2021 (33.18%). The overall reduction of 6.03% in the share of electricity from fossil fuels by 2030 is exactly the same as the overall increase in the share from green sources (see Graph 19). This confirms that the shares of these sources have replaced each other, keeping the nuclear share constant.



Graph 21: Actual and projected share of electricity production from fossil fuels, the 'Business As Usual' scenario, Ukraine (2011-2030)

Data sources: Our World in Data, 2022; author's calculations

As in the case of renewables, in the carbon intensive component of electricity generation it is also worth looking at the development trends until 2030 for each source separately. This will help to calculate more accurately how much electricity will be produced by any particular source. So, as Graph 22 below shows, it is coal that has made the largest contribution to the decline in the share of electricity generated from fossil fuels. Between 2011 and 2021, the share of coal declined by an average of 1.70% each year. During the same period, the share of gas trended downwards at 0.09% and the share of oil rose by an average of 0.08% each year. However, the projected trends to 2030 have been adjusted accordingly. Namely, the trend of each source for 2011-2021 was divided by the total trend of the carbon-intensive share of electricity generation over the same period (i.e., an average annual decrease of 1.71%). This is necessary to calculate the trend share of each source in the overall trend. This coefficient was then multiplied by a new projected to 2030 total annual decrease trend of 0.67%. This resulted in an adjusted trend of each source. Thus, for the period 2022-2030, the projected coal development has an average annual decline of 0.665%, gas shows an average annual decline of 0.037% and oil development shows an average annual increase of 0.032%.

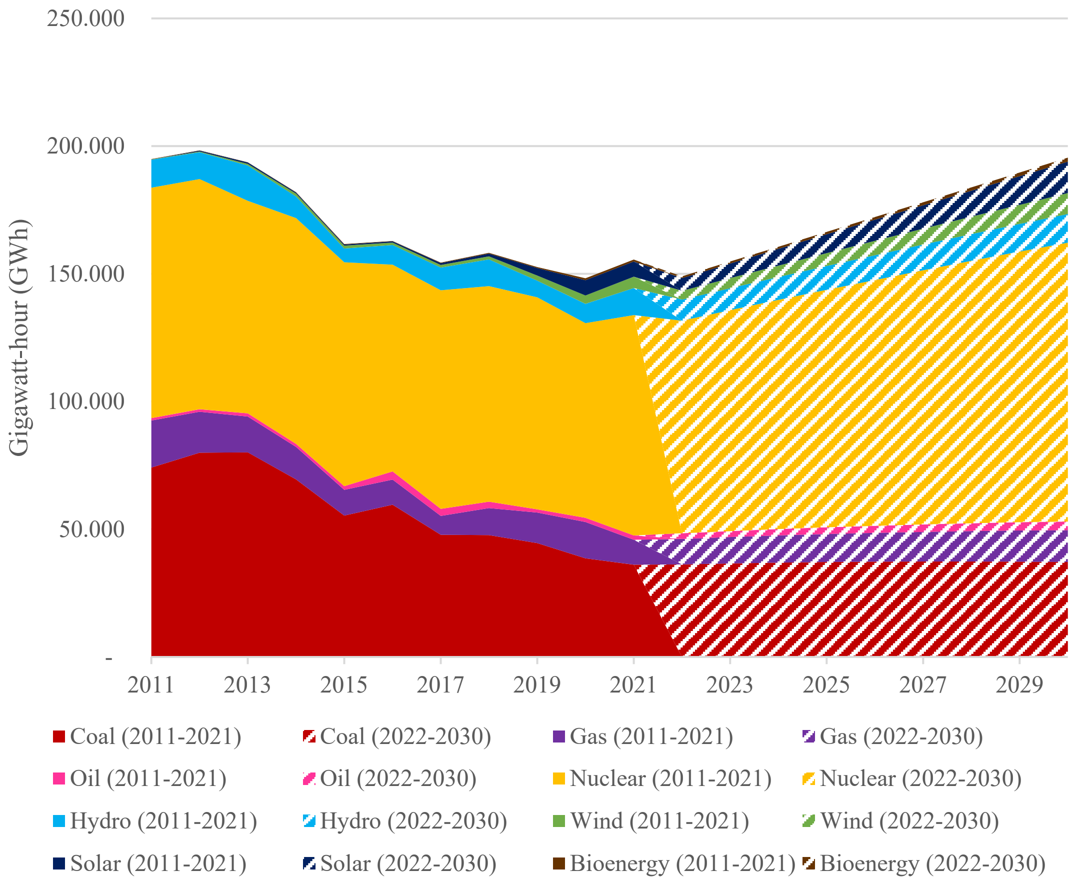


Graph 22: Actual and projected share of electricity production from fossil fuels by source, the 'Business As Usual' scenario, Ukraine (2011-2030)

Data sources: Our World in Data, 2022; author's calculations

The calculation of the development trends for each of the green and carbon intensive sources of electricity generation (as well as fixing the share of the nuclear component) now allows the projection of linear trend development in absolute values. The assumption used for its calculation is that electricity demand will grow until 2030, which will in turn lead to growth of electricity generation as a counter supply. Thus, it is assumed that the 2030 value will be equal to the peak trend value for the period 2011-2021 (see assumptions and limits of the analysis). According to this assumption the electricity generation must increase from a trend value in 2021 of 143,200 GWh to 195,470 GWh in 2030. In order to achieve this, an annual growth of 5,807.78 GWh is required in the period from 2022 to 2030 (see Graph 23).

Figure 23 below shows the actual electricity generation for 2011-2021 as well as the projected trend for 2022-2030. The methodology for calculating the projected values is to first calculate the total electricity generation for each year from 2022 to 2030, using a linear average growth of 5,807.78 GWh per year. The annual total is then multiplied by the previously projected shares of each electricity generation source (taking into account the fixation of the nuclear share). This results in the distribution of electricity generation from each source in absolute terms, which can be observed in the shaded area of Graph 23.



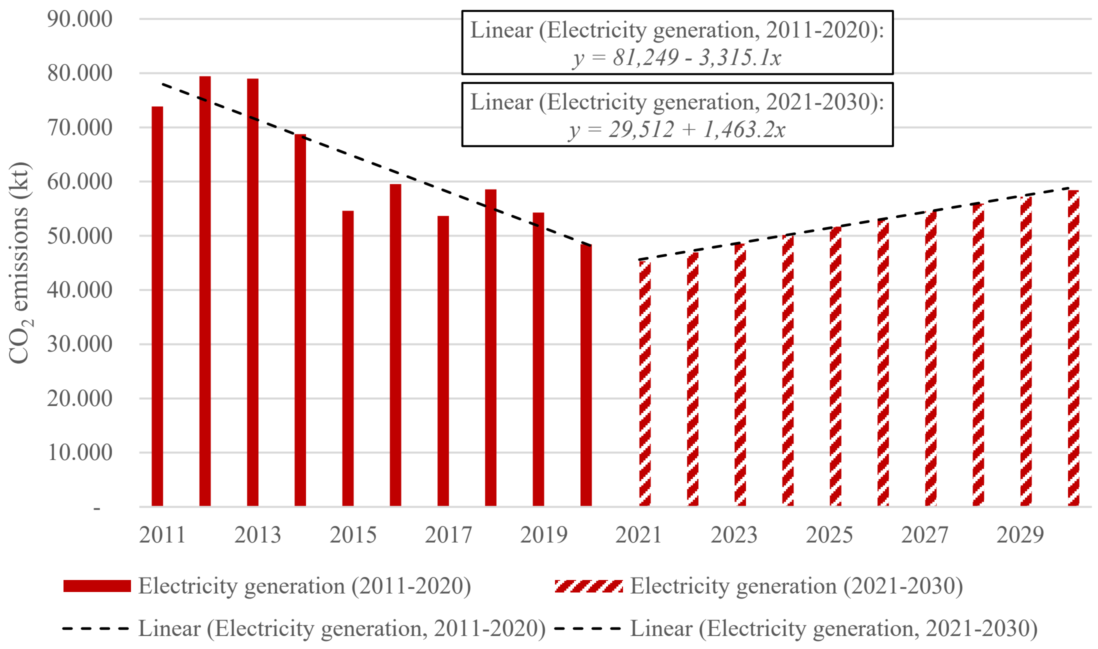
Graph 23: Actual and projected electricity production by source, the 'Business As Usual' scenario, Ukraine (2011-2030)

Data sources: Our World in Data, 2022; author's calculations

Projected to 2030, the absolute amount of electricity produced using carbon-intensive sources (coal, gas and oil) now allows the calculation of the growth pathway and the absolute number of CO_2 emissions in this scenario. It is important to note that in the case of the CO_2 projection, the actual period is 2011-2020, since 2020 is the latest year for which emissions data are available (see Annex I for a more detailed description of the data source). Hence, the projection period also shifts to 2021-2030. However, to project CO_2 emissions in 2021, the actual amount of electricity produced in 2021 is taken. For the period 2022-2030, the corresponding projected absolute values of electricity generation are used (see Graph 23).

The methodology used to calculate CO_2 emissions to 2030 is the same as that used to calculate avoided CO_2 emissions from the use of green energy in Graph 16. That is, the assumption is used that all carbon dioxide emissions in electricity generation come only from the use of coal, gas and oil. Accordingly, the annual ratio between the total CO_2 emissions from electricity generation and the absolute amount of electricity produced from carbon-intensive sources is first calculated. The trend of the ratio is then calculated and shows an average increase each year of 0.0165 kt CO_2 per GWh. This trend is then projected without any change until 2030. Finally, the projected trend development values of the ratio between CO_2 emissions and electricity generation from coal, gas and oil are multiplied by the projected absolute amounts of electricity generation from carbon-intensive sources for the period 2021-2030, calculated in Graph 23.

This leads to the following results shown in Graph 24. Firstly, for the actual period 2011-2020, CO_2 emissions from electricity generation decreased by an average of 3,315.1 kilotons each year. For the period 2021-2030, the trend becomes positive and shows an average annual increase of 1,463.2 kilotons of carbon dioxide emissions. That is, despite a projected average annual reduction of 0.67% in the total carbon dioxide-intensive sources (and its replacement with green sources), CO_2 emissions start to increase. This is because the declining trend in the share of coal, gas and oil after 2022 was adjusted (see Graph 21) and also because the total amount of electricity produced is expected to increase until 2030 (see Graph 23). Secondly, based on this projection of CO_2 emissions, electricity generation is expected to produce a total of 521,920 kilotons of carbon dioxide between 2021 and 2030.



Graph 24: Actual and projected CO_2 emissions in electricity generation, the 'Business As Usual' scenario, Ukraine (2011-2030)

Data sources: GHG inventories under the UN Framework Convention on Climate Change, 2022; Our World in Data, 2022; author's calculations

Finally, the projected absolute values of electricity produced from renewables for the period 2022-2030 allow the calculation of the investments needed to maintain the same green transformation dynamics as for the period 2011-2021. This requires looking at both the necessary installed generation capacity (GW) and the projected electricity production from renewables in absolute terms (GWh). The development trend of installed electricity generation capacity from each of the green sources over the period 2011-2021 is first calculated. For hydropower the average annual growth is 0.1181 GW, for wind 0.1421 GW, for solar 0.7772 GW, and for bioenergy 0.0247 GW (IRENA 2021, 2022a, see Annex I).

Although this scenario assumes an inertial projection of the development trends of the shares of each of the green sources, the projection of the installed capacity evolution has to be corrected because an increase of the total electricity production until 2030 has been projected (see Graph 23). Accordingly, the trend adjustment takes place as follows. It is assumed that the absolute difference between the maximum and minimum trend value of electricity generation for 2011-2021 corresponds to the absolute difference between the maximum and minimum trend value of installed capacity for the same period. This ratio is then multiplied by the absolute difference between the projected electricity generation figure for 2030 (which is the maximum value for the period 2022-2030) and the corresponding trend value for 2021. The resulting value indicates the absolute difference between the projected installed capacity for 2030 and the corresponding trend value for 2021. Having calculated the installed capacity value for 2030, the remaining values for the period 2022-2030 are distributed evenly from the corresponding trend value for 2021. After this correction the new annual average growth trends are as follows: hydro 0.1714 GW, wind 0.2279 GW, solar 1.2096 GW and bioenergy 0.0411 GW. With all the necessary data, the investment is calculated as follows using formula (1), derived by the author:

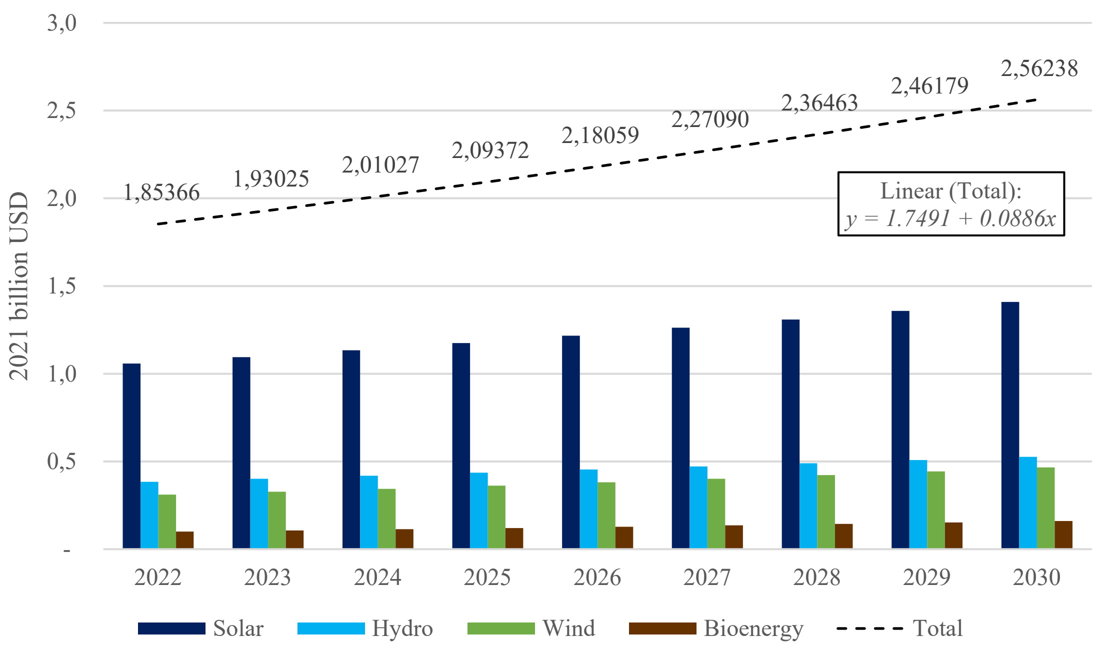
$$Investment_{(S;\,Y)} = \Big(\big(GW_{(S;\,Y)} - GW_{(S;\,Y-1)}\big) * 1{,}000{,}000 * Price[USD/kW]_{(S)}\Big) + \Big(\big(GWh_{(S;\,Y)} - GWh_{(S;Y=2021)}\big) * 1{,}000{,}000 * Price[USD/kWh]_{(S)}\Big), \quad (1)$$

where:

- *S* – Source of electricity generation (solar, hydro, wind, bio);
- *Y* – Year (2022, …, 2030);
- *Y-1* – Previous year;
- *Y=2021* – Value fixed at 2021 level;
- *GW* – Installed generation capacity in Gigawatts (trend values for 2011-2021 and projected values for 2022-2030);
- *GWh* – Amount of electricity generation in Gigawatt-hours (trend values for 2011-2021 and projected values for 2022-2030);
- *Price [USD/kW]* – Global weighted average total installed costs in 2021;
- *Price [USD/kWh]* – Levelized cost of electricity in 2021.

The investment is calculated according to the following method. The annual projected absolute increase in installed capacity (GW) is converted into kilowatts (multiplied by 1,000,000) and multiplied by the weighted average total installed cost. To this sum the annual production cost of electricity from new installed capacity only is added. The amount of electricity produced in 2021 is subtracted from the projected annual production quantity (trend value), multiplied by 1,000,000 (conversion to kilowatts) and multiplied by the levelized total cost of electricity. For the calculation, the annual increase in installed capacity ($GW_{(S;\ Y)} - GW_{(S;\ Y\text{-}1)}$) is applied, as the installed capacity of the current year includes the installed capacity of the previous year. It also takes the projected annual absolute quantity of electricity after deducting the electricity produced in 2021 ($GWh_{(S;\ Y)} - GWh_{(S;\ Y=2021)}$), as the investment takes into account the cost of electricity that is produced each year only with newly installed capacities.

These calculations lead to the results shown in Graph 25 below. The total investment in the 'Business As Usual' scenario for all green sources until 2030 equals USD 19.73 billion (at 2021 prices). The breakdown of the annual investments is shown in the graph, and the average annual growth, as shown in the dashed line, is USD 0.0886 billion. In terms of each individual source, solar power has the largest overall investment need (USD 11.02 billion). This is followed by hydropower (USD 4.09 billion), wind power (USD 3.46 billion) and bioenergy (USD 1.16 billion).



Graph 25: Investment needed for 'green' transformation of electricity sector, the 'Business As Usual' scenario, Ukraine (2022-2030)

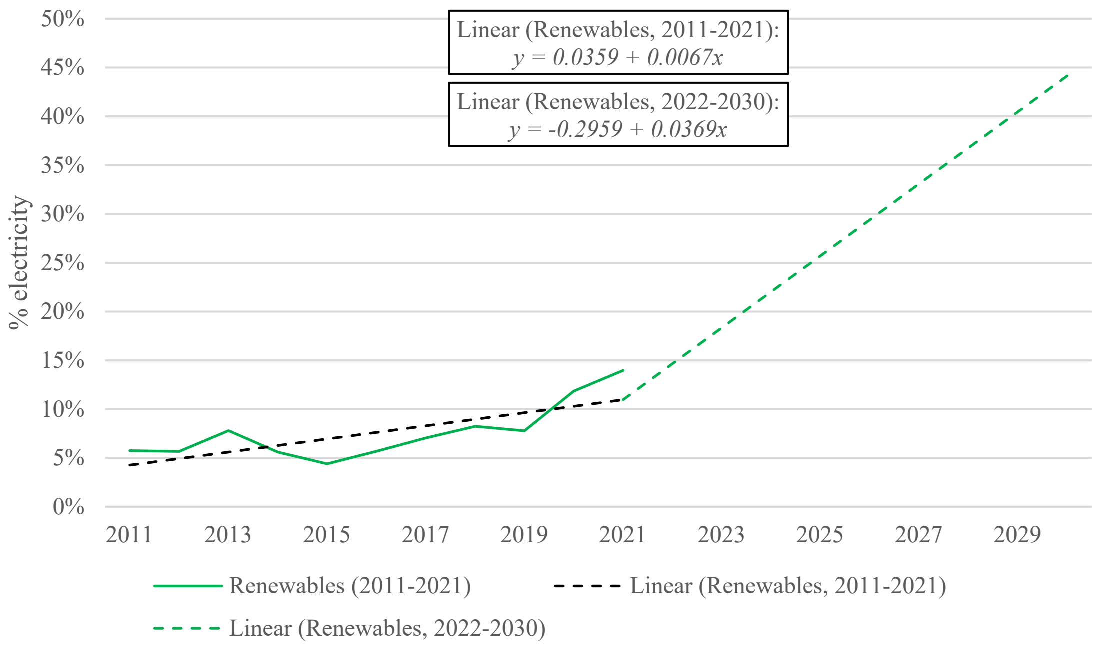
Data sources: Our World in Data, 2022; IRENA, 2021; IRENA, 2022a; IRENA, 2022b; author's calculations

To summarise, this scenario analysed the necessary investments (USD 19.73 billion) to maintain the development trends of the shares of each of the renewable sources as in the period 2011-2021. In addition, the scenario also showed the growth path of CO_2 emissions from electricity generation, considering the given trends as well as the assumptions used. Thus, this scenario has set a lower bound for the necessary investments for the inertial development of a green transformation of the electricity generation sector in Ukraine. Consequently, it is now worth analysing the upper bound of the required investments for a full green transformation of electricity generation, which is the subject of the next section.

(ii) The 'Full Green Transition' scenario

In contrast to the 'Business As Usual' scenario, which considered the inertial development of renewable sources for electricity generation, this scenario analyses the full substitution of the carbon-intensive component by green energy. Thus, according to this scenario, the share of coal, gas, and oil in electricity generation in Ukraine should be gradually reduced to 0% by 2030. And its place is taken by hydro, wind, solar and bioenergy. Nevertheless, the methodology remains the same. As in the first scenario, the analysis is based on projecting the shares of each of the sources because of the gradual increase in total electricity generation until 2030. In addition, the nuclear component remains fixed at the 2021 trend level (i.e., 55.86%) for the entire projection period (see assumptions and limits of the analysis).

Graph 26 below shows the actual and projected development of the share of green sources in total electricity generation. To begin with, a 2030 value is calculated which assumes that only nuclear (which is fixed at 55.86%) and a green component are in the energy mix of electricity generation. Thus, the total share of renewables in 2030 should be 44.14%. The annual increase needed to reach this final value is then calculated. As can be seen in the graph, this growth averages 3.69% per year. If the projected trend value of 2030 (44.14%) is compared with the trend value of 2021 (10.96%), a difference of 33.18% can be observed. This difference corresponds to the 2021 trend value for the whole carbon intensive component. Looking back at the results of the first scenario (see Graph 19), where this difference was 6.03%, a large gap can be observed in terms of the scale of green transformation.

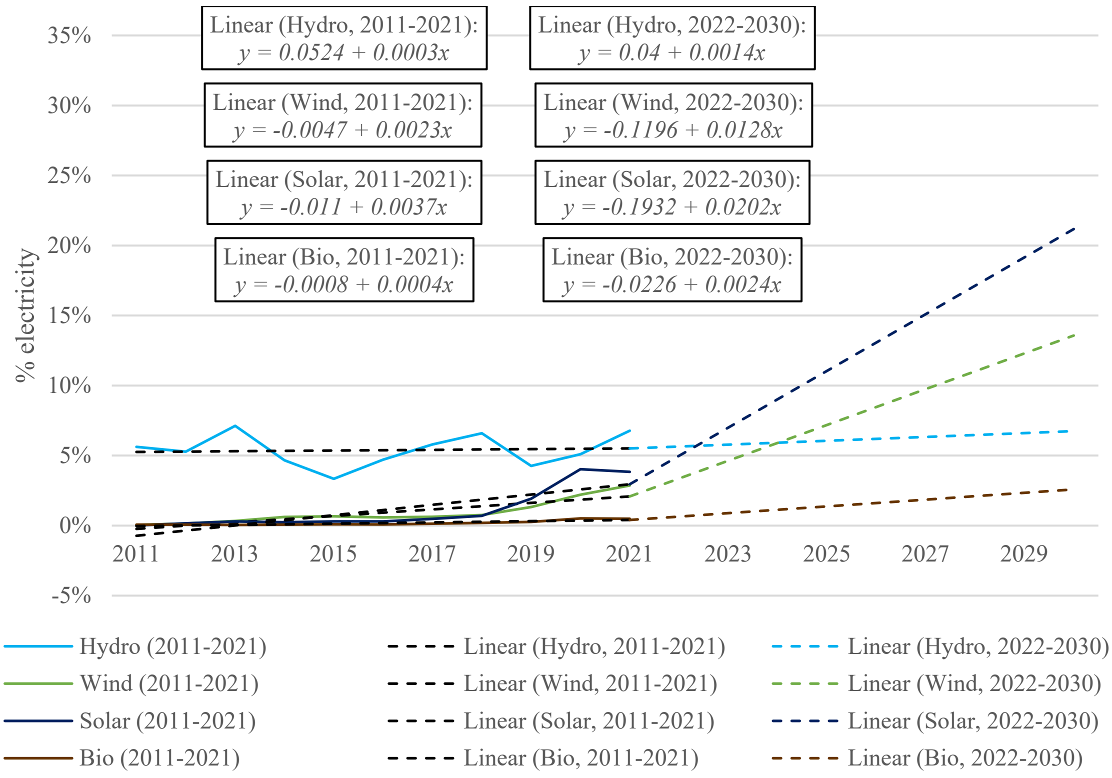


Graph 26: Actual and projected share of electricity production from renewables, the 'Full Green Transition' scenario, Ukraine (2011-2030)

Data sources: Our World in Data, 2022; author's calculations

Having considered the overall trend of green sources, it is also worth analysing how the shares of each source will develop. Graph 27 presents the corresponding results. In contrast to the first scenario (see Graph 20), where the hydro, wind, solar and bioenergy trends were developing inertially, in this case there is a need to adjust them according to the new overall trend shown in Graph 26.

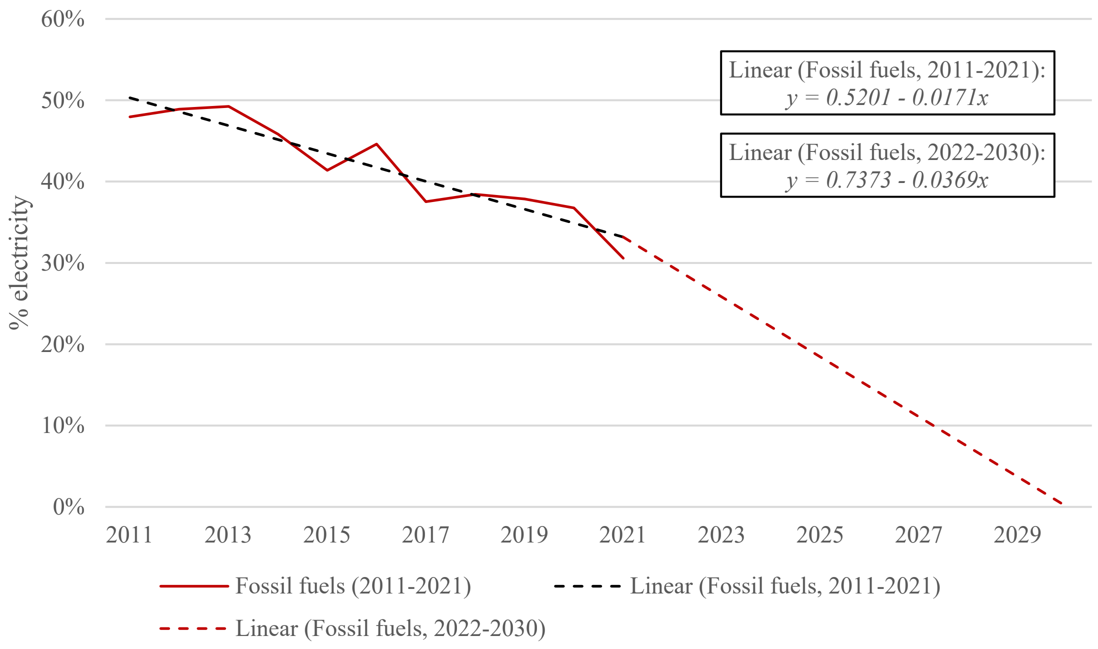
From this, the projected trends for the period 2022-2030 show the following development. The leading energy source is solar energy, with an average annual growth of 2.02%. This is followed by wind power with an average annual growth of 1.28%. Bioenergy development is driven by a positive trend of 0.24%. Hydropower shows the weakest development trend among all green sources, showing an average growth of 0.14% per year. The sum of the trends for all renewable sources corresponds to the overall growth trend shown in Graph 26 (the difference of 0.01% is due to rounding). It is also interesting to observe that already in the second year of projection, solar power becomes the main green source of electricity generation (7.00%), overtaking hydropower (5.79%). As for wind power, this source ranks second from 2025 (7.19%), also exceeding hydropower (6.06%) in the corresponding year.



Graph 27: Actual and projected share of electricity production from renewables by source, the 'Full Green Transition' scenario, Ukraine (2011-2030)

Data sources: Our World in Data, 2022; author's calculations

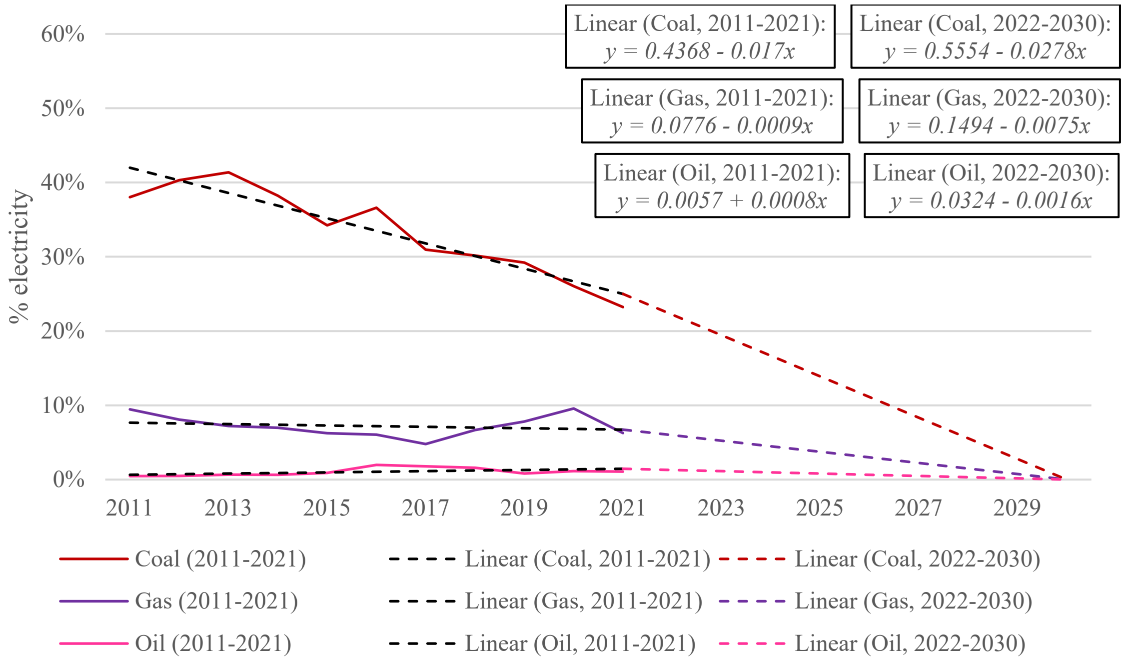
Moving on to the analysis of the carbon intensive component of electricity generation in Ukraine, the following points are worth noting. As this scenario simulates a full green transformation, it means that the share of electricity from fossil fuels must be reduced to 0% by 2030. The annual actual shares as well as trends for the periods 2011-2021 and 2022-2030 are shown in Graph 28 below. As can be seen, the projected trend becomes more negative than for the period 2011-2021 (annual average decline of 1.71%) and indicates a fall of 3.69% per year on average in the share of carbon intensive electricity generation. Accordingly, both the projected trend and the difference between the 2030 trend value (0.00%) and the 2021 trend value (33.18%) are exactly the same as those presented for renewables.



Graph 28: Actual and projected share of electricity production from fossil fuels, the 'Full Green Transition' scenario, Ukraine (2011-2030)

Data sources: Our World in Data, 2022; author's calculations

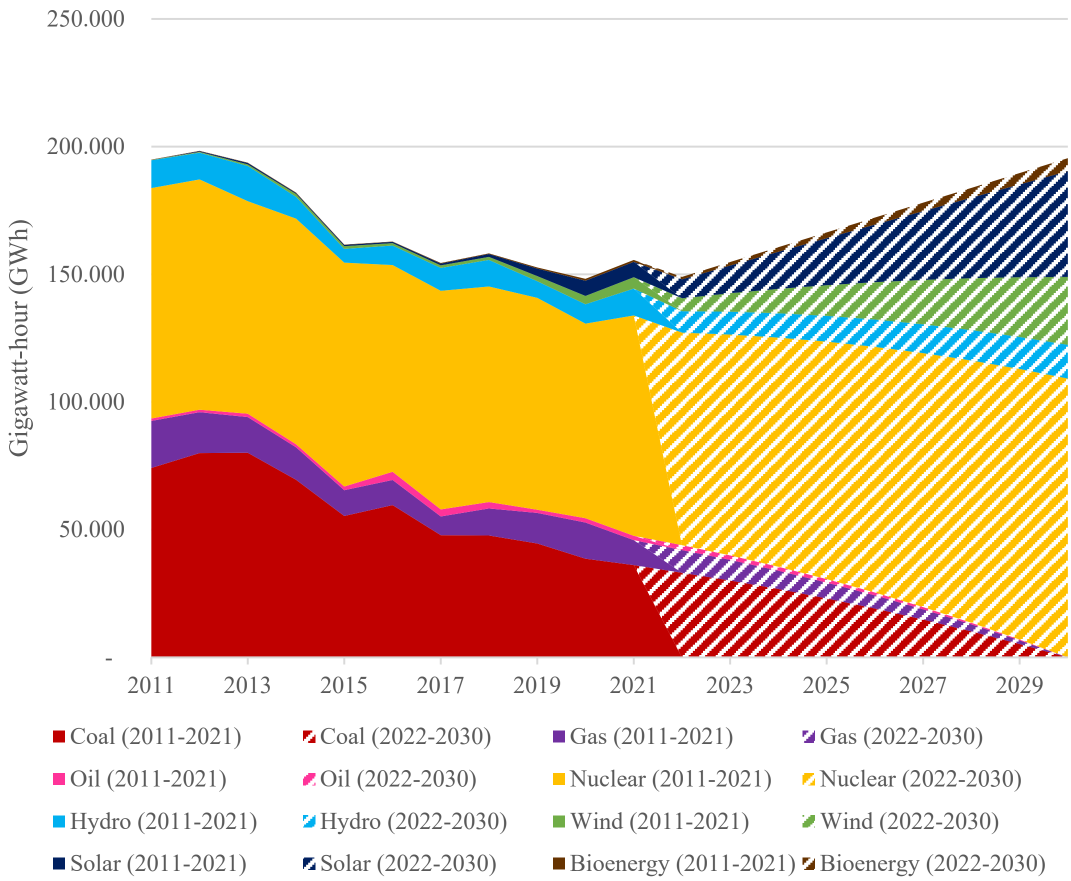
To further calculate electricity generation in absolute values from each of the sources, it is also worth looking at projecting the development of coal, gas and oil separately. Since the total share of electricity generation from fossil fuels should be reduced to 0% by 2030, this means that each of the carbon intensive sources should also be reduced to 0%. As can be observed in Graph 29 below, the projected development of the shares of coal, gas and oil for the period 2022-2030 shows a more negative trend compared to the period 2011-2021. A trend correction has been made by spreading the relative values evenly over the entire projected period up to the 2030 value of 0%, based on the trend values of each of the sources for 2021. Thus, the total elimination of the share of carbon-intensive sources of electricity generation in Ukraine until 2030 is reflected in an average annual decrease of the share of coal by 2.78%, gas by 0.75%, and oil by 0.16%.



Graph 29: Actual and projected share of electricity production from fossil fuels by source, the 'Full Green Transition' scenario, Ukraine (2011-2030)

Data sources: Our World in Data, 2022; author's calculations

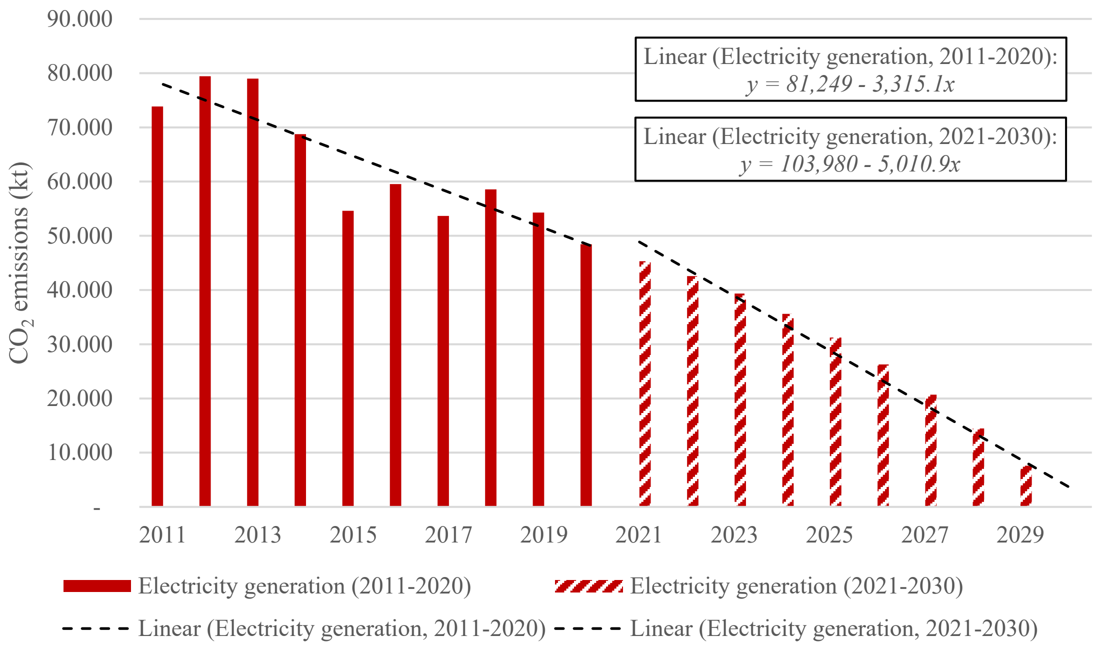
With the annual trend values for each of the sources for the period 2022-2030, the linear annual average development of the quantity of electricity generated can now be projected in absolute values. As in the first scenario, the assumption used is that the total electricity production will increase until 2030 from 143,200 GWh to 195,470 GWh with an annual average growth of 5,807.78 GWh (see assumptions and limits of the analysis). Graph 30 below shows the actual electricity production in Ukraine for the period 2011-2021 as well as projected results for the period 2022-2030. As can be observed, the carbon intensive component will completely disappear from the energy mix of electricity generation by 2030. Its gradual replacement by renewable sources indicates a complete green transformation of the Ukraine's electricity sector.



Graph 30: Actual and projected electricity production by source,
the 'Full Green Transition' scenario, Ukraine (2011-2030)

Data sources: Our World in Data, 2022; author's calculations

From the projected absolute values of electricity generation, the development of CO_2 emissions until 2030 can also be analysed. To calculate them, the same methodology as in the first scenario is used (see description to Graph 24). By substituting the electricity production inputs for the period 2022-2030 obtained in Graph 30, the following results are observed, as shown in Graph 31 below. First of all, it is worth noting that for the period 2021-2030, CO_2 emissions are projected to decrease more rapidly, by an average of 5,010.9 kilotons per year, than for the period 2011-2020 (an average annual decline of 3,315.1 kilotons). This projected development eventually results in the complete elimination of carbon dioxide emissions from electricity generation in Ukraine. However, despite this, CO_2 emissions are still present until 2030, amounting to 263,109 kilotons over the entire projection period.

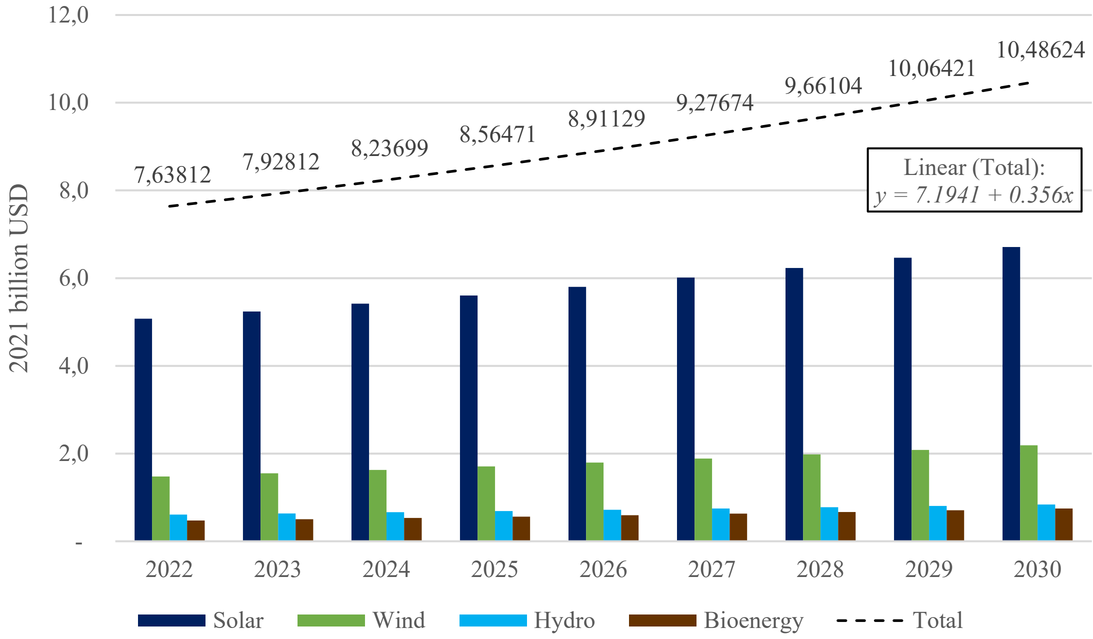


Graph 31: Actual and projected CO_2 emissions in electricity generation, the 'Full Green Transition' scenario, Ukraine (2011-2030)

Data sources: GHG inventories under the UN Framework Convention on Climate Change, 2022; Our World in Data, 2022; author's calculations

With all the necessary data on the projected amount of electricity produced for the period 2022-2030, it is possible to calculate the investment needed for a full green transformation of the electricity generation sector in Ukraine until 2030. For this purpose, as in the first scenario, it is necessary to take into account the development of not only the electricity produced, but also the required installed capacity for its generation. Given the adjusted renewable development trends for the period 2022-2030, as well as the increase of total electricity generation until 2030, there is a need to also bring the installed generation capacity into line. Using the same calculation approach as in the first scenario (see Graph 25) the adjusted average annual increase in installed capacity during 2022-2030 is 0.2732 GW for hydropower, 1.0704 GW for wind, 5.7592 GW for solar and 0.1914 GW for bioenergy.

The calculation of investments is based on formula *(1)* as well as the approach that was used for the first scenario and is presented in the description to Graph 25. Graph 32 below shows the results of the investment assessment based on the 'Full Green Transition' scenario for the electricity sector of Ukraine until 2030. The total investment for the period 2022-2030 for all renewable sources equals USD 80.77 billion (price level 2021). The graph also shows an estimate of the required annual investments, with an average annual growth rate of USD 0.356 billion. On a per-source basis, more than half of the total investment needed is for solar power, which amounts to USD 52.56 billion. For wind power, the investment estimate is USD 16.30 billion, for hydropower USD 6.49 billion and for bioenergy USD 5.42 billion.



Graph 32: Investment needed for 'green' transformation of electricity sector, the 'Full Green Transition' scenario, Ukraine (2022-2030)

Data sources: Our World in Data, 2022; IRENA, 2021; IRENA, 2022a; IRENA, 2022b; author's calculations

Thus, this scenario for the development of Ukraine's electricity generation sector has estimated the investments needed to fully substitute the carbon-intensive component of electricity generation with renewable energy sources by 2030 (USD 80.77 billion). In addition, a full reduction in CO_2 emissions has been analysed, based on the results obtained from projecting the development of electricity generation using fossil fuels.

To summarise, both scenarios have identified the scale of investment needed for green transformation of electricity sector in Ukraine until 2030. However, it is also worth analysing the actual availability of these investments, and the readiness of relevant investors to provide them. This is the subject of discussion in the next section.

3. Hypothesis testing

The scenarios presented in the last section simulated two extreme options for the development of the Ukraine's electricity sector in the context of a green transformation and outlined two corresponding amounts of investment needed to implement them. Within this scale, however, there are numerous likely pathways along which investment flows could develop. As a result, the availability and therefore sufficiency of the necessary funds will also depend on this. Thus, there are some nuances to be considered, as summarised below.

First, the 'Business As usual' scenario outlines the lower bound of investments needed only to maintain previous trends in the development of the green electricity generation component in Ukraine and may seem attractive at first glance. However, to implement it in the current situation it is worth considering not only investments for green transformation, but also the necessary funds to reconstruct the electricity generation capacity to its previous level. Thus, at the end of March 2023, the World Bank, together with the Government of Ukraine, the European Commission and the United Nations, published new estimates of the necessary funds for the reconstruction of Ukraine. According to them, more than USD 37 billion is needed for the period 2023-2033 for the *"power sector reconstruction, including transmission system operator, distribution system operators, power generation facilities"* (World Bank et al. 2023, 87). This is almost double the estimate provided by the first green transformation scenario in this thesis.

Second, some rebuilding of electricity generation capacity is already taking place in Ukraine (Jayanti 2023). This shows that for the time being the Government of Ukraine is prioritising a rapid and cost-effective rehabilitation of existing capacity rather than a strategic long-term and more expensive green transition. This is necessary both for supplying the population and various sectors of the economy with electricity and for fulfilling contracts for electricity sales to other countries. For example, in early April 2023 it was decided to resume electricity exports from Ukraine to the European Union, despite the damage to its electricity generation infrastructure (Reuters 2023). On the basis of these current needs, the appropriate nature and amount of investment that Ukraine needs in the first place is also determined.

Thirdly, even if the Government of Ukraine favours a green transition some time after the normalisation of the energy system, the scale of green investments will be strongly influenced by the green mix of electricity generation. Indeed, both scenarios presented in this study continue the previous development trends of the shares of hydropower, wind, solar and bioenergy in the total share of renewable sources. However, if an increase in the share of bioenergy or hydropower, which requires much higher investments than wind or solar power (IRENA 2022b, see Annex I), is decided upon, the amount of investment needed will change dramatically. This, in turn, may also affect the willingness of investors to provide funds for more capital-intensive projects.

After all, it should not be forgotten that one of the main disadvantages of green energy, particularly wind and solar, is their dependence on weather conditions. With only nuclear and green power in the electricity generation mix, it would be nuclear one that would have to cover the difference in electricity supply. Nevertheless, given the obsolescence of nuclear power plants in Ukraine (World Nuclear Association 2023), this will require additional investment to modernise them. However, it will be necessary in any scenario for Ukraine's electricity sector, especially given nuclear share in electricity generation (55.46% in 2021). Therefore, this will not have much impact on changes in the availability of investment, but it may have a negative impact on its sufficiency, as this means additional capital needs.

In addition to the caveats expressed above, it is also worth discussing how the likelihood of providing and amount of investment needed to maximise the achievement of the full green transformation scenario can be increased. First of all, both scenarios discussed the projected development of CO_2 emissions until 2030. The first scenario, despite the inertial development of the green transformation, still determined a positive trend of annual growth of carbon dioxide emissions, with a total of 58,413 kilotons in 2030. Whereas in the second scenario, CO_2 emissions would completely disappear from power-generating activity, due to a complete green transition. Consequently, this outcome of the second scenario may provide an additional incentive for ‘green’ investors to favour its financing. In addition, it may open up access to funds that are dedicated exclusively to initiatives that would lead to a reduction in carbon dioxide emissions from energy activities, e.g., Green Climate Fund established by the United Nations (Green Climate Fund, n.d.).

Furthermore, the importance of complete abolition of CO_2 emissions, as projected in the second scenario, can be seen in the conclusions reached by the carbon intensity analysis in the first section of the first chapter of this thesis. According to them, carbon dioxide emissions from electricity generation by 2020 account for about one-third of all emissions from energy-related activities, and one-fifth of all CO_2 emissions in the Ukraine. Thus, achieving the results of the full green transition scenario would bring Ukraine closer to meeting the EU's 2050 goal of full decarbonisation (European Commission, n.d.). This would play an important role not only in terms of the amount of investment ready to be provided by the EU, but also in future negotiations for Ukraine's accession to the EU.

Also, all possible global sources of investment should be considered, combining both public and private financial flows, in order to increase the amount of investment available to pursue development under the second scenario. In addition to the variety of actors involved, it is also worth considering the different nature of investments. For instance, it does not necessarily have to be direct cash flow, but also modern green technology, a skilled workforce to install and maintain green generating capacities, professional training for staff etc. All this makes the investment needs more diversified, which increases the likelihood of them being fully made available and thus implementing a full green transition.

After all, in the current economic and political realities, the EU is particularly interested in investing in green energy. This incentive stems from the cessation of crucial Russian gas supplies (Meredith 2022), as well as disputes between Member States over nuclear energy (Abnett 2023). In this context, Ukraine could be one of the main candidates for green investment by the European Union. And the EU could be interested in providing it, as it would strategically benefit from it. For example, in the long term it would allow the EU to import renewable energy from Ukraine to cover its electricity needs.

Thus, when putting into practice an estimate of the scale of investment needed to achieve a green transition, it is also worth considering the factors mentioned above. As has been shown, some of them may hinder and others may contribute to the outcomes outlined in the scenario analysis. The combination of these will largely determine the availability and sufficiency of the necessary investment, as well as the readiness of investors to provide it.

From this it can be concluded that the null hypothesis outlined in the introduction to this study is partially confirmed. Scenario analysis has revealed that a full green transition of the Ukraine's electricity sector requires 4 times as much investment as inertial development. This creates a sufficiently large interval in which electricity generation in Ukraine could be decarbonised. Accordingly, given all the above caveats and uncertainties, the most likely development scenario would be a partial green transformation within the scale of investment that has been provided in this study.

IV. Conclusions

This thesis has assessed the carbon and green intensity of Ukraine's electricity generation sector and the scale of investment required for its inertial and full green transformation. The following main conclusions can be drawn from the analysis.

First, the structure of Ukraine's electricity sector demonstrates that, as of 2021, more than half of its energy mix consists of nuclear and almost a quarter of coal. Moreover, the infrastructure that enables the use of these energy carriers is outdated and in need of a deep modernisation. A carbon intensity analysis indicates that the electricity sector, as of 2021, accounts for almost a third of the energy sector's CO_2 emissions and a fifth of Ukraine's total CO_2 emissions. In addition, the development of the ratio of CO_2 emissions per unit of electricity produced has shown virtually no decline, remaining more or less the same over the last 23 years. Accordingly, the green transformation of the electricity sector in Ukraine is one of the most promising areas for the decarbonisation of the Ukraine’s economy.

Second, the use of renewables for electricity generation in Ukraine can be considered to be in stagnation. Their active use began only in 2015. And it is the newest sources in use (such as solar and wind power) that have contributed the most to this. This has also helped to diversify the structure of green sources, which until then had only been represented by hydropower. Thus, solar and wind power are the main and growing driving force in the development of green electricity generation in Ukraine. This conclusion is also reflected in the assessment of necessary investments for the green transformation of the sector.

Third, the results of the first part of the study identified the scope for a possible green transformation of Ukraine's carbon-intensive electricity generation sector, as well as indicating those green sources that could be prioritised for use. This provided the basis for projecting scenarios for electricity generation until 2030, as well as calculating the investments needed to implement them. The first scenario, based on the inertial prolongation of green transformation trends from 2011-2021, puts the investment needed at USD 19.73 billion (price level 2021). The second scenario, which assumes a full green transformation (i.e., replacing the carbon-intensive component with renewable resources) requires

USD 80.77 billion. However, given the caveats regarding possible additional investments and their availability and adequacy, a partial green transition of the electricity generation sector would be the most plausible scenario. Consequently, the scale of such transition would determine the investment need within the framework presented in this thesis.

The role of these green investments is explained by their necessity. Firstly, by Russia's devastating missile attacks on Ukraine's carbon-intensive electricity generation infrastructure, and secondly, by the obsolescence of the remaining and repaired generation capacity built during the Soviet era. Combining both, it is clear that there is an opportunity for a green transformation, rather than rebuilding previous CO_2-intensive generating capacity. Green transit leads to high energy efficiency with the latest technology in the long term. In addition, the use of green energy means the creation of decentralised network of generation capacities. This, in turn, ensures the security of the entire energy system. However, as has been defined in this thesis, a green transformation requires a significant magnitude of investment, without which less costly reconstruction would rather be favoured. Therefore, the availability of sufficient investment and the willingness of investors to provide it is the cornerstone for putting this transformation into practice, making a significant contribution to the decarbonisation of the entire economy of Ukraine.

The results of this thesis also suggest a way forward for further research. Their subject could be an analysis of the creation of the necessary policy framework in Ukraine to maximise the outcomes of green transition. Possible policy proposals could include the following elements: creating a favourable investment climate to increase investors' confidence in the return on their investment, setting the right incentives for households and industry to switch to green energy sources, raising awareness of the importance of renewable energy, etc. Regarding Ukraine's energy policy specifically, the following points could be analysed and taken into account in future studies. Firstly, defining the structure of the green electricity generation mix, prioritising the use of a particular renewable energy source. Secondly, the choice between more modern and already established technologies in the market for using a particular renewable energy source. Third, the choice between a more advanced, smart, electricity-generating infrastructure (allowing real-time management of electricity use) and a less advanced, standard electricity transmission system. Fourth, ways to reduce pressure on the power system for smooth green transition by artificially reducing electricity demand.

This could be achieved, for example, by its variable use in activities where constant electricity consumption is not necessary. Consequently, cost-benefit analysis of the aforementioned factors will determine the final amount of investment needed.

To summarise, a successful green transformation, in particular of the electricity sector in Ukraine, requires a framework consisting of 3 elements: capital, technology and policies. The loss of even one element from this combination would jeopardise the achievement of the necessary green goals. This thesis has made an original contribution to defining the scale of capital needed and its role in the transition from carbon-intensive to green electricity generation in Ukraine. It has also pointed to the prospects for further research to put the presented estimates into practice.

Bibliography

Abnett, Kate. 2023. "Nuclear dispute hangs over EU renewable energy talks." *Reuters*, March 29, 2023. https://www.reuters.com/business/energy/nuclear-row-looms-over-eu-renewable-energy-talks-2023-03-29/.

Bojek, Piotr. 2022. "Renewable Electricity." *International Energy Agency*. Accessed March 15, 2023. https://www.iea.org/reports/renewable-electricity.

Carter, Dylan. 2022. "Ukraine fights to keep energy grid online in spite of Russian attacks." *The Brussels Times*, December 31, 2022. https://www.brusselstimes.com/342197/%20ukraine-fights-to-keep-energy-grid-online-in-spite-of-russian-attacks.

EBRD. n.d. "Green EBRD Investments in Ukraine." Accessed March 15, 2023. https://www.ebrd.com/what-we-do/sectors/ukraine-nuclear-safety-upgrade-green-investments.html.

European Commission. n.d. "2050 long-term strategy." Accessed May 1, 2023. https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en.

Fusion for Energy. 2023. "How can nuclear energy help Europe achieve its green transition?" Accessed April 22, 2023. https://fusionforenergy.europa.eu/news/how-can-nuclear-energy-help-europe-achieve-its-green-transition/#:~:text=The%20EU%20Green%20taxonomy%20includes,financial%20instruments%20to%20encourage%20investment.

Green Climate Fund. n.d. "About GCF." Accessed May 1, 2023. https://www.greenclimate.fund/about.

Jayanti, Suriya Evans-Pritchard. 2023. "Ukraine's energy sector survives winter." *Atlantic Council*, April 11, 2023. https://www.atlanticcouncil.org/blogs/ukrainealert/ukraines-energy-sector-survives-winter/#:~:text=In%20total%2C%20over%2060%25%20of,transformers%20and%20transmission%20lines%20targeted.

Meredith, Sam. 2022. "Russia has cut off gas supplies to Europe indefinitely. Here's what you need to know." *CNBC*, September 6, 2022. https://www.cnbc.com/2022/09/06/energy-crisis-why-has-russia-cut-off-gas-supplies-to-europe.html.

Ministry of Energy of Ukraine. 2023. "Iceland's experience in renewable energy development will help Ukraine decentralize its energy system: German Galushchenko." Accessed March 30, 2023. https://www.kmu.gov.ua/en/news/dosvid-islandii-u-rozvytku-vde-dopomozhe-ukraini-detsentralizuvaty-enerhosystemu-herman-halushchenko.

Power Technology. 2019. "Top ten nuclear power plants by capacity." Accessed February 18, 2023. https://www.power-technology.com/features/feature-largest-nuclear-power-plants-world/.

Probst, Benedict, Ivana Sabaka, Oleksii Mykhailenko, and Maren Preuß. 2021. *The economic implications of phasing out coal in Ukraine by 2030*. Edited by Peter Baum and Oksana Aliieva. Kyiv: 7БЦ. https://ua.boell.org/sites/default/files/2021-08/21-08_03_Economic%20implications%20of%20Ukrainian%20coal%20exit.pdf.

Reuters. 2022. "Russian missiles hit 30% of Ukraine's energy infrastructure in two days – minister." October 12, 2022. https://www.reuters.com/world/europe/russian-missiles-hit-30-ukraines-energy-infrastructure-two-days-minister-2022-10-12/.

Reuters. 2023. "Ukraine resumes electricity exports to Europe – minister." April 11, 2023. https://www.reuters.com/business/energy/ukraine-resumes-electricity-exports-europe-minister-2023-04-11/.

Schlein, Lisa. 2022. "UN: Half of Ukraine's Energy Infrastructure Destroyed by Russian Attacks." *Voice of America*, December 13, 2022. https://www.voanews.com/a/un-half-of-ukraine-energy-infrastructure-destroyed-by-russian-attacks/6874897.html.

Task Force. 2022. "Ukrainian energy sector evaluation and damage assessment – II (as of September 24, 2022)." *Energy Charter Secretariat*, September 30, 2022. https://www.energycharter.org/fileadmin/DocumentsMedia/Occasional/2022_09_30_UA_sectoral_evaluation_and_damage_assessment_Version_II.pdf.

Task Force. 2023. "Ukrainian energy sector evaluation and damage assessment – VI (as of January 24, 2023)." *Energy Charter Secretariat*, January 24, 2023. https://www.energycharter.org/fileadmin/DocumentsMedia/Occasional/2023_01_24_UA_sectoral_evaluation_and_damage_assessment_Version_VI.pdf.

The Global Economy. 2020. "Ukraine: Coal imports." Accessed February 18, 2023. https://www.theglobaleconomy.com/Ukraine/coal_imports/.

The Presidential Office of Ukraine. 2022. "Volodymyr Zelenskyy met with the European Commissioner for Energy." Accessed January 12, 2023. https://www.president.gov.ua/en/news/volodimir-zelenskij-zustrivsya-z-yevrokomisarom-z-pitan-ener-78841.

Wehrmann, Benjamin. 2022. "Renewable energy exports key pillar for Ukraine's reconstruction – chancellor Scholz." *Clean Energy Wire*, October 25, 2022. https://www.cleanenergywire.org/news/renewable-energy-exports-key-pillar-ukraines-reconstruction-chancellor-scholz.

Wikipedia. 2022. "List of power stations in Ukraine." Last modified December 12, 2022. https://en.wikipedia.org/wiki/List_of_power_stations_in_Ukraine.

Wikipedia. 2023. "Малі ГЕС України" [Small hydropower plants in Ukraine]. Last modified February 23, 2023. https://uk.wikipedia.org/wiki/Малі_ГЕС_України.

World Bank, Ukraine, European Union, and United Nations. 2023. *Ukraine Rapid Damage and Needs Assessment, February 2022-February 2023*. Edited by Anne Himmelfarb. Washington, DC: World Bank Group. https://documents1.worldbank.org/curated/en/099184503212328877/pdf/P1801740d1177f03c0ab180057556615497.pdf.

World Nuclear Association. 2023. "Nuclear Power in Ukraine." Accessed February 18, 2023. https://world-nuclear.org/information-library/country-profiles/countries-t-z/ukraine.aspx.

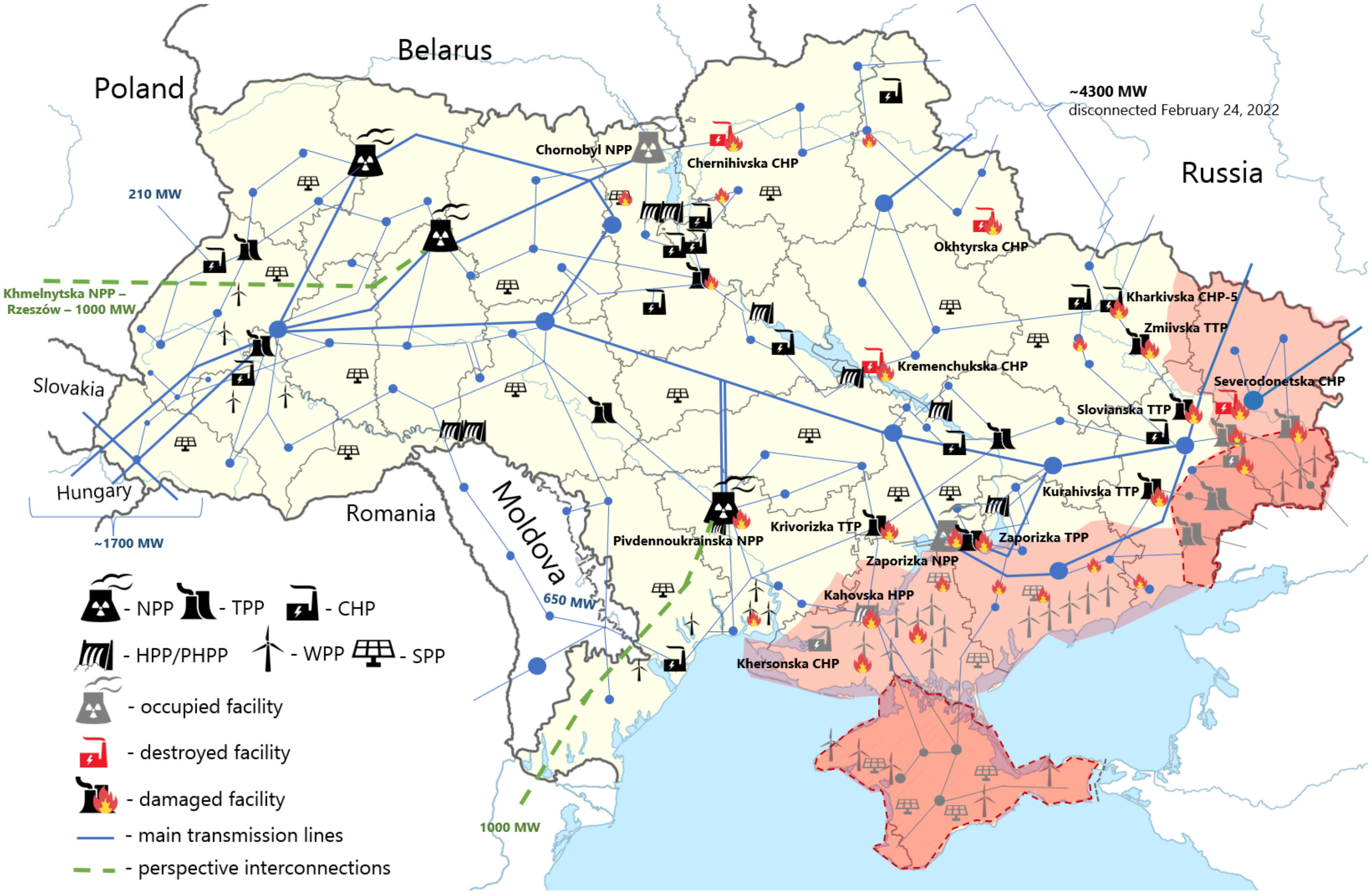
ANNEXES

Annex I. Data sources

Source	Dataset	Time span	Used in Graph №	Year	Link
Our World in Data	Ukraine: Energy Country Profile	1985-2021	1	2022	Link (accessed on 15/02/2023)
		1985-2021	2		
		1998-2020	7		
		1985-2021	8		
		1985-2021	9		
		2011-2021	10		
		2011-2021	11		
		2011-2021	12		
		2011-2021	13		
		1985-2021	14		
		1985-2021	15		
		1998-2020	16		
		1998-2020	17		
		2011-2021	18		
		2011-2021	19		
		2011-2021	20		
		2011-2021	21		
		2011-2021	22		
		2011-2021	23		
		2011-2021	24		
		2011-2021	25		
		2011-2021	26		
		2011-2021	27		
		2011-2021	28		
		2011-2021	29		
		2011-2021	30		
		2011-2021	31		
		2011-2021	32		
GHG inventories under the UN Framework Convention on Climate Change	Ukraine. 2022 Common Reporting Format Table	1990-2020	3	2022	Link (accessed on 15/02/2023)
		1998-2020	4		
		1998-2020	5		
		1998-2020	6		
		1998-2020	7		
		1998-2020	16		
		1998-2020	17		
		2011-2020	24		
		2011-2020	31		
The World Bank	GDP (current US$) - Ukraine	1998-2020	5	2022a	Link (accessed on 24/02/2023)
	Population, total - Ukraine	1998-2020	6	2022b	Link (accessed on 24/02/2023)

International Renewable Energy Agency (IRENA)	Renewable Energy Statistics 2021	2011	25	2021	Link (accessed on 18/04/2023)
		2011	32		
	Renewable Energy Statistics 2022	2012-2021	25	2022a	Link (accessed on 18/03/2023)
		2012-2021	32		
	Renewable Power Generation Costs in 2021	2021	25	2022b	Link (accessed on 22/03/2023)
		2021	32		

Annex II. Map of Ukraine's power generation capacity



Source: Task Force 2022, 15