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ScienceDirect

Energy Procedia 135 (2017) 410–423

Energy Procedia

www.elsevier.com/locate/procedia

11th International Renewable Energy Storage Conference, IRES 2017, 14-16 March 2017, Düsseldorf, Germany

The role of storage technologies for the transition to a 100% renewable energy system in Ukraine

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Abstract

A transition towards a 100% renewable energy (RE) power sector by 2050 is investigated for Ukraine. Simulations using an hourly resolved model define the roles of storage technologies in a least cost system configuration. Results indicate that the levelised cost of electricity will fall from a current level of 82 €/$\mathrm{MWh_e}$ to 60 €/$\mathrm{MWh_e}$ in 2050 through the adoption of low cost RE power generation and improvements in efficiency. If the capacity in 2050 would have been invested for the cost assumptions of 2050, the cost would be 54 €/$\mathrm{MWh_e}$, which can be expected for the time beyond 2050. In addition, flexibility of and stability in the power system are provided by increasing shares of energy storage solutions over time, in parallel with expected price decreases in these technologies. Total storage requirements include 0-139 $\mathrm{GWh_e}$ of batteries, 9 $\mathrm{GWh_e}$ of pumped hydro storage, and 0-18,840 $\mathrm{GWh_{gas}}$ of gas storage for the time period. Outputs of power-to-gas begin in 2035 when renewable energy production reaches a share of 86% in the power system, increasing to a total of 13 $\mathrm{TWh_{gas}}$ in 2050. A 100% RE system can be a more economical and efficient solution for Ukraine, one that is also compatible with climate change mitigation targets set out at COP21. Achieving a sustainable energy system can aid in achieving other political, economic and social goals for Ukraine, but this will require overcoming several barriers through proper planning and supportive policies.

Peer-review under the responsibility of EUROSOLAR - The European Association for Renewable Energy.

Keywords: energy transition; storage technologies; Ukraine, 100% Renewable Energy; energy system optimization

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10.1016/j.egypro.2017.09.513

1. Introduction

The landmark Paris Agreement of the 21st Conference of Parties to the United Nations Framework Convention on Climate Change recognized the need for global response to the impending threat of climate change [1]. As part of the agreement, such response involves limiting “global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C” through low greenhouse gas (GHG) emissions [1]. Among the countries ratifying the agreement was Ukraine, which targets that GHG emissions will not exceed 60% of the 1990 level in 2030 [2]. Importantly, Ukraine aims to achieve this target in a context of multiple, large-scale problems in the fore: armed conflict, net emigration, economic and industrial degradation [3], and over-dependence on imported fossil and nuclear fuel [4]. On one hand, it may seem ambitious to achieve such a GHG reduction target and fix the “many problems on the table” [2]. However, integrated and dynamic actions can attempt to tackle the multitude of problems through “efficient and effective policies and imposing of limitations of GHG emissions which are beyond current international obligations of Ukraine” [3]. On the other hand, Ukraine emission targets have been described as “unacceptable in terms of ambition” as they promote higher GHG emissions than are seen currently, and inadequate if Ukraine is to realize its “huge potential for climate action”[5].

Nomenclature

A-CAES	Adiabatic compressed air energy storage
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage
CHP	Combined heat and power
CSP	Concentrating solar thermal power
GDP	Gross domestic product
GHG	Greenhouse gas
GT/ST	Gas turbine/Steam turbine
GW/GWh	Gigawatt/Gigawatt hour
HHB	Hot heat burner
HVDC	High voltage direct current
ICE	Internal combustion engine
INDC	Intended nationally determined contribution
kW/kWh	Kilowatt/Kilowatt hour
LCOC/E/S/T	Levelised cost of curtailment/electricity/storage/transmission
LUT	Lappeenranta University of Technology
Mt	Megaton
MW/MWh	Megawatt/Megawatt hour
OCGT	Open cycle gas turbine
PHS	Pumped hydro storage
PP	Power plant
PtG, PtH	Power to gas, Power to heat
PV	Photovoltaics
RE	Renewable energy
SME	Small to medium enterprises
TES	Thermal energy storage
TW/TWh	Terawatt/Terawatt hour
WACC	Weighted average cost of capital
$_e$	electric units
$_{eq}$	equivalent units
$_{gas}$	gas units
$_{th}$	thermal units

It is argued that policy and action are needed to advance the energy transition of Ukraine beyond rhetoric. At the heart of such a transition appears the need for both greatly improving energy efficiency and a major deployment of renewable energy (RE) generation [4], [6]. However, no comprehensive study of a transition towards a more sustainable energy system for Ukraine currently exists. Such modelling of the future could go a long way towards realising the full potential of domestically available renewable resources and aid in identifying policies needed to support a transition towards sustainability. Together, such information can contribute to the overall discourse on energy in Ukraine and aid in the transition towards long-term sustainability.

GHG emissions in Ukraine have decreased in the years since gaining independence, from 944 Mt CO2-eq in 1990 to 353 Mt CO2-eq in 2014 (all values excluding Land Use, Land Use Change and Forestry). At a level of 37% of 1990 levels, Ukraine has already greatly surpassed the target set out in their Intended Nationally-Determined Contribution (INDC) report to the UNFCCC [7]. However, much of the reductions immediately after 1990 came as a result of GDP decline, decreased population and lower living standards similarly found in several countries after the collapse of the Soviet Union. Reversing these trends and achieving standards similar to those found in the European Union are also important goals for Ukraine, and these are to be achieved by massive reconstruction, increased industrial and agricultural output, improved infrastructure, and efficiency gains [3]. Realizing such projects will almost certainly result in increased energy use – particularly electricity, and may result in increased GHG emissions unless improvements are made responsibly and sustainably. Importantly, GDP growth in Ukraine since the year 2000 has been achieved in the context of stable or decreasing GHG emissions, demonstrating that GDP/GHG decoupling is possible. Therefore, greater reductions than those set out in the INDC appear realistic.

One of the biggest geopolitical challenges of Ukraine is its high dependency on energy supplies, especially natural gas and oil, from Russia. This dependency significantly decreased in the last two years. In 2015, gas imports from the EU have doubled, reaching 100 TWh, and have for the first time exceeded imports from Russia. The latter decreased dramatically from 142 TWh in 2014 to 60 TWh last year [4]. Dependency on coal, coming especially from the war-torn eastern regions of the country, is another major problem. Coal provides some 40% of primary energy supply and 30% of electricity production. This further undermines energy security in the country. Ukraine is still heavily dependent on nuclear power generation, accounting for more than 50% of the country’s electricity production and 20% of primary energy supply [4]. Yet, the existing 15 reactors are outdated and a major safety hazard, as proved by Chernobyl. Ukraine receives most of its nuclear services and nuclear fuel from Russia. Combined with the economic weakness, high debts, driven by the import costs of the energy raw materials, and a high unemployment rate lead to lack of political independence.

The issue of energy independence in Ukraine has moved to the fore in recent years. In particular, ongoing dependence on several energy carriers, such as nuclear fuel, oil and natural gas has been identified as a weakness of the current Ukraine energy system [8]. The current share of RE in Ukraine is reported as 1.4% in terms of installed generating capacity [9]. However, a feed-in-tariff in Ukraine has started stimulating investments especially in the solar energy sector. In 2014, only 100 kW of solar energy was installed on the private roofs in Ukraine. Meanwhile in 2016, this figure reached 10 MW. In 2016, the Ukrainian government also announced plans to install up to 4 GW of solar energy in the Chernobyl nuclear wasteland [10]. However, the potential of RE generation is much higher, with good domestic solar, wind, biomass, biogas and hydro resources. The extent to which Ukraine can become completely independent of imports has never been studied, and therefore offers a starting point for a vision of future.

Approximately 80% of global GHG emissions arise from the energy sector, while the balance comes from such sectors as agriculture and forestry, manufacturing, aviation, and waste management, among others. It has been argued that significant reductions in non-energy sectors may be disruptive or overly expensive burdens for societies [11], thereby placing an emphasis on the need to achieve net zero emissions in the energy sector if countries around the world are to “achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century” [1]. This has placed a focus on 100% renewable energy systems due to sustainability and reliability issues related to nuclear power and carbon capture and storage technologies [12]. For this reason, the aim of this work is to determine a transitional pathway for Ukraine to reach a 100% renewable, fully independent power system by 2050. Achieving a sustainable energy system can aid in achieving other political, economic and social goals for Ukraine, but this will require overcoming several barriers through proper planning and supportive policies. For this reason, this work also aims to identify potential barriers to achieving a sustainable energy system as well as determining possible solutions to overcome such barriers

2. Methods

The Ukrainian power system was modelled with the LUT energy system model described in [13]. This tool is based on linear optimization of energy system parameters under a set of applied constraints. A summary of the model is found in Figure 1. A full set of technical and financial assumptions used in this study can be found at [14].

2.1. Model summary

The target function of the model is to optimize the system so that total annual energy system cost is minimized. This cost is calculated as the sum of the annual costs of the installed capacities of each technology, costs of energy generation, and costs of generation ramping. In addition, the system includes distributed generation and self-consumption of residential, commercial and industrial prosumers by installing respective capacities of rooftop PV systems and batteries. The target function for prosumers is the minimization of the cost of consumed electricity, calculated as the sum of self-generation cost, annual cost, and cost of electricity consumed from the grid. From this, the cost of selling excess generation to the grid is subtracted. These target functions were applied in five-year time steps from 2015 to 2050 while two important constraints were built into the model. First, no more than 20% growth in RE installed capacities compared to total power generation capacities could be achieved for each five-year time step so as to avoid excessive disruption to the power system. Second, no new nuclear or fossil-based power plants could be installed after 2015. The exception to this constraint was for gas turbines, a highly efficient technology that can accommodate sustainably produced synthetic natural gas (methane).

The model is first calibrated to represent actual energy system performance in 2015. Importantly for Ukraine, this calibration involved recognizing great inefficiency in the power system. This was particularly related to low availability factors for thermal power plants (20%) and nuclear power plants (70%) as well as quite high transmission and distribution losses (11%) [8]. From 2020 onwards, power plant availability factors were increased in the model to a maximum 95% for thermal plants and 85% for nuclear plants. In addition, it was assumed that transmission and distribution losses would decrease by approximately one percentage point in each five year time slice from the current level to one in line with the EU average of 4.5% by 2050. Electricity demand was assumed to grow by 1.2% annually based on a trend projected for Europe [15]. While it is beyond the scope of this paper to analyse efficiency beyond the system level, it is important to note that such electricity demand can only be achieved through widespread end-user efficiency initiatives if significant growth is to occur in both population and industrial activity, as stated in the Ukraine INDC.

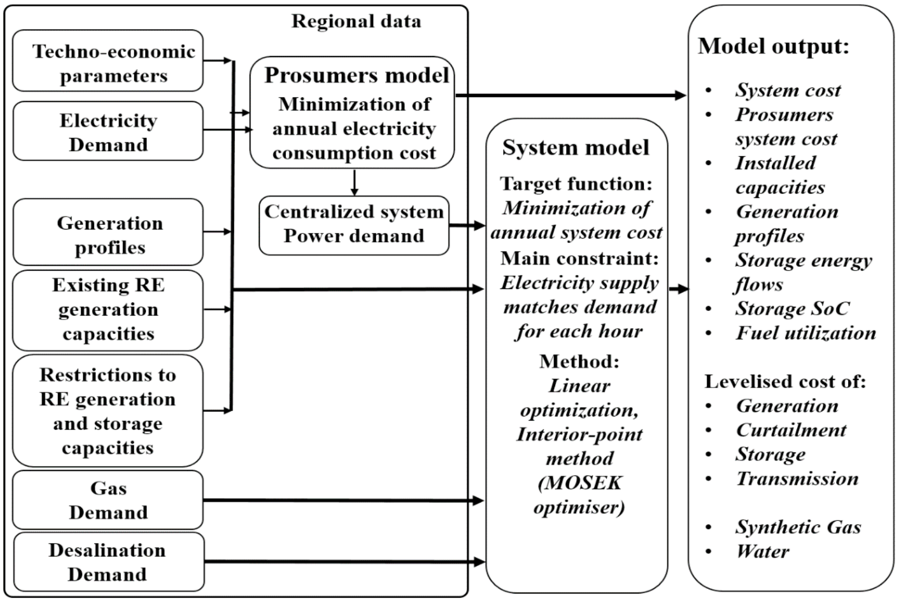

Fig. 1. Main inputs and outputs of the LUT energy system model [16]

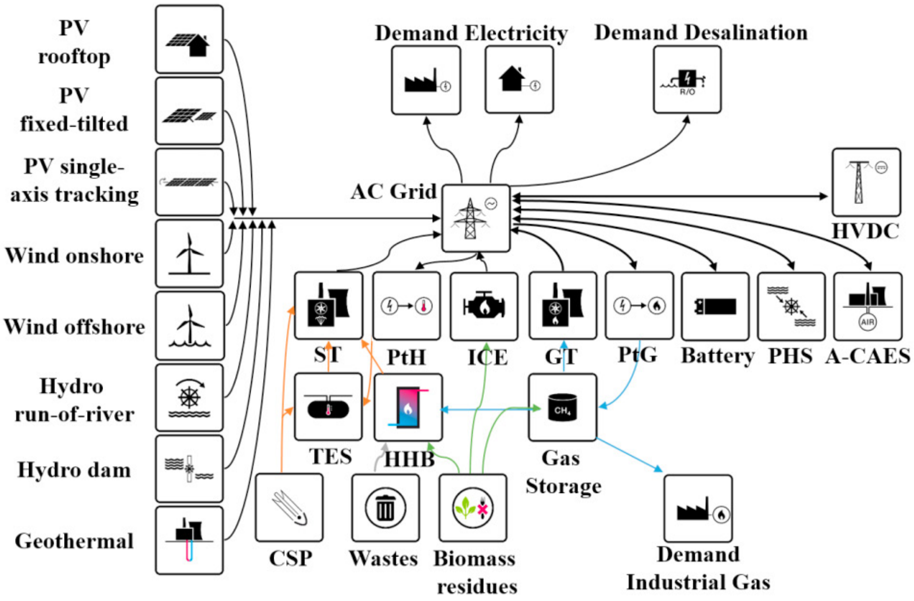

Fig. 2. Block diagram of the LUT energy system model [16]. Acronyms not introduced elsewhere include: ST - steam turbine, PtH - power-to-heat, ICE - internal combustion engine, GT - gas turbine, PtG - power-to-gas, PHS - pumped hydro storage, A-CAES - adiabatic compressed air energy storage, TES - thermal energy storage, HHB - hot heat burner, CSP – concentrating solar thermal power.

2.2. Applied technologies

Technologies introduced to the model can be classified into four main categories: electricity generation, energy storage, energy sector bridging, and electricity transmission. All technologies are shown in the Figure 2. For this analysis, the integration of desalination and non-energy industrial gas demand was not included. In addition, HVDC interconnections with neighbouring countries was not included in order to show complete energy independence of the Ukrainian energy system.

2.3. Financial and technical assumptions

Financial assumptions are made for all energy system components in five-year time steps. A full list of financial and technical assumptions can be found at [14]. Electricity prices for the residential, commercial and industrial sectors were derived by the same method as [17] and extended to 2050. For all scenarios, weighted average cost of capital (WACC) is set at 7%. However, WACC is set at 4% for residential PV prosumers due to lower expectations of financial return. Excess electricity generated by prosumers is fed into the national grid and is assumed to be sold for a transfer price of 0.02 €/kWh. Before such transfer, the model ensures that prosumers satisfy their own demand for electricity. No other financial incentives for solar PV production are assumed.

Current installed capacities of all technologies were provided by [18]. Upper limits for all the RE technologies and for pumped hydro storage were calculated according to Bogdanov and Breyer [13]. Upper limits for all other technologies are not specified. Due to energy efficiency reasons, it is assumed that available biomass, waste and biogas fuels are available throughout the year evenly. A synthetic electricity demand profile was created based on data from [19], [20].

2.4. Renewable energy potentials

Resource potentials for renewable energy categories were derived from a number of sources. First, generation profiles for solar CSP, solar PV (optimally tilted and single-axis tracking), and wind power (onshore and offshore) were calculated according to [13]. Capacity factors for onshore wind generation and solar PV can be seen at [14]. Second, a hydropower feed-in profile was based on precipitation data for the year 2005 as a normalised sum of precipitation throughout the country. Third, biomass and waste potentials were divided into three main categories: solid wastes, including used wood and industrial residues; solid residues, including straw, agricultural residues and forestry residues; and biogas, including gas produced from municipal biowaste, animal excrement, landfill gas and sewage gas. Solid waste potential is derived from [21]. All other biomass potentials are derived from the Bioenergy Association of Ukraine [22]. Excluded from the biomass potential of Ukraine are reported values for energy crops. While such energy crops may provide opportunities over the short-term for Ukraine, it is expected that available land will be needed for agricultural crops over the long-term, and not used for energy purposes. Costs for biomass were based on data provided by [21] and [22]. For solid wastes, a gate fee of €53 was assumed for 2015, raising to €100 in 2050. Finally, geothermal energy potential was calculated according to the method described in [16].

3. Results

Main modelling results are compiled in Figures 3-9. Further results and analysis can be found from the Supplementary Material [14].

Figure 3 shows how the model developed installed capacities for all technologies. Due to power system efficiency improvements, 2020 sees lower installed capacities providing greater amounts of power and little need for new installed capacities. From that point the development towards renewable generation proceeds in order to replace older fossil fuel and nuclear power plants. Wind power develops quickly, while solar PV and biomass power plants develop more quickly from 2030 onwards. Installed capacities appear to increase at a greater rate in 2050. As the final fossil fuel and nuclear power plants leave the system, they are primarily replaced by fixed tilted solar PV. The exaggerated increase in installed capacity can be explained by the lower number of full load hours for solar PV systems compared to thermal power plants. What is more, in 2050 PtG takes on a more prominent role in the energy system, thereby creating an increased demand for electricity and need for greater generation capacity. Figure 4 shows electricity generation increasing steadily to supply a growing, more industrious Ukraine. In 2050, the share of solar PV in total generation is 40%, followed by wind power, at 34%. The increase in electricity demand associated with PtG is also evident in 2050. A 100% renewable energy system is achieved for Ukraine by 2050.

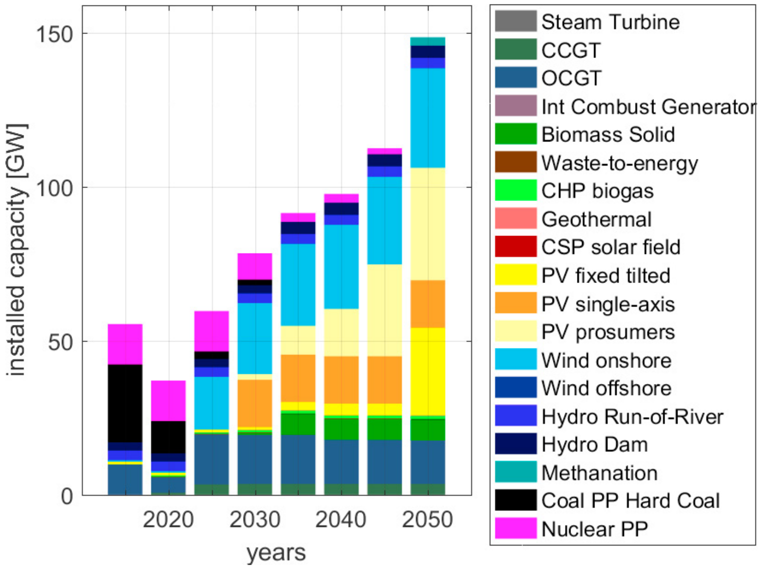

Fig. 3. Cumulative installed capacity for all generation technologies from 2015 to 2050.

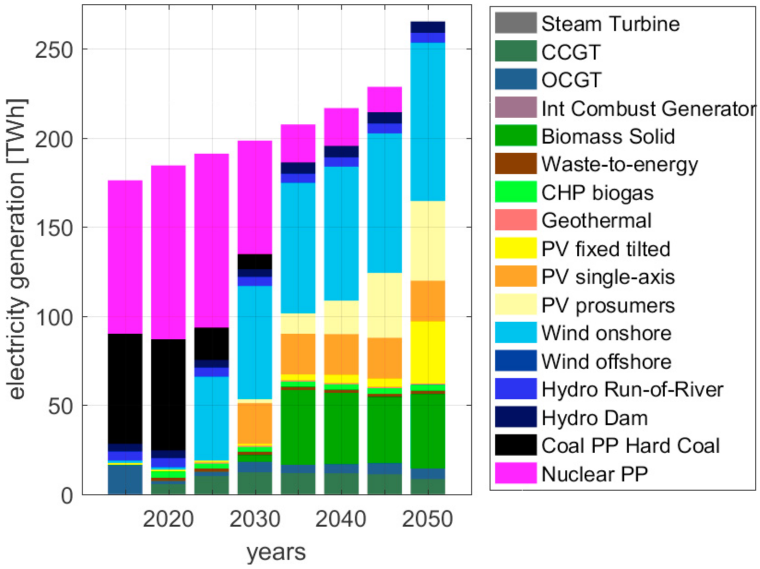

Fig. 4. Total electricity generation by generation technology from 2015 to 2050.

The role of storage technologies increases with the share of renewable energy (Figure 5). Traditional PHS provides most of the needed storage for the system from 2015 to 2025. However, the PtG process contributes to seasonal storage of gas in 2050, while batteries cover the shorter term storage demands from 2030 onwards. The share of renewable energy generation in the system reaches 58% in 2030, when battery storage appears in the system. The share of renewables is 86% in 2035 and 2040, and an increase in battery storage is evident. In 2040, renewables increase to 90%, and battery storage continues to increase, most notably for solar PV prosumers. As the share of renewables reaches 100% in 2050, batteries increase considerably and seasonal gas storage becomes a noticeable part of the energy system.

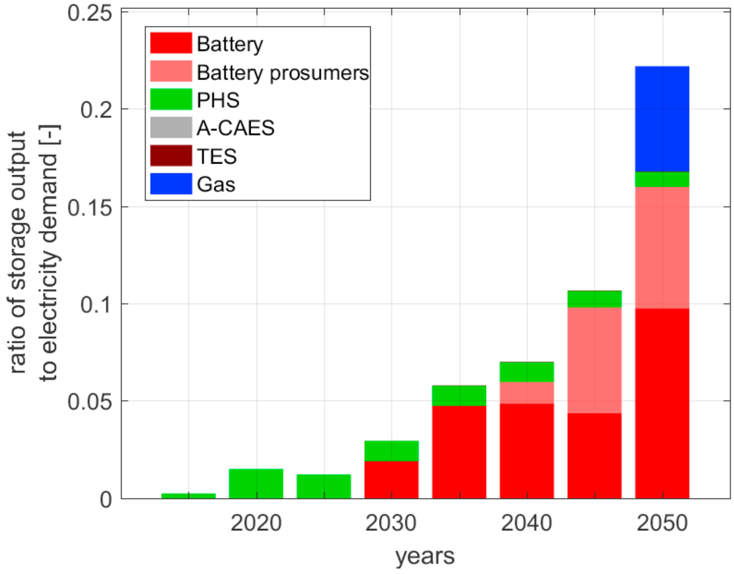

Fig. 5. Relative contribution of storage technologies to end-user electricity demand from 2015 to 2050.

Figures 6 and 7 show hourly results for all generation, storage and consumption over typical winter (January 9-15) and summer (June 23-29) weeks. From these figures it can be seen that wind power generation tends to be greater when solar PV generation is lower, and vice-versa, suggesting a seasonal complement. Curtailment is necessary at times of high wind energy generation, or when the combination of wind and solar PV generation is highest. However, in total, curtailment losses are less than 4% in 2050. The role of batteries as daily storage is noticeable, and appears strongly related to solar PV generation. During the summer week (Figure 7), the role of prosumer batteries is particularly evident. In addition, batteries cover much more of the evening demand during the summer week. The creation of storable gas through the PtG process is apparent during the summer week, and the use of this gas in the Gas-to-Power process is seen during the winter week. Hydro dams and biomass-based generation are also more evident during the winter week, a time of low solar PV production and increased overall energy demand. This demonstrates an important flexibility of the supply side.

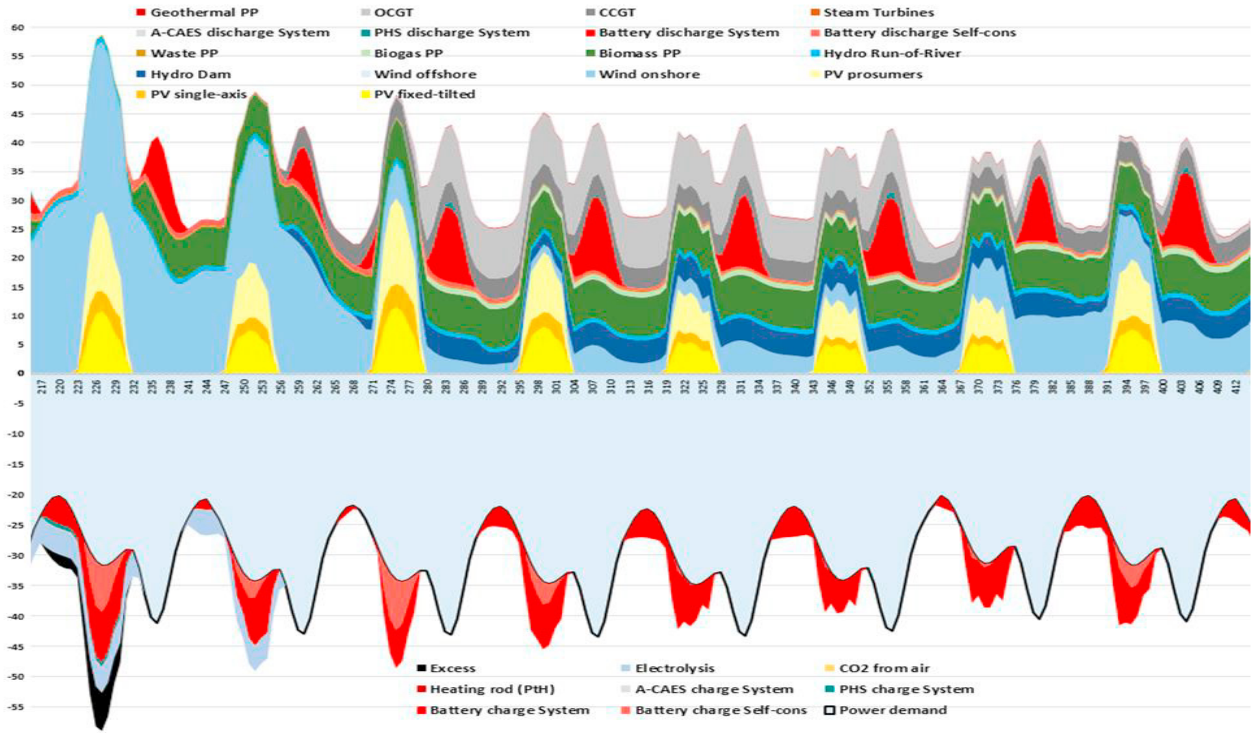

Fig. 6. Hourly results for a typical winter week (January 9-15).

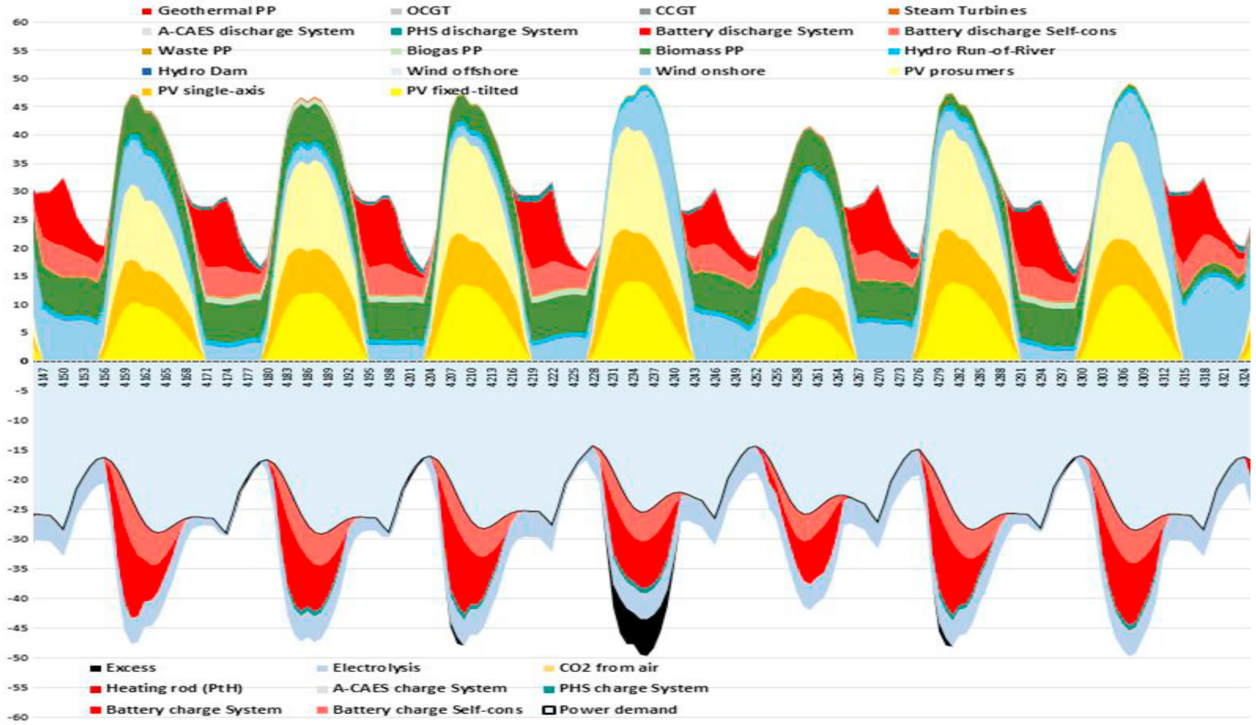

Fig. 7. Hourly results for a typical midsummer week (June 23-29).

Figure 8 shows carbon emissions falling significantly after the phase out of coal power after 2020. Further reductions occur as imported natural gas is replaced by domestically-produced methane. By 2050, the Ukraine energy system is completely decarbonised.

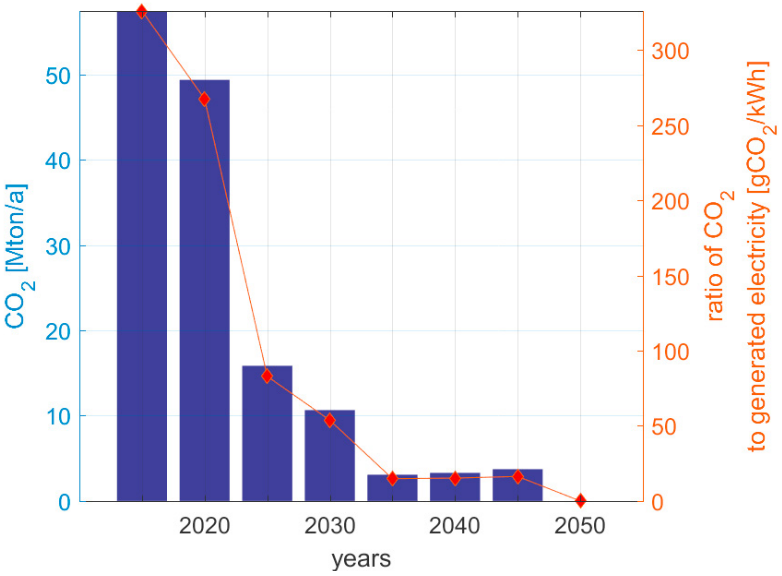

Fig. 8. Total carbon emissions and ratio of emissions to electricity generation from 2015 to 2050.

Figure 9 shows the trend of decreasing levelised cost of electricity (LCOE) over the years 2015 to 2050. Higher cost nuclear and coal-based generation is replaced by lower cost wind, solar PV and biomass-based power production. Lower capital expenditures, operational costs, fuel costs and emissions costs contribute to lower LCOE over time. If the capacity in 2050 would have been invested for the cost assumptions of 2050, the LCOE would be 54 €/MWh$_e$, which can be expected for the time beyond 2050.

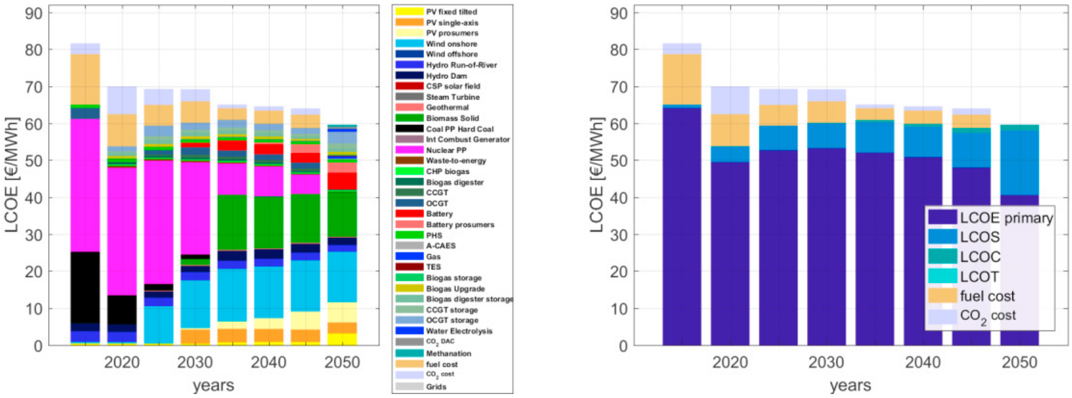

Fig. 9. Levelised cost of electricity and the contribution of technologies (left) and breakdown in cost categories (right). Levelised cost of electricity and the contribution of levelised costs of primary generation (LCOE primary), storage (LCOS), curtailment (LCOC), fuel cost, and carbon emission cost. Transmission costs (LCOT) are zero as interconnections with neighbouring countries were not utilized in this study.

4. Discussion

Results from modelling show that a 100% renewable power system is achievable for Ukraine by 2050. What is more, this represents a least cost solution for the country based on the assumptions used in this work. For the first time, it is possible to see the transition towards a 100% renewable Ukrainian power system.

Results for LCOE calculations for Ukraine in 2050 are similar to other studies using the LUT model which show a global range of about 50-70 €/MWh for 100% power systems in 2030 [13], [16], [23]–[29] These studies suggest that further integration of desalination and non-energy gas demands into the energy system model could result in further LCOE savings, suggesting an interesting area of further research for Ukraine. The findings of the current study are similar to those found in another comprehensive analysis of the Ukrainian energy system [30]. In their report, IRENA concludes that increased renewable energy shares will reduce Ukraine's overall energy system costs, which is the same structural finding of this research.

In addition, several other studies conclude that 100% RE systems are either less expensive [12], or not significantly more expensive than energy systems which do not feature such high shares of RE [31]–[33]. Importantly, the findings of the current study are in line with another that shows the higher cost of nuclear power or fossil fuel based carbon capture and storage (CCS) on an LCOE basis [34]. These are reported as 112 €/MWh for new nuclear and gas CCS, and 126 €/MWh for coal CCS in the UK. Of particular relevance is the share of levelised cost of storage (LCOS) within the LCOE calculation for 2050 Ukraine. From 2035 onwards, the share of LCOS increases from 10% to 20% of LCOE. However, given the possibility of integrating an expected electrified transport demand and potential substitution of electric vehicle batteries for some of the stationary batteries used in this model, further savings in LCOS can be foreseen, as well as possible revenue for electric car owners. Several studies have indicated that the integration of electric vehicle batteries into an energy system can not only support higher shares of intermittent RE, but can reduce the need for high capacities of stationary batteries [12], [35], [36]. This also represents a further area of inquiry for the Ukrainian energy system.

The roles of intermittent RE such as solar PV and wind energy are significant in the future power system modelled for Ukraine in 2050. Wind energy represents 39% of total electricity generation, while solar PV represents 45%. This intermittent generation is balanced by strategic use of hydropower by the model, as well as by power generated from biomass and waste. Electricity storage solutions also play a key role in maintaining the important balance between supply and demand. On a daily and multi-day level, batteries and PHS play a strong role in maintaining such balance. Results also indicate that PtG provides a longer-term, seasonal storage for the Ukraine power system. This result is in line with several studies that show the importance of a mix of storage strategies [37]–[39].

The role of storage in the future 100% renewable power systems is quite significant. In terms of absolute volume of storage, gas storage dominates the power system as PtG is utilized as a seasonal storage device after 2035. Before that time, the current installed capacity of PHS is sufficient to balance the system that is dominated by nuclear power production. As the current fleet of nuclear power plants reaches its lifetime and is replaced by renewable power generation, particularly solar PV and wind power, the relevance of storage increases. After 2035, storage output equals approximately 15% of electricity supply, increasing to 35% by 2050. Results indicate that the share of renewable energy in total generation is 58% in 2030, and 86% in 2035. In that time, the relevance of storage solutions increases significantly. This is in line with previous studies which suggest that electricity storage devices would be needed after a 50% penetration of renewable energy, and that seasonal storage would be needed after the share exceeded 80% [37], [38].

The change in the capacity mix for Ukraine represents a clear departure from a system currently based on coal, natural gas, and nuclear power. It should also be pointed out that this change aids in achieving four important goals. First, the gradual phasing out of existing capacity will mean no stranded assets. Second, Ukraine can seize the opportunity to reduce major inefficiencies associated with coal-based and nuclear power in particular. Currently, thermal power plants operate at capacity factors of approximately 20% and nuclear power plants operate about 70%. As aging capacity leaves the system, these capacity factors should improve somewhat over the short term according to modelling results. As this capacity leaves the system entirely and is replaced by much more efficient conversion technologies such as solar PV and wind, the entire system benefits and costs decrease as indicated by LCOE calculations. Third, Ukraine can avoid corruption and strong lobbyism that is highly associated with the current energy system [4]. Fourth, Ukraine can increase energy security through domestic investment in renewable energy generation and storage technologies. Perhaps one of the most explicit examples of this will be the recently announced 1 GW solar PV project that will be constructed in the exclusion zone around the infamous Chernobyl nuclear power plant [40].

IRENA [30] points out that several barriers exist to realising higher shares of renewable energy, and other sources outline similar barriers [4], [8], [41]. In particular, the high upfront capital expenditures associated with renewable energy generation mean that investors are sensitive to uncertainty and risk. Reducing such negative factors must come, therefore, from predictable and stable policies which "should be maintained over long periods to allow for the continuity of investments into renewable energy technologies" [30]. Of particular importance to the transition of the Ukraine energy system towards sustainability will be commitments to modernising existing energy infrastructure, decreasing energy intensity, and greatly increasing energy efficiency [41].

A decisive factor will be a modern, efficient and 100% renewable based energy system in Ukraine. Fluctuations of renewable energy can be balanced by means of different storage methods, including Power-to-Gas, Power-to-Heat, batteries, pumped storage hydro power stations, etc. and the integration of the demand-oriented flexibility of hydropower, bioenergy, hydropower and geothermal energy across all energy dependent sectors: electricity, heating, cooling, transport and industry. Oil and gas in the heating and transport sector should be replaced by electrification as much as possible. Although, sustainable biofuel will still play a significant role in the transport sector (construction machinery and agriculture). Fertile and degraded land areas in Ukraine offer great chances for biofuel production, and at the same time will help to mitigate climate change through the creation of carbon sinks.

One of the most important drivers hereto is a favourable political framework, including laws providing financial security to investors in renewable energy and energy efficiency, both domestically and abroad. Such laws can also enable a wide range of actors to invest, especially private people, small and medium enterprises, farmers, public utilities and financial institutions. A feed-in-tariff and a privileged grid access can guarantee such long-term investment security. A feed-in-tariff law should be based on the German model of the year 2000 and not on tendering. International experience has proved that tenders benefit only large business investors and hinder investments in renewable energy from civil society and SMEs. Also key is a change in the energy industry framework legislation, stimulation of competition through unbundling as well as reduction of monopolies and oligopolies, and combating corruption.

Know-how transfer, education and training in the energy sector through offensive programs at universities and vocational training schools as well as a state-financed campaign on raising public awareness about renewable energy and energy efficiency through decentralized energy agencies and energy consultants will be key. Also important is establishment of partnerships of municipalities in Ukraine with many best-practice municipalities in Germany and throughout Europe.

5. Conclusion

A 100% renewable power system is achievable for Ukraine by 2050. Such a system represents a least cost alternative for Ukraine, is lower in cost than the current system based on fossil fuels and nuclear power, can answer increasing demands for power in the future, and can result in complete energy independence for the country. However, shifts in energy policy are needed at a national level to support the transition needed to reach national goals and international commitments regarding carbon emissions reduction and climate change mitigation. In addition, further commitments towards increasing efficiency throughout the energy system appear necessary. It also appears that a more ambitious GHG emission target for Ukraine is achievable.

Diversification within the fossil and nuclear energy sector cannot serve as a solution. A new gas pipeline the EU has built in Ukraine serves only as a short-term solution since the EU is still heavily dependent on Russian natural gas supplies. At the same time as its own production of natural gas in the EU, especially in the UK, the Netherlands, Germany goes down, the EU will have problems with its own energy security. Therefore, the only long-lasting, economical and environmentally reasonable solution is rapid deployment of energy efficiency measures and a transition to domestic renewable energy sources. Ukraine has a high potential across all renewable energy sources: solar, wind, water, biomass due to large rural areas and the presence of geothermal energy resources. All these sources need to be deployed, as they will create many jobs, especially in the rural economy. With supportive policy, Ukraine has the ability, therefore, to move to the fore in European climate action.

Acknowledgements

The authors gratefully acknowledge the public financing of Tekes, the Finnish Funding Agency for Innovation, for the ‘Neo-Carbon Energy’ project under the number 40101/14. Special thanks go to Yuliia Oharenko and Oksana Aliieva from the Heinrich Böll Foundation in Kiev, and Komila Nabiyeva from the Energy Watch Group for valuable comments during the preparation of this manuscript.

Appendix A.

Supplementary materials for this article can be found at: https://www.researchgate.net/publication/313255514_Role_of_storage_technologies_for_the_transition_to_a_100_renewable_energy_system_in_Ukraine_-_Supplementary_Material

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