DECARBONATION OF THE NATIONAL ECONOMY OF THE REPUBLIC OF MOLDOVA BY ELECTRIFICATION AND USE OF RENEWABLE ENERGY SOURCES

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In this paper, we propose to present the concept and roadmap for decarbonation of the national economy of the Republic of Moldova until 2070. In this order, it is presented technologies for electricity generation and use, respectively based on these technologies there are estimated the required electricity for electrification of the main sectors (energy, transport, and industry) and, respectively, the required capacity of power plants using renewable energy sources.

1. Introduction

Signing Paris Agreement and European Green Deal, European Union (EU) took commitments to become a neutral continent until 2050 in terms of greenhouse gas emissions (GHG) – the main cause of climate change [1]. The Paris Agreement foresees limiting global average temperature growth below 2 ^{0}C by the end of the 21st century [2]. The Republic of Moldova (RM) is the EU Associated Country, a member of the European Energy Community, and signatory country of the Paris Agreement. Thus, the RM took commitments to combat climate change too.

Table 1

Renewable energy sources technical potential of RM

Renewable energy sources	Technical potential (TWh/year)
Photovoltaic [3]	10.8
Wind [4]	9.1
Biomass [5]	6.0
Biogas [6]	11.1
Syngas [6]	5.3
Hydro [5]	3.4

The main anthropogenic source of GHG is the fossil fuels combustion processes in the energy, transport, and industry sectors. With the acceleration of the process of urbanization, automation, and electrification of the industrial, residential, trading and public services (TPS) sectors, it is estimated that the use of

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electricity will increase rapidly during the XXI century, respectively without any climate change mitigation measures, the Earth as we know will be changed forever.

Decarbonation of these sectors can be achieved by substituting fossil fuel use with renewable energy sources (RES). The RM has considerable potential for renewable energy sources, especially wind, solar, and biomass. This potential can cover existent demand or at least can reduce considerably the dependency on fossil fuel imports of the RM (see table 1 and figure 1).

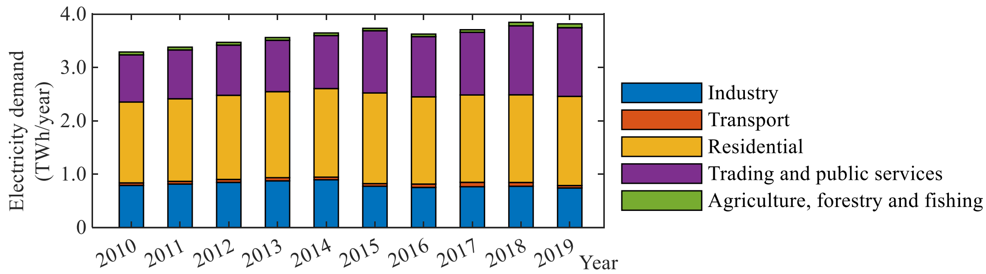

Fig. 1. Electricity demand of the RM [7]

The field of use of biomass is limited to the rural areas due to the necessity of large storage spaces and transportation on long-distance, of converting into other forms of fuel or energy that are easier to use, and pressure on the agriculture and forestry sector, etc. On the other hand, electricity is a superior form of energy that can be converted easily into other types of energy (heat, cool, chemicals, fuels, and others) replacing them [8-11]. Thus, for cities, the main opportunity for decarbonation is the use of electricity generated by wind and photovoltaic (PV) power plants and the electrification of the main sectors of the national economy.

The RM has insignificant reserves of fossil energy resources (coal, oil, natural gas), and its own energy demand is covered by imports, which ranged from 74-81% in 2010-2019. At the same time, the RES potential has not been used appropriately, the share of RES varying between19-26% in the same period. Total energy demand of the RM is about 114.8 PJ (2019). The main types of energy sources in the energy balance of the RM are electricity (11%), natural gas (29%), oil products (35%) and RES (22%). Most of the used RES represents biomass and waste used for heating and food preparation in rural areas. The share of electricity generation by the power plants using RES did not exceed 5% in electricity balance and 0.6% in energy balance [7]. The main electricity sources and their share in the electricity balance are presented in figure 2.

Due to the physical and moral wear, only 360 MW can be used to cover the electricity load from the total capacity of the local electricity sources (500 MW). On the other hand, existing interconnections with neighbor power systems cannot assure the power security of the country. The main source of electricity import is the Ukrainian power system and Regional Moldovan Power Plants from the Territorial Administrative Unit of the Left Bank of the Dniester (Transnistria) – the separatist region uncontrolled by the RM authorities. Existing interconnections with the Ukrainian power system have limited transport capacity due to frequent congestions. Moldovan and Romanian power systems are part of the different synchronized systems. Thus, the import of electricity from the Romanian power system is impossible without a back-to-back station.

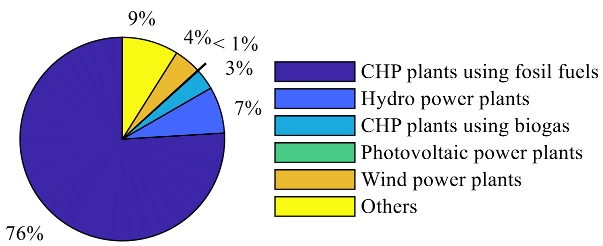

Fig. 2. Electricity sources and their weight in electricity balance of RM [7]

Natural gas is used for electricity and heat generation by CHP plants, building heating, hot water supply, and food preparation in the residential sector. The natural gas demand is covered by imports from Russian Federation (99.8%). The magistral gas pipelines cross Ukraine and Transnistria – economically, politically, and militarily unstable territories. The principal source of oil products is Romania and mostly are consumed in the transport sector.

Besides the economic and security aspects of fossil fuel consumption, their environmental impact cannot be neglected. Combustion processes are the main source of solid particles, nitric and nitrogen dioxides, and greenhouse gases.

2. The concept of the energy transition

As there is mentioned above, today the best solution for decarbonation of the national economy is the substitution of fossil fuels by RES. The main renewable source of electricity is wind and solar PV. These types of sources have many advantages as geographical spread, availability in large quantities, and low environmental impact.

A considerable disadvantage is their uncertainty and intermittency that is reflected in electricity generation, which can lead to difficulties in operation and management of the power system with the massive presence of these types of sources. Thus, there appear situations when electricity generation and demand do not coincide, and power generation management is difficult to realize without the existence of the reserve generation capacities (with a rapid start-up) or/and energy storage systems. The storage of the electricity generated by RES in the form of other types of energy and the electrification of different sectors of the national economy can help to maintain the flexibility of the power system and to increase its penetration by variable renewable energy sources (VRES).

In fig. 3 and 4 it is presented the concept of electrification and decarbonation of the main sectors on national economy of the RM. This concept involves the substitution of fossil fuels with electricity generated by VRES in traditional electricity, heating, and transport facilities.

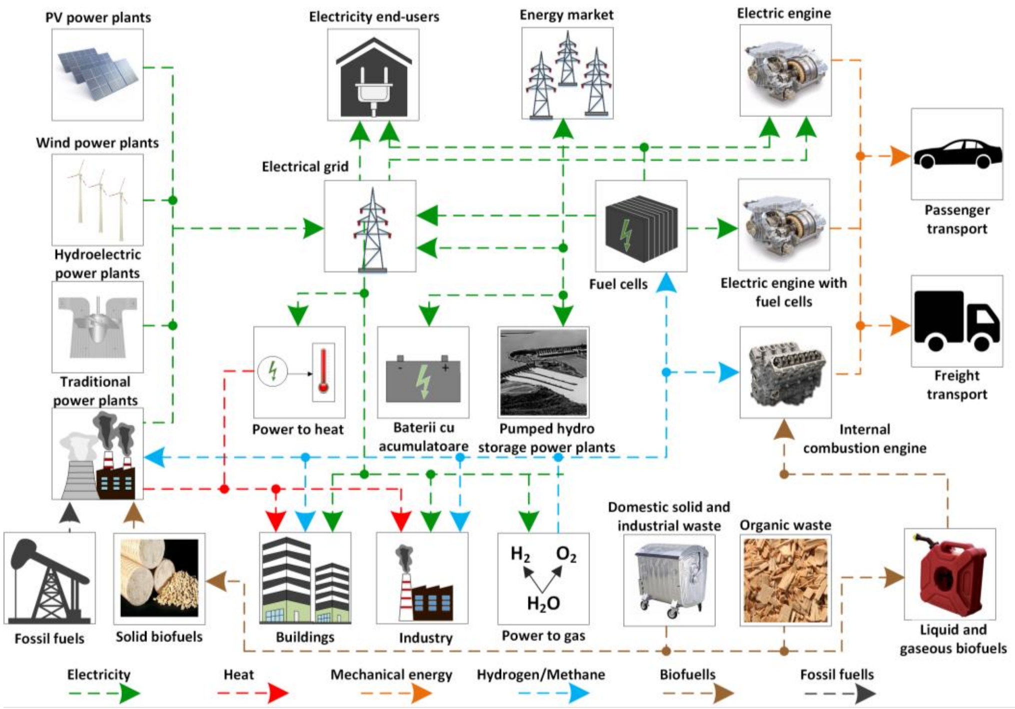

Fig. 3. The concept of decarbonation the national economy

Power-to-Heat. District heating systems are the biggest user of energy resources. In the RM, about 55.7% of the total heat demand corresponds to the residential sector and 24.9% to the industrial sector [7]. The main source of heat is CHP plants and district heating plants that use natural gas as fuel. Conversion of the electricity generated by wind and PV power plants can contribute to the decarbonation of the residential building and industrial sectors, balancing the power system in the massive presence of these types of sources and reduce the investment payback period of these sources. Heat pumps and electric boilers can be successfully used to convert electricity into heat and to cover the heat demand of the residential and industrial sectors.

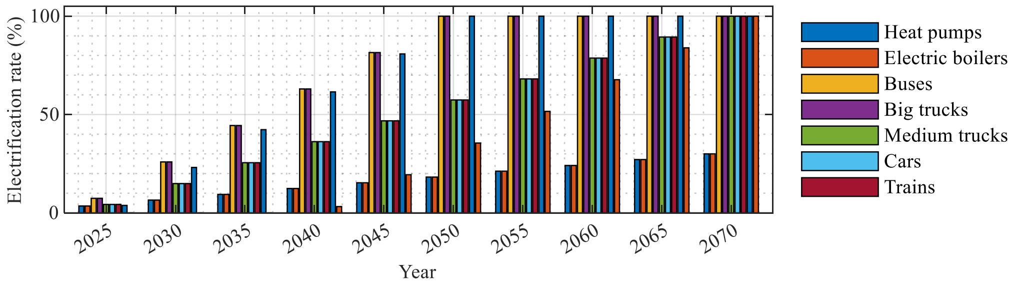

Fig. 4. The rate of electrification of the national economy

Power-to-X. The excess of generated electricity by VRES can be used for hydrogen production through electrolysis – green hydrogen. The green hydrogen can be used directly in internal combustion engines and fuel cells or can be used for the production of the various gaseous or liquid fuels (methane, methanol, synthetic natural gas, E-Gasoline, E-Diesel, E-Kerosene), named electrofuels, or chemicals for the national economy, which would partially or totally replace fossil fuels use.

Table 2

Energy system elements efficiency

Energy system elements	Efficiency (%)
Heat transport and distribution system	85.5
Electricity transport and distribution system	89.9
Heat plants	82.9
CHP plants (heat generation)	55.5
Heat pumps	350
Electric boilers	99

As the result of the hydrogen combustion process is the only water that was used for hydrogen production through electrolysis. Thus, green hydrogen is a climate-neutral fuel. A source of carbon dioxide is required to produce methane, methanol, or synthetic natural gas, and biomass to produce E-Gasoline, E-Diesel, and E-Kerosene. Comparing with biofuels, electro fuels require a smaller amount of biomass, significantly reducing the pressure on the agriculture and forestry sectors. As carbon source can serve atmospheric air, flue gases, biogas, or synthesis gas.

Power-to-X can contribute to the power system balancing by using the excess of the generated electricity by VRES for hydrogen production in periods of peak electricity generation by VRES or off-peak users load.

Power-to-drive. The transport sector is the second-biggest consumer of fossil fuels, respectively the second biggest source of emission GES. Electrification of transport can be realized in two ways: direct and indirect.

Indirect electrification supposes the use of hydrogen (or its derivatives) as a fuel in the internal combustion engines of traditional vehicles or the fuel cells of electric vehicles. Direct electrification supposes the use of vehicles with electric engines with accumulator batteries or/and connected directly to electric grids. Direct electrification can contribute to the decarbonation of the transport sector, to the increasing of the power system flexibility, and air quality improving in big cities with intense traffic. To increase the power system flexibility, smart charging can be applied – the charging in the period with the excess of the electricity.

Table 3

Transport fuel consumption and electricity demand in combined cycle

Transport type	Traditional transport		Electric transport	
	Fuel type	Fuel consumption (l/km)	Technology	Electricity demand (Wh/km)
Small and medium cars	Gasoline	0.06	BEV/FCHEV	109
Big cars	Gasoline	0.09	BEV/FCHEV	135
Medium trucks	Diesel	0.17	BEV	276
Big trucks	Diesel	0.26	BEV	422
Buses	Diesel	0.25	BEV	405
Trains	Diesel	1.92	BEV	2600

3. Methodology

To determine the evolution of the electricity load of the RM in the light of the proposed energy transition concept (2021 – 2070), the evolution of traditional electricity, heat, and fossil fuel consumption is required. The evolution of energy demand is a function of the characteristic parameter for each sector of the economy:

A. Electricity (traditional) and heat demand:
   a) the residential sector: total population; and total housing stock;
   b) the industrial sector: industrial production;
   c) the TPS sector: traded goods and services;
   d) the agriculture, forestry, and fishing (AFF) sector: agrozootechnical production;
   e) the transport sector: transported passengers by public transport.
B. Fossil fuel:
   a) buses: passenger transport by bus; and total population;
   b) medium trucks: transported freight; traded goods and services;
   c) large trucks: industrial and agrozootechnical production;
   d) cars: total population;
   e) rail transport: passenger transport; and freight transport.

For the period of 2021-2070, these parameters are predicted with help of *Curve Fitting Toolbox, MATLAB*, as a trend function:

$$f(x) = a \cdot x^b + c, \tag{1}$$

where x represent the year (for initial year being 2010, $x_1 = 1$);
a, b şi c – the coefficients that must be found (table 4).
The accuracy of function is determined with Coefficient of Determination:

$$R^2 = 1 - Var(V_{act} - V_{pred})/Var(V_{pred}), \tag{2}$$

where V_{act} and V_{pred} represent actual (real) and predicted values.

Table 4

Coefficients for function $f(x) = a \cdot x^b + c$ and its accuracy

Parameters		Function coefficients			Coefficient of Determination
		a	b	c	
Population	Urban	7346	0.9096	$1.468 \cdot 10^6$	0,992
	Rural	-5956	1.109	$2.093 \cdot 10^6$	0,996
Gross domestic product		$2.757 \cdot 10^5$	1.263	$5.293 \cdot 10^6$	0,968
Industrial product		234.9	0.7227	1512	0,925
Traded products on internal market		-1078	-0.8338	2602	0,898
Offered services on internal market		40.28	0.8993	679.2	0,999
Agrozootechnical product		53.46	1.009	1190	0,937
Transported passenger by electric transport		2.734	1.294	103.1	0,947
Electric transport units		17.72	0.7262	324.4	0,943
Housing stock	Urban	-74.66	$7.09 \cdot 10^{-5}$	$5.03 \cdot 10^{-8}$	0.998
	Rural	42.41	$2.95 \cdot 10^{-6}$	$7.06 \cdot 10^{-8}$	0,977
Mileage of passenger	By buses	1502	0.2162	941.6	0.952
	By trains	8116	-2.352	38.02	0.944
Transported freight	By trucks	308.8	0.8975	3023	0.954
	By rail	47.11	0.156	909.4	0.966

Predicted energy resources demand represents the multiplying the characteristic parameter by specific energy resource demand for given sector:

a) traditional electricity demand for residential sector:

$$W_{rez} = \frac{1}{2}\left(w_{pop} \cdot (PU + PR) + w_{floc} \cdot (HU + HR)\right), \tag{3}$$

where w_{pop} and w_{floc} – specific electricity demand per population, GWh/person, respective, per housing stock (GWh/m^2);
PU and PR – urban and rural population (persons);
HU and HR – urban and rural housing stock (m^2);

b) traditional electricity demand for industrial sector:

$$W_{ind} = w_{ind} \cdot PI, \tag{4}$$

where w_{ind} – electricity specific demand per industrial products (GWh/€);

PI – industrial products (€);

c) traditional electricity demand for TPS sector:

$$W_{csp} = w_{csp} \cdot (PC + PS), \tag{5}$$

where w_{csp} – specific electricity demand per traded products and offered public services (kWh/€);
PC and PS – traded products and offered public services (€);

d) traditional electricity demand for AFF sector:

$$W_{paz} = w_{paz} \cdot PAZ, \tag{6}$$

where w_{paz} – specific electricity demand per agrozootechnical products (kWh/€);
PAZ – agrozootechnical products (€);

e) traditional electricity demand for transport sector:

$$W_{rez} = \frac{1}{2}\left(w_{pas} \cdot Pas + w_{TE} \cdot TE\right), \tag{7}$$

where w_{pas} and w_{TE} – specific electricity demand per transported passengers (GWh/passenger), respective, per electric public passenger transport unit (GWh/unit);
Pas – transported passengers with electric public transport (passenger);
TE – electric public passenger transport, (unit).

f) heat demand for residential sector:

$$Q_{rez} = \frac{1}{2}\left(q_{pop}^{t.rez} \cdot PU + q_{floc}^{t} \cdot FLU\right), \tag{8}$$

where $q_{pop}^{t.rez}$ – specific heat demand per urban population (TJ/person);

g) heat demand for industrial sector:

$$Q_{ind} = q_{ind}^{t} \cdot PI, \tag{9}$$

where q_{ind}^{t} – specific heat demand per industrial products (TJ/€);

h) heat demand for TPS sector:

$$Q_{csp} = q_{csp}^{t} \cdot (PC + PS), \tag{10}$$

where q_{csp}^{t} – specific heat demand per traded products and offered public services (TJ/€);

i) heat demand for AFF sector:

$$Q_{paz} = q_{paz}^{t} \cdot PAZ, \tag{11}$$

where q_{paz}^{t} – specific heat demand per agrozootechnical products (TJ/€).

j) fuel demand for buses:

$$Q_{fuel}^{bus} = \frac{1}{2}\left(q_{PP}^{bus} \cdot PP_{autobuze} + q_{pop}^{bus} \cdot (PU + PR)\right), \tag{12}$$

where q_{PP}^{bus} and q_{pop}^{bus} – specific fuel demand per passengers' traveled distance by bus (TJ/passenger-km), respective, per total population (TJ/person);
PP_{bus} – passengers' traveled distance by bus (passenger-km);

k) fuel demand for trucks:

$$Q_{fuel}^{truck} = \frac{1}{2} \cdot \left(q_{PM}^{truck} \cdot PM_{truck} + q_{SPC}^{truck} \cdot (PC + PS)\right), \tag{13}$$

where q_{PM}^{truck} and q_{SPC}^{truck} – specific fuel demand per freight's traveled distance by trucks (TJ/tone-km), respective, per offered services and traded products (TJ/€);
PM_{truck} – freight's traveled distance by trucks (tons-km);

l) fuel demand for cars:

$$Q_{fuel}^{car} = q_{pop}^{car} \cdot (PU + PR), \tag{14}$$

where q_{pop}^{car} – specific fuel demand for cars per total population (TJ/person);

m) fuel demand for rail transport:

$$Q_{fuel}^{rail} = q_{PM}^{rail} \cdot PM_{rail} + q_{PP}^{rail} \cdot PP_{rail}, \tag{15}$$

where q_{PM}^{rail} and q_{PP}^{rail} – specific fuel demand per freight's traveled distance by rail (TJ/tons-km), respective, per passengers' traveled distance by rail (TJ/passenger-km);
PM_{rail} and PP_{rail} – freight's traveled distance by rail (tons-km), respective, passengers' traveled distance by rail (passenger-km);

n) fuel demand for residential sector:

$$Q_{fuel}^{rez} = \frac{1}{2}\left(q_{GDP}^{f.rez} \cdot GDP + q_{pop}^{f.rez} \cdot (PU + PR)\right), \tag{16}$$

where $q_{GDP}^{f.rez}$ and $q_{pop}^{f.rez}$ – specific fuel demand for residential sector per GDP value (TJ/€), respective, per population (TJ/person);
GDP – gross domestic product (€);

o) fuel demand for industrial sector:

$$Q_{fuel}^{rez} = \frac{1}{2}\left(q_{fuel}^{ind} \cdot PI + q_{GDP}^{f.ind} \cdot GDP\right), \tag{17}$$

where q_{fuel}^{ind} and $q_{GDP}^{f.ind}$ – specific fuel demand per industrial products (TJ/€), respective, per GDP value (TJ/€);

p) fuel demand for TPS sector:

$$Q_{fuel}^{csp} = \frac{1}{2}\left(q_{fuel}^{csp} \cdot (PC + PS) + q_{pop}^{f.csp} \cdot (PU + PR)\right), \quad (18)$$

where q_{fuel}^{csp} and $q_{pop}^{f.csp}$ – specific fuel demand for TPS per traded products and public services (TJ/€), respective, per population (TJ/person);

q) fuel demand for AFF sector:

$$Q_{fuel}^{paz} = \frac{1}{2}\left(q_{fuel}^{paz} \cdot PAZ + q_{pop}^{f.paz} \cdot (PU + PR)\right), \quad (19)$$

where q_{fuel}^{paz} and $q_{pop}^{f.paz}$ – specific fuel demand for AFF sector per agrozootechnical production (TJ/€), respective, per population (TJ/person).

To determine the electricity demand for the electrification of the district heating, transport, and fuel sectors, the efficiency of the conversion and use of energy resources in the current and transition conditions be considered. Thus, the electricity demand for electrification is calculated as:

a) district heating systems:

$$W_i^t = \frac{Q_{heat,i}}{3{,}6 \cdot \eta_{conv,i}} \cdot r_{electr}^t, \text{ (GWh)}, \quad (20)$$

where $Q_{heat,i}$ – the heat demand for economy sector *i* (TJ/year);
$\eta_{conv,i}$ – the conversion efficiency of electricity-to heat for economy sector *i*;
r_{electr}^t – the share of electric heating systems (%).

b) electric vehicles with batteries:

$$W_{tran,i}^{BEV} = \sum_{i=1}^{n} \frac{Q_{fuel,i}}{b_i \cdot \rho_i \cdot Q_i^r} \cdot w_{tran,i} r_{trans,i}, \text{ (GWh)} \quad (21)$$

where $Q_{fuel,i}$ – fuel consumption for electric vehicles (TJ/year);
$w_{tran,i}$ – specific electricity demand for electric vehicles (Wh/km);
$r_{trans,i}$ – the share of electric transport of type *i* (%).

c) electric vehicles with hydrogen fuel cells:

$$W_{tran,i}^{FCVEV} = \sum_{i=1}^{n} \frac{Q_{comb,i}}{b_i \cdot \rho_i \cdot Q_i^r} \cdot \frac{w_{tran,i}}{\eta_{electr} \cdot \eta_{FC}} \cdot r_{trans,i}, \text{ (GWh)} \quad (22)$$

where η_{electr} – the efficiency of alkaline electrolyzers, $\eta_{electr} = 74\%$;
η_{FC} – the efficiency of alkaline fuel cells, $\eta_{FC} = 63\%$;

d) electrofuels production:

$$W_{fuel,i} = \sum_{i=1}^{n} \frac{Q_{fuel,i}}{3{,}6 \cdot \eta_{efuel,i}} \cdot r_{fuel,i}, \text{ (GWh)} \quad (23)$$

where $Q_{fuel,i}$ – fuel demand (TJ);

$\eta_{efuel,i}$ – electrofuel production efficiency (%);

$r_{fuel,i}$ – the share of electrofuel *i* (%).

3. Results

The evolution of the final net electricity demand in the perspective of the presented concept of decarbonation of the national economy is presented in figure X. The electricity demand will increase 2 times until 2040 (8.49 TWh/year) and 4 times until 2070 (16.9 TWh/year) comparing to 2021 (4 TWh/year). The biggest electricity demand is corresponding to producing of electrofuels and substitution of the natural gas consumption (6.57 TWh/year) and traditional electricity demand (5.89 TWh/year). Thus, proposed measures can contribute to assure the energy security of country and diminishing dependence of national economy on price fluctuation for imported energy resources.

Decarbonation of the national economy by electrification and substitution of fossil fuels by VRES will lead to a reduction of GES emission of 5.3 million tons of CO_2 equivalent per year – a huge contribution to climate change mitigation.

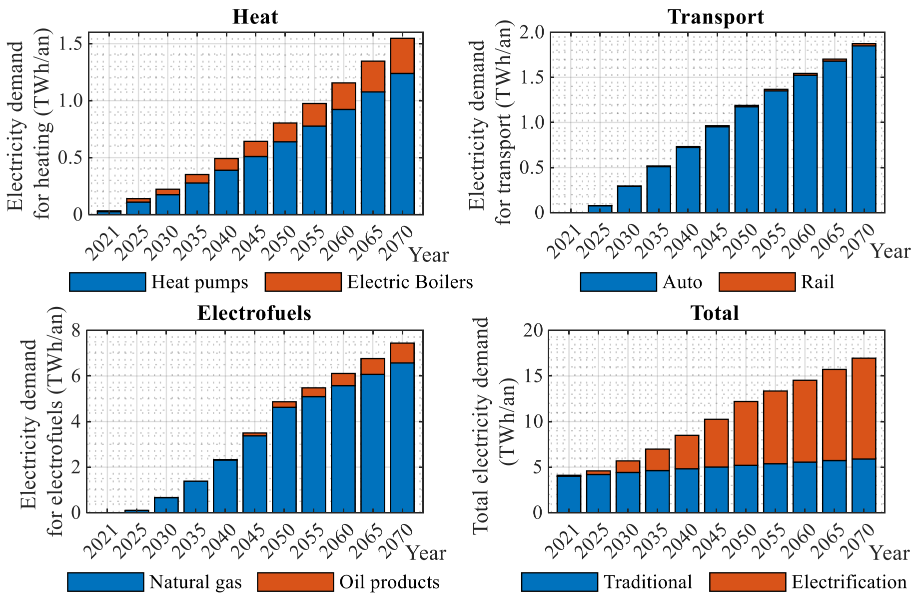

Fig. 4. The rate of electrification of the national economy

6. Conclusions

In this paper, there tried to present an estimation of the electricity demand from the perspective of the transition concept to 100% energy from RES. It is demonstrated that RES potential permits at least to cover the existing electricity demand and most of the possible future demand (2070). Obviously, this growth is considerable and its covering by plants using VRES requires considerable financial, scientific, and social efforts.

This result will be used for further analysis of power plant capacity using VRES, operation conditions of the power system in the massive presence of these types of sources, the environmental and economic feasibility of this transition.

R E F E R E N C E S

[1]. The European Green Deal, Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions, Brussels, 11.12.2019, COM(2019) 640 final.

[2]. Climate Change 2014: Synthesis Report – Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC, 2014.

[3]. *D. Braga*, "Photovoltaic Technical Potential in Republic of Moldova", 2019 International Conference on Electromechanical and Energy Systems (SIELMEN), 2019, pp. 1-6, doi: 10.1109/SIELMEN.2019.8905853.

[4]. *I. Sobor*, *A. Chiciuc*, *V. Rachier*, "Wind Energy Resources Atlas of the Repubic of Moldova", Technical University of Moldova, AWS Truepower SRL SL (Spania), Wind Power Energy SRL (Romania), ISBN 978-9975-87-245-7, Chisinau, 2017, p. 176.

[5]. *P. Andronic*, "Politica Energetică a Republicii Moldova (Energy Policy of the Republic of Moldova)", Technical University of Moldova, Engineering Meridian, No.1 (2015), pp.45-50.

[6]. *O. Capitan*, "Evaluarea potenţialului de biocombustibili gazoşi în Republica Moldova (Evaluation of the potential of gaseous biofuels in the Republic of Moldova)". Energetica Moldovei. Aspecte regionale de dezvoltare. Ediția III, 29 september – 1 octomber 2016, Chisinau, Republic of Moldova: Institute of Energy of the Academy of Sciences of Moldova, 2016, pp. 566-571. ISBN 978-9975-4123-5-3.

[7]. Statistics Bank of the National Bureau of Statistics of the Republic of Moldova. Available online: https://statbank.statistica.md (accessed on 11.05.2021).

[8]. *M. Child*, *D. Bogdanov*, *Ch. Breyer*, "The role of storage technologies for the transition to a 100% renewable energy system in Europe", Energy Procedia, Volume 155, 2018, Pages 44-60, ISSN 1876-6102, https://doi.org/10.1016/j.egypro.2018.11.067.

[9]. *N. Zhao*, *F. You*, "Can renewable generation, energy storage and energy efficient technologies enable carbon neutral energy transition?", Applied Energy, Volume 279, 2020, 115889, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2020.115889.

[10]. *K. Löffler*, *T. Burandt*, *K. Hainsch*, *P.Y. Oei*, "Modeling the low-carbon transition of the European energy system - A quantitative assessment of the stranded assets problem", Energy Strategy Reviews, Volume 26, 2019, 100422, ISSN 2211-467X, https://doi.org/10.1016/j.esr.2019.100422.

[11]. *A. Mazza*, *E. Bompard*, *G. Chicco*, "Applications of power to gas technologies in emerging electrical systems", Renewable and Sustainable Energy Reviews, Volume 92, 2018, Pages 794-806, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2018.04.072.