**MINISTRY OF EDUCATION**
UNIVERSITY POLITEHNICA of BUCHAREST

# DOCTORAL THESIS SUMMARY

## *FUNCTIONIG OF THE POWER SYSTEM WITH A VIEW OF THE MASSIVE INTEGRATION OF RENEWABLE ENERGY SOURCES*


**Author:** Dumitru BRAGA
**Doctoral supervisor:** Prof. dr. eng. Nicolae GOLOVANOV


**PhD COMMITTEE**

| | | | |
|---|---|---|---|
| **Chair of the committee** | Prof. dr. eng. Constantin BULAC | from | University POLITEHNICA from Bucharest |
| **Supervisor** | Prof. em. dr. eng. Nicolae GOLOVANOV | from | University POLITEHNICA from Bucharest |
| **Reviewer** | Prof. dr. eng. Ion STRATAN | from | Technical University of Moldova |
| **Reviewer** | Prof. dr. eng. Radu PORUMB | from | University POLITEHNICA from Bucharest |
| **Reviewer** | Prof. dr. eng. Dan MICU | from | Technical University of Cluj-Napoca |

**Bucharest, 2022**

## CONTENTS

## Acknowledgment

This doctoral thesis is dedicated to my mother, who guided me and implanted me the love of learning, through her own sacrifices provided me with the necessary conditions for studies at all stages of schooling, from primary to doctoral school. I also thank my wife for her understanding, constant encouragement, and unconditional trust. At the same time, I apologize to my children for the lack of paid attention during this doctoral thesis realization.

The doctoral thesis is the result of the effort made under the permanent guidance and support of the scientific supervisor Prof. Emeritus Dr. Eng. Nicolae Golovanov, to whom I am deeply grateful for the rigor, advice, and constructive critical remarks at each stage of my Dr. preparation.

I sincerely thank the members of the guiding committee for their advice, suggestions, encouragement, and always kind attitude. Special thanks to Prof. Dr. Eng. Radu Porumb, Prof. Dr. Stefan Gheorghe, Assoc. Prof. Dr. Eng. George Cristian Lazaroiu and Chief of Works Dr. Eng. Laurentiu Lipan for the support, motivation, and trust they offered me.

Thanks also are addressed to the team of professors of the Department of Power Engineering Systems, of the Faculty of Power Engineering, University POLITEHNICA from Bucharest, for the competence, professionalism, and motivation. I especially want to thank Prof. Dr. Eng. Ion Tristiu and Prof. Emeritus Dr. Eng. Mircea Eremia for their support, Prof. Dr. Eng. Lucian Toma and Prof. Dr. Eng. Mihai Sanduleac for their useful advice on the scientific reports presented at the department.

Last but not least, I would like to thank my colleagues from the Department of Energy of the Technical University of Moldova for their encouragement, appreciation, and support for the entire period of doctoral studies.

## KEY WORDS

Renewable energy sources; the potential of renewable energy sources; power system management; electricity forecasting; clustering technique; Nonlinear Autoregressive Neural Network technique; energy storage system; power system modeling.

## THESIS STRUCTURE

The paper is structured in 6 chapters, 206 pages, 176 bibliography sources and presents theoretical aspects, calculations, modeling, and interpretations of the results on the national power system functioning in the massive presence of renewable energy sources.

## CHAPTER I. INTRODUCTION

This introductory chapter presents the current global trends in the energy transition towards 100% energy from renewable sources (RES) and the current state of the national power system (NPS) of the Republic of Moldova. Also, it presents the vision on the transition towards 100% RES of the national economy of the Republic of Moldova and the purpose and objectives of the paper.

### 1.1. Global trends in energy field

The main concerns at the world level and, in particular, of the European Union (EU), are related to the use of RES and the diminishing climate change. These concerns have been reflected in EU legislative acts ("Winter Package", "Green Deal", "Fit for 55" Package, etc.). In recent years, the idea of a transition towards a climate-neutral economy has been amplified in the EU. According to these acts, this is a decisive decade for the EU to meet its commitments under the

Paris Agreement. The EU's long-term decarbonization goal, confirmed by the commitments in the "Ready for 55" package, is to reduce greenhouse gas (GHG) emissions by "55%" by 2030 compared to 1990 levels and to become the first climate-neutral continent by 2050.

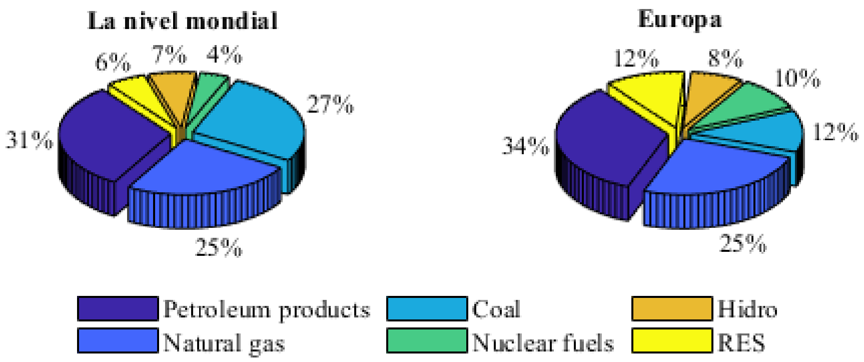


**Fig. 1.** The structure of the primary energy resources demand (2020) [1]

Nowadays, at the world level, the main source of energy is the fossil fuels (petroleum, natural gas and coal) used in the energy, industry, and transport sectors, presenting 83.1% (Figure 1) in the 2020 global balance [1]. At the same time, the processes of burning fossil fuels are an important source of anthropogenic GHG emissions.

The demand for primary energy resources is constantly growing. Thus, between 2006 and 2020, the global energy primary resources demand increased from 469.8 EJ to 556.6 EJ, by 1.32 %/year [1]. It is estimated that energy demand will grow considerably during the 21st century, and without any climate change measures, this problem cannot be mitigated.

The main types of RES used for electricity generation are hydro, wind, and solar energy. These sources are huge natural sources of energy, which can fully cover the existing and, most likely, the future energy demand of humans [3]. Due to the considerable impact that high hydropower has (flooding of land, change of flora and fauna, increase of the surface of the water mirror, etc.), wind and solar energy have a better perspective.

The impressive increase of the presence of wind and solar photoelectric power sources in the power system (EEA) requires solving several issues, including proper design of the electricity market, creation of the balancing electricity market, the requirements and costs of the system services, system adequacy and stability, and power system security, increasing the transmission capacity of electricity networks and interconnections, etc.

To ensure the stability and reliability of the power system, extend the lifetime of the equipment, reduce its maintenance costs, efficiently manage the existing and future RES capacity integrated into the power system, etc. it is required an efficient energy management system (EMS). The EMS must dispatch the RES capacities based on the data provided by a power forecast model. Therefore, the accuracy of the forecast models of electricity generated by solar PV and wind systems is crucial.

At the same time, the national power system is not ready for the energy transition from centralized fossil energy generation and energy production management to based distribution (inclusively using RES) and energy demand management. Thus, the massive integration of these types of sources into the existing power system is a major challenge for the functioning and control of the power system, endangering its reliability and stability [6]. Due to the intermittent nature of solar irradiance and wind speed, wind and solar energy are variable renewable energy sources (VRES).

The transition to 100% energy from RES involves enormous economic costs, which will fall on the shoulders of the population. Therefore, first of all, the population must be aware of the need for this transition, the problems it will face, and be ready to provide the necessary support for its realization.

## 1.2. The current state of the power system of the Republic of Moldova

In 2019, the total energy resources demand of the Republic of Moldova was "123 PJ" and the electricity demand 3 615 GWh. An impressive share of primary energy resources and electricity is used in the residential sector with 49.5% and, respectively, 44.5% and in the transport sector 27% and, respectively, 2% (Figure 2).

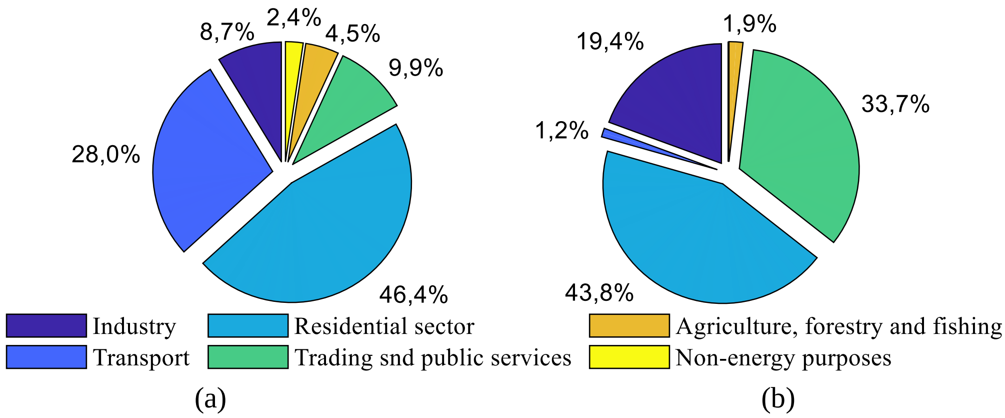


**Fig. 2.** The final demand of energy resources (a), and of electricity (b) of the Republic of Moldova (2019) [8]

The development of the country's economy is constrained by imports of energy resources (approx. 80%) and the increase of the price for this is aggravated by the fluctuations of the exchange rate of the national currency. The Republic of Moldova imports energy resources from the Russian Federation, Ukraine, and Romania. The primary production of energy resources in 2019 was 27.9 PJ [8]. The main share of production local energy resources is firewood 23.6 PJ (84.4%). The production of electricity and petroleum was insignificant, of 402 TJ and 203 TJ, respectively. The local primary energy resources are used mostly for heating and food preparation in rural areas in the residential sector (25.5 PJ). The electricity produced from RES is about 1%.

The Republic of Moldova signed the Paris Agreement, and it is the associate member of the EU and the member of the European Energy Community. Besides the advantages offered by these communities, it obliges the Government of the Republic of Moldova to transpose EU legislation into national normative acts and to implement the provisions of these acts.

The legislative acts, which regulate the RES field, are the Government Decision No. 102 of 05.02.2013 on the Energy Strategy of the Republic of Moldova until 2030 and Law No. 10 of 26.02.2016 on Promoting the use of energy from renewable sources. According to these acts, the objectives of the state policy in the RES field include:

- diversification of primary energy resources, including by capitalizing on RES;
- increasing the local electricity generation capacities;
- increasing the share of annual electricity production using RES;
- reducing GHG emissions by using RES and promoting energy efficiency.

For the Republic of Moldova, the main interest for the generation of electricity represents solar and wind energy and, respectively, for the heat generation (including by co-generation) biofuels.

## 1.3. Energy transition vision of the power system of the Republic of Moldova

The depletion of fossil fuel deposits in the accessible areas, the political, economic, or environmental situation at the regional or global level lead to an increase in the price of these resources. As the Republic of Moldova is dependent on imports of fossil energy resources, any price fluctuation, at regional or even global level, is a stress for the national economy, and especially for the population. Another reason for reducing the use of fossil energy resources is the low capacity of the energy interconnections with Romania and Ukraine, which would allow diversification of import sources of these resources or ensure energy security in the event of regional conflicts or natural disasters.

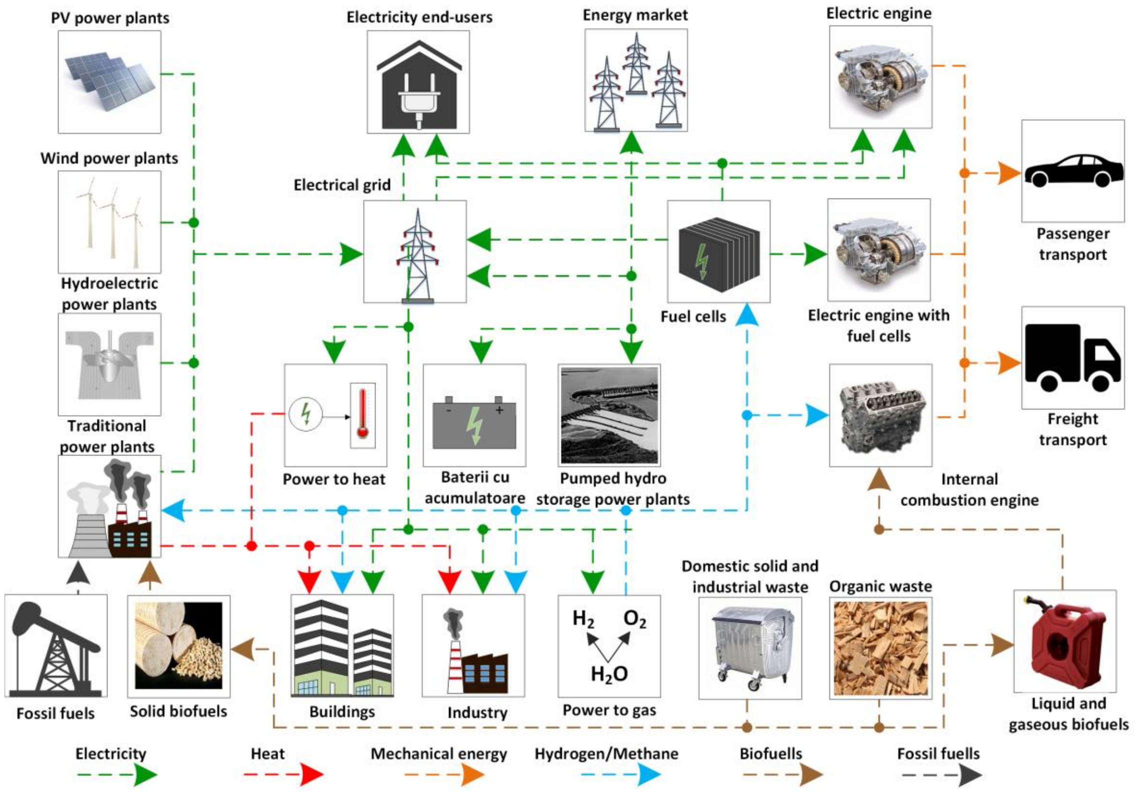


**Fig. 3.** The transition towards 100% energy from renewable energy sources

The main solution to overcome these challenges is the energy transition towards 100% energy from RES. The best argument for the energy transition is the important potential of RES of the Republic of Moldova, especially biomass, wind, and solar energy. This potential can allow the Republic of Moldova to cover the actual energy resources demand, or at least to considerably reduce the dependence on imports of fossil energy resources. To attract investment and develop the electricity sector, it is necessary to integrate the national power system into a regional energy market.

Electricity can be easily converted into other energy forms, especially heat, mechanical or chemical energy, widely used in all sectors of the economy. Electricity can be used for heating or air conditioning, domestic hot water supply, vehicle training, or even the production of synthetic fuels such as natural gas or petroleum products (Figure 3).

In line with the decarbonization requirements of the transport sector, urban passenger transport and private cars must be the first subject to electrification, followed by road freight and rail transport. Hybrid systems using heat pumps (PCs) and solar thermal collectors will replace distributed heat generation. An important role, as at present, will be given to CHPs equipped with steam turbines in central heating supply systems. They will cover the basic electricity load (during the winter period) because the basic function of these sources is to heat supply to users in urban areas.

To use the wind and photovoltaic potential and to regulate the voltage and frequency in the power grids by injecting/absorbing the active and reactive power from the grid, the ESS will be used. The surplus of electricity in the periods characterized by high values of wind speed and/or solar irradiance and reduced electricity demand will be partially stored in electrochemical, electromagnetic, and mechanical storage systems, and the rest will be used for methane and hydrogen production. The hydrogen produced will be partially used for fuel cells (FCs), and the rest will be injected into natural gas grids, replacing imported natural gas, or used to produce synthetic fuels.

Other solutions to improve the power systems' flexibility in the presence of RES are smart grids (SG) and smart consumers, which will allow limiting the peak and gap loads by modeling it according to the power generation possibilities and reducing power systems operating costs. Distributed generation and smart grids require the massive integration of Intelligent Electronic Devices (IED) and Communication and Information Technologies (TIC).

Due to the lower costs of energy generated using traditional sources, a financial system must be introduced to balance the costs and benefits of using the two forms of energy to stimulate the use of energy generated using RES and increase its share in the energy balance. Such a financial system may be based on mandatory quotas for energy use in RES or green certificates and a market for the trading of mandatory quotas or green certificates. For non-compliance with these obligations, financial penalties must be provided, which will represent considerably higher costs compared to those required to fulfill these obligations. Another tool that needs to be provided is feed-in tariffs, and by the growing share of RES in the power system, the transition to a competitive energy market must take place.

From a technical point of view, National Power System is not ready for this transition, as it was designed to operate according to the principle of centralized generation of energy by large fossil fuel sources and changing the generation schedule according to the end-user energy load schedule. This could easily be done, aiming that fossil fuels are available in the required quantities at any time. The energy transition supposes the use of wind and solar sources, which are characterized by quantitative and temporal variability, so that the generated energy by these sources often cannot cover the energy demand at the required time in the required quantities. And power plants using this type of source have considerably less power than traditional ones.

### 1.4. The purpose and objectives of the thesis

The thesis aims to identify, analyze and develop solutions for the energy transition to 100% RES and ensure the reliability and resilience of the national power system of the Republic of Moldova in the massive presence of RES.

The objectives of this thesis derive directly from the existing trends in the world and, in particular, in the EU, the agreements signed by the Republic of Moldova, and the situation in the energy sector. The overall objective is to contribute to ensuring the energy transition to 100% RES by increasing the penetration of the National Power System by RES, reducing dependence on imports of fossil energy resources, and reducing GHG emissions. Specific objectives of the thesis include:

- assessment of the energy wind and solar potential of the Republic of Moldova;
- identifying the locations for the placement of the power plants using VRES and estimation of their capacity and electricity generation;
- elaboration and application of electricity, solar radiance, and wind speed forecasting models;
- integration of VRES into the National Power System and a regional energy market, respectively;
- assessing the feasibility of the ESS used to ensure the adequacy of the ESS and smoothing the power generation graphs of power plants using VRES;
- assessing the feasibility of power plants using VRES;
- modeling the functioning of SEN in the massive presence of power plants using VRES;
- ensuring the quality of electricity;
- ensuring the National Power System adequacy.

# Chapter II. RENEWABLE ENERGY SOURCES POTENTIAL OF THE REPUBLIC OF MOLDOVA

This chapter presents the theoretical aspects of energy generation by VRES and the methods for assessing their energy potential. Also, there are estimated the theoretical and technical solar photovoltaic and wind sources potential, the potential locations for the placement of the photovoltaic power plants (PVPPs) and wind power plants (WPPs).

## 2.1. Photovoltaic energy potential of the Republic of Moldova

The evaluation of the solar photovoltaic (PV) technical potential of the Republic of Moldova is performed using the Global Solar Atlas (GSA), developed by the World Bank Group, that presents data on solar radiance at the global, regional, and country levels. GSA provides the necessary information for the PV potential assessment, the design of the PV systems, the choice of the optimal location, and the pre-feasibility evaluation of these systems. The GSA presents the average values, for a long period, for the PV resources (table 1).

**Table 1.** The solar radiance characteristics at the altitude of 2 m above the ground

| Characteristics | North | Center | South |
|---|---|---|---|
| Global horizontal irradiation, kWh/($m^2$·year) | 1220 | 1289 | 1363 |
| Global tilted irradiation at optimum angle, kWh/($m^2$·year) | 1419 | 1501 | 1588 |
| Optimum tilt of PV modules | $35^0/180^0$ | $35^0/180^0$ | $35^0/180^0$ |
| Air temperature at the altitude of 2 m over the ground, $^oC$ | 9.2 | 9.9 | 11.4 |
| Specific photovoltaic power output, kWh/$kW_i$ | 1159 | 1221 | 1285 |

**Table 2.** The photovoltaic solar technical potential of the Republic of Moldova

| Region | ATU | Used surface, $km^2$ | Installed capacity, MW | Generated electricity | |
|---|---|---|---|---|---|
| | | | | kWh/$kW_i$ | GWh/year |
| North | Sangerei | 10.62 | 440 | 1210 | 531.9 |
| | Glodeni | 5.67 | 235 | 1204 | 282.6 |
| | Falesti | 8.49 | 352 | 1208 | 424.9 |
| Center | Chisinau | 13.76 | 570 | 1232 | 702.2 |
| | Orhei | 0.70 | 29 | 1211 | 35.1 |
| | Ungheni | 13.53 | 560 | 1220 | 683.3 |
| | Soldanesti | 6.31 | 261 | 1203 | 314.3 |
| | Anenii Noi | 6.76 | 280 | 1235 | 345.6 |
| | Nisporeni | 7.71 | 319 | 1221 | 389.7 |
| | Straseni | 17.27 | 715 | 1214 | 868.1 |
| | Telenesti | 9.41 | 390 | 1204 | 469.0 |
| | Criuleni | 7.71 | 319 | 1225 | 391.0 |
| | Calarasi | 14.15 | 586 | 1216 | 712.4 |
| | Rezina | 7.58 | 314 | 1209 | 379.3 |
| | Ialoveni | 11.03 | 457 | 1232 | 562.8 |
| | Dubasari | 3.08 | 128 | 1227 | 156.5 |
| | Hancesti | 22.30 | 923 | 1232 | 1137.4 |
| South | Basarabeasca | 2.70 | 112 | 1327 | 148.5 |
| | Taraclia | 5.04 | 209 | 1262 | 263.3 |
| | Cantemir | 8.43 | 349 | 1257 | 438.6 |
| | Leova | 7.73 | 320 | 1254 | 401.1 |
| | Causeni | 0.61 | 25 | 1250 | 31.6 |
| | UTAG | 11.58 | 480 | 1251 | 600.0 |
| | Cimislia | 9.05 | 375 | 1242 | 465.3 |
| | Cahul | 0.28 | 12 | 1270 | 14.9 |
| | Stefan Voda | 0.23 | 10 | 1259 | 12.1 |
| Total | | 211.71 | 8767 | 1222 | 10761.6 |

To determinate the PV technical potential, the areas with direct solar radiance on the horizontal surface greater than 1200 $\mathrm{kWh/(m^2 \cdot year)}$ and the average annual potential for electricity generation greater than 1200 $\mathrm{kWh/kW_i}$ are accepted. According to GSA, such potential exists on about 90% of the country's territory, especially in the center and south part. The southern part of the country is characterized by flat plains suitable for the placement of PV farms. At the same time, the central part is more fragmented by hills and narrow valleys, with larger forested areas, especially in Hancesti, Ialoveni, Nisporeni, Ungheni, Calarasi, and Orhei districts.

Table 2 presents the PV technical potential of the Republic of Moldova, based on:

- the capacity of PV systems, which can be installed on 1 $km^2$, is 41 – 62 MW;
- the total area of the country of 30 319.8 $km^2$ (excluding UTASN – Territorial Administrative Unit on the Left Bank of the Dniester), and about 7 200 $km^2$ can be used for electricity generation by PV systems.

So, there are excluded areas of the fund of state-protected areas; national parks; natural and architectural monuments; scientific, natural, landscape and resource reservations; aquatic basins; forests and forest strips; airports and national roads; agricultural land. It is accepted an area covered by PV systems equal to 5% of the territory of the territorial administrative units (ATU) of the Republic of Moldova, that corresponds to the criteria mentioned above. Thus, the estimated PV technical potential of the Republic of Moldova is 10 761 GWh/an.

The final electricity demand of the Republic of Moldova was 3 813 GWh in 2019. Thus, theoretically, if energy storage is implemented, to cover the existing annual electricity demand, it is sufficient to use 1.6% of the available area of the country for PV systems.

## 2.2. Wind energy potential of the Republic of Moldova

In 2017, The Wind Energy Resources Atlas of the Republic of Moldova (WERARM) was developed by a team of researchers from the Technical University of Moldova (TUM), AWS TruePower, USA, and WindPower Energy (WPE), Romania. To elaborate the WERARM were used data regarding the measurements of the wind characteristics, collected by:

- 3 measuring poles, altitude of 10 ÷ 103 m, for 1 ÷ 2 years, WPE;
- 4 measuring poles, altitude of 10 ÷ 60 m, for 1 ÷ 3 years, TUM;
- 18 towers of meteorological stations, at an altitude of 10 m, for 22 years, State Hydrometeorological Service (SHS) of the Republic of Moldova.

The obtained data sets represent the average wind speed measured for intervals of ten minutes every three hours. These were stored in SHS databases. The Observed Wind Climate data were obtained by processing using the WAsP software. It contains wind rose, wind speed probability density histogram function $f(u)$, Weibull approximation, wind direction frequency $f_d$, Weibull distribution parameters $A$ and $k$, average speed u, power density $E$.

As a result, the maps of the wind energy resources of the Republic of Moldova at altitudes of 50 m, 100 m, and 150 m were created, which include wind speed, wind power density, Weibull $A$, and $k$ distribution parameters. Classifying the country according to the average annual speed and wind power density at the altitudes of 100 m, it is observed that [12]:

- on ~99% of the country the average speed is between 5 and 8 m/s;
- on ~6.8% of the country the power density is between 400 and 550 $W/m^2$;
- speeds of 6.5 ÷ 8 m/s are characteristic for the southern and northern regions of the country;
- the most suitable wind systems - class III, a tower height of 100 m;
- theoretically, the surface on which this type of turbine can be installed is 10 219 $km^2$ in the northern region, 8 136 $km^2$ in the central region, and 10 087 $km^2$ in the southern region.

To determinate the wind technical potential, the areas with a power density greater than 400 W/m2 are accepted and there are excluded: the state-protected areas; national parks; natural and architectural monuments; scientific, natural, landscape, and resource reservations; aquatic basins; forests and forest strips; urban and rural settlements; airports and national roads; urban areas and adjacent territory within a 500 m radius thereof; forest areas and adjacent territory within 200 m of them [12]. Thus, the area of surfaces with good potential (400 ÷ 500 W/m$^2$) and excellent (500 ÷ 600 W/m$^2$) obtained is 1830.2 km$^2$:

- southern region 1 007.6 km$^2$;
- central region 10.3 km$^2$;
- northern region 812.3 km$^2$.

The low potential in the central region is because here an important area is covered by forests and reservations. Considering that the electrical power of the wind installations that can be installed on 1 km$^2$ is 5 MW, the technical wind potential is 9 151 MW [12].

# Chapter III. POWER SYSTEM FUNCTIONING IN THE PRESENCE OF RENEWABLE ENERGY SOURCES

This chapter describes aspects of power system functioning in the presence of RES: power system reliability and resilience, electricity quality, socio-economic issues. It also presents solutions for the RES integration: reactive power control, energy storage, smart grids, cyber security, the electricity market, and pricing policy instruments. There are determined potential VRES power plant locations, power plant capacity, and electricity generation, and the power equipment for each power plant is chosen. A case study on the propagation of harmonic distortions in the power systems in the presence of VRES is also carried out.

## 3.1. The challenges of the massive integration of renewable energy sources into the power systems

The energy transition towards 100% RES involves the transition from centralized generation using fossil fuels and energy production management to distributed generation using RES and energy demand management. Last decades, due to the benefits of using RES, there has been a steady increase in the number of WPPs and PVPPs in the power systems, and the share of electricity produced by these sources in the global energy balance has also increased considerably. Also, the massive integration of RES into the existing power systems is a major challenge for the functioning and control of the power systems, jeopardizing their reliability and stability [6]. The intermittent nature of solar irradiance and wind speed, respectively, can be due to congestion in power grids, can influence the mechanisms and policy of the energy market, the flexibility and resilience of the powers systems, the existence of interconnections with other systems, etc. (figure 4). Power system management in the massive presence of RES must provide solutions to technical and economic challenges, including intermittent wind speed and solar irradiance, power systems functioning and maintenance costs, electricity quality, power systems adequacy, socio-economic and environmental impact, etc.

The integration of VRES into the power system also has a strong impact on the running costs of the power system. Variations in wind speed and solar irradiance cannot be predicted with high accuracy throughout the day and can vary from hour to hour or minute to minute. These variations in production may contribute to the increase in the operating costs (for balancing) of the power systems - ancillary costs (system services) and, consequently, to the cost of electricity produced by VRES.

Due to the limited possibility of VRES dispatching, during the period characterized by low wind speed and/or solar irradiance, the compensation of the electricity deficit and the balancing of power systems is achieved by injecting a larger amount of electricity, generated by classic dispatchable power plants, with a quick response and/or ESS. Energy demand management controls and disconnects non-critical loads if it is needed. The combination between generation and demand management can contribute to the power systems' flexibility.

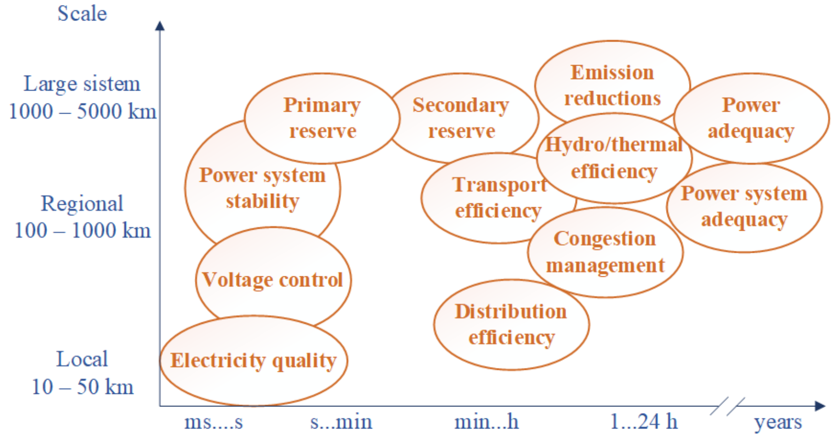


**Fig. 4.** The impact of VRES on the power systems [23]

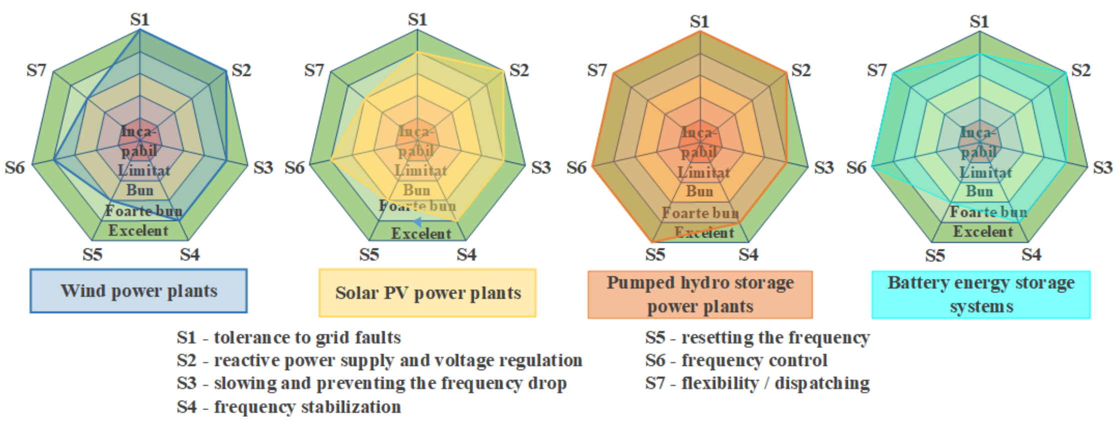


**Fig. 5.** The performance of the assured of reliability and resilience services performed by WPPs and PVPPs vs. PHSPPs and ESSs [72]

VRES can contribute to power systems' flexibility and stability by generation adjustment (figure 5). However, due to the intermittent nature of wind and solar irradiance, this service provided by VRES is considerably more expensive than that offered by traditional sources [71]. Efficient power systems management in presence of VRES requires integration of the IED for monitoring and control: advanced metering infrastructure, including smart meters, phasor measurement units, TIC systems, and SCADA. With the increasing use of Artificial Intelligence (AI) and computerized databases, the risk of cyber intrusions and the corruption of the process of generating, transporting, and distributing energy is increasing (Table 3).

**Table 3.** Statistics of recent causes of power interruptions [77]

| Cause | Percentage, % | Cause | Percentage, % |
|---|---|---|---|
| Malicious attack | 71.4 | Operator error | 28.6 |
| Resolved within 48 hours | 76.4 | Resolved after 48 hours | 23.6 |
| Affected > 100 000 people | 73.4 | Affected < 100 000 people | 26.6 |
| Solved internally | 50.0 | Solved externally | 50.0 |

An important aspect of VRES integration is energy quality - the ability of the power source to ensure a stable users energy supply without any disturbances: voltage variations (voltage sags, swells, interruptions, etc.), fast voltage variations (flicker), harmonics, frequency variation, power factor reduction, etc. (figure 6).

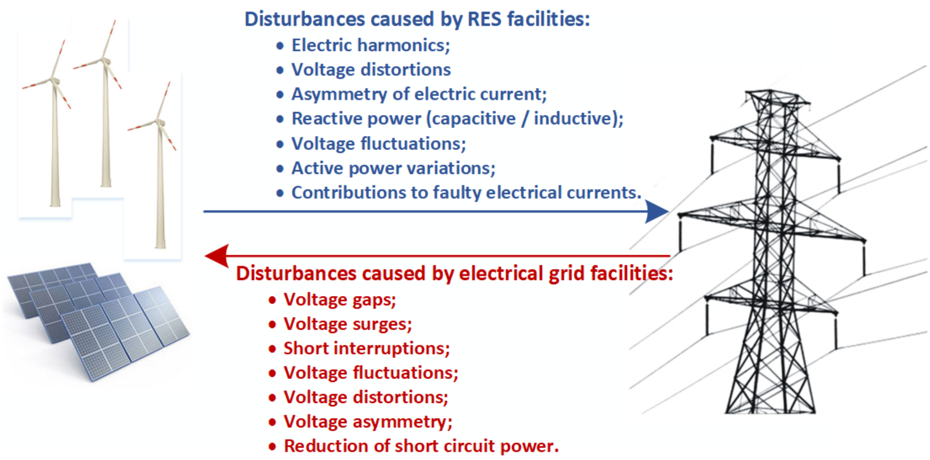


**Fig. 6.** Disturbances caused by power plants using VRES on power systems and vice versa

Uncertainties related to VRES power generation create impediments to participation in the energy market, as these uncertainties lead to a decrease in the efficiency of the operation of classical power plants that contribute to the balancing of the power systems. As a result, VRES energy producers, unable to guarantee the scheduling level of energy generation, are reluctant to participate in the day-ahead market (DAM).

The carbon footprint of VRESs energy is considerably lower than that generated by classic power plants using fossil fuels. The energy used for the construction of PVPPs and WPPs is equivalent to the energy generated by these sources for several months. The negative social and environmental impact of the PVPPs is the decommissioning of agricultural land. WPPs can damage the landscape by forming a concrete jungle through the location of wind farms, access roads, power grids, and substations [86].

Studies show that the sound produced by the rotation of the blades of wind turbines is not harmful to human health. Low-frequency noise from wind turbines can lead to anxiety and headaches. At the same time, to reduce the harmful effects on human health, the distance of the location of the wind installations from the localities and the limitation of the noise produced must be respected.

The equipment of wind systems can worsen the radars and television signals, creating interference with their signals [86]. This can lead to a reduction in the cost of land that includes WPP. The construction of power plants and power grids can lead to disruption of local ecosystems and require a long time to restore [80].

### 3.2. Solutions for the integration of variable renewable energy sources into the power system

Energy storage has an important role in energy quality ensuring, the reliability and efficiency of the power systems, and favoring new RES capacities integration into the power systems. ESS can facilitate the efficient integration of VRES into power systems by reducing peak loads and electricity cost. It is also ESSs contribute to increasing the power generation efficiency by excluding the functioning of additional classic power plants during peak hours and the use of only plants that operate permanently in the base area of the load curve. In the event of differentiated tariffs, ESS may increase the value of energy by storing and using it during peak hours. The combined use of VRESs and ESSs can increase the capacity factor of power plants, reduce the payback period, ensure local energy independence, mitigate transient regimes, increase low voltage ride through, ensure system start-up from blackout, ensure power systems adequacy, etc.

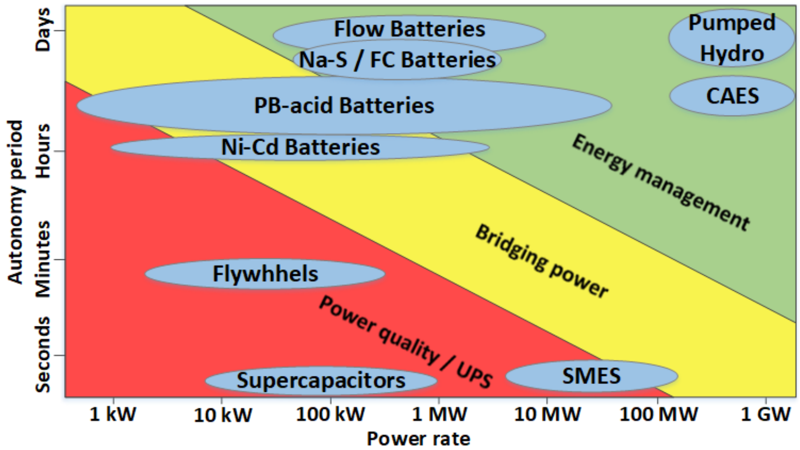


**Fig. 7.** Applications of the main types of ESSs [104]

A key element for the integration of VRES into the power systems, decarbonization, reliability, and economic efficiency of the energy sector are SG. Simultaneously with the promotion of distributed generation, the users change their status of passive operators, so that they can also become energy producers and inject the generated energy into the power grid. SG suppose two-way power flows, both from sources to energy users and vice versa (figure 8).

The integration of VRES, IED, and TIC, leads to the transformation of the power system from a physical system, as we know it, into a complex cybernetic-physical power system [76]. This fact changes considerably the aspect of a modern power system, respectively the requirements regarding existing security methods. As the power systems are dynamic, any delay or interruption in the data transmission process may affect the security of its functioning. Given these challenges, it is necessary to change grid codes to detect and prevent cyber-attacks. There are numerous cyber intrusion detection systems, that use various artificial intelligence techniques.

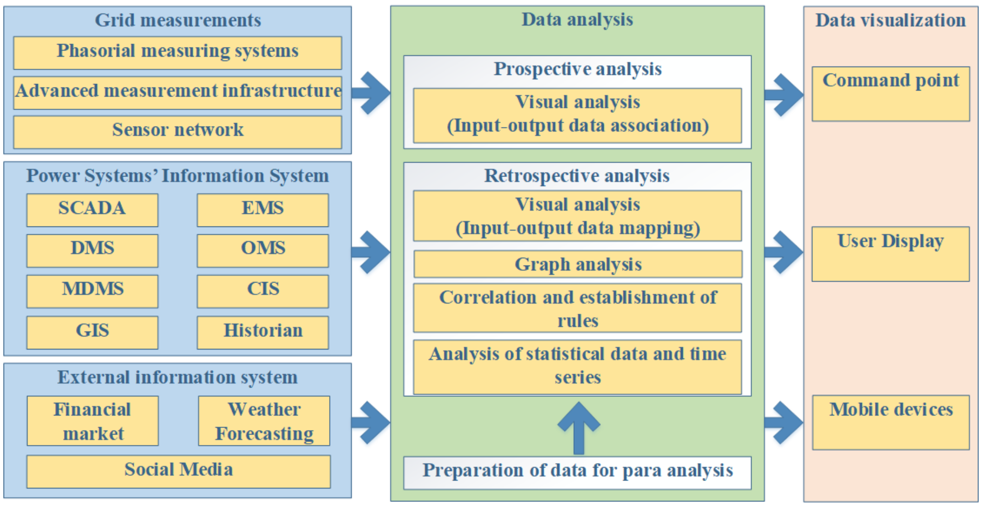


**Fig. 8.** Information flow in smart grids

The aspects that influence the electricity price in the electricity market are the electrical load and its seasonal characteristics, fuel costs, variable O&M costs of power plants, power system transport capacity, environmental regulations, weather characteristics, and other factors specific to the electricity market. Due to lower marginal costs, the electricity prices for electricity generated by PVPPs and WPPs are often lower than for electricity generated by traditional power plants, thus placing them higher in the order of merit in the energy market. Thus, VRESs harm the order of merit and lead to a reduction in energy prices in the day-ahead market.

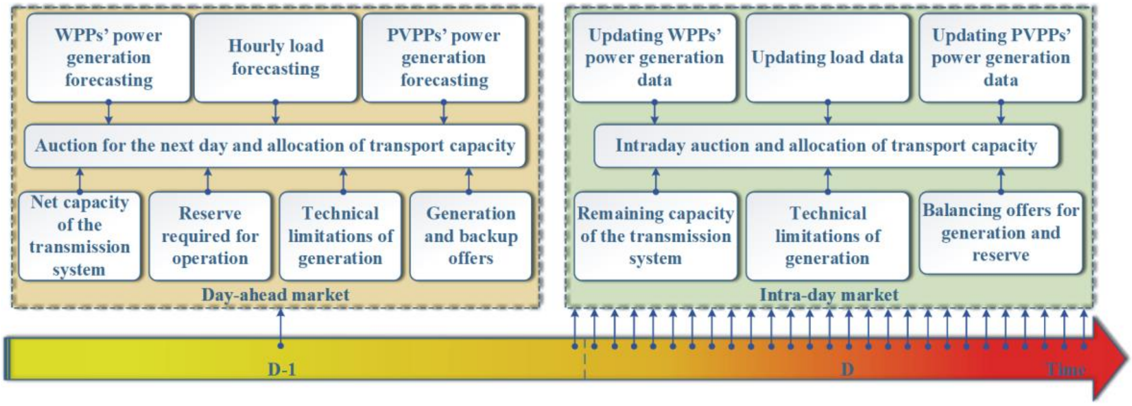


**Fig. 9.** The model of the day-ahead and the intraday energy market

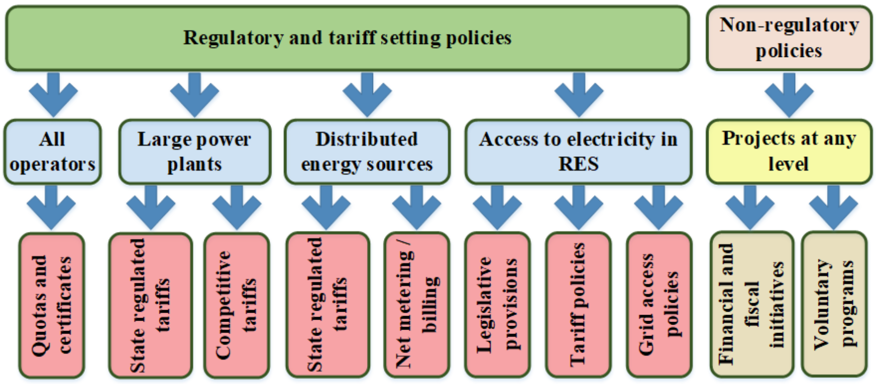


**Fig. 10.** The classification of energy policies [107]

The objectives set out in the strategies for integrating RES into the power systems are an important signal for encouraging investment in RES promoting and serve as a basis for support policies and measures, which allow the strategies to be transposed into concrete actions, including financial instruments and voluntary programs for energy users and producers (figure 10).

### 3.3. Wind and photovoltaic power plants

The proper choice of the WPPs site is very important for economic efficiency, population acceptability, and environmental impact. To determine the WPPs sites, the following must be considered: wind and terrain characteristics; extreme weather events; the presence of the access way, etc. When placing wind systems within the WPPs, it must be ensured that it is used the maximum possible power of the airflow, avoiding the negative influence of neighboring installations. Losses that may occur include: wake effect (5 ÷ 10%); blade surface contamination (1 ÷ 2%); internal electricity grid (1 ÷ 3%); technical failures (<2%); rapid changes of wind direction (< 1%).

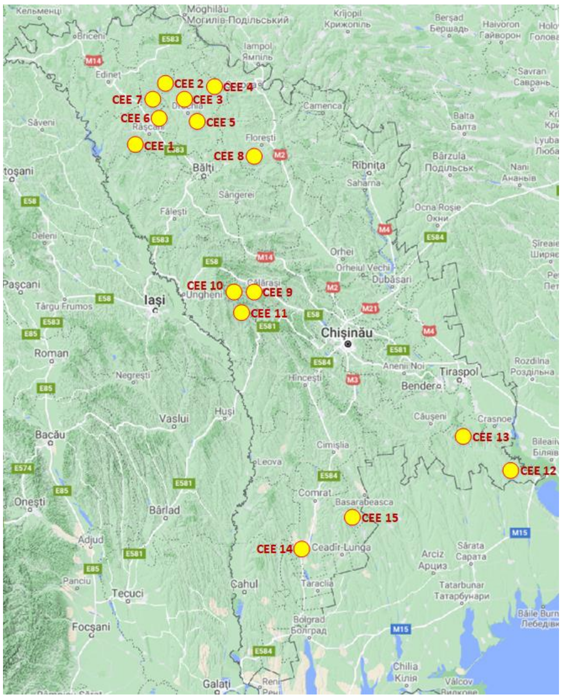


**Fig. 11.** Placement of the WPPs

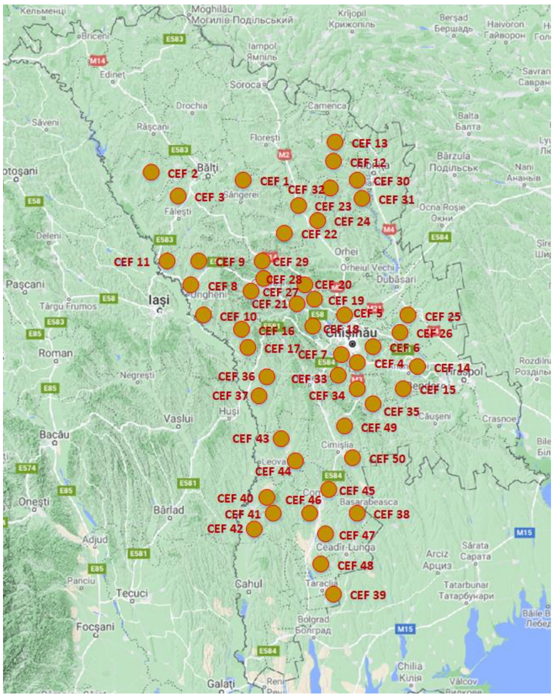


**Fig. 12.** Placement of the PVPPs

**Table 4.** Estimation of the annual WPP energy generation

| WPPs | Capacity, MW | Electricity, GWh/year | WPPs | Capacity, MW | Electricity, GWh/year | WPPs | Capacity, MW | Electricity, GWh/year |
|---|---|---|---|---|---|---|---|---|
| WPP 1 | 178 | 546.0 | WPP 6 | 68 | 218.4 | WPP 11 | 26 | 85.7 |
| WPP 2 | 108 | 293.6 | WPP 7 | 62 | 176.8 | WPP 12 | 284 | 1129.6 |
| WPP 3 | 42 | 125.2 | WPP 8 | 128 | 465.0 | WPP 13 | 104 | 402.5 |
| WPP 4 | 128 | 353.2 | WPP 9 | 46 | 173.8 | WPP 14 | 418 | 1470.6 |
| WPP 5 | 72 | 214.8 | WPP 10 | 72 | 274.5 | WPP 15 | 376 | 1271.2 |
| Total | | | | | | | 2112 | 7200.8 |

For the location of the WPPs, there are selected 15 sites are for WPPs placement (figure 11), with average annual wind speeds of 6.0 ÷ 7.2 m/s and the wind predominant direction northwest. The characteristics of the central region limit the installed capacity of the WPPs sites there, but in the southern and northern regions, other locations can be selected. For the wind characteristics of the Republic of Moldova, the capacity factor varies within the limits of 0.25 ÷ 0.35 (2100 ÷ 3100 hours). There is chosen the wind turbine V110-2.0 MW, Vestas, with a rotor shaft height of 100 m, suitable for low and medium wind speeds.

Besides the solar irradiance and the availability of surfaces, the PVPPs placements aim the uniform distribution in the country and, at the same time, the proximity as close as possible to the load centers. Based on these principles, 50 sites are chosen for the PVPP site with a total capacity of 1940 MW (figure 12).

For PVPPs there are chosen SPR-P17-335-COM PV panels, 1500 V series, SunPower (USA), mounted on the ground on fixed supports with an optimal angle tilt for each site ($35^0/180^0$ or $36^0/180^0$). The SINACON PV 5000, Siemens, equipped with a medium power transformer, a medium voltage switchboard, is chosen to transform direct voltage into alternating voltage. This inverter is capable of providing a power factor $\cos\varphi = 1$ on all supplied active power levels. A STATCOM connected to the 35 kV bus is applied for reactive power control.

**Table 5.** Estimation of the annual PVPP energy generation

| PVPPs | Capacity, MW | Electricity, GWh/year | PVPPs | Capacity, MW | Electricity, GWh/year | PVPPs | Capacity, MW | Electricity, GWh/year |
|---|---|---|---|---|---|---|---|---|
| PVPP 1 | 52.81 | 56.7 | PVPP 2 | 29.34 | 31.44 | PVPP 3 | 29.34 | 31.5 |
| PVPP 4 | 99.75 | 109.97 | PVPP 5 | 29.34 | 32.22 | PVPP 6 | 99.75 | 109.62 |
| PVPP 7 | 29.34 | 32.36 | PVPP 8 | 52.81 | 57.46 | PVPP 9 | 29.34 | 31.92 |
| PVPP 10 | 52.81 | 57.5 | PVPP 11 | 29.34 | 31.92 | PVPP 12 | 29.34 | 31.41 |
| PVPP 13 | 29.34 | 31.35 | PVPP 14 | 29.34 | 32.53 | PVPP 15 | 29.34 | 32.38 |
| PVPP 16 | 52.81 | 57.8 | PVPP 17 | 29.34 | 32.22 | PVPP 18 | 52.81 | 57.61 |
| PVPP 19 | 29.34 | 31.98 | PVPP 20 | 29.34 | 32.17 | PVPP 21 | 29.34 | 31.98 |
| PVPP 22 | 29.34 | 31.56 | PVPP 23 | 29.34 | 31.58 | PVPP 24 | 29.34 | 31.63 |
| PVPP 25 | 52.81 | 57.69 | PVPP 26 | 52.81 | 57.92 | PVPP 27 | 29.34 | 31.88 |
| PVPP 28 | 29.34 | 31.96 | PVPP 29 | 29.34 | 31.88 | PVPP 30 | 29.34 | 31.5 |
| PVPP 31 | 29.34 | 31.63 | PVPP 32 | 29.34 | 31.73 | PVPP 33 | 99.75 | 109.69 |
| PVPP 34 | 29.34 | 32.3 | PVPP 35 | 29.34 | 32.38 | PVPP 36 | 52.81 | 58.48 |
| PVPP 37 | 29.34 | 32.38 | PVPP 38 | 29.34 | 32.87 | PVPP 39 | 29.34 | 33.29 |
| PVPP 40 | 29.34 | 32.95 | PVPP 41 | 29.34 | 33.04 | PVPP 42 | 29.34 | 33.06 |
| PVPP 43 | 29.34 | 32.93 | PVPP 44 | 29.34 | 32.68 | PVPP 45 | 29.34 | 33.02 |
| PVPP 46 | 29.34 | 32.95 | PVPP 47 | 29.34 | 33 | PVPP 48 | 29.34 | 33.27 |
| PVPP 49 | 99.75 | 111.12 | PVPP 50 | 29.34 | 32.7 | Total | 1936.4 | 2127.11 |

**Study case: propagation of harmonic distortions in electric distribution systems**

To assess the VRES sources' impact on the electricity quality in the power systems, it is proposed to integrate into the Power System Calarasi one WPP of 46 MW and three PVPPs of 29.34 MW each. The main electrical load of Power System Calarasi is represented by the residential users. Due to the presence of power electronics at the interface of WPPs, PVPPs, and ESSs with the electric grid, their functioning is associated with the propagation of the harmonic disturbance into the power systems, which are manifested by voltage distortion in the PCC.

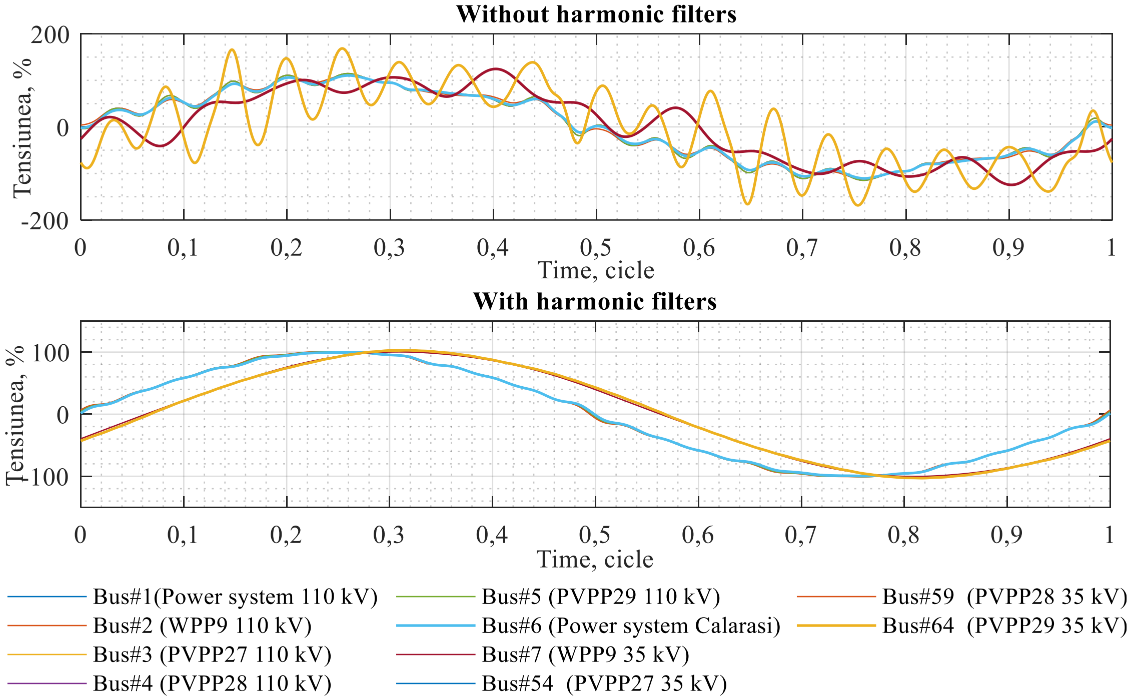


**Fig. 13.** The voltage distortions with and without the application of harmonic filters in the point of common coupling

These distortions can spread in the internal electric grid of the power plants, as well as in the power systems. The impact of harmonic distortions increases as the VRES capacities integrated into the power system increase and the short-circuit power of the power system decreases.

Figure 13 presents the comparison between harmonic distortion without and with the harmonic filters. It is observed that the highest value of THDU (without the harmonic filters) for WPPs the harmonics have ranks 5, 7, and 11, and for PVPPs 11, 13, 17, and 19. The impact of PVPPs is higher in comparison with WPPs ($THDU_{CEF} = 7{,}87$ versus $THDU_{CEE} = 6{,}83$).

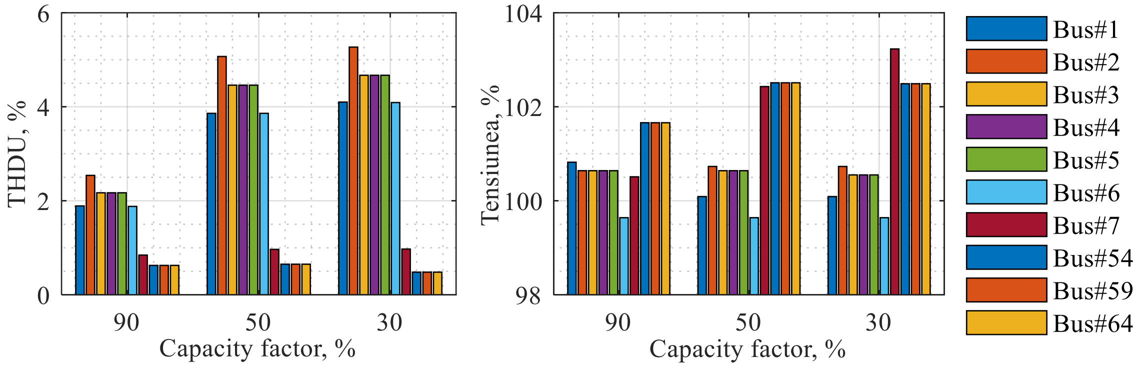


**Fig. 14.** THDU and voltage values in dependence on capacity factor

**Table 6.** The impact of harmonic distortion emissions on power plants connected to distribution power system

| Bus | With harmonic filters (all sources) | | With harmonic filters (all source except PVPP 27) | |
|---|---|---|---|---|
| | THDU, % | Voltage, V | THDU, % | Voltage, V |
| Bus #1 (Power grid) | 1.89 | 110 | 4.49 | 110.1 |
| Bus #2 (WPP 9) | 2.54 | 110.9 | 5.17 | 110.9 |
| Bus #3 (PVPP 27) | 2.17 | 110.8 | 6.74 | 110.9 |
| Bus #4 (PVPP 28) | 2.17 | 110.8 | 4.79 | 110.9 |
| Bus #5 (PVPP 29) | 2.17 | 110.8 | 4.79 | 110.9 |

In periods, characterized by high values of wind speed and/or solar irradiance, the increase of VRES electricity generation leads to an increase in the value of the fundamental component of the electrical voltage and, respectively, to a reduction in THDU. And vice versa, in periods characterized by the reduction of VRES electricity generation, the value of the fundamental component of the electrical voltage decreases, and the THDU increases (figure 14). The harmonic distortions generated by one of the sources connected to the power system are propagated in the grid, influencing the functioning of the other sources connected to the grid (table 6).

## Chapter IV. SOLAR IRRADIANCE AND WIND SPEED FORECASTING

This chapter presents the methods for forecasting solar irradiance, wind speed, and electricity generated by CEE and CEF, and the performance indicators of these methods. Two long-term forecasting models (<1 year) are proposed. The first solar irradiance forecasting model is based on the clustering method and the second solar irradiance and wind speed forecasting model on the Nonlinear Autoregressive Neural Network method.

### 4.1. Forecasting methods

In the absence of control of electricity production by these VRES, efficient forecasting allows anticipation of the electricity injected into the power systems and, therefore, better management of the electricity demand-generation balance (Figure 15). In the event of a high degree of power systems penetration by VRES, some rapid events may lead to system crash [6]. Forecasting models estimate electricity production by compiling meteorological and climatic characteristics and technical data of energy conversion systems.

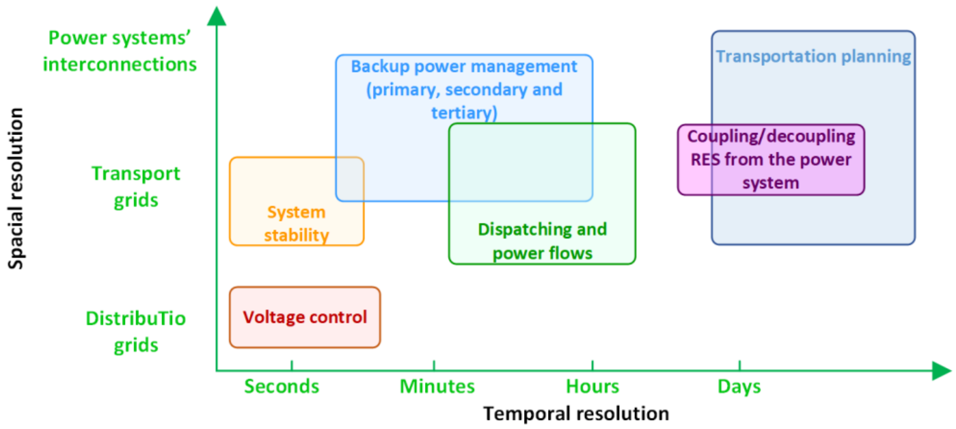


**Fig. 15.** Application of the forecasting models [126]

The accuracy of the forecasting is extremely important for the optimal choice of the location of solar PV or wind systems, for determining the power reserve, and power systems balancing. The forecasting accuracy is affected by the change of the time horizon, even if the other parameters or the forecasting method are not changed. The forecasting accuracy for a period of up to 72 hours is quite good, but with the increase of this period, the results of the forecasting become less credible. For the forecasting made four hours before, the average error is about 4%, for the forecasting made the day ahead - 10%, and at the increase of the forecasting period, it can reach 40% [131].

In the literature, the most common indicators of the accuracy of forecast models are [132]: Normalized Error ($nE$); Mean Absolute Error ($MAE$); Normalized Mean Absolute Error ($NMAE$); Mean Bias Error ($MBE$); Standard Deviation Error ($SDE$); Mean Square Error ($MSE$); Root Mean Square Error $RMSE$; Mean Absolute Percentage Error ($MAPE$); Correlation Coefficient ($R$).

A more accurate and universal error indicator system is essential for forecasting. For example, the $RMSE$ is more sensitive to the presence of wrong data compared to the $MAE$. Therefore, if there are doubts about the quality of the evaluation data set, the $MAE$ should be preferred as the main evaluation criterion, as it has greater stability when faced with large prediction errors.

### 4.2. Solar irradiance forecasting using clustering techniques

Most of the models presented in the literature represent the prediction model of solar irradiance or power generated by solar PV systems for the short or very short term. At the same time, models for medium- or long-term forecasting are extremely rare [135]. Considering these, three models are proposed using the clustering method for the long-term global horizontal irradiance (GHI) forecasting (<1 year):

Model 1. – hybrid model using *k*-means and standard mathematical statistics techniques.
Model 2. – hybrid model using *k*- means and NAR techniques.
Model 3. – hybrid model using *k*- means and NARX techniques.

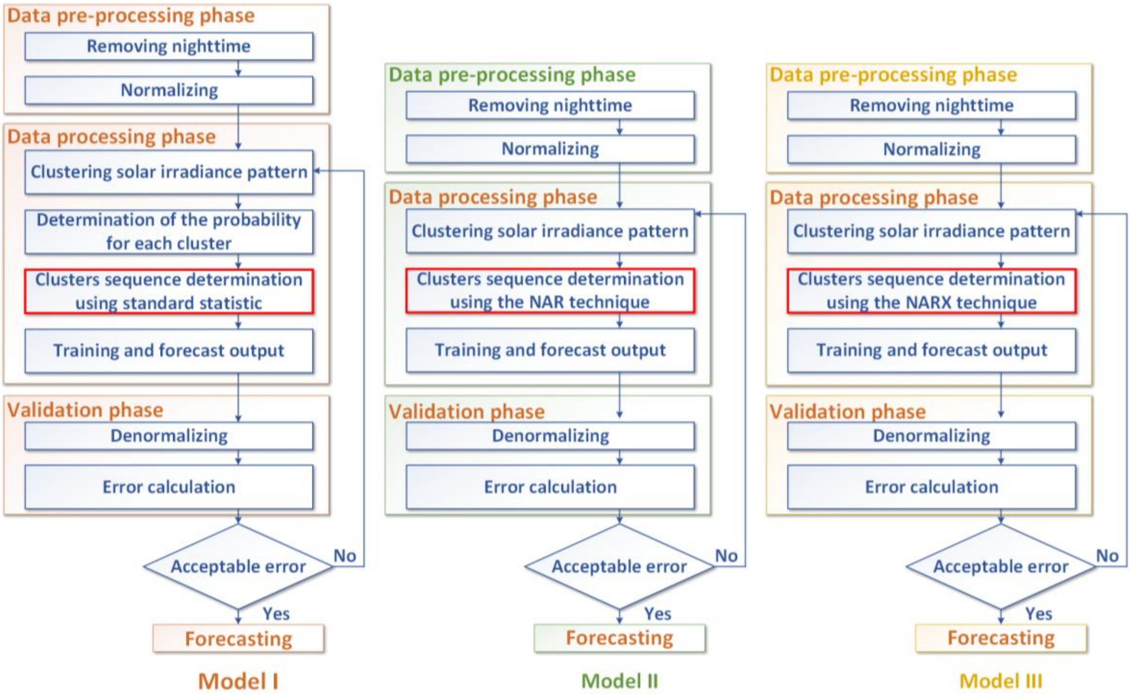


**Fig. 16.** Block diagrams of forecasting models using the clustering technique

As input data, for the three models, there are used the time series of GHI for a period of four years (2016 - 2019) for the municipality of Chisinau, Republic of Moldova. These data include the results of daily measurements at 06:30, 09:30, 12:30, 15:30, 18:30. Time series with time data are obtained by linear interpolation. Exogenous data used for model 3 include the average daily air temperature and humidity, atmospheric pressure, dew point temperature, wind speed, and direction for the same period and location.

To compare the characteristics of GHI for different year periods it is necessary to exclude the night period (time interval between sunset and sunrise) and bi-normalize solar irradiance (representation of solar irradiance and sunlight time by relative values between 0 and 1). The choice of the optimal number of K clusters can be made starting from the minimum values of the profile of the patterns and the sum of the Euclidean Distances between the centroids of the clusters [137]. For $K = 4$ the practical application consists of a simple classification of clusters in clear, predominantly clear, predominantly cloudy, and cloudy [141].

To build the sequence of days are used: standard math probability for Model 1. and *Neural Net Time Series Application*, *Deep Learning Toolbox*, *MATLAB®* for Model 2. and Model 3.

Figure 18 presents the sample of predicted solar irradiance. To assess the performance of the forecasting models, the results are compared with those provided by the persistent model, used for GHI forecasting for the same time horizon, period, and site (figure 19). The performance of model 1 is comparable to that of the persistent model and exceeds it insignificantly in the case of the GHI hourly forecasting. The best performance is recorded for models 2 and 3. Although model 3 uses a larger number of input data, its performance is insignificantly higher than a simpler model 2.

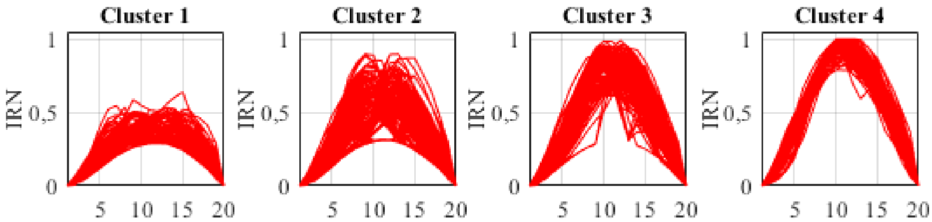


**Fig. 17.** Clustering of the normalized solar irradiance

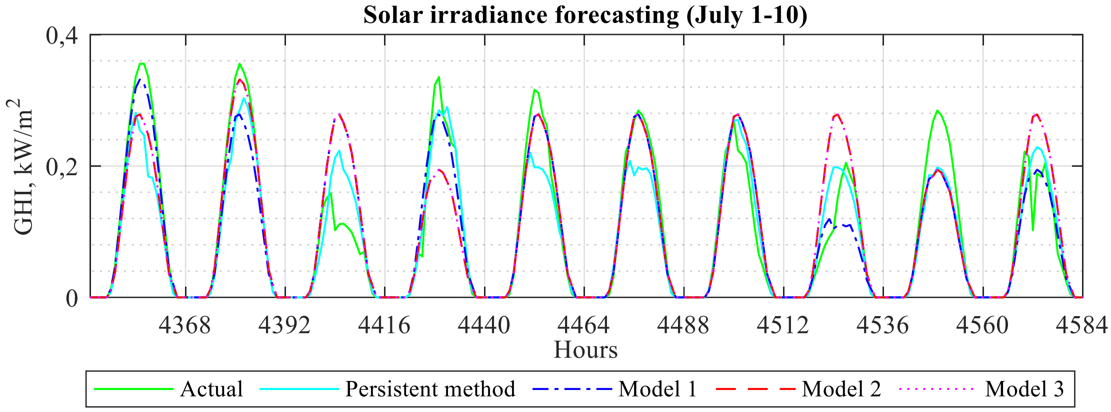


**Fig. 18.** Sample of actual and forecasted solar irradiance

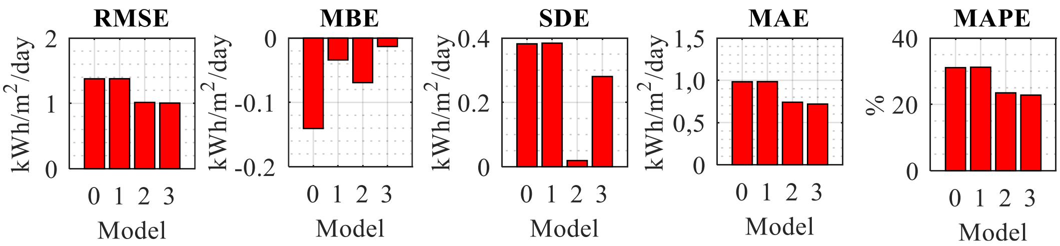


**Fig. 19.** The performance of the forecasting models using clustering:
0 –persistent method; 1 – Model 1; 2 – Model 2; 3 – Model 3.

Negative $MBE$ values indicate that all three models tend to overestimate the actual values of solar irradiance. However, this overestimation is insignificant. The correlation coefficient values for all three daily irradiance forecasting models are $R > 0{,}942$, which indicates a good correlation between the predicted and actual solar irradiance values. The accuracy assessment for these forecasting models shows relatively high indicators error values. These models can be used successfully to generate different scenarios of solar irradiance, which will be used to study the functioning of the power system in the massive presence of RES, the evaluation of the maximum RES capacity that can be integrated into the power systems, ESSs design, optimal operating costs, etc.

### 4.3. Application of Nonlinear Autoregressive Neural Network models

For the long-term (one-year) forecasting of GHI and wind speed, two models are proposed:

Model 1. *Nonlinear Autoregressive Neural Network* (NAR NN), and

Model 2. *Nonlinear Autoregressive Neural Network eXogenous* (NARX NN).

These hybrid models represent recurring dynamic networks, with multi-layered feedback connections of neural networks. Like any ANN model, these models include input layers, hidden layers, and output layers.

Input data (period 2016 – 2019):

A. GHI forecasting (for Chisinau municipality):

Model 1. Time series of GHI.


**Fig. 20.** The process of elaborating the ANN model

Model 2. Time series of GHI, air temperature and humidity, atmospheric pressure, wind speed and direction, and sky nebulosity.

B. Wind speed forecasting (for Chisinau municipality):

Model 1. Time series of wind speed.

Model 2.

Model 3. Time series of wind speed and direction, air temperature and humidity, and atmospheric pressure.

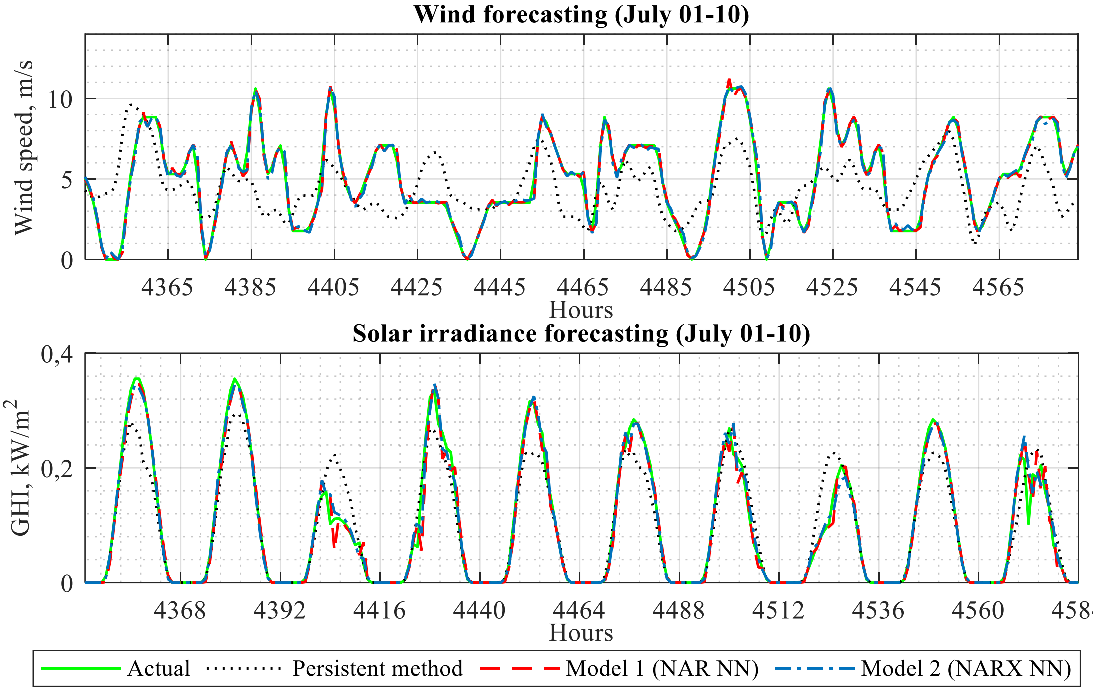


**Fig. 21.** Sample of actual and forecasted solar irradiance and wind speed

The *Neural Net Time Series*, *Deep Learning Toolbox*, *MATLAB®* application is used for the model training process. The *Levenberg-Marquardt* training algorithm is chosen due to the high level of accuracy and the short time required for the training process.

For performance evaluation and validation, the results of the forecasting of these models are compared with the results obtained by the persistent forecasting model. To view the results of the forecasting, figure 21 represents the actual (real) and forecasting time series sample (July 1-10) for GHI and wind speed.

Considering accuracy assessment (figure 22), it can be observed that both models have a high degree of accuracy, at the same level as the models presented in the specialized literature, and considerably higher than the persistent model. The forecasted data by these two models have a high degree of convergence towards the solution. If these models are compared, it is observed that model 2 (NARX NN) exceeds the performance of model 1 (NAR NN), although not as dramatic as in the case of the persistent model.

The main advantage of these models is the high performance, the low number of neural networks due to feedback connections, the short time required for training (<100 s), the applicability for other sites or periods without significant changes in the model structure. Disadvantages include a large amount of required data, which is not always available, and the results can sometimes be unpredictable. Thus, the results of the forecasting must be "filtered" to eliminate wrong data.

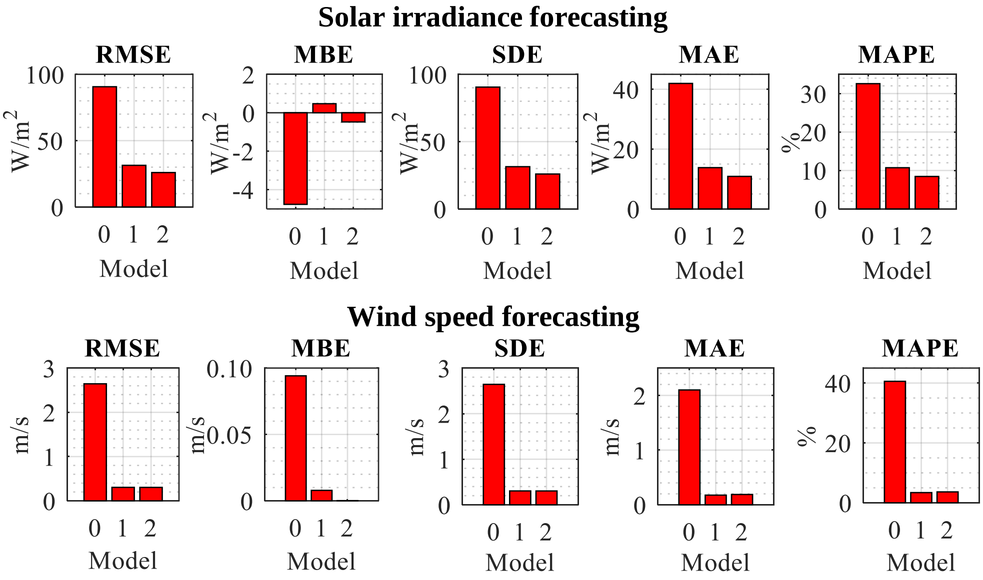


**Fig. 22.** The NAR NN and NARX NN models' performance:
0 – persistent method; 1 – Model 1 (NAR NN); 2 – Model 2 (NARX NN)

# Chapter V. ENERGY STORAGE SYSTEMS INTEGRATION INTO THE POWER SYSTEM

The main ESSs types and their application fields are analyzed. Also, there are analyzed the evolution of investment and O&M costs for PVPPs, WPPSs, and ESSs on the European market. For power plants using VRES, the Levelized Cost of Energy ($LCOE$) is determined. The potential sites for PHSPPs are chosen and the required balancing storage for the National Power System of the Republic of Moldova in the massive presence of RES are determined. To National Power System balance, the possibility of using hydrogen energy storage systems (HESS) using electrolyzers and alkaline fuel cells is also being considered.

The economic feasibility of using ESSs (PHSPPs and HESS) to balance the National Power System and to smooth the power generation graphs of VRES power plants (BESSs) is determined.

## 5.1. Electrical energy storage

The integration of VRES into the power systems requires the adoption of efficient, reliable, and feasible technologies for energy storage. To date, several technologies have been developed for storing excess energy generated by VRES to meet the energy demands independently of weather conditions (wind speed and solar irradiance) and to replace the energy generated by classic fossil fuels power plants (Figure 23).

The functions performed by the ESS are quite complex, and the storage solutions may vary depending on the storage time, the charge/discharge cycle, the environmental operating conditions, and the integration in the power generation or use systems, etc. (figure 24). Although theoretically, all ESS technologies characterized by high power density can provide system services, their efficiency differs depending on the type of ESS and the specific requirements for the given services. It is noted that the specific cost per installed capacity and that per stored energy are important regardless of the type of application.

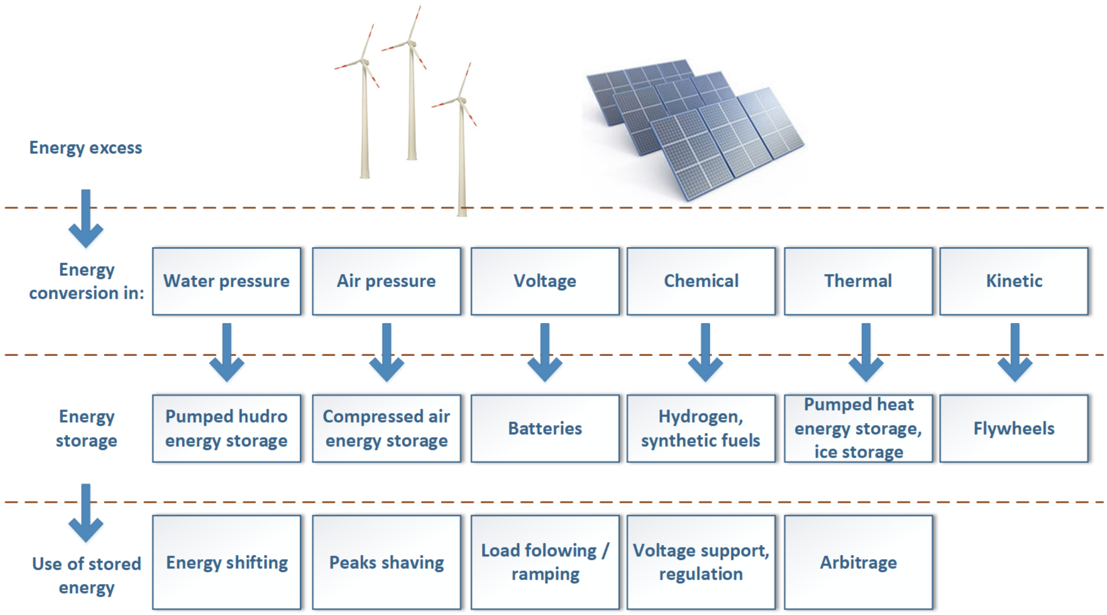


**Fig. 23.** Electrical energy storage systems

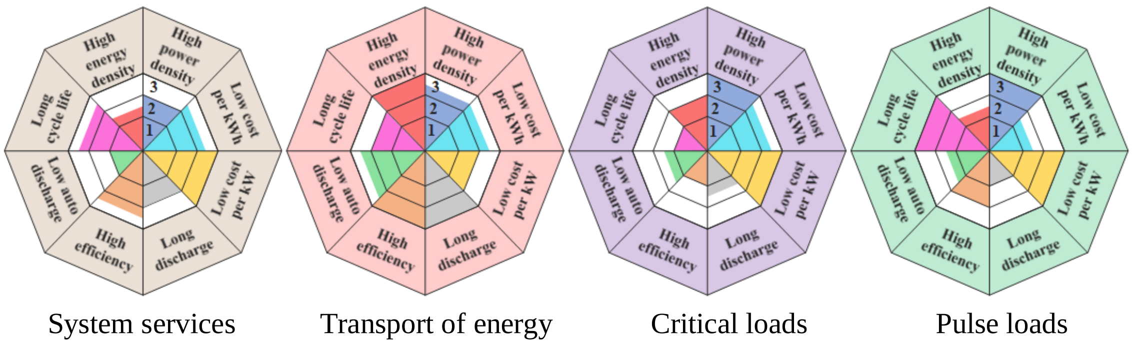


**Fig. 24.** The importance of the ESSs for different application:
1 – not very important; 2 – important; 3 –very important [103]

## 5.2. Feasibility assessment of the power plants using variable renewable energy sources

The cost of energy generated is one of the main criteria for assessing the economic feasibility of an investment project. The long-term cost of energy is often expressed by the $LCOE$, which is the ratio of the value of total discounted costs and the total volume of generated electricity over the entire study period. The evolution of the investment costs and the price of electricity generated by PVPPs and WPPs are presented in figure 25. Estimated $LCOE$ varies within the limits of 0.058 and 0.062 €/kWh for PVPPs and 0.036 and 0.046 €/kWh for WPPs (figure 26).

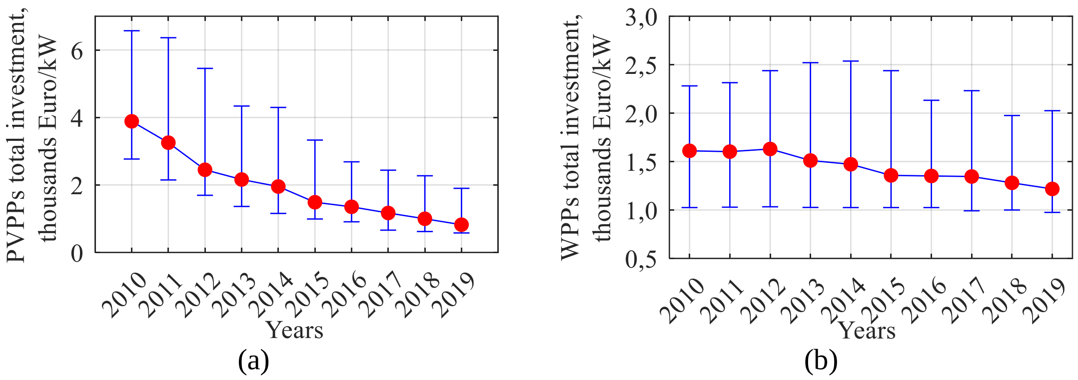


**Fig. 25.** Average total investment costs for PVPPs (a) and for WPP (b) [158]

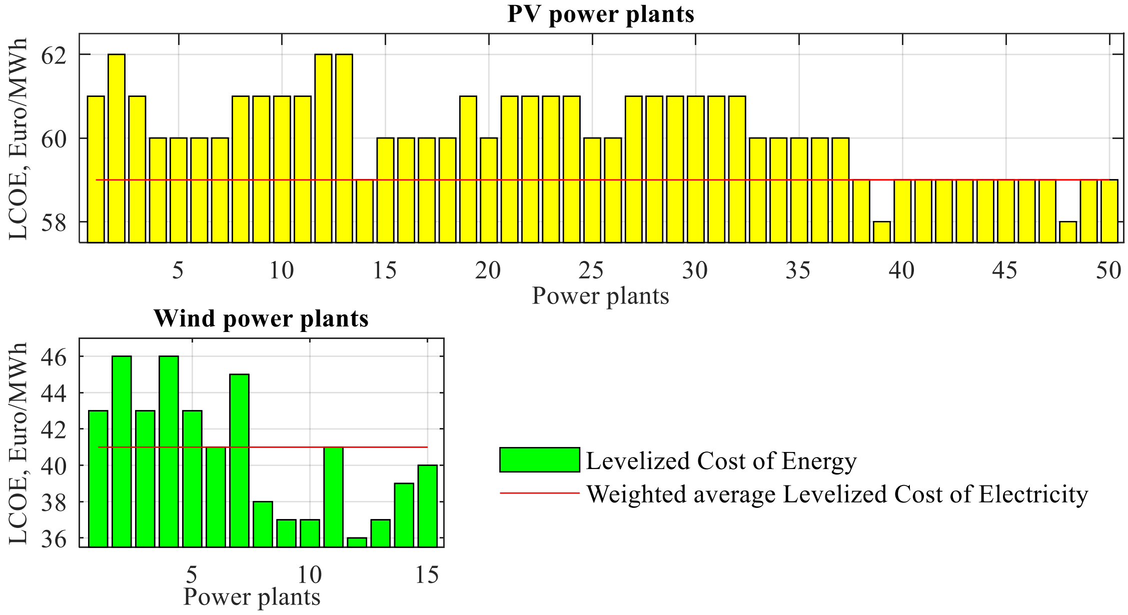


**Fig. 26.** The Levelized Cost of Electricity generated by PVPPs and WPPs

## 5.3. Energy storage systems applications

To determine the necessary power and capacity of the ESSs to balance the power system in the massive presence of VRES, the mixture of electricity from various local sources, including VRES, in the energy balance of the Republic of Moldova is determined, according to the accepted scenarios (table 7).

The accepted hypothesis to perform this analysis are:

- the electricity demand of the Republic of Moldova is accepted at the level of 2018 - 2020;
- the electricity demand is proportional to the population for each ATU;
- traditional sources: combined heat power plants (CHPs) in Chisinau and Balti municipalities, and hydroelectric power plants (HPPs) will continue to operate normally;
- electricity generated by the WPPs and PVPPs will replace the imported electricity;
- in the WPPs and PVPPs, the ESSs are not used to smooth the energy generation graphs or other energy demand management measures.

For modeling following data are used:

- generation loads and electricity demands graphs for the period 2019-2020;

- data series (2016 - 2020) on the solar irradiance and wind speed for the ATU: Chisinau, Edinet, Calarasi, and Stefan Voda;
- generated electricity by Termoelectrica J.S.C. and CHP-North J.S.C., Balti.

**Table 7.** Electricity demand coverage scenarios

| Scenario | PVPPs | | WPPs | | Balancing capacity | | |
|---|---|---|---|---|---|---|---|
| | Electricity ratio, % | Capacity, MW | Electricity ratio, % | Capacity, MW | Balancing capacity, MW | Balancing storage capacity, GWh | Stored electricity, GWh |
| Scenario I. | 100% | 2913.6 | 0% | 0 | 530.5 | 54.9 | 1520.9 |
| Scenario II. | 90% | 2622.2 | 10% | 87.7 | 517.3 | 27.5 | 1352.0 |
| Scenario III. | 80% | 2330.9 | 20% | 175.4 | 517.3 | 26.2 | 1190.1 |
| Scenario IV. | 70% | 2039.5 | 30% | 263.2 | 517.3 | 25.6 | 1057.4 |
| Scenario V. | 60% | 1748.1 | 40% | 350.9 | 517.3 | 31.0 | 969.8 |
| Scenario VI. | 50% | 1456.8 | 50% | 438.6 | 517.3 | 31.1 | 917.5 |
| Scenario VII. | 40% | 1165.4 | 60% | 526.3 | 517.3 | 31.2 | 881.9 |
| Scenario VIII. | 30% | 874.1 | 70% | 614.1 | 517.3 | 36.5 | 853.7 |
| Scenario IX. | 20% | 582.7 | 80% | 701.8 | 517.3 | 45.9 | 830.4 |
| Scenario X. | 10% | 291.4 | 90% | 789.5 | 517.3 | 46.7 | 810.9 |
| Scenario XI. | 0% | 0 | 100% | 877.2 | 517.3 | 47.5 | 794.9 |

**Feasibility of using PHSPPs and HESSs to balance the power system.** It is proposed to assess the economic feasibility of using PHSPPs and HESSs to ensure power system balancing in the massive presence of VRES. The Discounted payback period is used as an economic criterion to assess the feasibility and comparison of scenarios. The study period is chosen according to the standard lifetime of the fixed funds. The source of PHSPPs revenue will be sales of electricity on the balancing market. Considering that in the Republic of Moldova there is no free energy market, respectively the local market for balancing power system, PHSPPs revenues are determined by the assumption of integration into a regional free energy market. In the case of PHSPPs, the weighted average price of deficit electricity on the Romanian balancing market serves as the electricity trading price, and in the case of HESSs the weighted average trading price of excess electricity on the Romanian balancing market.

The total investment costs for PHSPPs include two main components:

1) software, which includes civil engineering works, construction of the necessary infrastructure and connection to electricity networks, minimization of environmental impact;
2) hardware, which includes the costs of purchasing electrical and mechanical equipment.

Operating and maintenance (O&M) costs for PHSPPs include the repair and modernization of mechanical and electrical equipment costs, but not its replacement. These expenses include two components of fixed costs $C_{\text{O\&M,fix}}$ and variable costs $C_{\text{O\&M,var}}$. According to the International Energy Agency, the average value of fixed O&M costs is about 0.06% of the total initial investment, and of variable ones about 0.003 €/MWh. It is assumed that the VRES electricity mix will be used to pump the water and, therefore, the $LCOE$ will be determined according to this mix. The calculations performed (table 8) show that the use of PHSPPs for balancing the power system in the Republic of Moldova is economically feasible only in scenarios I - III, and of HESS in scenarios I and II. Although the total discounted costs decrease as the share of energy from wind sources increases, the discounted investment payback period increases and exceed the assumed study period. The evolution of these indicators is caused by the decrease of the stored energy, respectively of the period of use maximum capacity of PHSPPs and, respectively, HESSs decrease from 2765 hours in the case of scenario 1 to 1515 hours in the case of scenario 11. Reduction of the stored energy and VRES $LCOE$ lead to a decrease in O&M costs and, at the same time, to a decrease of the total income with the energy traded during peak hours.

**Table 8.** The discounted payback investment period for the 11 scenarios

| Scenarios | Total discounted costs, million € | | Net present value, million € | | Discounted payback period, years | |
|---|---|---|---|---|---|---|
| | PHSPPs | HESSs | PHSPPs | HESSs | PHSPPs | HESSs |
| Scenario I. | 2003.2 | 1805.8 | 159.5 | 1144.4 | 19 | 19.9 |
| Scenario II. | 1791.0 | 1756.1 | 132.4 | 869.3 | 20 | 25.5 |
| Scenario III. | 1627.0 | 1750.2 | 67.9 | 576.6 | 23 | 38.5 |
| Scenario IV. | 1493.9 | 1745.3 | 13.7 | 336.6 | 31 | 65.9 |
| Scenario V. | 1400.8 | 1742.1 | -17.2 | 177.6 | 36 | 124.9 |
| Scenario VI. | 1337.4 | 1740.2 | -27.6 | 83.2 | 39 | 266.7 |
| Scenario VII. | 1288.1 | 1738.9 | -28.4 | 18.9 | 39 | - |
| Scenario VIII. | 1245.5 | 1738.0 | -25.6 | -32.2 | 38 | - |
| Scenario IX. | 1207.3 | 1737.3 | -20.6 | -74.9 | 37 | - |
| Scenario X. | 1172.8 | 1736.6 | -13.7 | -110.2 | 35 | - |
| Scenario XI. | 1141.4 | 1736.0 | -4.6 | -138.8 | 33 | - |

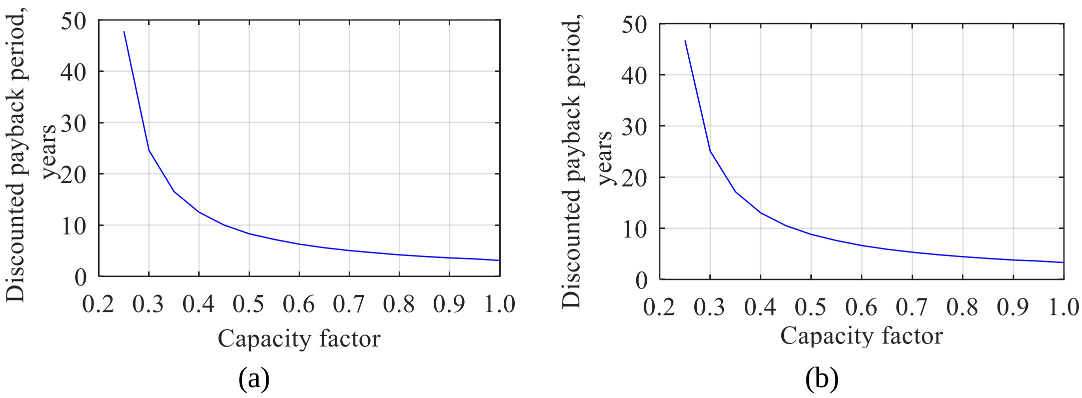


**Fig. 27.** Present Net Value in the dependence of the capacity factor PHSPPs (a) of HESSs

**Feasibility of using BESSs to smooth the energy generation graphs.** It is proposed to assess the feasibility of using some BESS types to smooth the energy generation graphs of VRES power plants on the example of the WPP7 wind power plant and the PVPP7 photovoltaic power plant. The BESS application aims to track by the power plants the electrical load in the power system and reduce the excess of injected electricity. For this analysis, the load and power generation graphs for WPP and PVPP are used and the following types of BESS are considered: Lithium Titanite (LTO), Lithium Iron Phosphate (LFP), Vanadium Redox Flow Battery (VRFB), Valve-Regulated Lead-Acid (VRLA) and Lithium Manganese Oxide/Nickel Manganese Cobalt (NMO/LMC) batteries.

**Table 9.** Calculation of the discounted investment payback period for BESS

| Characteristics | LTO | LFP | VRFB | VRLA | NMO-LMC |
|---|---|---|---|---|---|
| **General characteristic** | | | | | |
| Service lifetime, years | 20 | 15 | 15 | 10 | 10 |
| BESS performance, % | 98 | 94 | 78 | 83 | 97 |
| Depth of discharge, % | 95 | 90 | 100 | 60 | 90 |
| Auto discharge coefficient, %/day | 0.05 | 0.10 | 0.15 | 0.09 | 0.10 |
| **WPPs** | | | | | |
| Energy storage system capacity, MWh | 65.3 | 68.9 | 62.0 | 103.3 | 68.9 |
| Discounted payback, years | - | - | 5.4 | 8.3 | 8.1 |
| **PVPPs** | | | | | |
| Energy storage system capacity, MWh | 26.3 | 27.8 | 25.0 | 41.7 | 27.8 |
| Discounted payback, years | - | - | 5.2 | 8.0 | 7.9 |

It is accepted that the National Power System of the Republic of Moldova is part of a regional energy market, and the price of electricity will be taken as the weighted average price per DAM in Romania.

The results of the calculations show that the use of VRFB, VRLA, and NMO/LMC batteries type to smooth the power generation graphs is feasible in both cases (PVPP and WPP). The discounted payback period for these BESS types varies between 5.2 and 8.3 years. VRFB batteries have the lowest value, although VRLA batteries have the lowest specific investment cost. At the same time, the discounted payback period for Li-ion batteries (LTO and LFP) significantly exceeds their service lifetime period, and their use is not feasible, although they demonstrate the best performance.

# Chapter VI. POWER SYSTEM OF THE REPUBLIC OF MOLDOVA IN TRANSITION TOWARDS 100% ENERGY FROM RENEWABLE SOURCES

This chapter presents the strategies for the National Power Systems development of the Republic of Moldova according to the presented view to the transition of the national economy towards 100% RES - electrification of the heat supply system and transport sectors and production of synthetic fuels using green hydrogen.

There are presented the strategy for the transition towards 100% RES, the evolution of the electricity demand for 2021-2070 required for traditional electricity users, the electrification of the heat supply system and the transport sector, and the production of synthetic fuels and decarbonization of the National Economy.

The National Power System of the Republic of Moldova is modeled from the perspective of the massive integration of VRES. According to the electricity demand for the energy transition, two scenarios are proposed to cover the electricity demand and there are chosen: traditional power source and those using VRES, PHSPPs, and interconnections with neighboring power systems for the National Power System balancing. The economic comparison of these scenarios and the reduction of GHG emissions resulting from the implementation of the measures proposed in the paper are assessed.

## 6.1. The transition towards 100% energy from renewable sources

The Republic of Moldova, without UTASN, has insignificant electricity generation capacities (Table 10). Due to the existing technical-economic conditions, only about 360 MW of the total capacity (501.3 MW) is available. Thus, the largest share of electricity demand is covered by imports from Ukraine and UTASN. The Republic of Moldova is vulnerable and dependent on the financial, economic, and political situation in the region. The cost of electricity generated by local CHPs is higher than the cost of electricity for several reasons:

1) physical and moral wear and tear of the generation units;
2) predominance of traditional sources (using natural gas) in the energy balance;
3) the higher price of fuel (natural gas) compared to the countries/regions (including UTASN) which import

**Table 10.** Electricity generation by local sources

| Source | Electricity generation, GWh | | |
|---|---|---|---|
| | 2017 | 2018 | 2019 |
| CHP Source I, Chisinau | 619.3 | 651.0 | 601.3 |
| CHP Source II, Chisinau | - | - | - |
| CHP-North, Balti | 48.4 | 53.9 | 58.3 |
| HPP Costesti | 46.9 | 43.7 | 64.0 |
| PVPPs | 1.5 | 1.5 | 1.4 |
| CHPs using biogas | 21.6 | 27.9 | 28.7 |
| WPPs | 7.1 | 21.9 | 36.9 |
| Other HPPs | 0.04 | 0.3 | 0.3 |
| Others local source | 32.8 | 55.5 | 77.4 |

electricity in the Republic of Moldova;
4) massive disconnection of the centralized heat supply system.

The existence of interconnections with the neighboring power systems is extremely important to ensure the security of the country's electricity supply. Currently, the choice of the origin of the import sources of electricity is low, the interconnections being represented by 7 overhead power lines (OHL) of 330 kV and 11 OHL of 110 kV with Ukraine, 4 OHL of 110 kV, and one OHL of 400 kV with Romania. The power systems of the Republic of Moldova and Romania are part of different synchronous systems. Thus, the import of electricity from Romania is not possible without a back-to-back power station. The electricity import from Ukraine is limited due to congestion on the existing interconnections.

To ensure the security of the electricity supply of the Republic of Moldova, it is expected to expand the interconnections with the power systems of Romania and Ukraine and to integrate them into the ENTSO-E system. The asynchronous interconnection of the power systems of the Republic of Moldova and Romania will be realized in two stages:

- the back-to-back station with a capacity of 600 MW in Vulcanesti and the construction of the 400 kV OHL Isaccea-Vulcanesti-Chisinau, the modernization of the 330 kV Chisinau substation and the extension of the 400 kV Vulcanesti substation (first stage);
- the back-to-back station with a capacity of 300 MW in Balti and the construction of the 400 kV OHL Balti-Suceava (second stage);
- the construction of the second 330 kV OHL Balti - HPP Dnestrovsk.

The local generation capacity will be expanded by 1050 MW. Thus, the existing CHP sources (CHP Source I Chisinau and CHP Source II Chisinau) will be decommissioned and built another 1250 MW of new sources, including a CET of 450 MW with mixed cycle gas-steam and 600 MW using RES.

Massive integration of VRES into the power system requires efficient solutions for the conversion of electricity into other forms of energy (Figure 3): heat (Power-to-Heat), mechanical (E-Mobility), hydrogen (Power-to-Hydrogen), methane (Power-to-Methane), synthetic gas (Power-to-Syngas), methanol (Power-to-Methanol), diesel (Power-to-Diesel), chemicals (Power-to-Chemicals), etc. Thus, the conversion of electricity into other forms of energy in combination with energy storage allows the shaving of the peaks of the graphs of electric and heat load; residual heat recovery; increasing the capacity factor of local energy sources; power system balancing; national economy decarbonization, etc.

## 6.2. Electricity demand forecasting

The average annual electricity demand of the Republic of Moldova for the period 2015-2020 was 4.44 TWh. The largest share of the traditional electricity demand belongs to the Residential sector and the Trade and Public Services sector. At the same time, the electricity demand of the Transport and Agriculture, Forestry and Fishing sectors are negligible compared to the given sectors. It is proposed to replace the imports of electricity with the electricity generated by power plants using VRES.

The thermal energy sector of the Republic of Moldova is represented by centralized heat supply systems in the Chisinau, Balti, and Ungheni municipalities and the individual heat supply systems of the industrial and residential entities. It is proposed to electrify the residential sector by partially replacing fossil fuel heat supply sources with new sources using directly or indirectly electricity from VRES - heat pumps (PT) and electric resistance boilers (CER). The rest of the heat demand for space heating and cooling, domestic hot water preparation, and other technological needs of the industrial sector will be covered by CHPs, aiming to switch them to bio- or synthetic fuels derived from hydrogen green, and solar collectors.

The transport sector includes road transport, rail transport, air transport, and shipping. About 53% of passenger transport and about 86% of freight transport is done by road transport equipped with internal combustion engines using fossil fuels. River and air transport have a relatively small share in the balance of freight (<1%) and passenger (~ 25%). It is proposed to replace cars and small trucks with internal combustion engines using fossil fuels with vehicles with electric motors with accumulator batteries (BEV) and fuel cells (FCHEV). At the same time, it is proposed to replace large vehicles (buses and large trucks) and trains with diesel engines with electric ones connected to the grid and some equipped with batteries with fast charging batteries (BEV-grid).

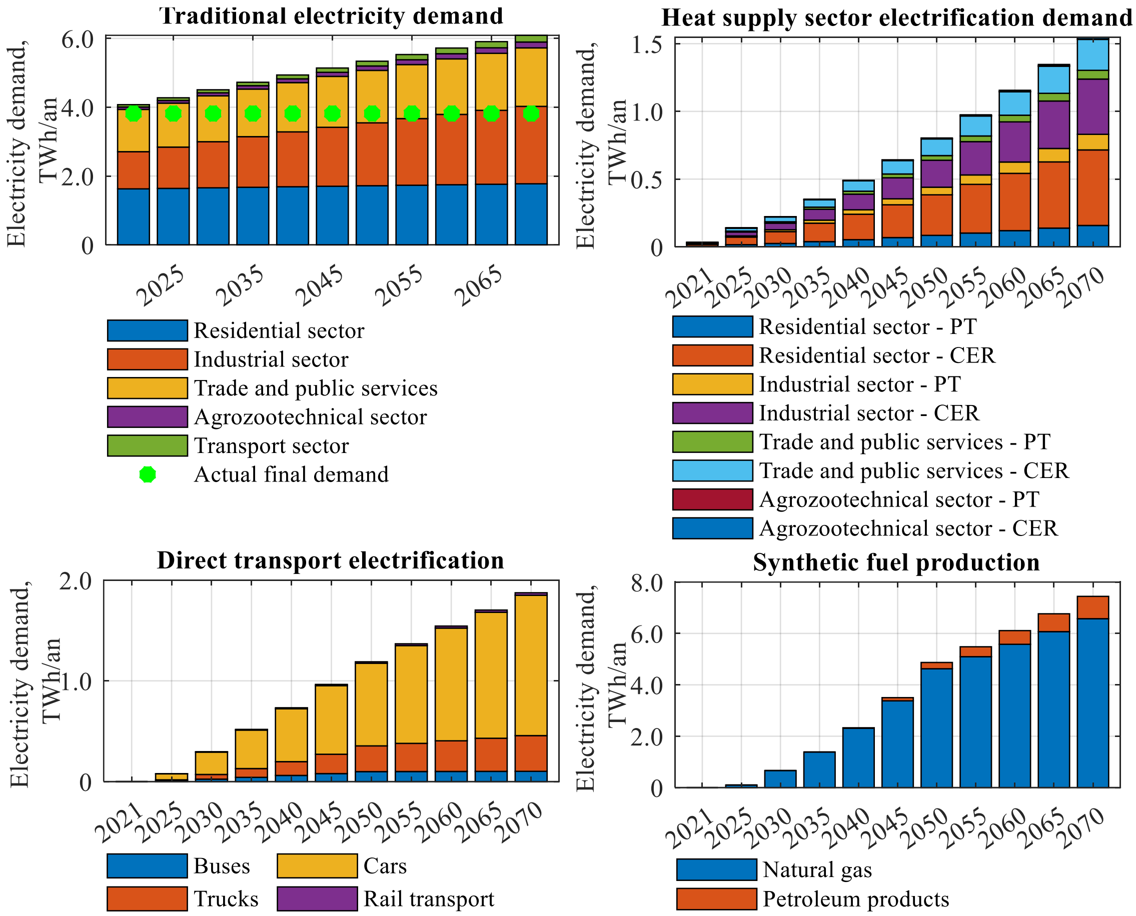


**Fig. 28.** The evolution of the electricity demand for the electrification of the heat supply sector (2021 – 2070)

Green hydrogen can be used directly or indirectly (diesel, methanol, methane, or synthetic natural gas) as a fuel in various sectors of the economy. The highest demand for natural gas is in the Residential (~ 61%), Trade and Public Services (~ 21%) and Industry (~ 15%), and oil products sectors in the Transport sector (~ 76%). Considering the aspects related to the transition of the heat supply and transport sectors, which are not covered by the measures proposed above, the supply of natural gas and petroleum products of the sectors of the national economy (excluding the heat supply and Transport sectors) remains. Petroleum products used in the residential sector include liquefied natural gas for heating, domestic hot water preparation, and food preparation (~ 100%), respectively can be substituted with methane produced by hydrogen methanation. At the same time, this has a share of 28% of the total final consumption of petroleum products (except for the transport sector and non-energy needs), the rest representing diesel (~ 58%) used in agriculture and other heavy hydrocarbons (~ 13%) used in the chemical industry.

It is proposed to cover about 25% of the fuel demand by synthetic fuels. Considering energy security reasons, fossil fuels will continue to be used, with the possibility of replacing them with synthetic fuels at a later stage. The results of the estimated electricity demand in the perspective of the energy transition towards 100% RES are shown in figure 28.

It can be observed that at the end of the proposed energy transition process, the final net demand will increase 4 times (from 4 TWh to 16.9 TWh). This growth is considerable and requires great financial, scientific, and social efforts.

### 6.3. The proposed structure of the national power system

Next, it is proposed to simulate the functioning of the National Power System of the Republic of Moldova in the massive presence of VRES considering the proposed development of the energy sector (until 2035), described above. It is proposed to analyze two scenarios, respectively, two variants of the National Power System structure. According to both scenarios, the main electricity source will be WPPs and PVPPs. Traditional electricity sources (CHPs and HPPs) will provide the necessary system services, partial supply of industrial and residential users with heat.

According to the first scenario, CHP Source I and CHP Source II from Chisinau, CHP-North from Balti, and HPP Costesti will continue their activity. Scenario two involves the continuation of the activity of only CHP-North and HPP Costesti, but CHP Source I and CHP Source II will be replaced by the 450 MW CHP (Chisinau) using the mixed gas-steam cycle.

The National Power System is used to balance electricity storage in HPSPPs and cross-border power flows. The first scenario assumes that the existing interconnections with the power system of Romania and Ukraine will be available, as well as the Isaccea - Vulcanesti interconnection involving the 600 MW back-to-back station in Vulcanesti, the modernized 330 kV Chisinau substation, the extension of the 400 kV OHL from Vulcanesti and the construction of the 400 kV OHL Isaccea-Vulcanesti. Scenario two provides for the extension of interconnections (in addition to the existing ones and the back-to-back station in Vulcanesti):

- 400 kV OHL Balti-Suceava and the 300 MW back-to-back station in Balti;
- 400 kV OHL Isaccea - Vulcanesti - Chisinau;
- the second 330 kV OHL Balti - HPP Dnestrovsk.

The electrical loads for the ATU for both scenarios are determined considering the following hypotheses:

- the electricity demand for each ATU depends on the population, the area of the housing stock, the industrial production, the marketed production, and the public services provided;
- the heat demand for heating and hot water supply for domestic consumption is proportional to the area of the housing stock and, respectively, the population of the ATU;
- the heat demand for the trade and public services sector is proportional to the value of the products marketed and the public services offered;
- the heat load of the industrial sector is proportional to the production of this sector;
- the charging of BEV vehicles (except for those directly connected to the grids) will be carried out during the night or the load gaps;
- the charging of BEV vehicles with connection to the electrical grid and fast charging will be done during the day (time interval 05:00 - 23.00);
- the electric charge for charging BEV vehicles is proportional to the number of vehicles registered for each ATU, and their charging is performed at night (time interval 20:00 - 07.00);
- the production of the synthetic fuel (hydrogen, methane, methanol, and diesel) will be carried out at night or in the load gaps.

Depending on the population, housing stock, transport, industrial product, etc., the electric load graphs are modeled, the electricity demand for each ATU is determined, and the WPPs and PVPPs are chosen from the list of proposed power plants according to the principle that the difference between the electricity demand and generation in the area should be minimal. However, since the central region is characterized by the greatest electricity demand and a low technical

RES potential due to the terrain characteristics, this principle has not been respected. Therefore, there is a deficit in the central region and a surplus of electricity generated in the North and South region.

Both scenarios involve balancing the electric load by using traditional electricity sources, PHSPPs, and interconnections with neighboring power systems. The ratio of energy from these sources is different for each scenario. To determine the power and capacity needed to balance the National Power System of the Republic of Moldova, the electricity mix based on local sources (CHPs, HPPs, WPPs, and PVPPs) is determined and the electricity generation graphs are constructed. To perform this analysis, some hypotheses are accepted:

- each zone is characterized by uniform values of wind speed and solar irradiance throughout its territory;
- WPPs and PVPPs cover the difference between the country's load and the generation graphs of CHPs and HPPs, except the Moldovan Regional State Power Plant from UTASN.

The forecasting and modeling of load and power generation graphs are performed using the forecasting tools described in Chapter IV considering the following data:

- generation and load graphs for the period 2019 - 2020;
- times series on solar irradiance and wind speed for ATU: Chisinau, Edinet, Calarasi, and Stefan Voda, for the period 2016 - 2020;
- electricity generated by Termoelectrica J.S.C., Chisinau, and CHP-North J.S.C., Balti, for the period 2019 - 2020.

The modeling results are presented in table 11. Considering the electricity generation and load graphs, and the National Power System balancing sources, the PHSPPs characteristics for each scenario are determined (table 12). To balance the National Power System in the massive presence of VRES, PHSPP Temeleuti will be used in the North region, PHSPP Boltun in the Central region, and PHSPP Vascauti and HPSPP Cisla in the South region.

For the National Power System function analysis in the massive presence of VRES, four cases are chosen for each scenario. Their choice is made from the condition of the system operating in extreme conditions (table 13).

The National Power System modeling is performed using the ETAP 19.0.1 program. The model largely reflects the existing National Power System with some exceptions, such as the capacity of transmission lines and of the transformers to ensure the transport of power and energy. Both scenarios provide full coverage of the electrical load required by end-users.

As the result of modeling, two stable models of the National Power System were obtained for all presented cases. To ensure the stability of the National Power System, considerable reactive power flows are recorded from neighboring power systems (table 14). As a result, there is a large loss of reactive power. One of the causes of the high values of reactive power losses is the oversizing of power lines and transformers to ensure the evacuation of active power from areas with excess power. Another reason is that in the process of covering the electrical load, priority was given to WPPs and PVPPs, to the detriment of synchronous sources, which can provide reactive power. The maximum losses of reactive power are registered in the hours of generation and load gaps.

**Table 11.** The requirements for power system balancing in the massive presence of VRES

| Region | Maximum balancing load, MW | Stored capacity, GWh | Annual electricity demand, GWh/an |
|---|---|---|---|
| Republic of Moldova | 894.17 | 59.0 | 731.20 |
| North | 284.86 | 38.15 | 315.84 |
| Center | 468.84 | 49.26 | 550.43 |
| South | 441.54 | 12.62 | 251.52 |

**Table 12.** PHSPPs features for different scenarios

| Region | PHSPPs | Storage capacity, GWh | Capacity, MW | Storage capacity, GWh | Capacity, MW |
|---|---|---|---|---|---|
| | | Scenario I | | Scenario II | |
| North | PHSPP Temeleuti | 5 | 125 | - | - |
| Center | PHSPP Vascauti | 50 | 250 | - | - |
| Center | PHSPP Boltun | 15 | 250 | 15 | 125 |
| South | PHSPP Cisla | 5 | 125 | 5 | 125 |
| Total | | 75 | 750 | 20 | 250 |

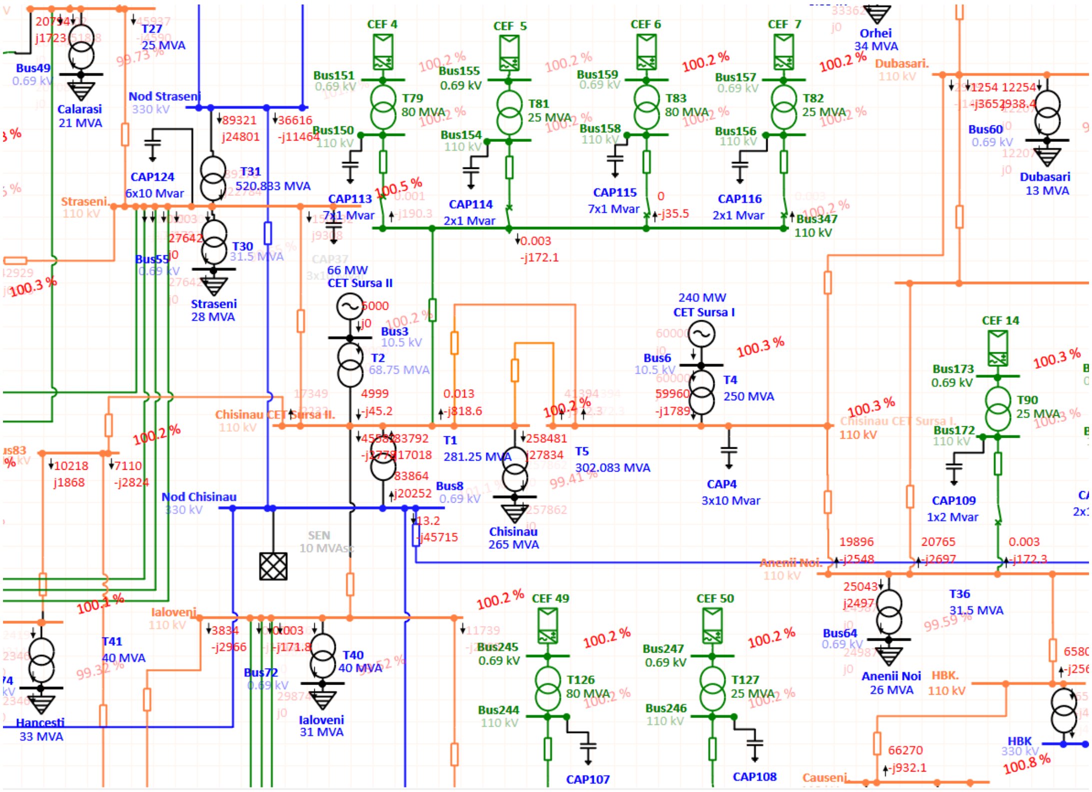


**Fig. 29.** Excerpt from the modeled national power systems scheme - Scenario 1, peak electrical load

At the same time, the losses of active power are relatively small (1 ÷ 11%), the maximum values being registered for the peaks of electricity generation, and the minimum ones for the generation and load gaps. In Scenario I, compared to Scenario II, there are lower values of losses, both active and reactive power since there are several local synchronous sources, which lead to a decrease in reactive power flows through electrical networks. The highest power flows are registered in the Balti – Rascani, Chisinau - Straseni, Balti – Drochia, and Balti – Glodeni OHLs. In all modeled cases there are cross-border flows of active and reactive power in both directions to ensure the stability of the National Power Systems in the massive presence of VRES (table 15). The highest power flows are recorded in the directions Balti – NHE Dnestrovsk and Vulcanesti - Isaccea, and additional Balti - Suceava in Scenario II, both in the case of maximum electric load and in the case of maximum generation. Obviously that in Scenario II with a lower storage capacity in PHSPPs, cross-border flows are considerably higher.

**Table 13.** Electrical loads used to model the national power system

| Region | Electrical load (hour, day), MW | | | |
|---|---|---|---|---|
| | Electrical load | | Electrical generation | |
| | Maximum (20:15, 08.12) | Minimum (18:15, 23.11) | Maximum (05:30, 11.11) | Minimum (11:15, 16.04) |
| North | 281.2 | 71.4 | 163.6 | 189.8 |
| Center | 563.2 | 149.4 | 317.0 | 384.6 |
| South | 513.9 | 49.3 | 432.8 | 133.1 |
| Total | 1358.3 | 270.2 | 913.3 | 707.4 |

**Table 14.** The modeling the power system in the massive presence of VRES

| Characteristics | Scenario I | | | | Scenario II | | | |
|---|---|---|---|---|---|---|---|---|
| | Load | | Generation | | Load | | Generation | |
| | Peak | Gap | Peak | Gap | Peak | Gap | Peak | Gap |
| Buses, units | 247 | | | | 250 | | | |
| Overhead power line, units | 257 | | | | 258 | | | |
| Synchronous sources, units | 8 | | | | 6 | | | |
| Power systems interconnections, units | 15 | | | | 16 | | | |
| Active power generation, MW | 1369 | 289 | 723 | 1010 | 1382 | 291 | 727 | 1031 |
| Reactive power generation, MVAr | -347.4 | -608.1 | -484.3 | -50.8 | -482.2 | -781.1 | -624.0 | -151.7 |
| Loss of active power, MW | 42.3 | 2.3 | 5.3 | 97.2 | 42.9 | 4.2 | 8.0 | 113.8 |
| Loss of reactive power, MVAr | -103.8 | -565.2 | -484.3 | 366.2 | -259.7 | -738.11 | -624.0 | 244.4 |

**Table 15.** PHSPPs functioning

| PHSPPs | | Scenario I | | | | Scenario II | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Load | | Generation | | Load | | Generation | |
| | | Peak | Gap | Peak | Gap | Peak | Gap | Peak | Gap |
| PHSPP Temeleuti | Active power, MW | 7.0 | 20.7 | 39.3 | -124.4 | | | | |
| | Reactive power, MVAr | -16.2 | -39.8 | -22.1 | -7.6 | | | | |
| PHSPP Vascauti | Active power, MW | -49.8 | 25.3 | 68.8 | -234.7 | | | | |
| | Reactive power, MVAr | -33.0 | -46.8 | -37.5 | 4.6 | | | | |
| PHSPP Boltun | Active power, MW | 21.2 | 39.4 | 74.9 | -234.3 | 12.5 | 15.4 | 11.8 | -96.3 |
| | Reactive power, MVAr | -37.9 | -67.8 | -49.2 | -15.2 | -15.6 | -23.8 | -18.6 | -10.3 |
| PHSPP Cisla | Active power, MW | 43.1 | 17.4 | 41.0 | -110.7 | 21.6 | 11.2 | 11.1 | -87.5 |
| | Reactive power, MVAr | -15.4 | -20.9 | -16.9 | 21.3 | -22.0 | -25.1 | -20.3 | 4.8 |

The most charged 330 kV and 400 kV OHLs are those that transport electricity from the South to the North (UTAG – Chisinau – Straseni – Balti – Dnestrovsk), as well as those that connect the main power nodes with PHSPPs (Chisinau – Boltun, Chisinau – Cisla, Balti – Vascauti, Straseni – Temeleuti). At the same time, in the south-eastern areas of the country (Stefan Voda and Causeni districts), where there is an important potential for wind energy resources, there is recorded congestion in the electricity grids, and in case of disconnection of Balti – Dnestrovsk OHL in the northeast (Scenario I) too. Thus, in terms of energy security, Scenario II is better, but in terms of ensuring energy quality and a higher degree of independence from neighboring power systems, Scenario I is preferable.

The National Power Systems models are compared using total discounted costs $CTA$ criteria. The study period is chosen according to the standard service life of the fixed assets. The service life of the CHE is 50 ÷ 70 ani and the basic equipment is about 30 years. The service life of electrical networks (OHL) is 35 ÷ 40 ani, and of transformers with powers higher than 12 MVA is 20 years. Based on the service life of the installation and the equipment used, the duration of the study period $T$ is chosen equal to 30 years. The calculation results for the two scenarios are presented in Table 17.

**Table 16.** Cross border power flows

| Regime | Power flows | Scenario I | | | Scenario II | | |
|---|---|---|---|---|---|---|---|
| | | Power system Romania | Power system Ukraine | | Power system Romania | Power system Ukraine | |
| Peak load | Nominal voltage, kV | 400 | 330 | 110 | 400 | 330 | 110 |
| | Active power, MW | 41.3 | -100.7 | -85 | -13.2 | -96.8 | -23.7 |
| | Reactive power, MVAr | -101.6 | -192.7 | 49.2 | -243.9 | -196.5 | 19.9 |
| Gap load | Active power, MW | 18.1 | 90.2 | 33.4 | 19.8 | 85.4 | 94.9 |
| | Reactive power, MVAr | -116.2 | -253.3 | -63.2 | -264.3 | -278 | -148 |
| Gap generation | Active power, MW | 48.1 | 210.2 | 70.4 | 33.2 | 95.8 | 127.1 |
| | Reactive power, MVAr | -108.4 | -215.9 | -34.4 | -250.3 | -240.3 | -88.5 |
| Peak generation | Active power, MW | -119.3 | -755.7 | -288 | 25.7 | -930.1 | -758 |
| | Reactive power, MVAr | -90.6 | -90.9 | 127.5 | -257.2 | 10.2 | 117.2 |

**Table 17.** Calculation of the total discounted costs

| Characteristics | Value | |
|---|---|---|
| | Scenario I | Scenario II |
| New 400 kV OHL length, km | 70.00 | 301.00 |
| New transformer stations capacity, MVA | 600.00 | 1200.00 |
| Total storage capacity in PHSPPs, GWh | 54.9 | 27.5 |
| Total PHSPPs capacity, MW | 750 | 250 |
| OHL total discounted costs, mil € | 15.4 | 66.2 |
| Substation total discounted costs, mil. € | 65.3 | 130.6 |
| PHSPPs total discounted costs, mil € | 1273.9 | 424.6 |
| OHL O&M costs, mil € | 130.3 | 560.1 |
| Substation O&M costs, mil. € | 552.2 | 1104.3 |
| PHSPPs O&M costs, mil. € | 233.8 | 77.9 |
| VRES LCOE, €/MWh | 45.5 | |
| Total discounted costs with electricity losses in electricity transmission grids, mil. € | 484.1 | 532.5 |
| Total discounted costs with electricity used for pumping, mil. € | 108.7 | 36.2 |
| Remnant costs of fixed assets, mil. € | 19.5 | 6.1 |
| Total discounted costs, mil € | 2844.0 | 2926.3 |

The calculations show that the power system presented in Scenario I is more cost-effective than Scenario II, although the difference between the total discounted costs values does not exceed 2.9%. This value can easily fall within the permissible error due to accepted assumptions and chosen the initial data. At the same time, the power system presented in Scenario II foreseen the construction of two interconnections (Vulcanesti - Isaccea, and Balti - Suceava), compared to one in Scenario I. These will ensure energy security and facilitate the integration of the Republic of Moldova in the ENTSO-E system. On the other hand, Scenario II foreseen a lower storage capacity in PHSPPs, which will lead to a considerably smaller area flooded by PHSPPs storage basins compared to Scenario II. Thus, the power system in Scenario II is more optimal in terms of energy, economic and environmental security.

The energy sector is the largest user of fossil energy resources at the world level. The replacing fossil fuels with RES is an opportunity to reduce anthropogenic GHG emissions, which is the main cause of climate change. Table 18 presents the results of estimating GHG emission reductions in achieving the energy transition for each sector of the national economy.

Thus, according to the energy transition scenario presented, it is possible to reduce GHG emissions by 5.3 million tons of CO2 equivalent by 2030, which is an important value and considerable support for climate change mitigation.

**Table 18.** The results of the calculation of GHG emission reductions

| Energy sources | GHG emission reduction, thousands tone | | | | | |
|---|---|---|---|---|---|---|
| | Residential sector | Industrial sector | Trading and public services sector | Agriculture, forestry and fishing sector | Transport sector | Total |
| Electricity | 671.5 | 590.6 | 555.5 | 39.3 | 40.4 | 1897.3 |
| Heat | 65.6 | 38.6 | 26.9 | 1.0 | - | 132.1 |
| Fuels | 77.7 | | - | - | 3266.5 | 3344.2 |

# Chapter VII. FINAL CONCLUSIONS AND PERSPECTIVES

This chapter presents the synthesis of the contribution brought in the doctoral thesis regarding the RES integration and the functioning of the National Power System in the massive presence of these sources.

## 7.1. General conclusions

The existence of local energy sources and the price for imported energy resources directly influence the development of the national economy and the energy security of the country. The Republic of Moldova has insignificant reserves of fossil energy resources, and the energy resources demand is covered by imports of energy resources from the Russian Federation, Ukraine, and Romania. The lack of own fossil energy resources must be the driving force behind the development and implementation of RES. The Republic of Moldova has a high RES potential, especially biomass, wind, and solar energy.

The use of energy resources in the residential (49.5%) and transport (27%) sectors considerably exceeds the average of developed countries, and that in the industrial sector (8%), on the contrary, is much lower. Currently, the share of RES in the energy balance is 22.1% (2019). However, almost 100% of RES represents biomass used to heat supply the residential and public sectors in rural areas. The share of RES in the power and transport sectors is negligible. Thus, the main objective at this time is the integration of RES in these sectors.

The use of biomass and organic waste for electricity generation using CHPs has a limited application with greater importance for heat generation for the residential and public sectors, and cogeneration based on it usually has a low capacity (up to 1 MW); the production of large quantities of biogas from animal manure is not possible due to the lack of livestock farms with a sufficient number of heads, and the modernization of wastewater treatment plants by implementing anaerobic water treatment requires too much investment to be covered by central or local public authorities. Thus, the most viable solution for the integration of RES in the electricity sector of the Republic of Moldova is the use of solar and wind energy. The evaluation of the technical RES potential shows that the power of the wind installations that can be installed on the territory of the country is 9 151 MW, and that of the solar sources (PV) 8 767 MW. This potential can cover the existing and estimated future electrical load. To cover the existing annual electricity demand of the Republic of Moldova of 3 615 GWh (2019) is sufficient the recovery of solar energy (PV) from 0.25% of the country's territory, and for the 8 491 GWh expected to be reached in 2050 in the Energy Strategy 2030 – 0.56% of the country's territory, but several measures should be provided that would adapt the existing National Power System for joint operation with RES.

The SEN of the Republic of Moldova is a small system (by task and geographical coverage) and its functioning in the massive presence of RES is associated with several challenges: the reduction of flexibility and security, the stability of frequency and voltage in electrical networks, the quality of electricity, the ability of WPPs and PVPPs to ride-through defects, the protection of electrical grids and energy-generating units, cyber security, the existence of the electricity market, etc.

To overcome these challenges, it is necessary to increase the capacity of electricity transmission lines and interconnections with other power systems to evacuate surplus energy from areas with a massive presence of RES; promote energy storage; integrate an efficient electricity forecasting system; promote smart systems. To ensure the quality of the generated electricity and the security of the power supply process, including cyber security, in line with the trend of decentralization of the power generation process, increasing the presence of VRES in the power system, grid codes need to be reviewed and updated.

To modernize the National Power System and promote the use of RES, it is necessary to integrate this system into a regional electricity market, which is much more efficient, as evidenced by the example of the Nordic energy market. State policy must provide for a system of incentives and penalties to promote the use of energy from RES. In the first stage, the mandatory quotas for energy from RES or feed-in tariffs can be implemented, and with the development of the RES sector, the transition to the competitive market can be made. Likewise, instruments such as net metering or net metering can be used to stimulate distributed generation using RES.

The electricity demand will increase in line with existing trends in the energy sector: promoting electrical transport, the transition from fossil fuel heat supply systems to those using electricity (heat pumps), the spread of electrical equipment and devices, especially in the residential sector, process automation and digitization. Thus, there require to forecast and create scenarios for the evolution of electricity demand.

In the literature, in the last two decades, a wide variety of models have been proposed for forecasting solar irradiance, wind speed, and energy generation by wind and solar systems, which differ in the forecasting techniques used, time horizon, geographic horizon, and, most importantly, their accuracy.

In the paper, several models were proposed and evaluated for the prediction of solar irradiance and wind speed, based on clustering techniques, mathematical statistics, and artificial intelligence. The proposed models can be successfully applied to generate various scenarios of annual solar irradiance or wind speed with applicability for conducting feasibility studies on the integration of RES into the power systems, long-term planning, or development of energy strategies. Models based on NAR NN and NARX NN methods have a high performance ($MAPE = 3{,}6 \div 4{,}85\%$), so these models can easily compete with many models proposed in the literature. The disadvantage of models, that use exogenous data (air temperature and humidity, atmospheric pressure, dew point temperature, etc.), is that the accuracy of the forecast depends on the quality of the input data. The results of the models using the NAR NN method can sometimes be unpredictable, so it is necessary to filter the data.

VRES integration requires the use of ESSs at the level of energy sources (smooth the power generation graphs) and the power system (balancing the power systems) and at the level of energy users (to smooth the load graphs). At the same time, it is necessary to make a rational choice of storage technology. The main barriers to using energy storage are:

- lack of adequate regulations that would stimulate and encourage the use of ESSs;
- the lack of a regional or national free energy market, which would allow the benefits of using ESSs;
- high costs of the main types of ESSs, especially in the case of immature markets, such as the Republic of Moldova.

The feasibility of PHSPPs and HESSs is strictly dependent on their capacity factor, which depends on the volume of stored electricity. Increasing the installed capacity of local energy sources can help increase the capacity factor, but in this case, it is necessary to construct new interconnections with other regional power systems and integrate them into a national or regional.

The use of PHSPPs and HESSs to balance the power system is feasible only if there is a balancing market and the financial responsibility of electricity producers to provide this service. The use of HESSs to smooth generation peaks of power plants is not feasible.

Some types of ESS with accumulator batteries, such as VRLA, VRFB, or NMO/LMC, can be successfully used to smooth load or generation peaks. The use of Li-ion accumulator batteries for this purpose is not feasible.

Following the world trends of substitution of the electricity generated by conventional energy sources based on fossil fuels and reducing GHG emissions, it is necessary to take seriously the energy transition to 100% RES. The energy transition of the national economy sectors is a noble goal, which is worth the effort of all state and civil society structures.

Electrification of the national economy sectors can contribute to favoring the integration of VRES in National Power Systems by contributing to the flexibility of the system and increasing the capacity factor of the power plants using VRES, respectively reducing the period of investment recovery.

Starting from the perspective of the presented scenario of the energy transition for the period 2021 - 2070 of the national economy, the electricity demand will double by 2035 and will triple by 2070. Thus, electricity occupies first place in the country's energy balance.

The modeling in the massive presence of VRES shows that the main challenges for increasing the presence of VRES and the functioning of the National Power System are the intermittent nature of wind and photoelectric energy, the reactive power contribution of these sources, the stability of frequency and voltage in electricity networks, and the evacuation of power and energy excess from areas with a surplus of VRES generation to those with a deficit of energy.

The interconnections with the neighboring electric power systems have major importance, as well as the transport capacities inside the National Power System for its functioning. In the analyzed models to achieve power evacuation during peak generation hours, it was necessary to oversize the elements of the power grids, which leads to additional losses of active and reactive power and higher initial investment costs.

In addition, the existence of interconnections with other power systems, to balance the generation graphs and the electric load graphs, it is necessary to have some reserve or energy storage capacities. The energy storage in PHSPPs has fully demonstrated its efficiency and usefulness for the power system's functioning.

Another problem is the reactive power contribution and voltage regulation in different areas of the power system. Thus, there is a need to import reactive power from other systems, while there is a surplus of active power.

From an economic point of view, the analyzed power systems variants in the massive presence of VRES are practically equivalent. The scheme with higher storage capacity in PHSPPs, compared to the one with higher capacities of interconnections with other systems, involves lower total discounted costs but has several disadvantages related to energy security and environmental impact.

The integration of VRES into the National Power System and the electrification of the national economy can contribute to climate change mitigation through a considerable reduction of GHG emissions.

## 7.2. Personal contributions

The personal contribution of the author includes:

1. The study on the existing methods for the energy potential technical assessment of the wind and photovoltaic resources of the Republic of Moldova.
2. The study on the existing methods for the forecasting of the solar irradiance, wind speed, and electricity generation by variable renewable energy sources.
3. Development of the forecasting models for the forecast of the solar irradiance and wind speed (hybrid model using *k*-means techniques and standard mathematical statistics; hybrid model using *k*-means and Nonlinear Autoregressive techniques; hybrid model using *k*-means and Nonlinear Autoregressive eXogenous techniques; Neural Network and Nonlinear Autoregressive Neural Network eXogenous).
4. The study on the impact of VRESs on the functioning of the power system and on the quality of electricity, as well as the existing solutions to overcome these barriers.
5. Identification of locations for WPPs and PVPPs placement, choosing power plants capacity, and estimation of the electricity generation and the Levelized Cost of Electricity generated by these sources.
6. Case study on the propagation of harmonic distortions in an electrical distribution system in the presence of variable renewable energy sources.
7. Determination of the energy storage systems capacity (PHSPPs and HESSs) necessary for the National Power System balancing in the massive presence of VRESs and the feasibility assessment of their application in the actual conditions of the Republic of Moldova.
8. The feasibility assessment of BESSs and HESSs application to smooth the generation curve of power plants using VRESs in the actual conditions of the Republic of Moldova.
9. The view on the transition towards 100% RES of the national economy and the estimation of the electricity demand for this transition.
10. The modeling of the functioning and economic comparison of two variants of the structure of the National Power System in the view of the energy transition, as well as the evaluation of the contribution to the decarbonization of the national economy.

The results of the research during the doctoral studies were used in national projects, presented in scientific events, and scientific publications.

**Scientific projects:**

1. *EcoNovative Technical Solutions for Energy Efficiency in Buildings and Elaboration of Smart Grid Development Options with Advanced Renewable Energy Sources Integration in the Republic of Moldova*, 20.80009.7007.18. (2020 – present).
2. *Towards an energy autonomy of the Republic of Moldova*, 15.817.03.01A (2016 – 2018).

**Scientific manifestations:**

1. *“Efficient district heating of the residential sector: challenges and solutions”,* National Conference “Efficient district heating: Solutions and challenges”, organized by Termoelectrica J.S.C., Chisinau, Republic of Moldova, October 17, 2018.
2. "*The view on the transition of the Republic of Moldova towards 100% energy from renewable sources*", Conference "Energy from renewable sources. Distributed generation. Proconsumers”, organized by the Romanian National Committee of the World Energy Council, Electrica, Hidroelectrica and ANRE.

**Scientific publications:**

1. D. Braga, *Decarbonation of the national economy of the Republic of Moldova by electrification and use of renewable energy sources*, Scientific Bulletin, University POLITEHNICA from Bucharest. (In process of publication).

2. D. Braga, *Integration of Energy Storage Systems into the Power System for Energy Transition towards 100% Renewable Energy Sources*, 2021 10th International Conference on ENERGY and ENVIRONMENT (CIEM), 2021, pp. 1-5, doi: 10.1109/CIEM52821.2021.9614778.
3. D. Braga, *Optimal Capacity and Feasibility of Energy Storage Systems for Power Plants Using Variable Renewable Energy Sources*, 2021 International Conference on Electromechanical and Energy Systems (SIELMEN), 2021, pp. 087-091, doi: 10.1109/SIELMEN53755.2021.9600392.
4. D. Botoc, A., T. Plesca, D. Braga and M. Siroux, *The Influence of the Magnetic Field on the Gadolinium Material*, 2020 International Conference and Exposition on Electrical and Power Engineering (EPE), 2020, pp. 288-291, doi: 10.1109/EPE50722.2020.9305668.
5. D. Braga, G. Chicco, N. Golovanov, R. Porumb, *Long-Term Solar Irradiance Forecasting*. In: Problemele Energeticii Regionale. 2020, nr. 1(45), pp. 94-109. ISSN 1857-0070.10.5281/zenodo.3713424.
6. D. Braga, *Photovoltaic Technical Potential in Republic of Moldova*, 2019 International Conference on Electromechanical and Energy Systems (SIELMEN), Craiova, Romania, 2019, pp. 1-6, doi: 10.1109/SIELMEN.2019.8905853.

## 7.3. Further research perspectives

The studies presented in the doctoral thesis can be continued in the following directions:

- assessment of the impact of energy demand management on the functioning of the National Power System in the massive presence of VRES;
- the integration of RES in the centralized heat supply system and industry to decarbonize these sectors;
- choosing of the optimal location of power plants using VRES and their connection in the NPS;
- the application of ESS to ensure the quality of electricity in the NPS in the massive presence of VRES.

## SELECTIVE BIBLIOGRAPHY

[1] Statistical Review of World Energy 2021. Disponible online: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf (accessed pe 19.10.2021)

[3] IRENA, Renewable Energy Statistics, The International Renewable Energy Agency, Abu Dhabi, 2019

[6] S. D. Ahmed, F. S. M. Al-Ismail, M. Shafiullah, F. A. Al-Sulaiman and I. M. El-Amin, Grid Integration Challenges of Wind Energy: A Review, in IEEE Access, vol. 8, pp. 10857-10878, 2020, doi: 10.1109/ACCESS.2020.2964896.

[8] Banca de date statistice Moldova, Biroul național de statistică al Republicii Moldova.

[12] I. Sobor, A. Chiciuc, V. Rachier, Atlasul resurselor energetice eoliene al Republicii Moldova, Universitatea Tehnică a Moldovei, AWS Truepower SRL SL (Spania), Wind Power Energy SRL (România), ISBN 978-9975-87-245-7, Chișinău, 2017, p. 176.

[23] H. Holttinen, (2008). Estimating the impacts of wind power on power systems - Summary of IEA Wind collaboration. Environmental Research Letters. 3. 10.1088/1748-9326/3/2/025001.

[71] R. Chen, J. Wang, A. Botterud, and H. Sun, Wind power providing flexible ramp product, IEEE Trans. Power Syst., vol. 32, no. 3, pp. 2049-2061, May 2017, doi: 10.1109/tpwrs.2016.2603225.

[72] M. Milligan, Sources of grid reliability services, Electr. J., vol. 31, no. 9, pp. 1-7, Nov. 2018, doi: 10.1016/j.tej.2018.10.002.

[76] T.B. Rasmussen, G. Yang, A.H. Nielsen and Z. Dong, A review of cyber-physical energy system security assessment, 2017 IEEE Manchester PowerTech, Manchester, 2017, pp. 1-6, doi: 10.1109/PTC.2017.7980942.

[77] D. Kundur, X. Feng, S. Mashayekh, S. Liu, T. Zourntos, K.L. Butler-Purry. (2011). Towards modelling the impact of cyber attacks on a smart grid. IJSN. 6. 2-13. 10.1504/IJSN.2011.039629.
[80] R. Mckenna, P. Ostman V. D. Leye, andW. Fichtner, Key challenges and prospects for large wind turbines, Renew. Sustain. Energy Rev., vol. 53, pp. 1212-1221, Jan. 2016, doi: 10.1016/j.rser.2015.09.080.
[86] G. Shafiullah, A.M. Oo, A. S. Ali, and P. Wolfs, Potential challenges of integrating large-scale wind energy into the power grid - A review, Renew. Sustain. Energy Rev., vol. 20, pp. 306-321, 2013, doi: 10.1016/j.rser.2012.11.057.
[103] M. Farhadi and O. Mohammed, Energy Storage Technologies for High-Power Applications, in IEEE Transactions on Industry Applications, vol. 52, no. 3, pp. 1953-1961, May-June 2016, doi: 10.1109/TIA.2015.2511096.
[104] J.K. Kaldellis, D. Zafirakis, Optimum energy storage techniques for the improvement of renewable energy sources-based electricity generation economic efficiency, Energy, Volume 32, Issue 12, 2007, Pages 2295-2305, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2007.07.009.
[107] IRENA, IEA and REN21 (2018), Renewable Energy Policies in a Time of Transition. IRENA, OECD/ IEA and REN21.
[131] A. Ulbig, Grid integration challenges of renewable energy sources and prospective solutions, presented at the Swiss Federal Inst. Technol. Zurich, 2013
[132] Q. Hu, R. Zhang, Y. Zhou, Transfer learning for short-term wind speed prediction with deep neural networks, Renewable Energy, Volume 85, 2016, Pages 83-95, ISSN 0960-1481, https://doi.org/10.1016/j.renene.2015.06.034
[135] U.K. Das, K.S. Tey, M. Seyedmahmoudian, S. Mekhilef, M.Y.I. Idris, W. Van Deventer, B. Horan, A. Stojcevski, Forecasting of photovoltaic power generation and model optimization: A review, Renewable and Sustainable Energy Reviews, vol. 81, Part 1, 2018, pp. 912-928, doi; 10.1016/j.rser.2017.08.017.
[137] G. Chicco, V. Cocina, F. Spertino, Characterization of solar irradiance profiles for photovoltaic system studies through data rescaling in time and amplitude, 2014 49th International Universities Power Engineering Conference (UPEC), Cluj-Napoca, 2014, pp. 1-6. doi: 10.1109/UPEC.2014.6934619.
[141] D. Braga, G. Chicco, N. Golovanov, R. Porumb,. Long-Term Solar Irradiance Forecasting. In: Problemele Energeticii Regionale. 2020, nr. 1(45), pp. 94-109. ISSN 1857-0070.10.5281/zenodo.3713424
[158] IRENA (2020), Renewable Power Generation Costs in 2019, International Renewable Energy Agency, Abu Dhabi.