University POLITEHNICA of Bucharest
Power Engineering Faculty
Energy Generation and Use Department

DOCTORAL THESIS SUMMARY

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Doctoral Commission

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Thesis summary

Alternative energy generation systems with low environmental impact and economically advantageous are a major global issue. In view of the technological evolution of the integrative equipment of energy conversion systems, the fact that most of them have become economically competitive with conventional ones but also the concentration of energy policies towards increasing the share of renewable sources in the coverage of energy demand, the energy mix becomes progressively more complex. Therefore, in the last decade alone, capacities installed in renewable technologies have doubled, following a similar trend at global and continental level; at the level of each country, however, there are a number of factors that particularize the evolution over time of installed capacities. Taking into account the economic implications of renewable energy variability, both in terms of integration into the electricity system and maintaining an adequate level of stability and reliability, studies in this area are currently of great interest.

Although there are numerous advantages of the expansion of the use of renewable energy sources, the lack of synchronization between their production and energy demand at some point hinders their faster development. Electricity storage is the solution that enables not only to increase the efficiency of energy generation using renewable technologies, but also to separate production and consumption over time and space. This facilitates the transition to distributed systems and improves system-wide performance. Additionally, decarbonization technologies complementary support the integration of renewable energy and enhancements of system performances.

As a consequence of growing energy demand, traditional energy sources are approaching depletion and harmful greenhouse gas emissions are going through the roof. To ensure maintaining the energy balance at all time and mitigating environmental impact, RES had to increase their penetration. Compared to traditional and fully controllable energy sources, RES are characterized by highly fluctuating features, so they are often exploited in combination with energy storage systems (ESS) in hybrid interconnected or remote power systems. Innovative solutions available on the market enable improved systems reliability and enhanced power quality. Technical progress in the field of both distributed generation and ESS integration

indicate hybrid energy systems, comprising multiple generation/storage systems as a viable solution to overcome the issues related to RES uncertainty.
Assessments conducted by the International Energy Agency (IEA) estimate that, as a result of the pledges implemented consequently to the Paris Agreement on climate change, global CO2 emissions growth rate will be diminished down to an annual average of 160 million tones in 2040 (if compared with the average annual rise of 650 million tones seen since 2000). According to these strategies, RES generating capacities increased by 183% worldwide in the past 14 years. This 14 years timespan is selected in order to cover the first year when new RES technologies (particularly wind energy) are present in the energy balance in Romania, as this country is the focus area of the study presented in the thesis.
The doctoral thesis entitled *Modeling and simulation of hybrid energy systems in the framework of integrating decarbonization technologies,* addresses the challenges related to high renewable energy penetration hybrid systems and innovative solutions to mitigate potential drawbacks while increasing the operational performances.
In this regard, Chapter I presents a detailed review of the current energy framework, providing comprehensive comparisons and analyses of the Romanian system in the context set by European and global policies. Renewable energy characteristics are investigated, carbon dioxide emissions are evaluated and technic economic evolutionary trends are discussed, based on extensive review of real data and scientific literature.
Chapter I presents a detailed review of the current energy framework, providing comprehensive comparisons and analyses of the Romanian system in the context set by European and global policies. The novel contributions of this chapter are related to the renewable energy evolution investigation and environmental impact of the energy system, evaluated in terms of CO2 emissions. Extensive real datasets and statistics are processed in order to provide a comprehensive review and highlight prospects for renewable energy, carbon dioxide emissions technic economic evolutionary trends in the field of hybrid renewable energy systems.
An analysis is conducted in this chapter with regards to the correlation between RES territorial availability in Romania and population distribution, aiming to discuss possible feasible solutions for increasing RES share in Romanian energy balance. Based on potential estimations and statistical records, the RES availability and population regional spread are overlapped for all 42 regions, including the capital. It is evident that the maximum values are not correlated

(being evaluated at 2572.5 MW in region 15, respectively 7913.6 people per km^2 in region 10, which represents the capital), posing transmission and infrastructure loading issues in centralized systems.

Further, real data records for demand and generation by sources (nuclear, coal, hydrocarbons, hydro, wind, photovoltaic and biomass) for the last ten years in Romania, an algorithm was developed using Matlab software in order to calculate some representative quantities per annum: total demand; total energy generated and by primary source; renewable energy share in electricity demand, including hydro energy; average used capacity for each source; and total carbon dioxide emissions. According to the results, by 2024 total CO_2 emissions from Romanian energy sector shall decrease with 44.86% since 2007 and with 22.82% compared to 2020. Nuclear power and renewable energy, excepting hydro, contribute the least to the total amount of CO_2 emissions. The participation of hydro energy in the total amount of CO2 emissions is comparable to that of hydrocarbons power plants for the Romanian power system. Increasing renewable energy share in electricity generation as a result of several factors, such as environmental constraints, technical and economic aspects or social implications leads to a corresponding reduction of CO_2 total emissions. As previously shown, this dependency follows approximately a decreasing linear trend.

Forward, ***Chapter II*** presents a detailed variability analysis of renewable energy in Romania, based on 14 years long data records at a real system level. A specific methodology is defined for this scope, investigating the confidence interval for each RES source, highlighting the most variable typologies. Further, to answer the challenges of such variability, several mitigation solution are carefully reviewed. Storage technologies and power-to-gas approaches are analyzed. The analysis based on the confidence interval of mean peaks, allows also to highlight the mismatch between demand profile and RES generation profiles, with particular reference to the wind source. To answer the challenges of such variability, several mitigation solution are carefully reviewed. Among them, storage technologies and power-to-gas approaches are reviewed in detail.

Chapter III investigates the methanation principle and reviews the basic principle, performance comparison of different technologies and discusses the integration perspectives in the context of the renewable energy integration. Chapter III presents the carbon dioxide methanation principle, as a mean to obtain carbon neutrality and reviews the basic principle, performance comparison of different technologies and discusses the integration perspectives in the context of the renewable energy integration.

In a framework highly oriented towards innovation and new technology development, intensive research is necessary to enable market penetration and wide diffusion of cutting-edge solutions. Improved and highly efficient technologies are still needed to achieve acceptable levels of emissions while ensuring mitigation of RES related effects on power systems behavior. In high-penetration renewable energy systems, the variability of electricity generation sources must be mitigated, in order to enable their optimal exploitation. For this purpose, they have to comprise flexibility resources (such as storage devices) additional fully controllable generating units (diesel groups, for instance) and, sometimes, flexible demand. In this environmentally restricted and increasingly uncertain power generation context, the paper addresses the selection of catalysts for a methanation tank possibly coupled to a diesel generator, considering a further innovative and integrative approach within hybrid energy systems. It is highlighted the need to establish a compromise solution, affordable and able to ensure high values of CO2 conversion rate and selectivity in the formation of CH4, under conditions of pressure and temperature that involve low energy consumption.

Chapter IV introduces the concept of methanation technology employment for carbon dioxide emissions reduction. First, the composition of the flue gases is investigated, then the integration of a faculties in hybrid energy systems to achieve carbon neutrality. Technologies for the conversion of electricity into long-term gas-to-gas (P2G) energy agents play a key role in the contemporary development of low-carbon energy systems. P2G is a viable solution for storing highly variable renewable energy in the medium and long term, thus ensuring the satisfaction of time imbalances between energy production and demand in the current uncertain context . The basic principle of P2G consists in the production of a combustible gas (which can be stored or injected in the distribution network) using:

- renewable energy for obtaining hydrogen (H_2) by electrolysis;
- an additional source of carbon dioxide (CO_2) for the production of Synthetic Natural Gas (SNG), with a high content of methane (CH_4), in the methanation reaction.

It is highlighted that methanation decarbonation is technically feasible through a combination of technologies (methanation reactor, electrolyzer for H_2 production, etc.). As a result, the production of CH_4 in decarbonation processes is not currently economically competitive with conventional production technology if the use of atmospheric CO_2 is intended. A possible more accessible and implementable solution in a shorter time is by "reusing" CO_2 emitted by polluting installations. This concept falls within the field of carbon capture and use technologies, which can eliminate CO_2 emissions generated in the operation of various polluting plants (such as conventional power plants). Therefore, the functionality of the technology discussed in this paper shows a huge research potential, being yet less investigated and exploited.

It is emphasized that the decarbonation of the exhaust gas and the utilization of its CO_2 content as a carbon source for methane production supports overcoming critical issues in current energy systems (such as fossil fuel-based power units flue gas carbon capture applications). The utilization of CO_2, additionally to its storage seems a very attractive option for emission control and reduction. At the moment, CO_2 employment as chemical feedstock is narrowed to only some processes: synthesis of urea, salicylic acid, and polycarbonates production. Still, the real usage accounts a very low percentage of the available CO_2 potential.

Low CO_2 emissions power generation scenarios are thoroughly investigated, most of the time comprising decarbonization installations. CO_2 methanation is not widely used currently, with only a few pilot projects operating (with rated powers below 6 MW). Consequently, further research and demonstration are required.

It is highlighted that the integration of methanation installations at the outlet of combustion plants is a multi-disciplinary, tackling chemical and energy aspects. The remarkable contribution of the proposed depolluting approach refers to the interconnection of modern and classical technologies to obtain green energy and, aiming the decarbonization of the energy sector.

Extensive simulations for hybrid models are presented in ***Chapter V***. All the simulations models are defined in relation to real data corresponding to the south east of Romania, where a complex pilot installation is implemented. All simulations regard the components of the installation and their validation.

First, a wind turbine – diesel generator system is modeled. It is demonstrated that, implementing a second voltage source, such as Diesel generators, enhances the reliability and performances of intermittent power sources, improving the continuity of supply. The model addressed in this research allows the analysis of interaction among its components. Moreover, it comprises meteorological input data, to consider the properly the inherent wind variability

Second, a PV array – fuel cell is investigated, defining a particular fuzzy logic controller for it. It can be noticed that the fuzzy logic controller enables a faster transition between the states in answering to both reductions and increases of power required to the PEMFC. Moreover, the PEMFC power is always bring to the target value. It is highlighted that the fuzzy controller allows an improved performance of the systems in terms of supplying the load following the reference.

Third, a PV array – battery system is analyzed. Four types of battery technologies, represented by a Li-ion, a Ni-Cd, a NiMH and a Lead-Acid are taken into account to observe their behavior at parity of power. Given that first three technologies of electrochemical storage show very similar behavior in dynamic conditions, choosing one of them is mainly based on economic criteria, not only as investments involved, but also as costs related to the reliability of supply. Further research targets employing hybrid storage systems and perform simulations also subsequent connecting the micro-grid to the mains.

Fourth, a wind turbine – battery system is represented. This research addressed a simulation model for an application of model predictive control on managing the exploitation of a battery energy storage system in a wind energy power plant, aiming to establish a suitable configuration of the controller. The proposed structure of the MPC showed a stable behavior in the dynamic simulated scenario. In further research we shall develop the control structure and assess its performance in particular frameworks, based on available statistical data.

Last, a complex hybrid structure is proposed to exploit the advantages of poly-generation configurations, including storage devices and uninterruptible power supply technologies. More in detail, the RES have been selected taking into account the local availability, to increase energy independence on a local level. The storage section comprises two devices, with different response characteristics and timeframe suitability (Li-ion battery for short time and reversible solid oxide fuel cell for medium to long time). The microgrid could operate in interconnected mode, in order to ensure overproduction flow towards areas with production lack. Furthermore, a diesel group equipped with a methanation unit is integrated within the microgrid, emphasizing carbon capture and utilization features in a sustainable development framework.

The hybrid architecture analyzed in this research comprises a small scale application connected to the grid, but able to operate as a stand-alone system. It comprises a 1.5 kW wind turbine, a 5 kW PV array, a 8.8 kW diesel generator and a 5.6 kWh battery. The proposed configuration corresponds to a pilot installation in Romania, located in the Constanta region.

The multi-generation configuration, correlated with the storage capability and methanation facilities, with corresponding control and monitoring system falls within the renewable smart grid concept.

This research addresses the feasibility of a high RES penetration power system focused on the Romanian conditions. The conducted analysis proves that there is still over 50% unexploited RES potential available on a regional scale over the Romanian territory. This enables a further increase of RES share in meeting the national energy balance, currently varying around 50% if including large hydro power plants. Thus, if implementing similar approaches to the one introduced in the present study, Romania could achieve a further up to 10% increase of RES share. If correlated with the proposed decarbonization technologies, the reduction in harmful emissions would be significant.

High penetration rates of RES require a multi-criteria approach for selecting the proper storage technology and power/capacity sizing. Recent studies indicate that a storage capacity of 6% of the annual energy demand is enough to achieve 100% RES share. For this purpose, power-to-gas technologies are needed, also in hybrid configurations with other storage technologies, achieving both long- and short-term balancing of RES fluctuations.

Contributions of the thesis are detailed in ***Chapter VI***, together with the general conclusions and further research perspectives. The main contributions of the present doctoral thesis consist of the original approach in analysis, modeling and simulation of hybrid energy systems in the context of increased RES penetration and neutral carbon targets. Extensive simulations are conducted in Matlab environment. The quality and impact of the research results are demonstrated through the large number of scientific papers published in Q1 and Q2 journals, ISI and Scopus conference proceedings, as detailed in the publication list.

From a flexibility perspective, it is highlighted that requirements are reduced if adjacent systems share their backup power resources. As the proposed microgrid configuration is equipped with complimentary generation and storage technologies, such distributed architectures enable increased energy independence and high operation performances, alternating as convenient the online source to meet the energy demand.

It must be mentioned that an additional RES share augmentation can be achieved if exploiting the wave energy potential available on in the Black Sea. Although there are several investigations depicted on the literature on this regard, because there are still no operational facilities, this RES category it is not considered in the present study.

In conclusion, passing to a decentralized generation structure is a feasible alternative in Romania, but given the strong territorial mismatch between RES potential and energy communities establishment, independent and economic affordable microgrids are not yet a viable solution. Interconnected poly-generation microgrids, including hybrid storage sections and uninterruptible power supply facilities are, based on the proposed outline, enable highly efficient and sustainable power system development.

Further detailed analyses are to be carried out to define particular microgrid configuration and evaluate their performances.