SUMMARY IN ENGLISH

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The title of the doctoral dissertation:

Modeling and optimization of energy storage, including thermal energy storage, in a power system with generation from sources difficult to forecast.

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Through this paper, the author has attempted to join the stream of wide-ranging research works, which are related to transformational changes aimed at decarbonizing the economy. The design of the paper is based on three main pillars, which constitute chapters No. 7, 8 and 9. The remaining chapters are supplement it and fulfil the goals agreed upon with the dissertation supervisor as well as meet the requirements set by the director of IMP PAN and the Scientific Council of IMP PAN.

In the conclusion, which is the last chapter of this work (chapter 10), the author refers to the implementation of his objectives, defined at the stage of formulating the research objective and proving the truth of the dissertation.

Starting with the basic chapters, defined by the author at the beginning as the pillars of this dissertation, it should be pointed out that Chapter 7 analyzes the variable nature of wind and photovoltaic power generation. To adequately represent the nature of this work, data from a German system, in an area bordering Poland, managed by 50Hertz Transmission GmbH was used. The correlation between the average power generated by wind and solar sources is noticeable for the analysed area, however, for longer time intervals (weeks and months). On the other hand, for smaller time intervals (hours, days), in order to ensure stable and predictable generation from RES sources that are difficult to forecast and to ensure the operational security of the power system, appropriate technical solutions should be sought. One option that can be used is energy storage. This problem (or perhaps more appropriately, "issue") is of particular importance in the case of wind power, which, due to its more difficult forecasting, can significantly affect the power balance of the power system in short periods of time. The analysis shows that for the annual time interval, the total maximum capacity utilization of wind and solar PV oscillates around 70%. Additionally, based on the calculations performed, it can be assumed that the optimal *mix* of energy generation in Poland will be provided by sources that are difficult to forecast (wind power plants and photovoltaic power plants) with their comparable installed capacity (see Fig. 124). Moreover, it was pointed out that a very important issue related to the energy transformation and e.g. the use of energy storage facilities, are the costs of this transformation, which were estimated at between PLN 841 billion and PLN 3,125 billion, with the higher value including the expenditures on the construction of energy storage facilities.

The aim of chapter 7 was to prove the truth of the dissertation statement (see chapter 1.2) and to accomplish two additional objectives, no. 1 and no. 5 (see chapter 1.1).

The next chapter, defined as the basic chapter (Chapter 8), presents a case study of the operation of a power system with a significant share of difficult-to-predict RES sources with a variable generation profile, the operation of which is compensated by conventional power plants supported by hybrid energy storage (mechanical energy storage [CAES] cooperating with thermal energy storage [UTES]).

As repeatedly emphasized in this dissertation, improving flexibility and ensuring security and uninterrupted supply of electricity is one of the key challenges of the transformation of power systems, including the National Power System. These challenges are derived from EU policies and strategies aimed at achieving climate neutrality, mainly through a high share of renewable sources in electricity generation, which the author has thoroughly analysed in the chapter 2. In this context, CAES systems, with the level of achievable power as a determinant, are now a serious alternative to pumped hydroelectric energy storage power plants. The basic components of CAES systems are: (1) an air compression station, (2) a compressed air tank which is also a mechanical energy storage (in existing solutions these are usually underground reservoirs, e.g. in the form of rock caverns, salt caves or deep mines), (3) an expansion station with combustion chambers and gas turbines, and (4) a generator. In this paper, the concept of compressed air storage (CAES) coupled with underground thermal energy storage (UTES) is presented and considered at three levels, namely: (1) global energy production level, (2) central energy conversion and storage level, (3) local thermal energy storage level.

Then, a solution is proposed that can improve the operating conditions of the NPS to some extent by compensating the variable production of electricity by the difficult-to-predict RES with the operation of the energy storage in the CAES system (appropriate to the current operating conditions of the NPS: (1) air compression [excess energy production from the NPS], (2) generator operation [power demand from the NPS]).

Two different storage facilities (1) with underground heat exchanger (UHE) and (2) without it (D-CAES) were analysed. The efficiency of the first cavern charging and discharging process was $\eta_{CAES} = 52{,}09\%$, which is satisfactory considering the intermittent operation of difficult-to-predict renewable energy sources such as wind and photovoltaic farms. In addition, the newly proposed CAES with UHE as a component of UTES leads to an increase in efficiency to $\eta_{CAES} = 52{,}26\%$.

The Underground Heat Exchanger (UHE) is a component that reduces heat loss to the environment from the CAES system, thereby increasing energy conversion efficiency. To capture this effect, a zero-dimensional CAES system model was coupled and developed with a local Thermal-FSI approach. Both power output and efficiency of the CAES cycles with and without the underground heat exchanger (UHE) were determined. From a thermodynamic and ecological point of view, CAES with UHE as a component of UTES is a promising technology that can meet the requirements of a "new power system" highly saturated with difficult-to-predict RES sources while meeting stringent environmental standards. On the other hand, high capital expenditures and low power densities as well as not fully known operational problems limit the application of such energy storage systems to pilot sources only. According to the author, we still have to wait for a more common implementation but it can be assumed that the needs for energy storage will force this type of investment and at the same time provide appropriate business justification for them.

In addition, the advantages of the zero-dimensional mathematical model should be emphasised. The equations used in these models are expressed in terms of parameters that are relatively easy to determine. Since UHE can work with gas turbines or other devices, this model is built in such a way that it can be implemented into general code that computes thermodynamic cycles. Another advantage of the model is its compatibility with CFD numerical codes, thanks to which the parameters of the model can be coupled to 2D/3D models in a local approach.

Chapter 8 resulted in the implementation of the main task that was also a second additional objective (see Chapter 1.1).

The third pillar of this dissertation is an economic analysis and examination of the business case for the concept involving energy storage. This task was carried out as part of the work on Chapter 9. The analyses performed as part of this chapter indicate that the current level of capital expenditures for energy storage does not allow it to achieve the minimum rate of return (IRR=WACC) acceptable to the investor. Given the potential revenues to be generated from the Capacity Market and price arbitrage, a decrease in capital expenditures of approximately 13% for lithium-ion storage would be necessary (taking into account the reservation mentioned in footnote 270). For other storage technologies, the reduction in input would have to be significantly higher to make the investment economically justified.

The costs of energy storage technologies are steadily decreasing, which may indicate that in a few years the amount of capital expenditures will be at a level justifying the rationality of investing in electrochemical energy storage systems. Analyses indicate that it is more cost-effective to operate energy storage using price arbitrage than the RES balancing option (see Chapters 9.4 and 9.5), with particularly large differences in this regard for lithium-ion storage.

Lithium-ion storage has the lowest cost of energy storage in terms of both cost per MWh of capacity and 1 MW of discharge power and, importantly, has the highest level of efficiency. The advantages of lithium-ion storage include high discharge power and short response time, making them ideal for stabilizing power quality parameters in the NPS.

A key consideration is the continued rapid development of technology that will drive down the cost of energy storage technology. It should be noted that the development of energy storage is one of the key elements for the feasibility of implementing climate policy by 2050, i.e. achieving climate neutrality through the use of appropriate energy conversion and storage technologies at the level of the entire European Union.

Chapter 9 resulted in implementing the fourth additional objective (see Chapter 1.1).

The remaining chapters, which, as indicated in the introduction to this dissertation summary, are necessary to complete the dissertation and fulfil the objectives agreed upon with the supervisor, as well as to meet the requirements set by the director of the Institute of Fluid-Flow Machinery of the Polish Academy of Sciences and the Scientific Council of the Institute of Fluid-Flow Machinery of the Polish Academy of Sciences. They provide necessary and rich background to the primary chapters. On their basis the author of this paper made decisions about the choice of particular assumptions for the conducted analyses and simulations.

Chapter 2 was a starting point, a necessary confirmation that both the subject matter of the work, as well as the outlined area of interest, is consistent with the policies, strategies and tasks defined at the global (UN), regional (EU) and local (Poland) levels. The analysis shows that starting with the *United Nations Charter,* which established the United Nations, through the Stockholm Conference and the hugely important UN Secretary General U Thant's report "Problems of the Human Environment" from 1969, the *United Nations Framework Convention on Climate Change* of 1992, to the *UN Climate Change Conferences* resulting from the UNFCCC, the world united around the UN is slowly but increasingly effectively implementing principles that unequivocally put concern for the future of the planet at the heart of its concerns.

One of the driving forces behind these changes is the European Community, which through successive reforms, known as the energy and climate change packages, implements the decisions made at the forums of UN agencies and introduces its own, individual and ambitious goals.

In the author's opinion, the most important in the current era are: (1) *The Paris Agreement*, which was the first-ever universal and legally binding global agreement on climate change protection and (2) *The European Green Deal*, which is a set of policies, strategies, actions, and tools to achieve climate neutrality for the Community in 2050.

Poland is transforming its energy sector through legislation and, first and foremost, through strategic documents in the area of energy, i.e. successive energy policies, and - to the extent possible - successively decarbonising its economy. The currently implemented policy (PEP2021-2040) implements this task through three pillars: (1) a just transition, (2) a zero-carbon energy system, and (3) good air quality. The announced revision of PEP2021-2040 includes a fourth pillar (4) of energy sovereignty.

The megatrends shaping policies and strategies clearly identify the development of renewable energy sources as the foundation for the changes to come. Much space is also devoted to the most common element in the Universe, hydrogen (H_2), seeing in it (or its derivatives) the element linking today's separately functioning sectors into a single hydrogen supersector.

In every strategic document, regardless of where it is implemented (UN, EU, Poland), renewable energy sources are at the centre of attention. It is on RES development that decarbonisation strategies are based.

The work on Chapter 2 resulted in the implementation of the third additional objective (see Chapter 1.1).

Chapters 3. and 4 in turn are devoted to an overview of technologies in the field of renewable energy generation (Chapter 3.) and energy storage (Chapter 4.).

The research done by the author of this dissertation in reviewing the literature as well as current statistical, commercial, technical and operational data was used in formulating the chapter assumptions: 7, 8 and 9.

Chapters 5 and 6 provide an overview of statistical data in the field of energy, including the area of selected renewable energy sources (Chapter 7) and present the operating characteristics of difficult-to-predict energy sources (VRES) (Chapter 4).

The aim of the work on Chapters 3, 4, 5 and 6 was to indirectly prove the truth of the thesis set by the author, implement the main task and additional objectives (see Chapter 1.1).

The conclusions of the above-mentioned review enriched the author's knowledge and will undoubtedly be used in future research work. The work on the dissertation also systematised the author's knowledge on the dynamics of the development of the energy sector in general and the area of renewable energy sources in particular (in a global, regional and local perspective). This knowledge will certainly be applied in professional work, to the benefit of its quality.

Gdańsk | May 30, 2022