Profesor Jan Popczyk

Common Energy Transformation Platform
Association of Polish Electrical Engineers
– Chairman of New Concepts and Energy Technologies Section
Silesian University of Technology

TRANSFORMATION OF THE ENERGY INDUSTRY
the paradigmatic triplet, the map and the trajectory

TRANSFORMACJA ENERGETYKI
paradygmatyczny triplet i mapa oraz trajektoria

Abstract: *Transformation of the contemporary energy industry based on fossil fuels into electrical monism (2050) results in a profound change in energy balances. This paper presents an energy balance for a standard single-family house in Poland, as well as that of the Polish economy and that of the global economy. The analysis of the fundamental drivers of these changes (thermodynamic, electrical, economic and social) allows to formulate the development paradigms of the new energy sector: the prosumer paradigm, the exergy paradigm and the virtualization paradigm (the last one in relation to power engineering). It is the triplet that helps to propose the new power market design and facilitates rationalization of the transformational trajectory (2018-2050) by means of market mechanisms.*

Streszczenie: *Transformacja współczesnej energetyki paliw kopalnych w monizm elektryczny (2050) oznacza szokową zmianę bilansów energetycznych (w artykule przedstawia się dla ilustracji charakterystyczny bilans dla domu jednorodzinnego w Polsce, dla Polski i dla świata). Analiza fundamentalnych podstaw tych zmian (termodynamicznych, elektroenergetycznych, ekonomicznych i społecznych) pozwala sformułować paradygmaty rozwojowe nowej energetyki: prosumencki, egzergetyczny i wirtualizacyjny (ostatni w odniesieniu do elektroenergetyki). Jest to triplet, który ułatwia zaproponowanie nowej architektury rynku energii elektrycznej oraz tworzy możliwość racjonalizacji trajektorii transformacyjnej (2018-2050) za pomocą mechanizmów rynkowych.*

Only new concepts, implemented with the help of new technologies, may become a disruptive innovation which is indispensable for the power industry.

One concept, three methodical paradigms, three acronyms identifying the energy transformation environment and three electricity markets that give it its dynamics

The importance of electrical monism (the idea that all energy needs/services could be satisfied by electricity alone) stems from the fact that it is directly linked to the practical idea of useful energy. The paradigmatic triplet (prosumer, exergy and virtualization paradigms) is the starting point for the unification of the methodology of a "new" energy sector. The three acronyms – PE (prosumer energetics), II (independent investors' sector), LCPG (large-scale corporate power generation) – define the key players of the initial energy transformation state (hereafter state A). The significance of three electricity markets – namely the emerging markets (1) and (2) vs the descending market (LCPG) – lies in the fact that they directly determine the trajectory of the energy sector transformation on the horizon 2050 (hereafter state B).

Tab. 1. Useful energy and demand for electrical monism, the paradigmatic triplet, the 3 acronyms identifying the environment of energy transformation and the 3 markets determining its dynamics

Useful energy E_u and demand for electrical monism	Renewable energy required to satisfy energy needs, taking into account implementation of the passive house standard, electrification of heat supply by means of heat pumps, electrification of transport by means of electric vehicles, and fulfilling the potential of energy efficiency improvements in "traditional" electricity uses.
The prosumer paradigm	The paradigm of the prosumer value chain effect, augmented by the factory effect (scalability), replacing the scale effect of the LCPG energy industry
The exergy paradigm	The paradigm of reducing large chemical and nuclear exergy losses by means of high exergy electricity from renewable energy sources RES (and the use of non-energy raw materials for the implementation of the passive house standard and exergy losses of the lower heat source of the electricity driven heat pump).
The virtualization paradigm	The paradigm of sharing power grids (the paradigm of the TPA + principle allowing for the intensification of the power grid use by means of competition on the electricity market within power grid constraints managed by smart access grid terminals).
Prosumer energetics (PE)	Prosumer energetics – from a household to multinational corporations like KGHM
Independent investor energetics (II)	Independent investors energetics (RES sources, energy efficiency of the demand side, smart infrastructure)
Electrical power industry (LCPG)	Large scale corporate power generation LCPG based on fossil fuels
Shrinking power generation market (LCPG)	The Polish energy market in the initial state A (2020) shaped by the TPA principle (as part of the power engineering reforms initiated in the world at the turn of the 1980s and 1990s) and IN the "zero" final state B (2050).
Emerging power generation market (1)	Polish energy market which is about to develop on HV-MV electrical grid infrastructure. Independent investors operate on this market.
Emerging power generation market (2)	Hypothetical Polish energy market ("zero" A state), which is expected to develop in the following decades within infrastructure-urban corridor of inverted T shape. This market is scheduled to use AC-DC high voltage (110 kV and above) network infrastructure.

Due to its innovative characteristics, transformation of the energy sector will naturally consolidate the methodology of the new energy sector. From the practical point of view this methodology will emphasize the significance of useful energy which is at the core of a future power system (state B). The idea of electrical monism (satisfying all energy needs by means of useful energy – state B) will provide a theoretical context of transformation from energy sector based on fossil fuels (state A). Obviously, this dynamic process would include considerable trial and error.

In this paper it is hypothesized that to consolidate the methodology of a new energy sector it will be useful to employ a hybrid approach with the so-called "closed induction-deduction-induction loop" (see below). The inductive beginning of the methodical loop results from the already advanced technological development including three large technology segments such as energy-efficient receivers (loads), renewable energy sources and intelligent infrastructure. Such an approach is also justified by the fact that groundbreaking concepts for the needs of electricity markets are created increasingly often.

Furthermore, the commercialization of new energy technologies provides already mass availability of empirical evidence (results of applications of these technologies). On the other hand, groundbreaking concepts of power system virtualization by means of control shields (dedicated to the needs of the real-time electricity market) – using smart access terminals of the emerging electricity market (1) to the LCPG shrinking market (in accordance with the TPA$^+$ principle) – enable their (concept) simulation testing. This again provides us with an abundance of empirical data, in this case in the form of simulation results. The availability of empirical data is in turn the foundation of inductive reasoning.

Taking this into account the first part of the article presents draft estimation of energy markets/balances on a local (standard Polish household), national (Polish economy) and global level. Since these estimations brought unexpected results, an effort has been made to "find" their theoretical explanation. Thus the second part of the paper was briefly devoted to the theoretical premises of the paradigmatic triplet. A preliminary and concise description of each paradigm was also provided. Thermodynamic, electro technical and information technology foundations as well as the theoretical findings of life, social and economic sciences provide a basis for a study of energy transformation by means of deductive reasoning.

Although the ideas of paradigmatic triplet are far from being universally accepted (they are not commonly included in textbooks yet), nevertheless a fundamental and irreversible shift from macroeconomics to microeconomics (hence from the corporate energy policy to prosumer energetics in the formula of electrical monism) can be seen in the global energy sector. Under these circumstances a return in the methodical loop to the inductive approach (building macroeconomic reality through microeconomic decisions) seems to be justified. Therefore, the third part of this paper is briefly devoted to the issues of the new power market design and creating market mechanisms capable of giving a rational dynamic to the transformation of energy sector (via control shields equivalenting).

Part I
PRIMARY, FINAL AND USEFUL ENERGY MARKETS

The effects of [demand] electrical monism and energy transformation can be most clearly seen in primary, final and useful energy (electricity) balance sheets. Energy balances for a standard Polish household, for the Polish economy and for the world are shown in Fig. 1, Fig. 2, and Fig. 3 respectively. These energy balances are very instructive showing scalability of a methodology of the new energy sector (methodological context) and a huge potential to reduce energy consumption by diminishing conversion losses from primary energy to useful energy (practical context). Energy transformation may be viewed to avoid losses of chemical and nuclear exergy by means of electricity (which may be regarded as pure exergy) generated from renewable sources. The awareness of this fact helps to overcome "prisoner of one's own imagination" syndrome which is understood here as an inability to perceive potential effects of energy transformation. This syndrome affects politicians, societies and scientists as well. Furthermore, the understanding of energy transformation helps to use more efficiently substantial resources of a traditional energy sector (LCPG).

Standard Polish household perspective

A household may be regarded as the smallest entity in the process of energy transformation. Fig. 1 shows an ‘energy environment’ of a standard Polish household from a residential multi-family building. It is stressed here that to understand the essence of energy transformation it is necessary to employ a holistic approach to this process.

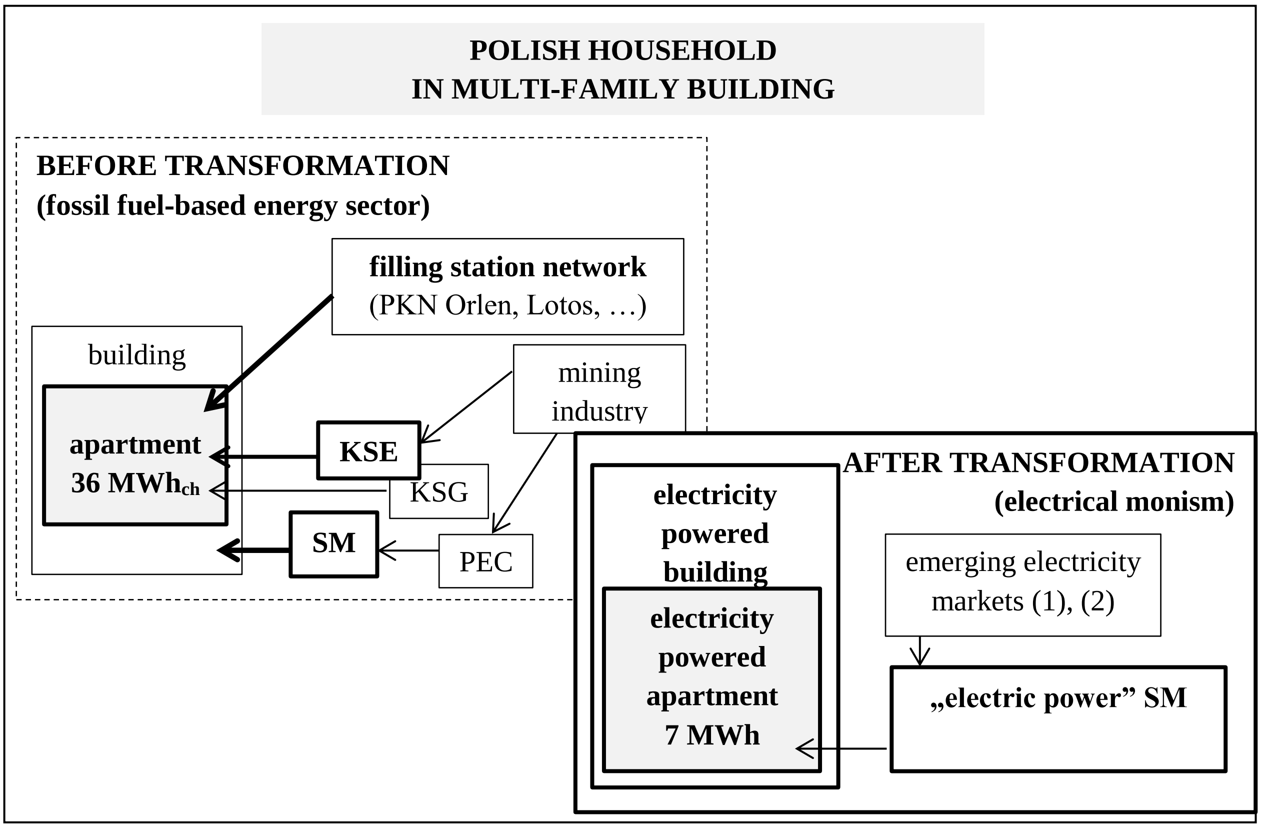

Fig. 1. The extensive environment of an energy cooperative within a housing cooperative
SM – housing cooperative; KSE – Polish Power System, KSG – Polish Gas System,
PEC – heating plant or cogeneration plant.

On the one hand it is important to find a way to satisfy all the energy needs of a building (its inhabitants, households) by means of electricity alone – i.e., to achieve a standard of “electricity powered apartment” with the annual energy consumption equal 7 MWh – characteristic for a future power system (state B).

The essence of energy transformation should also be sought at the intersection of three infrastructure systems (see below).

Firstly, at the interface of the building infrastructure which consists predominantly of receivers/loads and different installations which will be gradually developed during energy transformation towards electrical monism (state B). These installations include PV sources, trigeneration gas generators and diesel power generators, electric receiver, installation and car batteries and domestic hot water (DHW) storage tanks, and in a broader sense, intelligent infrastructure and the thermal inertia of a building. Secondly, at the interface of cooperative infrastructure (also community and property development infrastructure) which currently consists of network infrastructure (electrical, heating and gas) operated by the traditional energy sector (LCPG) and “common” loads. This infrastructure is expected to grow gradually with new PV sources, trigeneration gas generators and diesel power generators, electrical grid, intelligent infrastructure and electrical transport infrastructure. Thirdly, at the interface of the traditional energy sector (LCPG) infrastructure which presently consists of a power infrastructure (KSE), a gas infrastructure (KSG), and a district-heating infrastructure (PEC). In the future it will be gradually replaced by the emerging electricity market infrastructure (1) and (2) (see the fifth report in BŹEP).

Fig. 1. shows an average annual household demand for chemical energy of fossil fuels before the energy transformation (state A). This demand which is amounting to 36 MWh_{ch}, is met by coal (production of electricity and heat), gas (production of heat) and transport fuels. It was calculated using the following assumptions. The annual electricity consumption per household was assumed at 2 MWh. This demand is met by coal-fired power plants. The annual heat consumption of a household was estimated at 18 MWh (flat (apartment area 60 m^2, annual heat consumption per unit area 300 kWh/m^2 – building from the 1970’s, before thermo-modernization). The annual domestic hot water (DHW) energy consumption per household equals 3 MWh, and the annual transport fuel consumption per household was estimated at 10 MWh which corresponds to a mileage of about 15 000 km. An average annual demand for energy per household after the energy transformation (state B) is also shown in Fig. 1. This demand will decline to just 7 MWh of useful energy in the form of electricity. It was calculated using the following assumptions. An average number of people per household during energy transformation and after it is constant. Similarly, an average mileage of a car (cars) doesn’t change. The unchanging annual electricity consumption per household reveals a hidden assumption that expanding the volume of services for which electricity is used (excluding heat pumps and electric vehicles) is counterbalanced by the increased efficiency of electricity receivers/loads. Moreover, annual heat consumption per unit area decreased after thermo-modernization to 100 kWh/m^2 and the annual domestic hot water (DHW) energy consumption per household remained unchanged revealing a hidden assumption that any hypothetical increase in the annual domestic hot water DHW consumption per household is counterbalanced by the increase in thermodynamic efficiency of heat sources supplying and using domestic hot water (DHW). Furthermore, it was assumed that the electrification of heat by means of a monovalent heat pumps with the COP 3,2 (or an equivalent mono-energy system) would be adopted to meet heat demand of a household. Finally, the shift from ICE to EV means that in the operational efficiency of a car in mixed traffic (urban and extra-urban) would rise from 17% to 50%.

The national Polish perspective

It is a tough challenge for Poland to transform its energy sector as shown in Fig. 2. Roughly speaking (in the business as usual model) this challenge involves replacing 3000 TWh of chemical energy (including nuclear energy) by 200 TWh (i.e. 15 times less) of electricity from renewable energy sources because of transformation of the entire energy industry until 2050. Although the actual reduction in energy consumption may be lower than suggested here, nevertheless this energy transformation means a qualitative change in the energy sector (presumably the biggest in the history of the power industry).

POLISH ENERGY MARKETS [TWh]

PRIMARY ENERGY SUPPLY

Data for 2020 include chemical energy of black coal, lignite coal, oil and natural gas. Data for 2050 include also energy of natural uranium for two nuclear power stations, each consisting of two 1600 MW reactors

2020	2050
1000	1500/3000 (P)

GROSS FINAL ENERGY

electricity, heat, transport fuels produced from fossil fuels

2020	2050
600	1100 (H)

NET FINAL ENERGY

electricity produced from renewable sources

2020	2050
200 (H)	200 (A)

Fig. 2. Different scenarios of the Polish primary and final (gross/net) energy markets [TWh/year] by 2050; (P) – „business as usual" scenario, (H) – hypothetical or equivalent market, (A) – „electricity market" scenario

The three paragraphs below present a brief commentary on the estimates presented in Fig. 2, in the context of energy scenarios for a household in Poland (Fig. 1) and for the world (Fig. 3).

In „business as usual scenario" Polish energy sector continues its heavy dependence on fossil fuels and fossil fuel technologies up to 2050. In this scenario primary energy supply in 2050 is the sum of chemical energy of hard and brown coal, crude oil, natural gas and nuclear fuel (the Polish energy policy assumes the construction of two nuclear power plants 2x1600 MW each, nevertheless it remains unclear whether these power plants will ever be built). Primary energy supply in Poland grows from 1000 TWh in 2020 to 1500 TWh in 2050 under the assumption that consumption of coal, oil and gas grows by 1.3% annually (a moderate growth by contemporary standards). Total primary energy supply grows to 3000 TWh in 2050 if we include nuclear energy in Polish energy balance, because no less than 1500 TWh of nuclear fuel must be used annually in the two nuclear power plants mentioned above (annual electricity generation in these plants is estimated at 50 TWh). Note that the overall efficiency of electricity generation in a nuclear power plant is very low, because of a combined efficiency of a nuclear reactor together with a steam generator, and the efficiency of a steam turbine, with the former being below 10% and the latter below 45%, thus giving the total efficiency below 3%. The estimation of primary energy supply in a “business as usual scenario” by 2050 (Fig. 2) assumes that the growth of the Polish energy market is realized through incremental innovations within existing technologies in a traditional (LCPG) energy sector with “passive” energy consumers. The estimated gross final energy market in 2050 amounting to 1100 TWh corresponds to the annual growth of 1,9% (from 600 TWh in 2020, Fig.2) which is again quite moderate by contemporary standards.

On the contrary the estimation of a net final (usable) energy market amounting to 200 TWh (a hypothetical or an equivalent value in state A, and an anticipated value in state B Fig. 2) assumes a radical transformation of energy sector by means of groundbreaking innovations. In other words, this process includes the formation of a new energy model – namely an electrical monism – resulting from the transformation of existing energy markets (LCPG) into a new energy reality by contenders. These contenders – namely prosumers (prosumer energetics PE) and independent investors (energy sector II) – are bound to revolutionize energy markets by means of groundbreaking innovations affecting all four aspects of an energy system; technological, economic, legislative and social.

This estimate of a useful energy market considers a radical shift in meeting energy needs of individual customers (in particular this change involves an implementation of passive house standard, and an electrification of heating and transport services), but also the whole economy including the industry (in this case it is vital to carry out the reorganization of the industry towards the industry 4.0 standard). Qualitative transformation of the energy services market is expected to stabilize the usable energy volume. Namely, the hypothetical energy volume in state A (2020) is equal to the anticipated energy volume in state B (2050), although the energy volume per capita increases slightly by 8,6% due to population decline from 38 mln in 2020 (state A) to 35 mln in 2050 (state B) (Fig.2).

The global perspective

The general structure of global energy markets including (primary, gross and net (useful) energy is shown in Fig. 3. This structure includes three aspects – namely the subjective aspect (population), the time aspects (energy transformation period) and the objective aspect (energy). The objective aspect is the most important because none of the world problems which are aggravating today may be solved even if the entire world population would have the access to the mobile phones and the Internet, without having access to a reasonable amount of electricity.

The importance of the time aspect stems from the fact that there are deadlines that are considered critical in energy transformation. From this perspective the turn of the current decade marks the transition in the global energy sector including not only the mining industry (hard and brown coal), the power sector including nuclear energy, but also the transport sector and the natural gas sector (including shale gas). This transition affects the use of ‘raw’ fossil fuels and the use of electricity, heat and transport fuels. On the other hand, the horizon 2050, commonly associated with the goals of global climate and energy policy, should be considered more and more from the perspective of global sustainable development goals.

Finally, the energy aspect is critical from the point of view of a widespread implementation of a technological environment with such technologies as ICT, RES, LED, PH, HP, EV and UPS. Moreover, the energy aspect underlines the need for creating new, prosocial groups of interests which serve the community better than the existing ones. These groups of interests are supposed to recognize, on the one hand, mechanisms of competition corresponding to the actual work productivity, and on the other hand, willing to extend the scope of economic freedom and personal freedom of individuals.

GLOBAL ENERGY MARKET [10^3 TWh]

PRIMARY ENERGY

(Data include chemical energy of black coal, lignite coal, oil and natural gas as well as uranium energy used by nuclear power plants)

2020	2050
190	**380 (P)**

GROSS FINAL ENERGY

electricity, heat and transport fuels
produced from fossils fuels, consumed by „passive" energy consumers

2020	2050
85	**170 (H)**

NET FINAL ENERGY

electricity from renewable sources (RES)
produced during energy transition (PE-II-LCPG), key technologies; ICT, RES, LED, PH, HP, EV, UPS)

2020	2050
38 (H)	**75 (A)**

Fig. 3. Global primary and final (gross/net) energy markets [10^3 TWh/year] in 2020 and 2050[1];
(P) – "business as usual" scenario, (H) – hypothetical or equivalent market, (A) – anticipation

Part II
THE PARADIGMATIC TRIPLET

A working hypothesis (in the sense of the scientific method, or the organization of cognition and education) that it is useful to find a "genetic code" of the global energy transformation, is presented in the chapter. The starting point for this higher-level hypothesis is another hypothesis (lower-level) which says that the current transformation of energy sector is – from a scientific perspective – a multi-paradigmatic process, i.e. it is potentially shaped by many paradigms.

[1] List of acronyms; RES – Renewable Energy Sources, ICT – Information and Communication Technology, LED – Light-Emitting Diode, PH -, HP – Heat Pump, EV – Electric Vehicle, UPS –Uninterruptible Power Supply.

At this lower (level), the paradigms define a cognitive environment which enables us to look for the essence of energy transformation, i.e. to seek laws – by means of inductive and deductive reasoning – that reveal links between practical ideas on how to transform the energy sector and enable us to create tools allowing a rational a priori verification of these ideas (which, as a matter of fact, may be numerous). It is emphasized that a verification of false ideas carried out in passive mode, i.e. posteriori, is always extremely expensive in the case of the energy industry.

In this context, the paradigmatic triplet directs investigation and lays the foundations for understanding the energy transformation as an autonomous process taking place in a social and natural environment. Above all, the triplet creates a framework for determining practical solutions shaping the transformational trajectory, which consists of political decisions, legal regulations and market mechanisms.

The following terms are introduced for the sake of clarity (to ensure greater transparency in further considerations); state A (i.e. energy transformation in its current state), state B (a state related to 2050 time horizon, in which the energy transformation process is expected to reach its maturity, as indicated by its "genetic code". State B can also be written as (A+30), which practically means that state A formally refers to the state of energy transformation in the year 2020.

State A represents the energy industry that is based on fossil fuels. In the most general sense, fossil fuels are natural resources that are not in thermodynamic equilibrium with the surrounding environment. This definition provides an inseparable (expressive) link between the energy industry and the concept of sustainable development (together with a climate policy), and explains the central role of thermodynamics in the scientific method typical of the energy industry in state A. Therefore, at least one of the paradigms of the new energy industry should refer to thermodynamics and its method.

Secondly, state A describes the energy industry at the end of the industrial era which – from the civilizational perspective – shaped two modern socio-political systems – namely state interventionism and corporatism. That is why one (at least one) of the paradigms should refer to dramatic social tensions that are so characteristic of the globalization era. This paradigm should refer to methods used by sociology, economy, legal sciences as well as other social sciences.

Thirdly, state A refers to the energy industry whose research method and best practices were created before the digital revolution. This fundamental message explains the inadequacy of the methods used by this energy industry (state A) regarding the technological environment (smart materials, broadly defined ICT industry, digitalization) caused by the digital revolution via globalization mechanisms, and to the digital (network, cloud) society. Again, these considerations explain why one (at least one) of the paradigms should refer to electricity (broadly defined electrical engineering) and computer science, including the issues of power systems and ICT, especially in the context of network (computer, ICT, power system) sharing.

The conceptual space of the paradigmatic triplet

The conceptual space of the paradigmatic triplet involves a five-element set of concepts. First, there is a concept of resources. This concept is broadly defined and includes material resources (natural resources make part of it) and social resources. Secondly, there is a concept of entropy, which is also broadly defined including thermodynamic entropy and information entropy.

Thirdly, there is a very important concept of exergy. The exergy balance is used in this report as the main premise to define useful energy as a work necessary (in thermodynamic terms) for the implementation of prosumer, holistic energy services (in the environment of electrical monism).

In other words, it is the maximum work possible that can be extracted from various forms of energy (determined in relation to the environment) currently from the nuclear energy and the chemical energy of fossil fuels, and – in the horizon 2050 – from electricity generated from renewable energy sources (taking into account the decrease of exergy of external heat sources resulting from the operation of electricity driven heat pumps, and the decrease of exergy of non-energy raw materials, especially those used in the construction industry during the implementation of a passive house standard.

The laws of electrical engineering constitute the fourth element of the conceptual space. They are generally defined as electrical laws in network AC power systems, i.e. the physical laws governing the most complex and extensive, and at the same time, the most politically sensitive, technical infrastructure. This category includes also the laws in electrified and computerized receivers and loads, as well as in the prosumer energy installations, i.e. the laws of electrical engineering of AC, DC and strongly deformed waveforms.

The fifth conceptual environment, which is crucial in the context of energy transformation, includes the reversal of socio-economic pressures influencing the energy industry – so far macroeconomy influenced microeconomic phenomena, now this trend is about to change with microeconomy shaping global economics. This trend, which represents certainly a fundamental change from a socio-economical point of view, is somewhat related to a methodological shift in the energy industry with an emphasis on inductive rather than deductive reasoning. While deductive reasoning may be linked to a fossil-fuel based, policy-driven corporate energy industry (LCPG), which – in the course of time – has set and pursued its own goals (namely to protect interest groups), inductive reasoning, on the other hand, is clearly connected to the new power industry of prosumers and independent investors (II) that addresses energy needs of individual subjects (in the environment of electrical monism).

Resources. From the perspective of the paradigms of energy transformation the concept of resources is abstract, however it is difficult to question its practical usefulness if we consider that it refers to highly diversified goods (material, economic and social e.g. social capital). These goods are involved in energy transformation (they undergo transformation, being also the drivers of transformation).

Material resources directly involved in the energy transformation include fossil fuels and renewable energy resources, technical infrastructure (primary and auxiliary) and many others. The natural environment is indirectly involved in energy transformation, providing a “space” in which the energy industry works. Energy generation exposes the natural environment at the risk of irreversible degradation (the issue of external costs of the energy industry). Material resources can generally be defined as “hard” resources, however the issue of external costs is tightly linked to a “soft/fluid” sphere of legal and regulatory solutions, that may potentially avert the risk of the degradation of the natural environment and promote infrastructure development (power generation and network technologies on the energy market, environmental protection installations, circular economy technologies and digital technologies of prosumer energy management), thus creating new material resources of the energy transformation.

A separate issue at the level of the energy transformation paradigms is to ensure adequate representation of problems related to financial capital. From the point of view of energy transformation, "adequate" representation is the one that determines, to what extent financial capital represents "hard" and "soft" resources. Nowadays this issue should be considered in the context of the transformation of financial markets into high risk markets. Thus, financial resources during the energy transformation are changing from hard to soft resources.

The distinct determinants of energy transformation that may be referred to as human capital include such elements as know-how, intellectual capital and its management (individual competencies and organizations), as well as social capital and its potential use in the energy transformation. Social capital represents this kind of resources that are increasingly important because the energy transformation is becoming the largest and the most democratic testing ground for innovations, both hard and soft. Regardless of this, human capital represents soft resources in the paradigmatic triplet.

Entropy. The concept of entropy (both thermodynamic and in the information theory) plays an import role in the context of the energy transformation, providing a valuable insight into the process of transformation in its intellectual, ethical and practical/technical (engineering and economic) aspects.

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Thermodynamic entropy. It is a thermodynamic function of state. Changes in the value of this function during a passage from one state (microstate) to another depend only on these states, but do not depend on the actual course of the process. It the context of thermodynamic processes this is a generalized displacement. Temperature and entropy form a pair of conjugated variables (temperature differences drive changes in entropy). Just another pair on conjugated variables in thermodynamic processes consists of pressure and volume. (For all mechanical systems conjugated variables are force and displacement. Work is the product of these variables).

The thermodynamic force is always an intensive variable, whereas the “displacement” is always an extensive variable. The product of these two variables is an energy transfer (work or heat). The intensive variable is the derivative of the internal energy with respect to the extensive variable, with all other intensive variables being equal.

According to the second law of thermodynamics, a change in entropy is defined (in quasi-static processes) by its exact differential:

$$dS = \frac{1}{T}\delta Q, \tag{1}$$

where: S – entropy, T – temperature, δQ –heat transfer (elementary heat

Entropy of a (certain) thermodynamic state P is given by:

$$S(P) = \int_0^{T_P} \frac{C(T)dT}{T}, \tag{2}$$

where: C – heat capacity, T_P – temperature in state P.

In statistical thermodynamics entropy can be given:

$$S = k\ln(W) \quad \text{lub} \quad S = -k\sum_i p_i \ln(p_{i)}, \tag{3}$$

where: k – Boltzmann's constant, W – the number of ways the microstate (microscopic configuration of a thermodynamic system) can reorganize itself without influencing the microstate (macroscopic properties of the thermodynamic system) p_i – the probability of microstate i.

The second law of thermodynamics (as well as other laws of thermodynamics) has a formulation resulting from experience and observations. In this sense, entropy in classical thermodynamic is an accepted physical quantity. Equation (3), however, allows to explain the essence of entropy: any isolated system left to itself either does not change (its disorder remains constant) or increases its disorder. Bearing this in mind we can consider a thermodynamic (entropy) arrow of time: each macroscopic isolated system, which had a smaller entropy had to be on the timeline earlier (i.e. in the past) than any macroscopic system with greater entropy.

The thermodynamic arrow of time (the increase of entropy over time) linked to the second law of thermodynamics as formulated by R. Clausius (heat can't spontaneously flow from a source with a lower temperature to a source with a higher temperature) leads to the conclusion that the universe evolves to the state of heat death (thermodynamic equilibrium), which means the disappearance of thermodynamic processes, S = max.

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Entropy in information theory. The (statistical) interpretation of thermodynamics is closely linked to information entropy which is a measure of the average amount of information [that would be needed to define the full microstate of the system] – the mathematical quantity definable and measurable in the probabilistic space. According to the fundamental concept of information theory, the amount of information (stored, sent, transmitted, received) does not refer to the meaning of the message being forwarded, but it is related to the probability that the message will be received (read). The formula for information entropy is given by:

$$H(p_1, p_2, \ldots, p_m) = -c\sum_{i=1}^{m} p_i \log_2 p_i, \tag{4}$$

where: p_i – the probability of a message (message carrier); in this specific case the base-2 logarithm is used, which is related to the binary system commonly used in the information theory where base-2 logarithms are used to define entropy. Information entropy is usually measured in bits (8 bits equals 1 byte).

From the perspective of the paradigms of energy transformation, entropy is a measure of disorder of a thermodynamic system, and a measure of energy dissipation. Entropy is linked to the second and third laws of thermodynamics, as well as to the hypothesis of the heat death of the universe. According to the second law of thermodynamics the total entropy of an isolated system can never decrease over time. The second law can be expressed in many ways, also without the reference to entropy. Usually we are interested in changes of entropy, not in entropy as such. In thermodynamics, entropy of a perfect crystalline substances at 0 °K (reference state according to Planck), is equal to zero ($S = 0$) – this doesn't apply to nuclear reactions in which atomic nuclei are rebuilt. Nernst's theorem provides a link between entropy and the third law of thermodynamics. As stated by Nernst's theorem at a temperature of 0 °K total entropy of substrates involved in a chemical reaction is equal to total entropy of products of this reaction.

When there is no uncertainty in a system (the probability of one of the states is equal to 1)information entropy $S = 0$. Entropy is maximized $S = max$. when all the states of a system are equally probable. Seen from this perspective the concept of information entropy is closely related to computer science, and as such it may influence the transformation of energy industry. However, if you use the generalized concept of entropy – a set of functions describing diversity, uncertainty and randomness of a system, it becomes clear that information entropy provides an effective tool to describe a market, particularly the electricity market.

Two potential areas of applications of information entropy for the needs of the electricity market are particularly important. The first is sharing the network infrastructure (creating new regulations, replacing the network monopoly with the TPA + principle). The second is shaping final prices of electricity (creating new principles of setting final prices, moving away from tariffs that reflect average annual prices, replacing them with real time price setting incorporating the idea of marginal costs).

The fact that information entropy is maximized for a uniform probability distribution of state variables (statistical, probabilistic) leads to a far-reaching conclusion on both issues: both network monopoly and average prices (tariffs for final consumers) mean entropy death of the electricity market.

Exergy. Exergy is a physical quantity that characterizes energy in terms of its practical usefulness. Exergy describes the ability of a system (which comes into equilibrium with its environment) to convert energy into useful work. The importance of exergy in thermodynamics stems from the fact that exergy balances allow to capture thermodynamic inefficiencies [of energy conversion processes] that are missing from energy balances. Thus, exergy is a useful concept that can explain the essence of transformation of the energy industry.

From the point of view of power engineers, the concept of exergy may help reduce thermodynamic inefficiencies [of energy conversion processes], however – as it is stressed by physicists themselves – exergy analysis determines the possibilities of improving thermal processes, but it is only through economic analysis that we can determine if these efforts are economically viable. Prof. J. Szargut – the founder of Polish school of exergy – who proposed in his book [3] 19 guiding principles to combat exergy losses considering the principles of economics, stated that it is always necessary to invest to improve thermal processes.

It is very useful to study the link between exergy and economics. On the one hand, it defines fuels as natural resources (rare commodities that are not in a thermodynamic equilibrium with the environment (earth system), on the other hand it characterizes electricity as having the highest exergy (alongside kinetic energy). Furthermore, renewable energy sources utilise exergy from beyond the earth system (generally energy of the sun in form of solar radiation), which refers not to the equilibrium of the earth system, but to that of the solar system.

In the book [3], the lecture on exergy begins with the equation linking the internal exergy (in the thermodynamic shield) B_z with the exergy B of the stream flowing through the shield:

$$B_z = B - V(p - p_{ot}), \tag{5}$$

where: $V, p -$ volume and pressure inside the shield, $p_{ot} -$ outer pressure (outside the shield).

The components of exergy stream B_z are as follows; kinetic exergy, potential exergy, thermal exergy (physical and chemical), nuclear exergy, electric charge (electricity) exergy and other forms of exergy. The decrease of thermal exergy of thermodynamic medium stream involved in a physical change or a chemical reaction is equal to the maximum work done by a reversible operating flow machine exchanging heat with the environment at the temperature T_{ot} (the work done by the machine is considered positive, whereas the work done on the system is considered negative). The increase of thermal exergy ΔB_t is given by:

$$\Delta B_t = I_w - I_d = T_{ot}(S_w - S_d), \tag{6}$$

where: $I_w, I_d -$ enthalpy discharged from the system to an external source, and enthalpy supplied from an external source to the system, respectively, $S_w, S_d -$ entropy discharged to an external source and entropy supplied from an external source, respectively.

The equation of exergy efficiency η_B of the generalized thermodynamic process (generalized in the sense of extended, composed of many subprocesses differing in qualitative terms) is given by [3]:

$$\eta_B = \frac{B_{u\dot{z}} - B_{sn} + L_{u\dot{z}} + E_{elu\dot{z}} + \Delta B_{\acute{z}ru\dot{z}} + \Delta B_{uu\dot{z}}}{B_N + L_N + E_{elN} + \Delta B_{\acute{z}rN}}, \tag{7}$$

where: $B_{u\dot{z}} -$ useful exergy of useful products of the process, $B_{sn} -$ exergy of non-energy raw materials, $L_{u\dot{z}}, E_{elu\dot{z}} -$ useful work, useful electricity produced in the process, $\Delta B_{\acute{z}ru\dot{z}} -$ increase of exergy of the external heat sources, heating or cooling of these heat sources is the purpose of the process, $\Delta B_{uu\dot{z}} -$ useful increase of system exergy, $B_N -$ exergy of propellants (fuels), $L_N, E_{elN} -$ driving operation, driving electricity, respectively, $\Delta B_{\acute{z}rN} -$ decrease of exergy of the external source of driving heat.

The exergy efficiency given by equation (7) is purely operational, i.e. it doesn't take into account exergy needed to build a technical system (a work device, a power train, an installation and an infrastructure), nevertheless it is very instructive. It is a starting point to demonstrate in a formal manner the predominance of demand electrical monism over the energy industry based on fossil fuels.

Namely, equation (7) referring to exergy efficiency encourages us to formulate the concept of achievable efficiency of energy transformation η_{TE}, expressing the normalized relative value of reduction of energy demand resulting from the transition from state A (chemical energy of fossil fuels, contemporary ways of meeting the energy needs by customers) to the state B (electrical monism: electricity from renewable energy sources, new ways of satisfying the energy needs by prosumers, including the use of heat pumps).

The laws of electrical engineering. Transformation of the energy industry in which fossil fuels will be replaced by renewable energy sources, changes the relationship between thermodynamics and electrical engineering. In the energy industry based on fossil fuels, the significance of thermodynamics stems mainly from the combustion of fuels in boilers and for the occurrence of thermal processes in energy machines, in energy producers and consumers (prosumers). In the energy industry based on the RES, the dominance of electricity results mainly from the existence of the mono electricity market of the RES, and from the implementation of demand electrical monism. In this context it is justified to summarize the energy transformation as a process in which the energy industry that relies on thermodynamic processes is replaced by the energy industry that relies on electrical engineering. Needless to say, this description has a very limited meaning (it must be used very carefully).

While the laws of thermodynamics govern/limit energy efficiency of devices (power stations, loads) which is fundamentally important in the energy industry based on fossil fuels, the laws of electrical engineering determine the technical constraints of power grid systems that limit competition on the electricity market and thus limit macroeconomic efficiency of the allocation in energy resources on the market. Seen from this perspective the significance of the laws of electrical engineering in the energy industry treated (their “resistance” to technological progress in electrical engineering) is not as profound as that of the laws of thermodynamics. For this reason, three aspects of the laws of electrical engineering will be considered in this paper.

Contemporary “surface” (covering a certain area) AC power systems define the first aspect. The second aspect is that of a DC power system that have a potential to revolutionize the entire sector of electricity use, and to transform AC power systems into selective “linear” transmission systems linking large wind farms with infrastructure and urban corridors. The third aspect covers the issues of computerized receivers and loads as well as prosumer power installations (that satisfy all the energy needs of prosumers) together with the problems of rapid implementation of digital technology in the areas mentioned above. These issues are seen from the perspective of the electric power theory.

Technical network constraints – current (branch/line) and voltage (node) – are of great importance in the modern AC power systems because they limit competition in the electricity supply market. On the other hand, the issues of stability (static and dynamic) in the operation of these systems decline in importance because of the increased efficiency of protection devices in power systems.

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The TPA principle and electrical engineering in the electricity market. The principle of third-party access to the power grid (TPA) has stimulated competition in the electricity market (third structural change), but also initiated the transformation of power engineering. Here we use power flow network perspective to differentiate formally (i.e. applying not only linguistic but also mathematical notation) optimization procedures in monopolistic and market-based (competitive) power engineering.

The ERO optimization procedure to determine the economical distribution of loads between power sources was from the 1950s to the end of 1980s the most representative example of the economy of interconnected generation and transmission systems. At the same time, it was the starting point for analysis of nodal marginal costs in network systems on the electricity market, with the competition facilitated by the TPA principle.

The ERO optimization procedure assumes that the composition of generation units is known. Calculations are made for a fixed network configuration assuming a constant power output at individual nodes. In general, the ERO optimization procedure is to minimize the following function (8):

$$K(P_{\mathrm{G}}) = \sum_{i=1}^{n_G} k_i(P_{Gi}), \tag{8}$$

where: $K(\mathbf{P_G})$ – total variable cost of electricity generation in all sources operating in the power system, $k_i(P_{Gi})$k – non-linear characteristic/function determining the variable cost of electricity generation in the i source, P_{Gi} – power generated by the i source, n_G – the number of power sources in the system.

If you omit transmission losses, as well as constraints in power generation sources and network limitations, then the task of minimizing function (8) with one equality constraint resulting from the power balance in a combined power system given by the equation (9):

$$\sum_{i=1}^{n_G} P_{\mathrm{Gi}} - \sum_{i=1}^{n_W} P_{\mathrm{Li}} = 0, \tag{9}$$

where: P_{Li} – active power in node i, n_w – the number of nodes in the network.

Equation (9) can be solved analytically with the use of a Lagrange function.

The problem of minimizing the function (8) contains three types of inequality constraints, apart from the equality constraint (9) supplemented by power losses in the network. These constraints include: upper and lower power limits of power sources, upper line capacity (current or branch confinement for the lines and the transformers), as well as upper and lower voltage limits in the power grid nodes (voltage confinement else nodal). Kuhn-Tucker's theorem is used to solve – with the iterative method – the problem with inequality constraints.

From economic point of view the characteristics/functions that determine the variable costs of electricity generation in individual power sources are essential in minimizing function (8). In practice, these costs have generally been assessed in the past for each power source based on its technical efficiency determined by measurement and the average unit fuel price. Even more often, instead of minimizing the cost in equation (8) it was the amount of fuel that was minimized. Moreover, it was the general principle in the monopolistic power industry to use average costs in the optimization procedure. One must bear in mind, however, that the competitive market operates on marginal costs.

According to the classic definition the short run marginal cost (SRMC) in a node and the locational marginal price (LMP) [of electricity] is a derivative of the total variable cost of energy generation in the system relative to the demand in the node. In the Polish power system (defined by a technological structure of its power sources) the term "short period" has meant so far 15 minutes (in the SOWE system) or one hour (in the WIRE system). Therefore, the constant active power generated in a node may be used as a measure of energy received/generated in the node during a 15-minute period or in one-hour period. The definition of a short-term node cost can therefore be written as follows (10):

$$LMP_i = SRMC_i = \frac{\partial K(P_{\mathrm{G}})}{\partial P_{\mathrm{Li}}}. \tag{10}$$

The short-run marginal cost of electricity SRMC (short-term node price) should be determined for the power system operating under optimal conditions. To determine the SRMCs, one should find the optimal power flow OPF minimizing the objective function (8) (considering the limitations). The relationship between the OPF and the SRMC of electricity in the network nodes has been described in [4]. The authors presented the concept of a nodal price of electric energy called the *spot price of electricity*, which exhibited temporal and spatial variation. The optimization of OPF for the Polish wholesale electricity market [5] required the following modification of the objective function (8):

$$KCZ(\mathbf{P}_{Gp}, \mathbf{P}_{Gr}) = \sum_{i=1}^{n_G}\left[\sum_{p=m+1}^{m+n} C_{ip}P_{Gip} - \sum_{r=1}^{m} C_{ir}(P_{Gir}^{o} - P_{Gir})\right], \tag{11}$$

where: $KCZ(\mathbf{P}_{Gp}, \mathbf{P}_{Gr})$ – total cost of covering the demand in the SEE system; $\mathbf{P}_{Gp} = [P_{Gip};\ i = 1, 2,..., n_G;\ p = m+1,..., m+n]$; $\mathbf{P}_{Gr} = [P_{Gir};\ i = 1, 2,..., n_G;\ r = 1, 2,..., m]$; P_{Gip} – capacity ready for production/operation within band p under the incremental offer of a generating unit i; P_{Gir}^{o} – capacity provided within band r under the reduction offer of a generating unit i; P_{Gir} – capacity ready for production/operation within band r under the reduction offer of a generating unit i; C_{ip}, C_{ir} – unit price of electricity from a generating unit i within band p *or* r under the incremental/reduction offer; m, n – the number of bands under the reduction/incremental offer declared by a generating unit i.

Decision variables optimized in the OPF procedure under market conditions include generation capacities declared by individual generating units within the bands of balancing offers, whereas the prices offered within these bands are parameters in the optimization procedure. The calculations don't change the composition of generating units. The optimization procedure finds the minimum of the function (11) in the area defined by technical equality and inequality constraints.

Considering the objective function (11) and the classical definition of the SRMC (10), the LMP in a node i, in conditions of the Polish electricity market can be given by (12):

$$LMP_i = SRMC_i = \frac{\partial KCZ(P_{Gp}, P_{Gr})}{\partial P_{Li}}. \tag{12}$$

The LMP (9) can be broken down into the following components with a simple physical interpretation: the LMP of the effective power in the reference node, the cost of transmission losses (resulting from the apparent power flow), the cost of branch /current constraints and the cost of node/voltage constraints. In the analytical form, these components are given by:

$$LMP_i = \left(1 + \frac{\partial P_{str}}{\partial P_{Li}}\right) LMP_b + \frac{\partial Q_{str}}{\partial Q_{Li}} LMP_{qb} + \sum_{g=1}^{n_g} \mu_g^{max} \frac{\partial S_g}{\partial P_{Li}} + \sum_{j=1}^{n_w} \left(-\mu_{Uj}^{min} + \mu_{Uj}^{max}\right) \frac{\partial U_j}{\partial P_{Li}}, \qquad (13)$$

where: LMP_b, LMP_{qb} – the LMPs of effective and reactive power (respectively) in the reference node, P_{str}, Q_{str} – effective and reactive power (respectively) losses in the network, S_g – apparent power flow in a branch g, U_j – voltage module in the node j, μ – Kuhn -Tucker coefficients vector for inequality constraints, n_g – number of branches.

The LMPs provide very strong localization signals and considerably improve competition conditions in the connected [power] systems. In practice, this means transferring generation to lower voltage levels closer to the consumers. It should be emphasized, however, that the idea of competition based on the TPA principle and the global development of the LMPs methodology, coincided with the rapid development of gas CHP technologies using natural gas as a fuel. As a result, the trend of bringing generation closer to customers with heat reception has strengthened considerably (the Californian crisis in 2000-2001, which could be effectively solved by means of a rapid deployment of CHP, has contributed significantly to this).

The proposed model of the marginal prices operating on the wholesale electricity market is not enough for the needs of the emerging electricity market. This explains the revolutionary character of the necessary market transformation, especially if we consider the existing tariff system on the end-user market. For example, there is little doubt that 5-minute load profiles should become the standard in nomination procedures within the emerging electricity market. The transition from tariffs based on average prices to tariffs based on 5-minute marginal prices is a requirement for breaking the energy monopoly of the LCPG, which essentially leads to an "entropic death" of the market.

The reversal of socio-economic influences. It's all about the reversal of impacts – so far macroeconomics has influenced microeconomics, however currently microeconomics begins to influence macroeconomics. Obviously, the scale effect and the paramilitary aspects of the declining corporate energy industry (and power generation in particular) helped to establish the dominance of the global economy over local economies. It was this dominance that has prevented the energy industry to shift from mimetic development to a transition based on breakthrough innovations that change the operation of global markets – essential to macroeconomics.

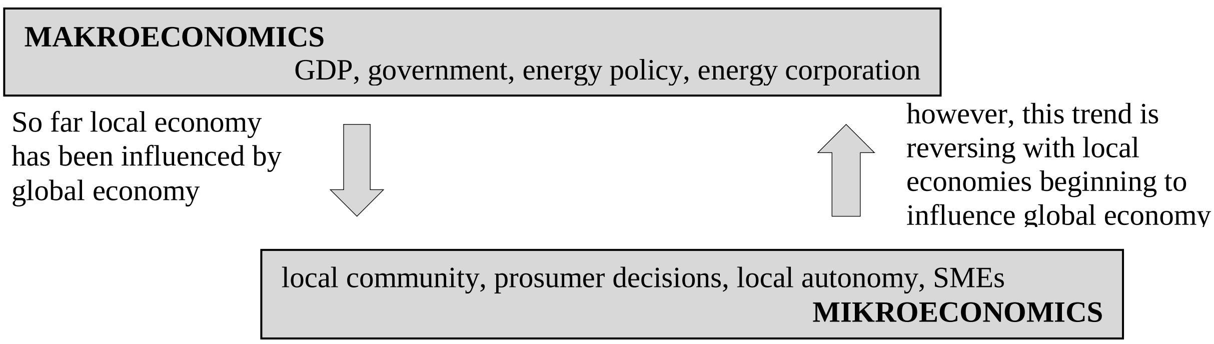

Fig. 4. The reversal of impacts in global and local economy – a simplified view

It is emphasized that the shift of impacts in the energy industry that has strengthened the role of local economies in relation to the global economy, wouldn't be possible without favorable circumstances which included development of small and micro-scale power generation technologies (photovoltaics in particular), as well as the progress in power engineering and ICT technology that facilitated energy management at the prosumer level. These circumstances included also the individualization of consumer preferences linked to the growth in prosumer activity and the increase of labor productivity based on social capital.

The transformation of the power industry which manifested itself in the reversal of the economic influences will stimulate the general process of the civilization changes that have already become clearly visible. This process results in the following economic phenomena; people's assets vs. GDP, negative interest rates of central banks vs the increase in the amount of fiat money, the proliferation of financial gambling vs the concentration of capital by the wealthiest people in the world (as evidenced by the entries in the company's balance sheets that are made without any reference to existing material goods).

The paradigms

In terms of the methodology of the new power industry that is shaped by the macroscopic reversal of the socio-economic impacts (the new direction of the impact is from microeconomics to macroeconomics), it is emphasized that the principles of thermodynamics have been formulated as a result of a very large number of studies (observations, experiments) on the macroscopic properties of bodies.

From this perspective the zeroth law of thermodynamics is the law of equivalence of states of thermodynamic systems (the concept of empirical temperature can be derived from this law). The first law of thermodynamics is the law of conservation of energy in thermodynamic systems. The second law of thermodynamics is the law of constant growth of entropy (it defines the direction in which thermodynamic processes occur spontaneously). The third law of thermodynamics states that the entropy (of a system) approaches zero as its temperature approaches (absolute) zero. However, based on statistical thermodynamics (using deductive methods), numerous deviations from the classical laws of thermodynamics (in the microscopic world) are being reported more and more often.

There is little doubt that the thermodynamic perspective is of great importance for the methodology of the new energy industry. Linking this perspective with the entire conceptual space of the paradigmatic triplet allows to name/define each of the three paradigms and their brief description (Table 1, as well as explanations and comments scattered in the article) as well as to create a preliminary list of synonyms of the paradigms. However, it should be emphasized that the paradigmatic triplet is basically very eclectic. Needless to say, now it would be too early to say whether the triplet would become less eclectic (i.e. “harder”) or even more eclectic (i.e. “softer”) as the methodology of the new energy industry would consolidate.

Undoubtedly, to consolidate the methodology of the new energy industry, it is appropriate to exploit “problems” of thermodynamics (classical macroscopic thermodynamics and microscopic statistical thermodynamics), economics (the crisis of a paradigm derived from the neoclassical doctrine which is based on the macroeconomic approach reflecting the general equilibrium by means of aggregate and static models) and electrical engineering (the failure of classical AC systems in the power industry caused by the presence of RES that require extensive implementation of power electronics; the need to move towards AC-DC hybrid systems and deformed waveforms).

The prosumer paradigm (Table 1). The proposed list of synonyms for the prosumer paradigm: the anti-corporate paradigm, the pro-effectiveness paradigm, the pro-educational paradigm, the behaviouristic paradigm.

The exergy paradigm (Table 1). The proposed list of synonyms for the exergy paradigm: the anti-entropy (delaying the growth of entropy over time) paradigm, the pro-effectiveness paradigm, the transformation of the thermodynamic energy industry into the electrical energy industry paradigm.

The virtualization paradigm (Table 1). The proposed list of synonyms for the virtualization paradigm: the anti-monopoly paradigm, the use of LV-MV grid paradigm, the TPA^+ principle paradigm, the microtransaction paradigm, the supremacy of microeconomics over macroeconomics paradigm, the macroeconomics because of microeconomics paradigm, ...

PART III

TRANSFORMATION TO ELECTRICAL MONISM

It is hypothesized that the electricity market leading to electrical monism is the most powerful tool for practical implementation of the transformation of the energy industry from state A to state B. In practice, this electricity market may be defined as an effective management platform that enables conversion of electricity (the substrate) into a complete set of prosumer's energy services (lighting, multimedia, computer, laundry, services providing environmental comfort, transportation services,…..industry services;…).

Obviously, this market should contain mechanisms that enable two kinds of interactions. Firstly, the objective interactions between the three sectors of the energy market within the existing energy industry LCPG (namely electricity, heat and transport fuels market). Secondly, the objective interactions between the existing energy industry LCPG and the new energy industry represented by the prosumer energetics PE and the independent investors II. Understandably, to ensure the effectiveness of the new electricity market (as indicated by the formation of the state of electrical monism) is the presence of the hardware and software infrastructure that links non-prosumer power generating units and prosumer power demand. This infrastructure enables "mechanisation" of the power market [6,7].

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A practical transition to the new electricity market. The paradigmatic triplet of energy transformation provides the framework for determining practical solutions on the electricity market. This market represents the main driving force shaping the trajectory of energy transformation from state A to state B. In this context, it is emphasized that (evolutionary) energy transformation can't be reduced to a mechanical reproduction of the program contained in the initial conditions (state A). Instead, this is a creative process which encourages innovation by means of the market mechanisms (microeconomic decisions), and not by means of energy policy imposed from the macroeconomic level (from the level of superstructure, which has lost its competences).

Therefore, states A and B in the transformation of the energy industry cannot be directly understood in terms of the thermodynamic state equation which provides a description of state [of a system] using three thermal parameters such as pressure, temperature and specific volume (of course, only two of them are independent). The essential property of the state equation is that it is not sensitive to the trajectory of the transition of the system from one state to another. On the other hand, the equation of state may be a source of inspiration for shaping the transformational trajectory of the energy industry between states A and B.

It is too early to say whether the state B of the energy industry defined by the following conditions (complete re-electrification based on RES, electrical monism) could be achieved (regardless of the transitional trajectory) by 2050 given the current technological, economic and social conditions. Table 2 provides a simple and preliminary version (it requires a thorough verification) of a chart providing coefficients of the energy industry transformation to electrical monism. The central category of electrical monism is the usable energy $E_{uż}$ in the form of electricity from RES, which is used to satisfy all the energy needs of prosumers.

Tab. 2. Electrical monism – practical (estimated) coefficients of energy transformation

Energy market		driving „factor”	„binding” unit	estimation	
				formula	numerical
electricity sector		population, economy	kWh/ (person., GDP)	(-)	1
heat sector	heating heat	population, housing	kWh/m^2	$\frac{E_{PH}}{E_g} \cdot \frac{1}{COP}$	$\frac{1}{3} \cdot \frac{1}{3} = 0,1$
	domestic hot water	population	kWh per capita	$\frac{1}{COP}$	$\frac{1}{3} = 0,3$
transport sector		population, transport	kWh per car	$\frac{\eta_s}{\eta_{EV}}$	$\frac{0,2}{0,6} = 0,3$

In order to combine useful energy $E_{uż}$ (expressed in practice in: MWh, GWh, TWh) with coefficients from Table 2, it is useful to introduce [a notion of] a standardized relative (superscript) useful energy into the modelling of transformation trajectory of energy balances, by means of the coefficient of energy balance structure (14) of final energy E_k, which takes (in the state A) specific values for each characteristic case (e.g. for a single-family household, for a given country, for the world).

$$w = \sum_{i=1}^{4} w_i = 1, \qquad (14)$$

where: $w_1 = w_{el}$ – relative share of electricity in the energy balance, $w_2 = w_{CG}$ – relative share of heating heat in the energy balance, $w_3 = w_{CWU}$ – relative share of heating heat used to produce domestic hot water in the energy balance, $w_4 = w_t$ – relative share of chemical energy of transport fuels in the energy balance.

Coefficients (14) and coefficients presented in Table 2 can be used to express useful energy $E_{uż}^{B*}$ in state B (which is equivalent to the normalized final energy E_k^{A*} in state A) by the following formula (15):

$$E_{u\dot{z}}^{B*} = E_k^{A*}\left(w_{el} + w_{CG}\cdot\frac{E_{PH}}{E_g}\cdot\frac{1}{COP} + w_{CWU}\cdot\frac{1}{COP} + w_t\cdot\frac{\eta_s}{\eta_{EV}}\right). \quad (15)$$

Equation (15) is time-independent, which means it is also independent on transformational trajectory. It depends only on the pre-transformational state A and the post-transformational state B. The equation (15) is a kind of state equation. It is practical to assume that in the pre-transformation state A energy $E_k^{A*} = 1$ (it is also a very natural methodical approach). Then the structure w in equation (14) is a conjugated variable – the usable energy $E_{u\dot{z}}^{B*}$in the post-transformation state B is solely determined by this variable.

Design of the transformational electricity market

The compliance with the technical infrastructure of the National Power System NPS (Fig. 5) is the key element of the proposed design of the new electricity market (state A of the transformation process). In practice, this compliance – which is achieved by the system of control shields OK1 to OK5 – provides an essential condition for the correctness of methodical design; control shields are generally used to separate a characteristic part of the power grid infrastructure (IEE), enabling the operation of the electricity market.

Fig. 6. shows the extremely simplified version of market design that enables the operationalization of the proposed new electricity market. The operationalization of the new market design must ensure a complete reconstruction of pricing. The shrinking market operating within the entire NPS is to be remodeled to enable a real-time electricity pricing, intended both for "passive" consumers and the recipients of TPA principle. The emerging market, operating on the MV/LV grid infrastructure (market 1), and on hybrid transmission systems (market 2), is to be redesigned to facilitate different versions of real-time pricing considering local conditions (diverse models of the dispersed market).

It is hypothesized that there is a substantial scalability potential for solutions on all potential platforms of the emerging market (1) such as energy clusters, energy cooperatives, virtual power plants and virtual power minisystems. Obviously, this scalability is closely related to the properties of the prosumer energetics such as the susceptibility to fundamental segmentation, facilitating unification of energy solutions for each segment [of the electricity market]. The importance of the control shields CS system stems from the fact that it integrates prosumers and all potential platforms of the emerging market (1), with the PPS infrastructure, as shown in Fig. 5.

It is essential to build an intelligent *hardware and software* infrastructure that could provide a link between the PPS shown in Fig. 5 and the new electricity market design presented in Fig.6. This infrastructure would allow to safely (technically) share the LV-MV network and would facilitate a strong competition in the environment of a single-component of the current marginal prices. The *hardware and software* infrastructure would consist of network access terminals (developed under the TPA^+ principle) that would provide an interface connecting currently two electricity markets – namely the shrinking one and the emerging one (the second report from BPEP series) [2].

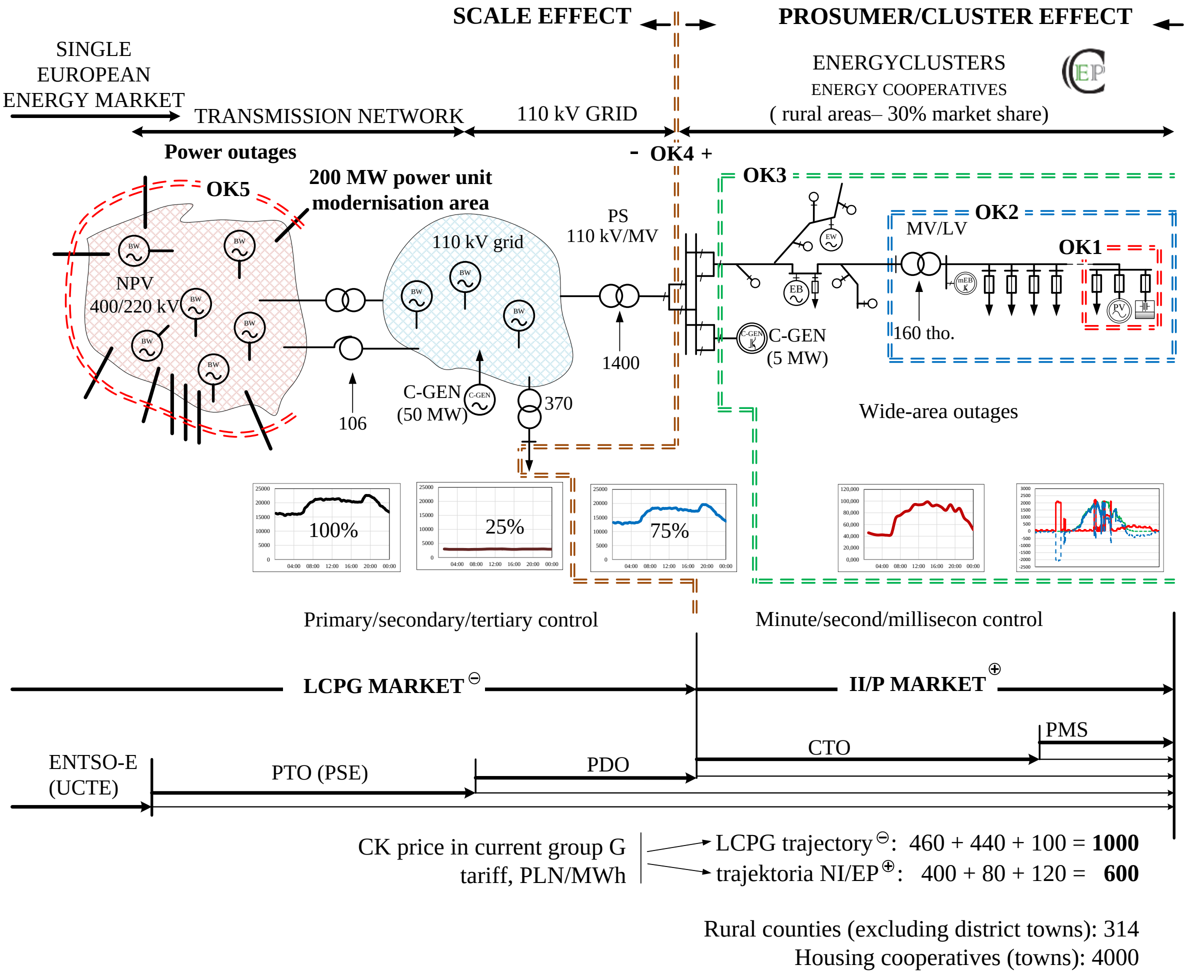

Fig. 5. From the centralized (TSO, DNO) to the distributed operator systems (especially in OK1 to OK2 control shields) – the synthesis of issues related to the reconstruction of the operator system in the National Power System

The "preliminary" market design (Fig. 6) is presented to "overcome" the prevailing perception of the electricity market from the perspective of the LCPG – about 7 million electricity supply contracts concluded by individual households inhabiting multi-family buildings managed by cooperatives and housing communities are an essential part of this vision. Another reason to show design of the new electricity market is to protect passive customers as well as the LCPG industry against crisis in the energy industry. Unfortunately, the destructive effects of this crisis can no longer be avoided. It is essential that the design of electricity market should be debated upon in the following months (not years) by a panel of experts.

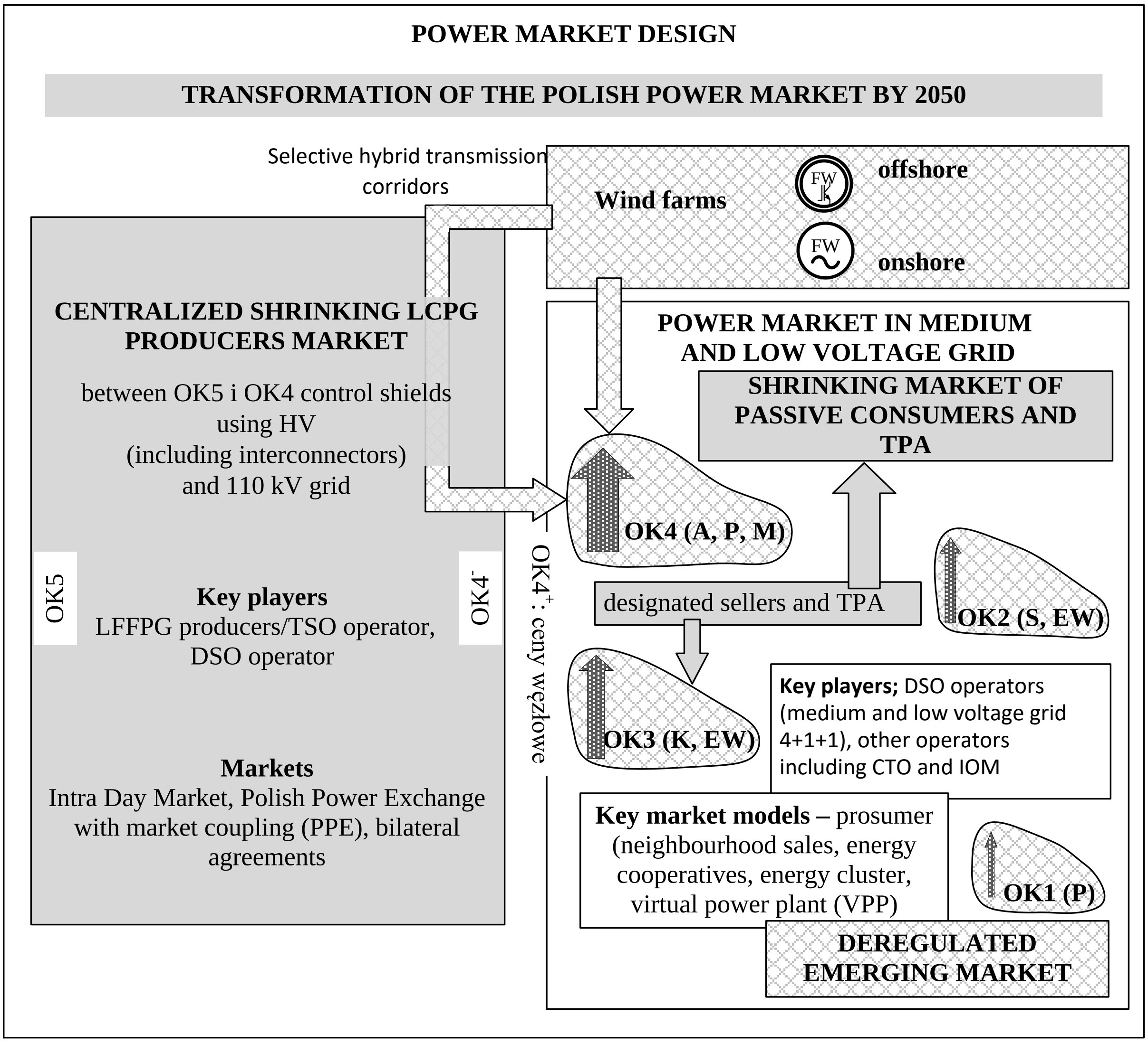

Fig. 6. Transformation of the Polish power market by 2050 with the shrinking fossil fuel market and the emerging renewable energy market

Transformational trajectory

The theoretical validity of the paradigmatic triplet can most effectively be assessed by the results of its implementation in the transformation of the whole energy industry LCPG into the new electricity market based on useful energy. There are two independent aspects of this verification. Firstly, the paradigmatic triplet should facilitate development of an effective market design, that will simulate the dynamic growth of the new electricity market based on RES and – in the same time – will allow for the gradual (evolution instead of revolution) decline of the LCPG energy industry which is based on fossil fuels. Secondly, the new electricity market should evolve into the market of investment goods and services that will focus on the prosumer energetics. Useful energy will be used on this market to satisfy all the energy needs of prosumers. Similarly, during the first electrification at the beginning of the 20th century (in Poland this process took place in the inter-war period) – when there was no power industry – there were industrial entrepreneurs who produced electricity in their own generating units, to build a competitive advantage.

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Control shields equivalenting and the need to reverse its direction (*the proposal for Poland*).

The process of "transferring" electricity generation to the prosumer level, initiated on a large scale by the development of PV sources, revealed the inadequacy of the LCPG business model to the current market requirements and exposed its total inability to respond to the challenge. Not surprisingly, the inability of the LCPG energy industry to submit a commercial offer to the PE-II energy sector causes the latter to be in the position to submit commercial offer to the former.

Globally there is a growing awareness in the EP-II energy sector of its market advantage over the LCPG energy industry. That is why the direction of control shields equivalenting should be reversed. Namely, the purchase-sale offer issued by the LCPG power industry on the market should include the recognition of control shields equivalents of the PE-II energy industry. However, if the initiative is taken over by the PE-II energy industry, then it becomes the PE-II energy industry obligation to recognize market equivalents of the LCPG energy industry.

The recognition of market equivalent of the LCPG energy industry on OK3 control shields provides a spectacular example of this process (Fig. 5). These are virtual control shields of energy clusters (in rural areas). The OK3 control shield containing OK2 and OK1 control shields, is embedded into the (physical) OK4 control shield. In Poland, transformation of the power industry in rural areas should be accomplished no later than in 2040 – according to the report series which are to be found on the Internet under the name of BŹEP (1) and BPEP (2). If we consider that rural areas attain a 30% share of the Polish electricity market, and that the European climate policy adopts a time horizon until 2050, then it seems reasonable to accept states A and B as reference points of the transformation process in Poland.

In fact, the transformational trajectory A → B is driven by an economic calculation, mainly by investment. The principles of an economic calculation should be implemented by a well-functioning electricity market. Guidelines for creating a good market design and effective market mechanisms should come from the penalty function build on a transformational trajectory as a function of time. The transformation of all the four elements of equation (15) poses a great challenge.

However, this statement doesn't apply (at least at the preliminary stage) to the first component of the equation (18). In fact, it is reasonable to hypothesize that there is still a significant potential to improve the efficiency of traditional electricity use (within the current scope of functions) by using incremental innovations. Therefore, equation (16) provides a good approximation of the transformation of the power industry, by considering the temporary increase in the efficiency of traditional electricity use, as well as and reduction of transmission losses and power plants own consumption, resulting from the decline of the shrinking (LCPG) electricity market and the expansion of the emerging markets (1) and (2):

$$E_{u\dot{z}}^{B*} = E_k^{A*}\left\{w_{el}[(1-p_e)\cdot(1-p_{s-e})]^{t_{A\to B}} + w_{CG}\cdot\frac{E_{PH}}{E_g}\cdot\frac{1}{COP} + w_{CWU}\cdot\frac{1}{COP} + w_t\cdot\frac{\eta_s}{\eta_{EV}}\right\}, \qquad (16)$$

where: p_e – index of annual growth rate of electricity consumption efficiency by recipients (prosumers), p_{s-e} – index of annual reduction of transmission losses and power plants own electricity consumption (due to the reduction of the shrinking electricity market).

If we assume that the annual efficiency index $p_e = 7‰$, the annual reduction of transmission losses and power plants own electricity consumption index $p_{s-e} = 7‰$, and also if we use all the indicators of energy transformation from Table 2, then considering the actual national final energy structure in the state A ($w_{el} = \frac{170\,TWh}{600TWh}, w_{CG} = \frac{180\,TWh}{600\,TWh}, w_{CWU} = \frac{50\,TWh}{600\,TWh}, w_t = \frac{200\,TWh}{600\,TWh}$) we get: $E_{uż}^{B*} = 0{,}33\, E_k^{A*}$.

This result is consistent with the data presented in Fig. 2. Moreover, it is emphasized that this result and the data are strongly (but not entirely) correlated. Equation (16) together with Fig. 2 provide a very good basis for a qualitative and quantitative depiction of the transformational trajectory of the Polish power industry in the horizon of 2050 (Fig. 7). The transformation of heat and transport fuel markets are "embedded" in this trajectory by means of the "equation of state" (15).

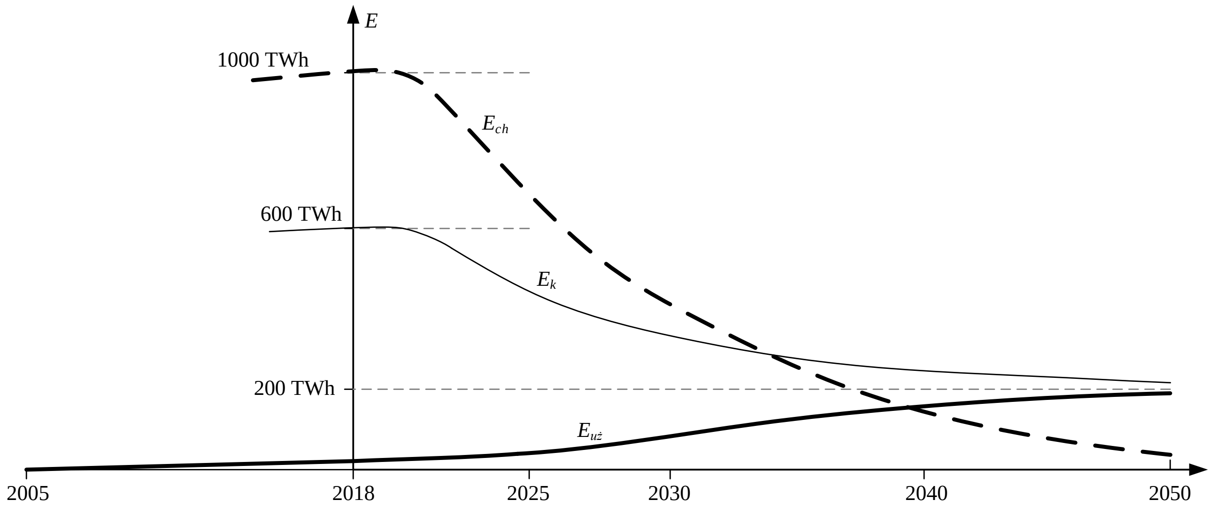

Fig. 7. How to achieve state B (electrical monism) – transformational trajectory of the Polish power industry

The result obtained by means of equation (16) and the transformational trajectory shown in Fig. 7 are surprising. More important is their critical analysis from the perspective of the "efficiency" of political, economic and social systems (the first and the second paradigms) in efforts to transform A → B. In the case of Poland and considering these findings, there is a special need for a critical analysis of the two 30-years periods preceding the 30-years transformation period A → B. The first period 1960-1989 is characterized by the extreme centralization of the energy industry (operation of ministries, associations and energy communities) and numerous investment projects including 200-500-360 MW coal power units, nuclear power units and 220-400-750 kV transmission line. This period ended with a heavy crisis (the liquidation of Energy and Brown Coal Authority, the cancellation of construction of the Nuclear Power Plant in Żarnowiec, 750 kV power line out of service, ...).

The second period 1990-2020, began with the structural market decentralization reform 1990-1995, linked to the systemic state reform and to the inclusion of the PPS into the European power security space. The creeping transformation that followed witnessed the growing dominance of energy corporations and a large construction program including 400 -800-900-1100 MW coal power units and a gigantic nuclear power program. At the end of this period Polish power industry was hit by a heavy crisis and the Ministry of Energy was founded to handle it by means of blocking the transformation process.

The forty-years period between 1920 and 1960 is also important [from the perspective of transformational trajectory], although – for obvious reasons – not as much as the periods that followed. This is when the first Polish regional power system (namely the Pomeranian power system – its construction started in the 1920s) and the power infrastructure of the Central Industrial Region CIR (its construction began in the 1930s) were built.

An effective transition from state A to state B requires an accurate assessment of the changes of the development model of the power industry at individual historical stages. From this perspective, even a very simplified analysis confirms the usefulness of the proposed paradigmatic triplet transferring the weight of the description of the energy industry problems in the 2050 horizon from the "deductive" to the "inductive" method.

CONCLUSION

The accelerating global transformation of the energy sector – in the case of Poland is illustrated (only potentially) by the equation (16) and the transformational trajectory presented in Fig. 7 (curves $E_{ch,}\, E_{k,}\, E_{u\dot{z}}$) – is much more than just the re-electrification of renewable energy resulting from the climate and energy policy. That is why it is so important to capture its essence and build a new methodology of energy issues (the name "energetics" is no longer used here). The eclectic paradigmatic triplet proposed in this paper may become a starting point in the long process of consolidating this methodology.

From a theoretical point of view, it will be important to search for an optimal structure of the equation (16), its part in the parentheses. Namely, the balancing structure: methodological requirements of the mathematical description of the transformation process, the potential of available computational techniques and the "universality" of access of human resources to the problem (the growing involvement of the public, regardless of the fact that the issues of energy transformation are still extremely exclusive). Obviously, this structure should also be "intuitively translatable" to the design and the mechanisms of the electricity market.

From a practical point of view, it will be important to incorporate price sensitivity/elasticity models of supply and demand (of electricity) into the structure of the equation (16), however this should be done in a completely new way. What is suggested here is that the price sensitivity/elasticity should be considered in the environment of real-time marginal prices on the control shields between the three power markets: the shrinking LCPG market and the emerging PE-II markets (1) and (2) energy EP-NI (which is quite different from the price elasticity of electricity in the current understanding).

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