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Energy Systems Research is an international peer-reviewed journal addressing all the aspects of energy systems, including their sustainable development and effective use, smart and reliable operation, control and management, integration and interaction in a complex physical, technical, economic and social environment.

Energy systems research methodology is based on a systems approach considering energy objects as systems with complicated structure and external ties, and includes the methods and technologies of systems analysis.

Within this broad multi-disciplinary scope, topics of particular interest include strategic energy systems development at the international, regional, national and local levels; energy supply reliability and security; energy markets, regulations and policy; technological innovations with their impacts and future-oriented transformations of energy systems.

The journal welcomes papers on advances in heat and electric power industries, energy efficiency and energy saving, renewable energy and clean fossil fuel generation, and other energy technologies.

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Topics

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Contents

The Current State of Mongolia's Energy Sector and Prospects for Development with Entry Into the Russian and Nea Energy Markets

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***Abstract* — The paper addresses research into the prospects for the development of Mongolia's energy sector with its gradual entry into the international energy markets of neighboring countries through the involvement of local resource potential and the expansion of energy transmission and transportation systems. Rational use of rich primary natural energy resources (coal, solar energy, and nuclear energy), in combination with a favorable geographic location of the country, should contribute to the achievement of the crucial goals to transform Mongolia into an energy exporting-importing country, which is stipulated by the raw materials and energy strategy of the country for the next 15-30 years.**

In this context, the research considers an integrated approach to the development of the energy system of Mongolia and highlights three hierarchical development levels of backbone transmission lines. The research outcomes are presented as a structure of Mongolia's energy sector with internal and external functional connections.

The conclusion emphasizes the need to build a scientifically grounded rational network structure of the main backbone transmission lines, which will shape the Unified energy system with developed connections to the electric power systems of Russia and China, and through them, to the super grid of the NEA countries. This will allow Mongolia to occupy its place in a successfully developing energy and economic space of the region, which is beneficial not only for Mongolia but also for the NEA countries.

***Index Terms*: energy sector, development prospects, generating capacity, energy system, hierarchical levels of EPS development, an integrated approach to development, Mongolian-Russian energy cooperation, energy strategy.**

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I. Introduction

The stable development of the Mongolian economy largely depends on the successful operation of the country's fuel and energy industry, which plays an essential role in meeting the ever-increasing domestic demand for electricity, heat, and fuel. Moreover, it reduces electricity imports to cover the baseload and the need to export fuel and electricity in the future. Thus, the successful operation of the energy sector determines the national energy security, which was, is, and remains a very urgent task. In the light of modern environmental and other requirements, this task cannot be accomplished only through the modernization and expansion of the exploitation of existing coal mines and the development of new coal deposits, as well as the modernization and expansion of existing coal-fired power plants and construction of new ones. Although, these ways are necessary conditions for strengthening the named branches of the Mongolian economy.

For reference. Since 1995, private mining companies have been widely involved in the mining sector. Since 2000, their activities have expanded to the mining and export of coal. More than 30 coal deposits are currently being developed. Large-scale coal mining is carried out only in the Central and Southern regions. Mongolia's mining industry fully meets the domestic demand for coal. The main consumers are power plants, which account for about 80% of the total coal demand.

The expansion of Ulan Bator CHPP-3, CHPP-4, and Darkhan CHPP with cogeneration units, and the installation of new turbine generators at the thermal power plant of the Erdenet Mining and Processing Integrated Plant in recent years have although increased the available capacity by about 300 MW, still have not improved much the overall efficiency of the energy sector, and contributed only to an increase in the reliability of electricity and heat supply to cities, which is undoubtedly a significant aspect of energy supply. The shortage of available capacity of existing power generating sources has been especially strongly felt in recent years during the period of winter maximum electrical loads.

Given the modern requirements of stable development and environmental safety, this problem can be solved by

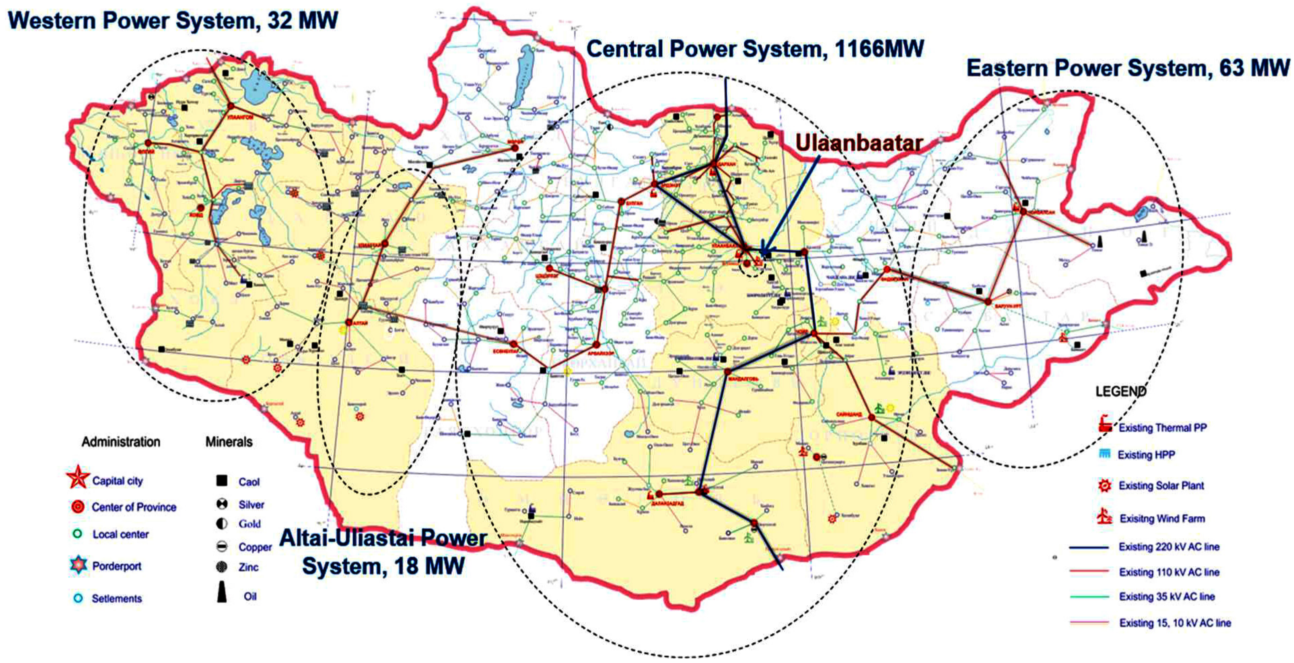

Fig.1. Electric power systems of Mongolia and a scheme of backbone transmission lines (as of 2020)

involving alternative types of energy resources available in the country. These resources are wind, solar and hydro.

Before deciding on what direction to choose for the development of the resource base and the expansion of generating capacities of Mongolia's energy systems, one should analyze the current state and existing situation in the energy and fuel industry of the country.

II. Current state of mongolian electric power system

New legal framework for the activities of entities with various ownership forms, the attraction of foreign investment in the energy sector of Mongolia in 2001-2013, and an increase in the state budget funds allocated for the development of energy facilities as of 2020, made it possible to increase the total installed capacity of power plants of all the electric power systems in Mongolia to 1,472.0 MW and the length of 220 kV and 110 kV transmission lines to 7,436.6 km (Table 1). There are also qualitative improvements in the technical equipment at these facilities and in the state of the electric power systems. At the same time, the real available capacity does not exceed 1000 MW.

Table 1. Characteristics of generating capacity and structures of the power transmission lines of the electric power systems within the unified energy system of Mongolia

It is also worth noting that the structure and configuration of the main part of the Mongolian energy system, formed as a result of the construction and commissioning of new power transmission lines in the period from 1997 to the present day, almost fully correspond to the general scheme [1,2], developed in the last stages of socialist construction (Fig. 1).

Eastern electric power system - Southern electric power system - Altai-Uliastai electric power system - Western electric power system – Central electric power system

The total electricity generated in Mongolia in 2019 was 7,003.3 million kWh, and the country imported 1,715.8 million kWh of electricity. As evidenced by an analysis of electricity generation by the structure of generating capacity, 91% of electricity was produced at thermal power plants (TPPs), consisting mainly of combined heat and power plants (CHPPs), 8.1% - at solar (SPPs) and wind power plants (WPPs), 1.2% was generated by hydropower plants (HPPs) and 0.04% - at diesel power plants. Hence, as is seen, the cogeneration capacities are decisive in the mix of generating capacities, and their electric load depends on the heat load of cities, and not only during their operation in winter but also in summer. In this situation, the EPS can hardly be maneuverable, which is necessary due to the uneven daily electrical load curves. The strong interconnection between electrical and thermal power at CHPPs, the lack of flexible capacities significantly complicate the reliable and high-quality supply of electricity to consumers.

Therefore, it is necessary to introduce thermal condensing and hydraulic capacities in the structure of basic generating capacities and, along with these, create various kinds of peak capacities. The construction of a hydroelectric power plant in the northern region of Mongolia plays an important role here. Design and technical work for the construction of such a plant in the Selenga river basin was carried out in due time by Soviet R&D and design organizations.

Currently, Mongolia lacks effective mechanisms to stimulate the commissioning of energy sources designed to cover peak and semi-peak loads of power systems and to attract private and foreign investment for these purposes. At the same time, Mongolia has some experience in creating such mechanisms for SPP and WPP. For several

Table 1. Characteristics of generating capacity and structures of the power transmission lines of the electric power systems within the unified energy system of Mongolia.

№	Electric power system (EPS)	Total installed capacity, MW	Voltage level of transmission lines, kV				
			220	110	35	15	10-6
1	Central EPS	1,222.9	1,617.26	3,825.68	6,197	1,694	9,619
2	Eastern EPS	36	-	845	1,232.14	604,49	694.2
3	Western EPS	12	-	913.7	977.8	912,8	1,497.4
4	Altai-Uliastai EPS	19,1	-	253	929	533	525
5	Southern EPS (Electric grid of Southern district)	182	-*	-*	431	161	236
	TOTAL	**1,472.0**	**1,617.26**	**5,819.38**	**9,766.94**	**3,905.29**	**12,571.6**

years (since 2007), there has been a stimulating tariff policy for renewable energy sources stipulated by the Law on Renewable Energy [3]. The implementation of this policy has increased the installed capacities of WPPs and SPPs in recent years. The cost of a unit of installed capacity of these sources sharply decreased in 2019, therefore changes were made to the tariff setting system for electricity received from these sources connected to the power system [3].

For reference. New capacities (over 200 MW) that have been built and commissioned to date, namely, wind and solar power plants, not only do not increase the maneuverability of the energy system but also make it even less dynamic and flexible. Therefore, to regulate and cover the peak power, it is necessary to have a hydroelectric power plant or other peak regulating system batteries such as pumped storage power plant and capacitor storage.

The daily electrical load of Mongolian energy systems is uneven in nature, both in winter and in summer. For example, for the Central energy system, the difference between the evening maximum and the night minimum is 280-350 MW (30-35%).

The state energy strategy [4] suggests that the share of electricity sources based on the renewable energy resources in the total generating capacity should be increased to 20% by 2020 and up to 30% by 2030 to provide stable and sustainable development of the country and to reduce the production of greenhouse gases and other harmful emissions from the energy sector. The coal power industry should also pay attention to the introduction of new environmentally friendly technologies, such as coal combustion in boilers with a circulating fluidized bed and/ or with a vortex furnace. As for the coal-fired electricity-generating sources intended for the electricity export, these should be an environmentally friendly thermal power plant (EFTPP) with one of the specified coal combustion technologies and the subsequent complete processing of all waste into end products of consumer quality [5]. To implement this decision, the Government of Mongolia and the Ministry of Energy need to pursue a unified, consistent, and purposeful integrated approach, taking into account both the development and deployment of productive forces and the transformation of the country's energy sector itself.

Mongolia is known to be rich in mineral resources, including high-quality coal [6, 7]. The export of goods is of great importance to the national economy. More than 80% of exports are raw materials: copper concentrate, gold, coal, zinc and iron ore, oil. In recent years, coal has surpassed the export of other goods and become the most important export product to support the national financial system [8]. Mongolia is a relatively new coal exporter. The growth of coal production began in 2004, mainly for export to China. It is still Mongolia's main market for coal exports. In 2018, coal exports amounted to 62% of the total production [8]. Coal export revenue continuously grows. In 2018, it amounted to USD 2.8 billion, which is 23% higher than in 2017 [9]. Therefore, Mongolia seeks to increase the export of these resources by expanding foreign trade with the countries of North-East Asia (NEA). To this end, Mongolia has begun the work aimed at extending the railway network, which will allow some promising strategic deposits of mineral resources, including uranium, which are close to the railway, to be involved in the economic activity. Rational use of rich primary natural energy resources in the form of coal, solar energy, and nuclear raw materials in combination with a favorable geographic location of the country should contribute to the achievement of the most important goals stipulated in the raw materials and energy policy of Mongolia to transform the country into an energy exporting-importing country. The intensification of discussions on the issue of the 'Power of Siberia-2' gas pipeline running through Mongolia's territory since last year can also be seen as a new direction for the development of energy cooperation between Mongolia and neighboring countries. Furthermore, the implementation of this project may, to a certain extent, change the view on the structure of the fuel and energy balance of Mongolia.

The expected commissioning of new mines and mining-and-processing entities, as well as the growing power consumption in the social sphere of the southern, southeastern, and eastern regions and in general throughout

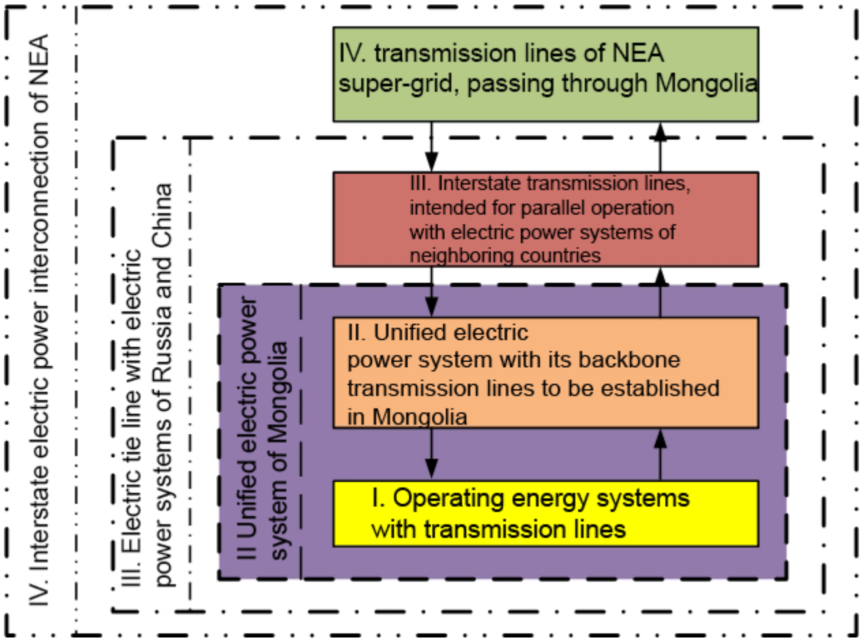

Fig. 2. Hierarchical scheme of the development of Mongolia's electric power system.

the country, lead to a significant increase in demand for electric power. Stabilization of the socio-political situation, and, as a consequence, the economic growth in the country over the previous ten years, increased the average annual electricity production by more than 100 million kWh/year. Before 2000, the average annual growth had been 3.8%, and since 2000, there has been a stable increase in annual electricity production, which averages 236 million kWh / year, or about 5% per year. This, and the commissioning of new generating capacities in the near future, require the connection of the country's peripheral energy systems to the largest Central energy system by new power lines, which is a prerequisite for creating the basis for building a unified energy system of Mongolia.

III. An integrated approach to energy development of Mongolia

Scientifically and practically, this integrated approach to the development of the Mongolian energy sector, including the creation of new generating capacities and new backbone transmission lines, both technically and temporally, is divided into two levels of implementation. The first level provides an increase in the reliability and sustainability of the internal energy supply. The second one is oriented (preparation for the orientation) towards electricity export-import supplies and integration into the interstate electric power interconnection of the NEA countries. Methodologically, however, we can distinguish four hierarchical levels of development throughout the system as a whole (Fig. 2). The first is the currently existing energy systems, the second is the Unified energy system of Mongolia, the third is an energy system operating in parallel with the energy systems of neighboring countries, and the fourth is a component of the international energy interconnection based on the super grid of the NEA countries.

The solutions to be obtained at each level should be organically linked with each other, and one should be a continuation of a previous level and an output of a higher level of hierarchical development of the country's unified energy system. To solve the above issues of the development of energy systems and the establishment of a unified energy system of Mongolia on scientific grounds, the researchers of Mongolia conduct joint scientific research in collaboration with the scientific teams of the SB RAS (Melentiev Energy Systems Institute and Kutateladze Institute of Thermophysics) [5,13-16].

Energy companies holding licenses for the development of coal deposits offer many projects for the construction of condensing power plants of various capacities at large coal mines. However, to date, none of these proposals has been practically implemented. Here it is worth noting that the implementation of such projects, firstly should fit in the location and capacity of the general scheme of the unified energy system, satisfy the demand for electricity output and operating conditions, and secondly, should comply with the technical and economic requirements of the coordination and regulatory authorities of the country's energy sector. At the same time, under the current circumstances, the construction of large condensing capacities, especially under the terms of a concession, is not advisable since neither consumers nor the energy system is prepared to receive a large amount of electricity they produce. For example, the 700 MW condensing capacity, consisting of two 350 MW units, to be constructed at the Baganur coal mine, does not yet fit into the operating conditions of the Central energy system, whose generating capacities consist mainly of combined heat and power plants producing

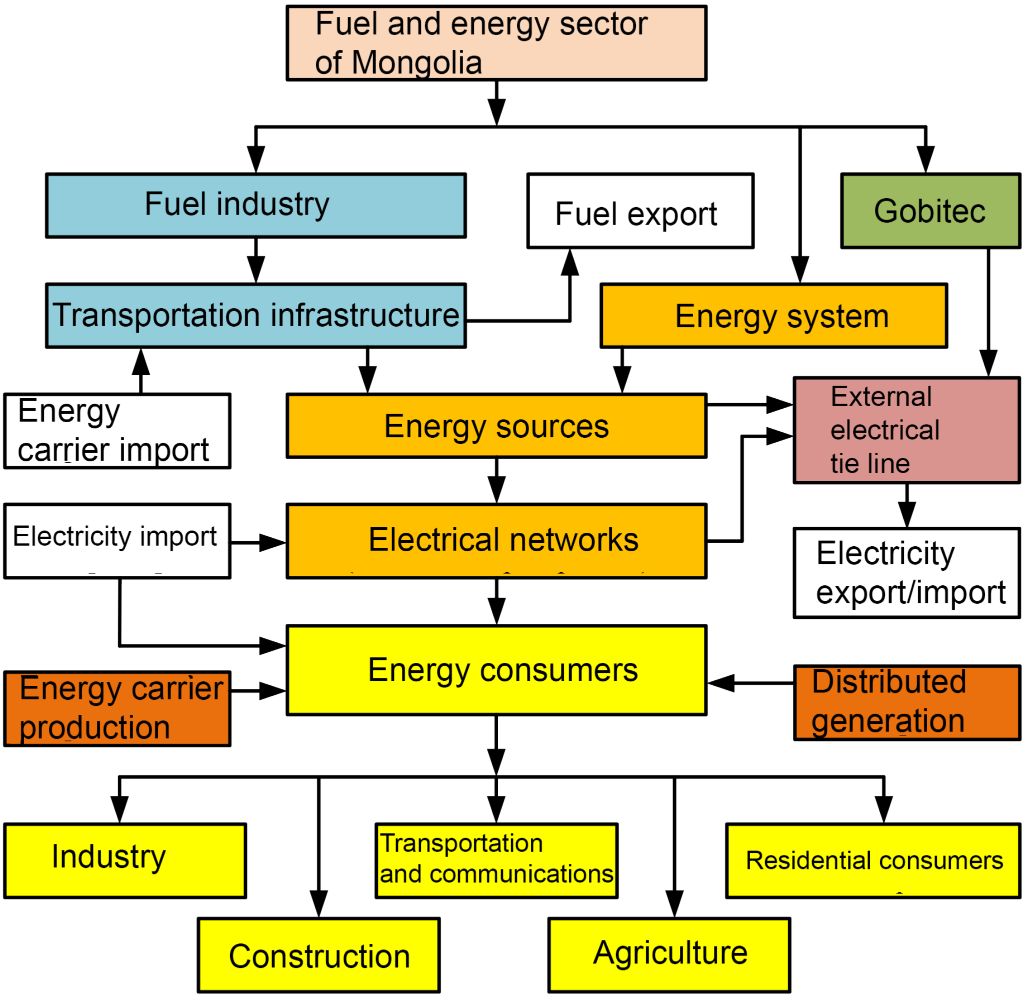

Fig. 3. Block diagram of the fuel and energy complex of Mongolia

electricity and heat. Therefore, in the current situation, to have a short-term solution to the problem of providing the Central energy system with generating capacity, it is necessary along with the construction of a condensing power plant and hydropower plant (in the future, there may be a nuclear power plant) to technically reinforce the electrical tie with the Russian power system. Thus, electricity import from the Russian Federation has been and remains one of the essential issues for the Central energy system and other energy systems (for example, Western ES) in Mongolia.

Traditionally, Mongolia has extensive experience in the economic and energy cooperation with Russia, which continues. The priority areas of mutually beneficial energy cooperation between Mongolia and Russia are still in the coal industry and the electric power industry. In the coal-mining sector, Russia and Mongolia can significantly expand their cooperation through the implementation of a joint project for the development of the world's largest Tavan Tolgoi coking coal deposit [5]. The Mongolian parliament approved [6] the construction of a 1.1 thousand km railroad from the Tavan Tolgoi deposit to the Russian border for the possible export of the deposit's coking coal to the markets of the Asia-Pacific region (APR) countries through Russian Far Eastern seaports. A mutually beneficial area of cooperation between the two countries in the coal sector is the creation of joint ventures for the comprehensive and advanced processing of Mongolian brown coal. The cooperation of the two countries in the electric power industry is possible in two directions: the reconstruction of existing equipment and the construction of new power plants and the reinforcement of the interstate electrical tie line. Here it is noteworthy to mention the Russian-Mongolian initiative to establish an interstate electric power system Russia-Mongolia-China [10] and form the Asian Super Grid [11, 12]. In recent years, with the participation of Russian energy machine-building companies, work has been continuously carried out to upgrade turbine generators and expand the heating capacity of Ulan-Bator CHP-4. Russia is the major supplier of petroleum products to the Mongolian market.

Mongolia will be a reliable participant in the energy space of the NEA countries. With the creation of such a large-scale system, the construction of large generating capacities operating for the export of electricity, such as the environmentally clean Shive-Ovoo coal-fired thermal power plant with a capacity of, for example, 4800 MW, becomes justified [5]. The implementation of these projects will contribute to the mutually beneficial energy cooperation with the countries of the region and help cope with the reliability problems of the unified energy system and energy supply of Mongolia.

As a result, the developed fuel and energy sector of Mongolia will be represented by the following structure (Fig. 3), which reflects, approximately, all internal and external functional connections of its components.

At the same time, the above issue of reinforcing the external electrical tie of the Unified energy system of Mongolia will arise, which will affect the interests of Russia and China and increase the opportunities for our country to enter the international energy market and become one of its energy trade partners. Mongolia will also have to solve the problems, first of all, concerning the investment in newly created energy facilities at all hierarchical levels and the cost of electricity produced, and answer the questions whom to sell it, at what price, and others. Nevertheless, we should find positive solutions to problems both for the common interests of the region and for individual countries in the light of cooperation and sustainable development. The transboundary power transmission lines under construction, which are intended to strengthen the external tie line of the Unified energy system of Mongolia, can also be used to export electricity from Russia to China. When the transnational electric power network and the energy interconnection of the NEA countries becomes a reality, it will be possible to implement the most optimal operating parameters of all energy sources in these countries and provide an uninterrupted and reliable power supply at minimal costs.

IV. Conclusions

1. The development of Mongolia's unified energy system is an urgent issue, first of all, for this country and the countries of Northeast Asia. At present, it represents five disparate power systems and has limited opportunities for participation in interstate energy cooperation with the NEA countries.
2. Prospective plans for the development of mining deposits and the active building of the industrial and social spheres and housing complex in Mongolia require the creation of a new level of the energy sector with its most significant direction towards the unified energy system with developed external ties, allowing the country to enter the international energy markets.
3. The goal of the research is to design a scientifically grounded rational network structure of the backbone power transmission lines to form the unified energy system and to provide state investment for its implementation.
4. Meeting the domestic demand for electricity in the coming fifteen-year period requires at least 3 GW of capacity (2.5 times more than the existing capacity) to be commissioned and more than 1000 km of backbone power transmission lines with a voltage of over 220 kV to be constructed. It is also essential to reinforce the interstate electric tie lines with Russia and China.
5. Mongolia's participation in the economic and energy cooperation of the NEA countries with its rich reserves of mineral resources, including high-quality coal and high solar energy potential, is beneficial for the countries in the region and serves their common interests.

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On The Establishment of the National Renewable Energy Center in Vietnam: a Technological and Economic Study of the Potential of Renewable Energy Sources

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***Abstract* — Currently, the structure of Vietnam's energy sources is changing, with renewable energy sources starting to play an increasing role in meeting the electricity demand and reducing greenhouse gas emissions from fossil energy sources. Vietnam's energy development strategy suggests building some renewable energy centers, of which Ninh Thuan is the first province to become the national renewable energy center. This is because of Ninh Thuan's endowment as a province having the highest renewable energy potential in Vietnam. The development of a large renewable energy center allows power system planners to overcome the mismatch in timescales associated with expanding transmission power grid and renewable energy generation. Besides, the renewable energy center can facilitate large-scale renewable energy and storage projects. The province of Ninh Thuan, however, is located far from the main load centers of Vietnam, which is why the economic indicators need to be calculated and analyzed. This paper presents the results of an analysis of economic indicators of major renewable electricity sources in Ninh Thuan (onshore wind power, offshore wind power, and solar power) to provide scientific arguments for developing a renewable energy center in Vietnam.**

***Index Terms*: energy structure, energy sources, electricity demand, gas emissions, fossil energy sources, renewable energy.**

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I. Introduction

The overall global renewable power capacity increased to around 2,378 GW by the end of 2018 and reached more than 33% of the world's total installed power generating capacity [1]. A new renewable power installed capacity was estimated at 181 GW worldwide in 2018, of which the total capacity of solar power accounted for 55% of renewable capacity additions, followed by wind power (28%) [1]. The power system can receive a large proportion of renewable energy without using fossil fuels and nuclear power that provide "base load," relying on the flexibility of the electricity system, power grid connection, advanced technology solutions such as information-communications technology (ICT), power storage systems and virtual power plants. It helps both to balance the change in the electricity generation stage and to optimize the power system and reduce generation costs. As a result, some countries successfully control peak loads or surpass the target of 100% of electricity produced from renewable energy.

There is a tremendous difference between renewable energy centers (wind and solar power) and traditional power centers, such as a thermal power center in the national power system. This is due to the specific features of its primary energy sources. For the development of a thermal power center, the preferred conditions for its location are near large load centers or a power grid or infrastructure (coal ports, for example). In the case of renewable energy (RE) center, the preferred condition is the geographical areas with high solar radiation or good wind speed and efficient land use. This difference makes it challenging to synchronize and optimize the transmission and distribution grids so that RE resources can be fully utilized in the considered geographical areas to reduce transmission losses as the load centers are usually far from the RE sources. Some countries build large RE centers such as Asia RE Hub - AREH [2] in Western Australia and RE Zone [3] of Texas, USA. A large RE center (RE

Hub or RE Zone) is a geographic area supporting cost-effective renewable energy (RE) development, including high-quality RE resources, suiTable 1. Input parameters topography, and strong developer interest. The large RE centers allow power system planners to overcome the difference in timescales associated with developing transmission power grid and RE generation. Besides, RE Hub or RE Zone can release a significant pipeline of large-scale renewable energy and storage projects.

Vietnam's electricity consumption increased steadily in recent years, from 90 TWh in 2010 [4] to 227 TWh in 2019 [5], with an annual growth rate of about 11 %/year. At the same time, the power system's maximum installed capacity also rose from about 20000 MW in 2010 [5] to about 55000 MW in 2019 [6]. Vietnam's electricity demand is expected to reach about 570 billion kWh by 2030 [7]. Currently, Vietnam is changing energy source structure, in which renewable energy sources will play a crucial role in meeting electricity demand and reducing greenhouse gas emissions from fossil energy sources. Solar power is projected to reach 4,000 MW in 2025 and 12,000 MW by 2030, while the wind power capacity may increase to 2,000 MW by 2025 and 6,000 MW by 2030 [8]. At the end of 2019, the actual installed solar power capacity reached about 5.6 GW [9], while the total wind power installed capacity was about 425 MW [10]. The feed-in-tariffs (FIT) introduced for solar and wind power projects were 7.09 US$ cent/kWh for ground-mounted PV project and 7.69 US$ cent/kWh for floating solar projects [11], 8.5 US$ cent/kWh for onshore wind, and 9.8 US$ cent/kWh for offshore wind [12].

Vietnam's energy development strategy suggests building some renewable energy centers, of which Ninh Thuan is the first province to become a national renewable energy center as it has the highest renewable energy potential in Vietnam. The national renewable energy center to be established in Ninh Thuan will play a significant role in supporting the development of the renewable power industry in Vietnam.

However, the province of Ninh Thuan is situated far from the main load centers of Vietnam, which is why the economic indicators need to be calculated and analyzed. This paper presents the results of the assessment of economic indicators of key renewable electricity sources in Ninh Thuan (onshore wind power, offshore wind power, and solar power) to provide scientific arguments for developing a renewable energy center in Vietnam.

II. Potential of solar and wind energy sources in Ninh Thuan province

1. Geographical site

Ninh Thuan, located in the southern part of the Vietnam Central Coastal region, borders Khanh Hoa in the north, Binh Thuan in the south, Lam Dong in the west, and East Sea in the East.

The province has a total natural surface of 3,360 km2, 7 administrative units, including 1 city and 6 districts. The city of Phan Rang - Thap Cham constitutes a political, economic, and cultural center of the province. It is situated at a 350 km distance from Ho Chi Minh City, 60 km from the international Cam Ranh airport, 105 km from the city

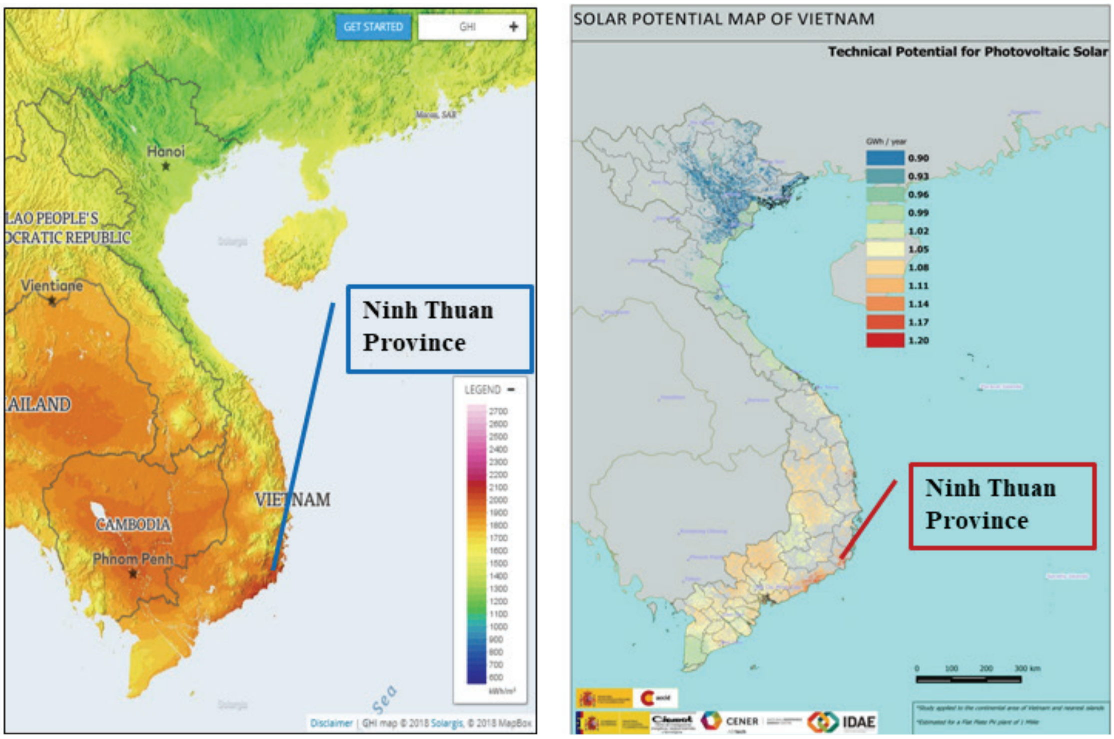


Fig. 1. The solar energy potential of Ninh Thuan province [6]

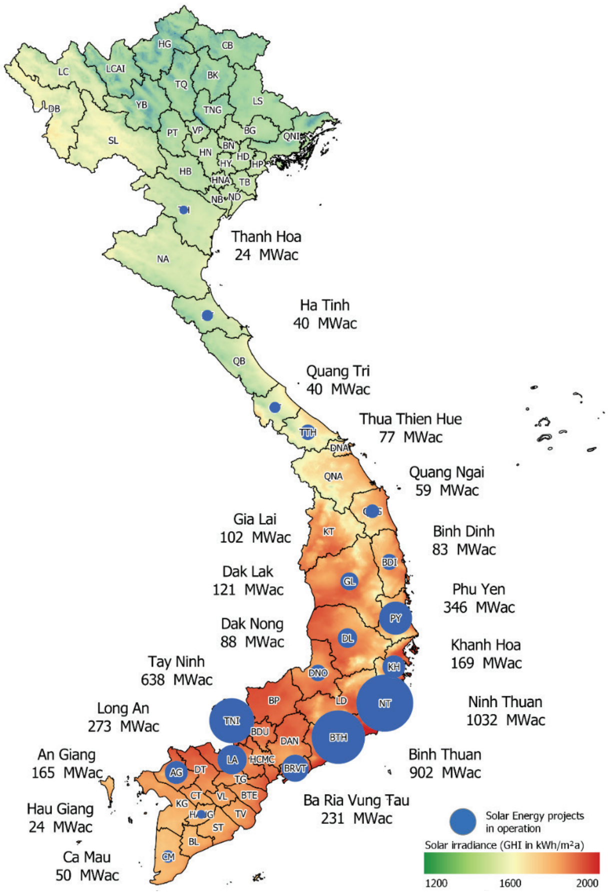


Fig 2. Installed solar power capacity in Vietnam [6].

of Nha Trang, and 110 km from Da Lat with favorable conditions for socio-economic development.

2. Solar energy potential

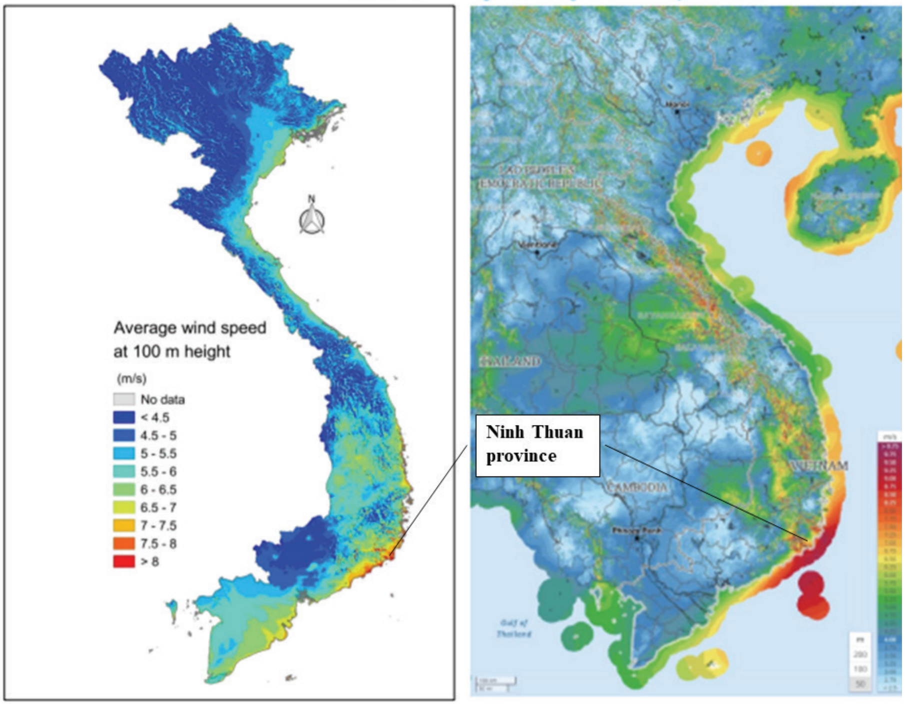
Ninh Thuan is located in an area with an annual average solar radiation of about 5.5 kWh/m2 a day, the average number of sunshine hours is about 2,600-2,800 hours per year (equivalent to 200 sunny days/year), and a total solar power installation scale of about 1,500 MW. In Ninh Thuan, there is the area of Ninh Phuoc district and Thuan Nam district, where the high solar energy potential can be effectively exploited [13].

Until August 2019, the number of completed solar power projects in Ninh Thuan had been the highest in Vietnam, with a total installed capacity of about 1032 MW [6].

3. Wind energy potential

Ninh Thuạn province has also the highest wind power potential in Vietnam, with an annual average wind speed of about 7m/s at a height above 65m. The whole province has 14 potential wind regions with an area of about 8,000 ha concentrated mainly in three districts of Ninh Phuoc, Thuan Nam, and Thuan Bac. Storms are rare in Ninh Thuan, and the wind blows steadily for ten months at a speed of 6.4 - 9.6 m/s, ensuring stability for wind power development. The technical wind power potential is 1,442 MW, and the highly feasible area of Ninh Thuan is 21,642 ha [14].

Up to August 2019, Ninh Thuan had commissioned the largest number of wind power projects in Vietnam with a total installed capacity of about 109 MW, as shown in Figure 4 [6].



a). onshore b). offshore

Fig 3. Wind energy potential in Vietnam [15].

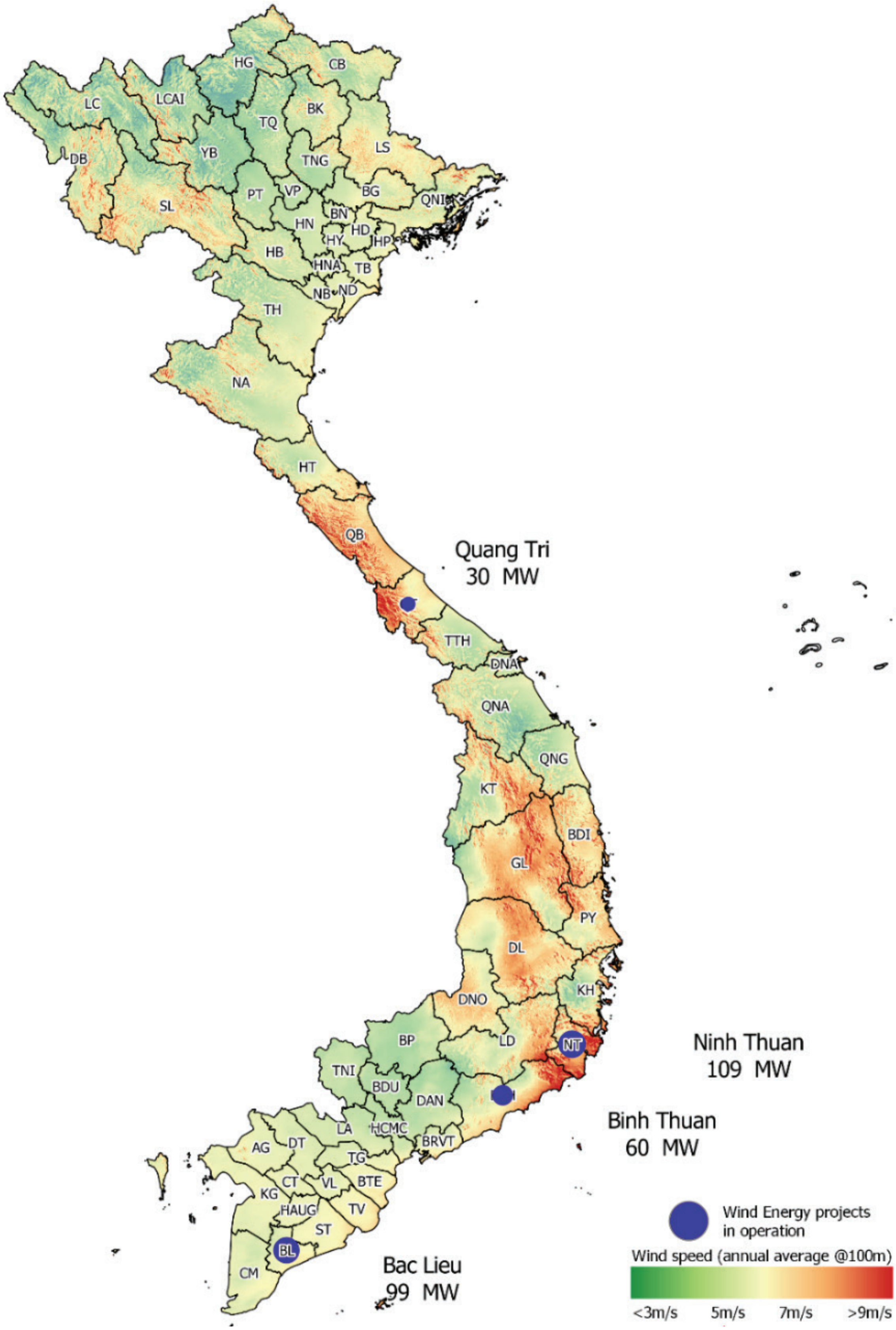
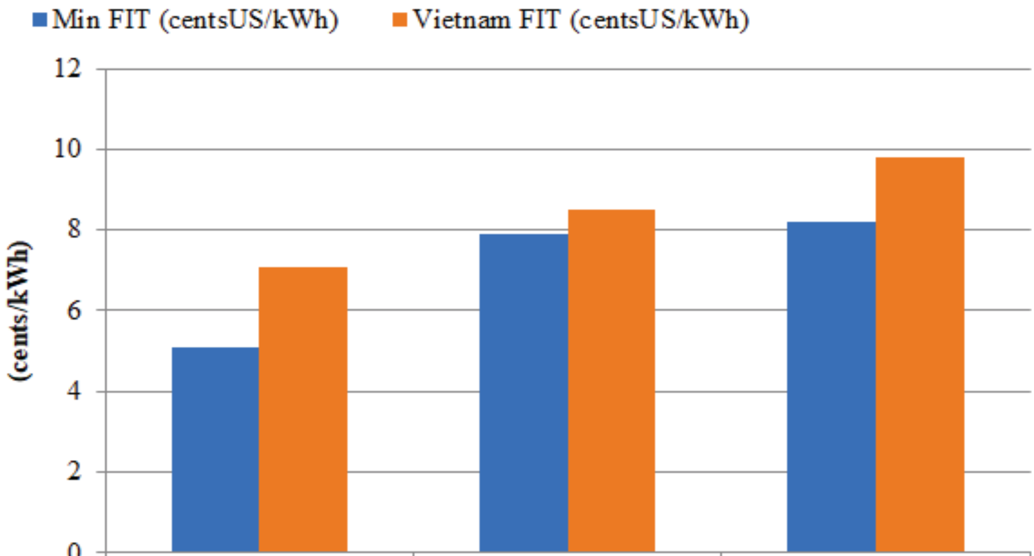


Fig 4. Installed wind power capacity in Vietnam [6].



	Solar power	Onshore wind power	Offshore wind power
Min FIT (centsUS/kWh)	5.1	7.9	8.2
Vietnam FIT (centsUS/kWh)	7.09	8.5	9.8

Fig 5. Minimum FIT versus Vietnam FIT.

Table 1. Input parameters

Parameters	Ground-mounted PV power	Onshore wind power	Offshore wind power
Initial Investment Cost ($)	25,278,015	53,892,216	66,723,695
Operations and Maintenance Costs ($)	126,390	1,077,844	1,334,474
O&M Growth Rate (%)	2	2	2
Capacity (MW)	30	30	30
Annual Electricity Output (MWh)	48,450*	73,584	86,724
Project Lifespan (years)	25	25	25
Discount Rate (%)	6	6	6

*Note: Power degradation of solar power is no more than 2.5% in the first year, then 0.7% per year until the 25th year.

III. Methodology

In this study, the electricity of solar farms is calculated using the PVSYST program [16, 17], while the output from the wind turbine is determined based on the design data of wind farm projects, which were used to plan the wind power development in Ninh Thuan [14].

The economic potential was assessed considering annualized investment costs and the annual operations and maintenance (O&M) costs. The objective was to calculate the minimum feed-in tariff (FIT). Currently, the FIT level can be determined from the calculation of the levelized cost of electricity (LCOE) produced from renewable energy (RE) projects [19]. By which, the investor can recover different costs (capital, O&M, fuel, financing) while realizing a return on his investment that depends on the assumed financing costs. LCOE is used to assess the average lifetime costs of providing one MWh for a range of power production technologies or power savings. The cost elements comprising the LCOE include investment costs, fuel costs, operation and maintenance costs, environmental externalities, and system costs for solar and wind power plants. LCOE is calculated by the following formula

$$LCOE = \frac{\sum_{t=1}^{n}(I_t + Mt + Ft)}{\sum \frac{E_t}{(1+r)^t}}$$

where:

- I_t: Investment cost by the year t
- M_t: Operations and Maintenance costs by the year t
- F_t: Fuel costs by the year t
- E_t: Electricity production by the year t
- r: Discount rate
- n: Project lifetime (year)

Table 2. Calculated economic indicators

Parameters	Ground-mounted PV power	Onshore wind power	Offshore wind power
Net present value (NPV) ($)	27,074,753	69,214,650	84,046,360
LCOE (US$ cent/kWh)	5.1	7.9	8.2

IV. Results

The key parameters used for the calculations are shown in Table 1.

The LCOE and minimum FIT of minimum renewable electricity sources in Ninh Thuan (onshore wind power, offshore wind power, and solar power) are indicated in Table 2.

Figure 4 presents the results of the comparison of the minimum FIT of onshore wind power, offshore wind power, and solar power projects in Ninh Thuan with the existing Vietnam FIT for such projects in the country. The min FIT of onshore wind power in Ninh Thuan is closer to Vietnam FIT than solar power and offshore wind power.

V. Conclusions

This study has presented the potential of solar power and wind power in the province of Ninh Thuan, where the annual average solar radiation is about 5.5 kWh/m2/day and wind speed is 6.4 - 9.6 m/s.

The calculation of the economic indicators shows that the minimum FITs of onshore wind power, offshore wind power, and solar power projects in Ninh Thuan were lower than the current Vietnam FIT. The gap between the minimum FIT and Vietnam FIT for onshore wind power was smaller than for offshore wind power and solar power projects.

Acknowledgments: This study was funded by the province of Ninh Thuan under the project for "Development of Ninh Thuan province into the national renewable energy center".

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Infrastructural Cyber-Physical Energy Systems: Transformations, Challenges, Future Appearance

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***Abstract* — The directions for the transformation of the key hierarchically-structured infrastructure energy systems, i.e., electric power, heating, and gas supply systems, as influenced by intensively expanding adoption of technology innovations in physical (power) and information-and-communication subsystems are studied. The peculiarities of the transformation of the energy systems structure at their different hierarchical levels are analyzed. Changes in the properties of future energy systems as influenced by innovation-driven processes and facilities are discussed. Interpretations of new properties of transforming energy systems, i.e. flexibility and resiliency, which have recently been the subject of much research effort are analyzed. It is argued that in the future the above energy systems will acquire the features of integrated cyber-physical systems. The fundamental role of developing control systems for future infrastructure cyber-physical energy systems is emphasized.**

***Index Terms*: Infrastructural energy systems, hierarchical designs, technology innovations, transformation, structure, properties, cyber-physical systems, control.**

I. Introduction

The key energy infrastructure systems are electric power systems (EPS), heating systems (HS), and gas supply systems (GSS). They have an elaborate multi-level structure and play a crucial role in ensuring a guaranteed energy supply to consumers with their increased requirement for reliability and quality of energy supply in accordance with the new paradigm of user-oriented energy systems. By way of illustration, Figure 1 [1] presents the structure of the EPS as a super-mini-micro-system where level of the super-system incorporates large power plants, system energy storages of large capacity, and main electrical power network of high and ultra-high voltages; the level of the mini-system is that of mini-sources of the electric power up to 25 MW of unit capacity, mini-storages, and the distribution network of 6-110 kV; the level of the micro-system subsumes micro-sources and micro-storages of the electric power of unit capacity up to 25 kW and the local power grid of 0.4-10 kV.

Heating systems differ from electric power and gas supply systems only in their scale and location in urban areas. They are structured as a hierarchical system as well (Figure 2) and are differentiated into super-systems that cover large heat sources (combined heat and power (CHP)) plants, boilers, etc. with a capacity above 25 Gcal/hour), transit and main heat networks (HN) coming from them, mini-systems with a heat capacity below 25 Gcal/hour as part of heat sources (cogeneration plants, boilers, non-conventional and renewable energy sources), distribution networks of small diameters and individual heat points, and micro-systems in the form of individual non-conventional and renewable energy sources built directly at one or several consumers with their heat consumption systems, as well as micro-systems of buildings and structures.

As for GSSs, at the level of the super-system one should deal with process facilities that supply gas to the network of its supply mains, starting from the fields and main compressor stations at the field outlets and down to the points of its delivery to gas distribution stations and units. The main facilities of GSSs at this level are main and intermediate compressor stations, high pressure gas trunklines, and underground gas storage facilities that compensate for seasonal unevenness of gas consumption. The share of natural gas transportation allotted to liquefied natural gas (LNG) transport, mostly via waterways as shipped by gas carriers, is ever increasing. At the same time, natural gas liquefaction plants, tankers, and regasification terminals themselves should also be counted as belonging to the facilities of the GSS super-system.

At the level of the GSS mini-system, one should consider gas distribution networks of high pressure (0.3 to 1.2 MPa) from gas distribution stations, as well as medium (0.05 to 0.3 MPa) and low (up to 0.05 MPa) pressure networks

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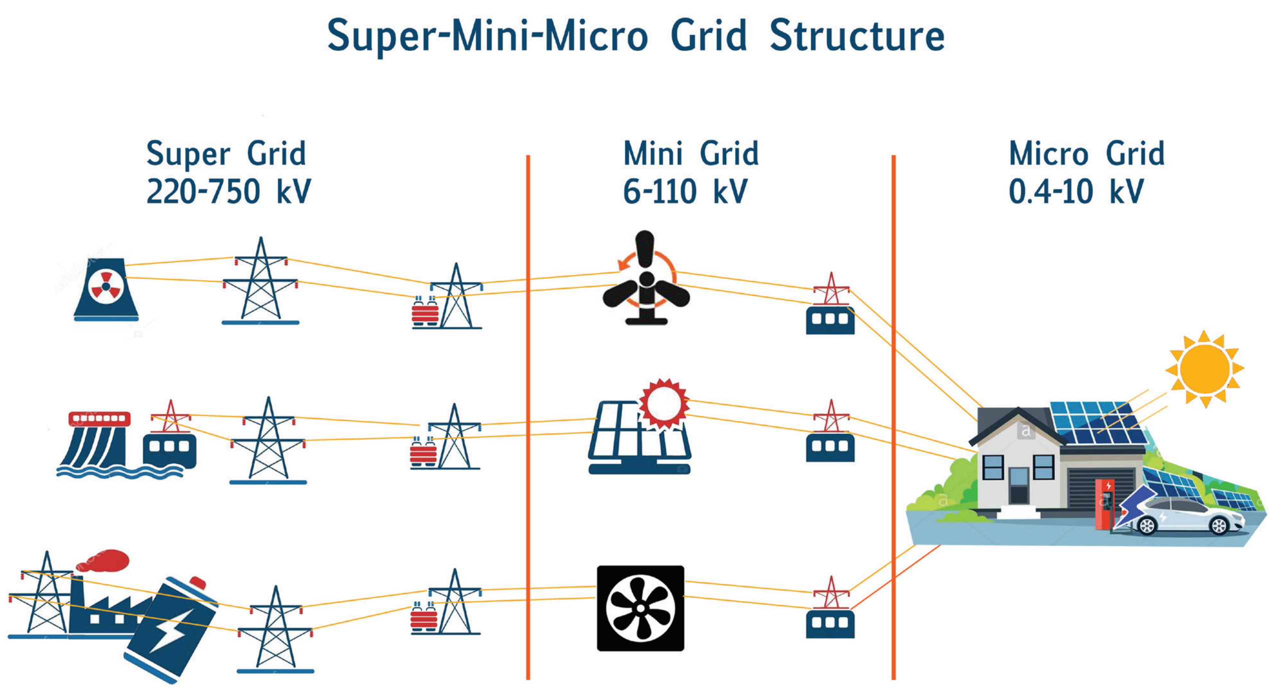

Fig. 1. Super-mini-micro-electric power system.

from gas distribution units down to shut-off devices at the inlets to gas-fired thermal power plants, boilers houses, gas chemical complexes, and buildings with gas equipment. Moreover, at this level one should take into account the systems of discrete transport (primarily road transport) of liquefied and compressed natural gas. The level of micro-systems is represented by internal gas pipelines running from their entries into buildings and structures to connection points of consuming devices and appliances: gas boilers, turbines, equipment of gas-chemical enterprises, and other gas-consuming gas receivers.

The above energy systems in the process of development are transformed in terms of their structure and properties due to the expanding adoption of technology innovations in production, transport, distribution, storage, and consumption of energy, intensive development of renewable energy sources, as well as the activity of consumers in the processes of their energy supply, etc.

This study analyzes the main directions of transformation of the structure and properties of future EPSs, HSs, and GSSs, discusses the transformation trends these energy systems have in common and their unique features, as well as topical problems and challenges associated with the discussed trends that determine the future appearance of these key infrastructure systems.

Taking into account the above–mentioned specific features of infrastructural energy systems, Chapter 2 of this paper deals with the structural trends in energy systems development. The transformation of energy systems properties is discussed in Chapter 3. Integrated cyber-physical energy systems of the future are the focus of Chapter 4. Directions of control systems development for integrated energy systems are discussed in Chapter 5. Some conclusions are presented in Chapter 6.

II. Structural trends in energy systems development

A. Electric power systems

Trends in the transformation of the EPS structure at the super-system level are determined by a number of long-established and emerging factors. The key long-established factor is the realization of system effects from the joint operation of EPSs, that are considered as system services. The Association of System Operators of the world's largest EPSs G015 draws attention to the need for a new understanding of such system services under market conditions [2].

A relatively new factor is the formation of mega-centers of power generation with the use of renewable energy resources, such as the largest hydroelectric power plants – HPP (the "Three Gorges" HPP on the Yangtze River in China, a large-scale hydroelectric power plant on the Congo River in Central Africa, etc.), mega-parks of wind power plants in the North Sea and the Arctic coast of Russia, solar power plants in the Sahara and Gobi deserts, and others. By way of illustration Figure 3 shows a mega-project for the development of Western European Interconnection based on wind parks in the North Sea and solar power plant parks in the Sahara desert [3].

Electricity generated by these mega-centers should be distributed over ultra-long distances, which is feasible given the active development and reduction of the cost of long-distance power transmission technologies of ultra-high AC and DC voltages. This served as the basis for the

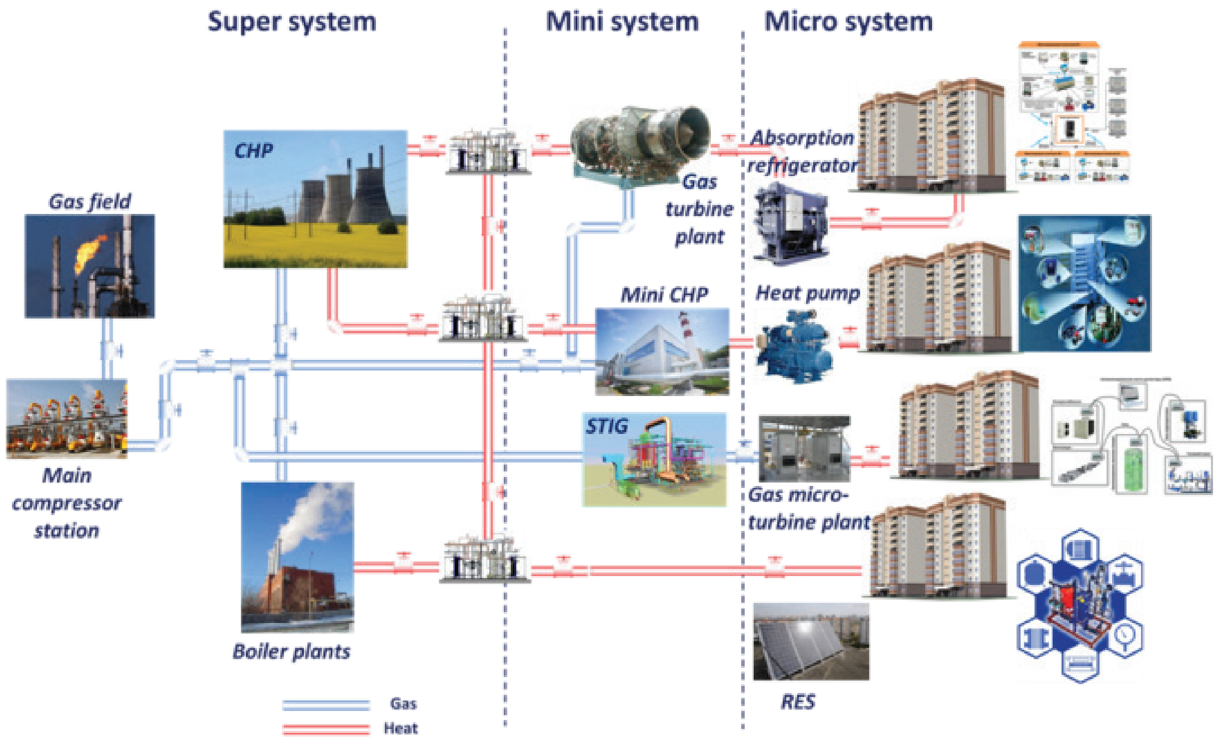

Fig. 2. Super-mini-micro-heating system.

proposal to form the Global Energy Interconnection (see Figure 4) [4].

On the other hand, active development of distributed generation continues, which radically redefines the structure and properties of mini-systems. However, the sometimes proposed extreme scenario of EPS development that makes use of distributed generation only when major power plants are withdrawn from operation seems unrealistic. The mixed scenario of development of relatively large power plants at the level of super-systems (centralized power supply) and distributed generation units at the level of mini-systems (decentralized power supply) has a high probability of implementation success. The function of power supply of large consumers remains the responsibility of large centralized sources, which is practically impossible to attain by means of distributed generation, along with ensuring the reliability of power supply and quality of electricity in terms of frequency and voltage.

The general structural trend for super-systems and mini-systems is the continuing increase in the density and complexity of main and distribution power networks. The structure of large EPSs is becoming more and more heterogeneous, with cases of system "voltage-wise" instability in concentrated parts of the EPS being more and more probable, while the problems of "angle-wise" instability in its extended parts with long electrical connections persevere.

The growing complexity of the structure of developing EPSs with the general growth of installed capacity and scale of EPSs lead to the more devastating aftermath of severe system accidents of cascade nature, which is confirmed, in particular, by the US EPS historical data for 1991-2005, shown [5] (see Figure 5).

Micro-systems have traditionally been formed as based on alternating current. Nowadays, many electrical receivers operate on direct current. Rectifier-inverter units are used for their connection with the EPS. On this basis, DC micro-systems or hybrid DC/AC micro-systems are developed. The unique project of implementation of DC micro-systems is the program of power supply of isolated individual consumers of Mongolia "100,000 Solar Houses (gers)" [6].

Both stand-alone and joint operation of micro-systems with EPSs generates a number of urgent problems for studies on substantiation of micro-systems development and control of their operation under various conditions.

Thus, structural changes in EPSs at all three levels-super-, mini-and micro-systems-lead to changes in their properties and new problems that are to be solved.

B. Heating systems

Heating systems, often integrated with electric power and gas supply systems through heat sources (CHP plants), heat networks, and consumers, stand out as relatively local in nature. In accordance with the energy policy of Russia, their development is aimed at the prevalence of district heating. In terms of capacity and production of thermal energy, they reach a large scale and therefore are aptly classified as large energy systems. Thus, the heating systems of Moscow in terms of capacity (over 52 thousand Gcal/h) and

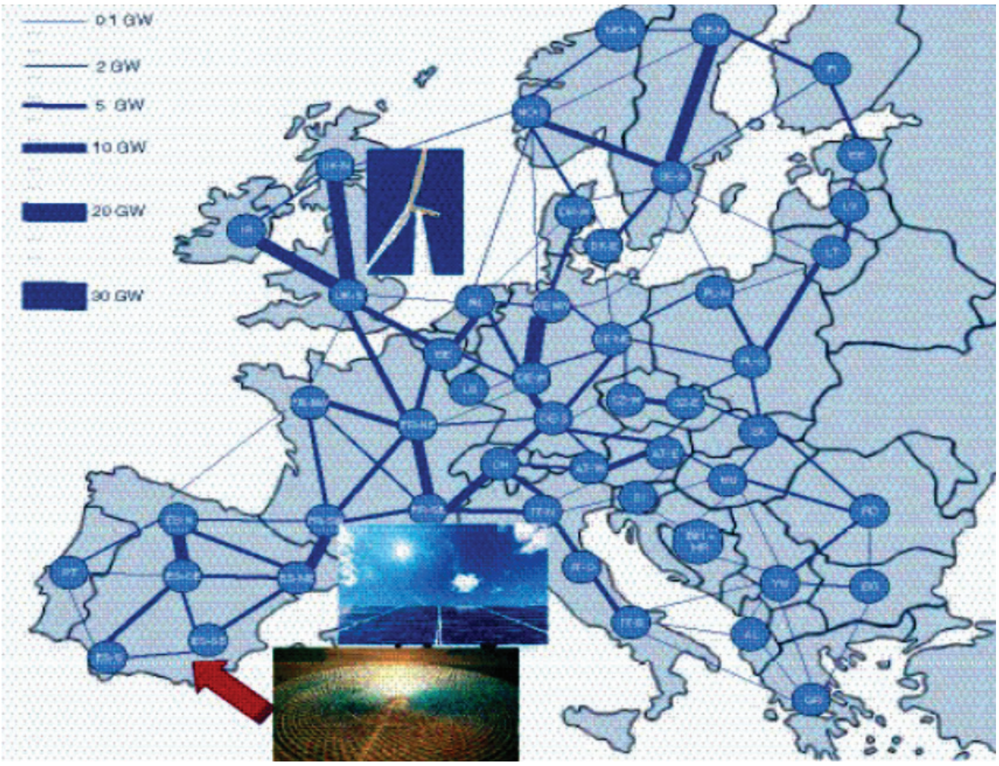

Fig. 3. Mega-project of West European interconnection development.

thermal energy production (over 95 million Gcal/year) exceed the HSs of such industrial regions as Irkutsk, Novosibirsk, Sverdlovsk regions, Krasnoyarsk Krai, etc. in terms of their size. All three process structures of systems (super-, mini-, and micro-systems) can exist either as part of a single centralized system, or separately, performing each their own functions.

Relatively new trends are manifested at all structural levels and are related not only to processes and equipment used in the systems of production, transport, and consumption of thermal energy, but also to changes in the processes of their operation, administration and control models (see Figure 6).

At the level of large systems, there is a growing tendency to merge scattered systems at the level of main heat networks with the organization of heat sources into unified HSs. Gas-powered steam-turbine CHP plants are being upgraded into combined cycle and gas turbine power plants based on cogeneration units. They have a wide power range depending on whether they belong to super- or mini-systems. In both types of HSs, new materials (composites, metal-filled plastics, etc.) and modern technology of trenchless laying of thermal networks are actively adopted. The system of automation and regulation in heat networks at the consumer side undergoes significant changes, it is focused on providing remote control with variable regulation of heat transfer medium flows, with automated units for maintaining and altering pressure and flowrate values, monitoring of consumption level, and the possibility of its regulation.

A very pronounced trend of transformation can be seen at the level of mini- and micro-systems, in which non-mechanized manual labor is replaced by automation and regulation systems.

Structural transformations on the basis of the outline-based division into subsystems (sources, networks, consumers) are accompanied by the transition to new technologies of systems operation in real-time and consumer activity.

Changes in the principles of construction and operation of the HSs being developed determine their structural complexity and require the appropriate development of methodological and theoretical support.

C. Gas supply systems

The main trends in the transformation of the GSS structure at the super-system level are related to the features of prospective changes in the structure of production, trunkline transport, and natural gas consumption.

As for the structure of gas consumption, it is based on various options for the development of energy consumption in the world, including Europe [7, 8, etc.], and even taking into account a significant anticipated growth of the role of renewable energy sources (RES) in the generation of electricity and heat (by 2040, RES may take up 15% of the world fuel balance as compared to 3% today), it can be assumed that consumption of natural gas will not decrease at least until 2040, but it may also increase slightly due to the active development of the gas chemical industry. Of all regions of the world, the largest growth in gas consumption

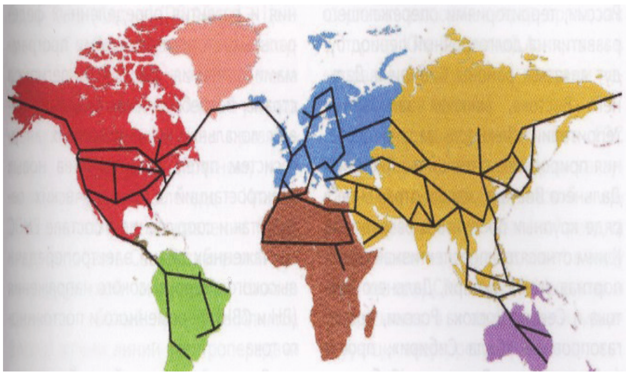

Fig. 4. Possible scenario of Global Energy Interconnection.

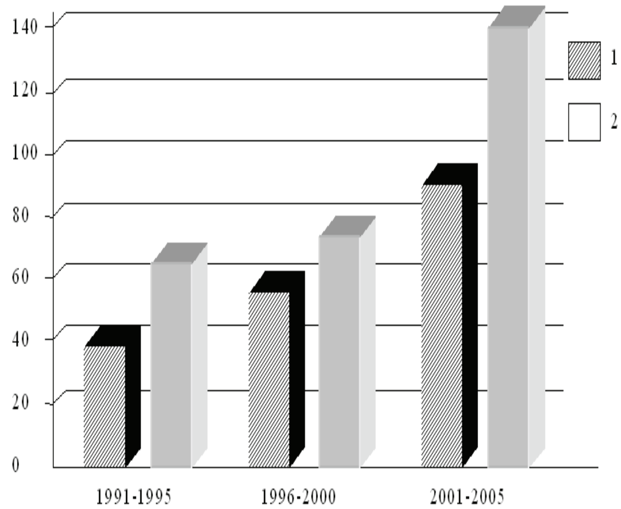

Fig. 5. Tendency for electric power system (EPS) blackout problems [25]. (1) The number of outages affecting more than 50,000 consumers; (2) The number of outages greater than 100 MW.

will take place in developing but not yet sufficiently industrialized regions. Pipeline infrastructure in such regions of the world is undeveloped or non-existing. This creates prerequisites for active development of the LNG transportation system with further development of the natural gas liquefaction and regasification plants network. The same holds true for the entire world as well, where for reasons of lesser dependence of gas producers on binding to specific consumers, it seems that the mainstream LNG transportation by sea will be developing at a faster pace than pipeline transportation.

In this case, the main structural transformations may concern the increase of maneuverability in response to changes in supply and demand. For example, over the last few years natural gas shortages in the USA have been transfigured into its abundance, which led to the development of plans to expand the area of regasification terminals to establish natural gas liquefaction capacities [9, etc.]. Implementation of such projects in the world will allow both exporting and importing natural gas using the same infrastructure depending on the market situation.

As for the structure of natural gas production, due to the high level of development of already proven conventional gas-bearing fields, costly access to new fields located mostly in hard-to-reach conditions, and engineering challenges posed by shale gas extraction, as well as taking into account the environmental problems of this process, the technology behind gas production from gas hydrates and world ocean-dissolved gas is the most promising in the world. Estimates of methane content in gas hydrates in the world are huge and according to various estimates they reach several hundred trillion cubic meters [10, 11, etc.]. However, with all the successes of industrial and

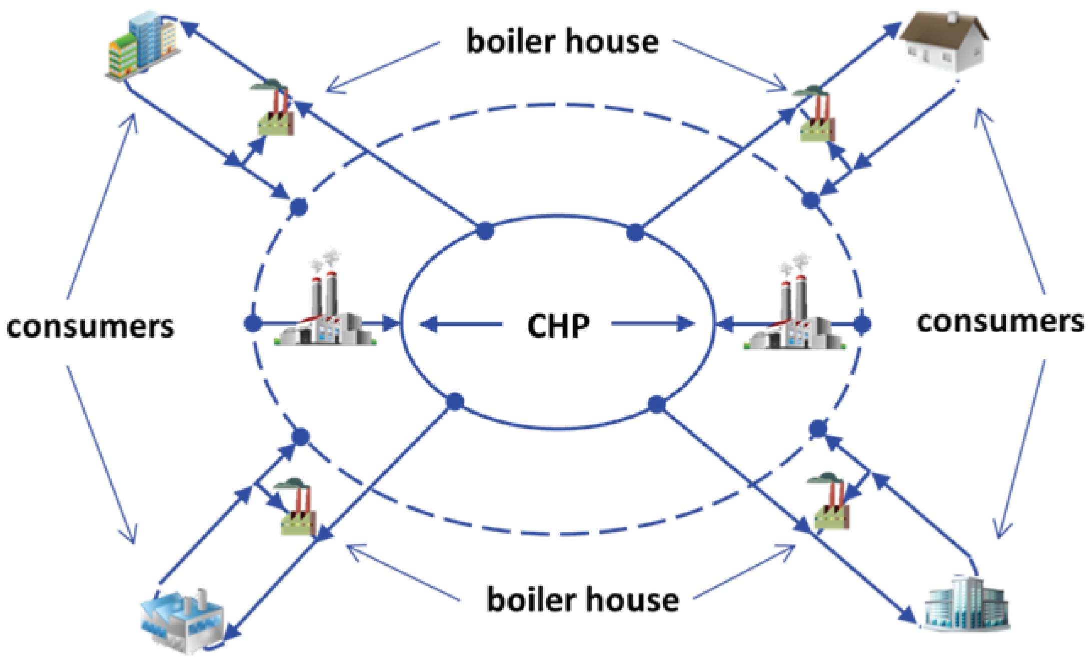

Figure 6. Heating plants interconnection for joint work on heating network

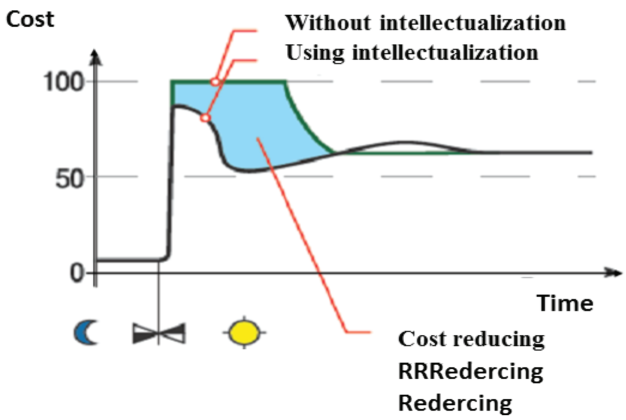

Fig. 7. Effect of HS intellectualization.

experimental extraction of methane from gas hydrates (the experiments run by teams from Japan and China, etc.) [12, etc.] there are still obviously serious issues with the economic feasibility of extracting methane trapped inside the frozen lattice of gas hydrates molecules. This requires either lowering the pressure in the deposit, or heating the area near the well, or injecting carbon dioxide to replace methane in the hydrate. All these methods are still unacceptably expensive. In any case, humanity's quest for utilizing these resources will be answered in the future. The structure of sales gas production will shift towards gas hydrates development, and the gas trunkline system, in this case it is likely to be maritime LNG transport, will be tied to the point of its production facilities.

With potential changes in sources of sales gas supply due to depletion of the old fields and the need to access new ones, gas trunkline systems as well will undergo structural transformations. Individual gas trunklines tied to specific depleted fields will lose their relevance. One will have to build new gas trunklines tied specifically to new sources. Apparently, gas trunkline systems tied to regasification terminals and associated with LNG transportation via waterways will be developing at a faster pace. These terminals serve as gas suppliers to the gas pipeline network regardless of changes in gas production locations.

At the level of mini-systems of gas supply to the consumers, the GSS will change structurally in line with the scientific and engineering progress at the gas consumers side. Thus, as the share of NGV fuel use in transport increases, the networks of liquefied and compressed natural gas refueling will increase. Such refueling stations are adapted to the transport infrastructure and can be built at considerable distances from the gas transmission networks. Accordingly, the structure of discrete (road, railway, and water) transport of both LNG and compressed natural gas (CNG) will be developing at a faster pace as the number of such refueling stations grows.

Micro-systems of gas supply are unlikely to undergo drastic structural changes in the future. In all likelihood, they will be the same pipeline distribution across buildings, enterprises, and facilities using innovative intelligent shut-off and control gas pipeline valves with the incorporations of various levels of smart systems to control the energy consumption of the respective consumers.

III. Transformation of energy systems properties under the impact of technology innovations

A. Electric power systems

Recently, due to the broader adoption of generating units running on renewable energy resources, that are characterized by unsteady power output, and increased activity on the part consumers to control their own electricity consumption in real-time, the uncertainty of the current operation mode of the EPS has increased significantly, which encouraged the study of the flexibility of the EPS and justification of the means to increase it. The flexibility of the EPS is a relatively new concept characterizing its ability to maintain the normal or close to normal state under the influence of internal (sudden changes and fluctuations of generation and load, flows along lines) and external (random disturbances) random (uncertain) factors [13].

Modern EPSs while utilizing conventional energy and electrical power engineering technologies and control systems possess a sufficiently high level of flexibility due to the presence of self-adaptation and self-stabilization properties in relation to internal and external destabilizing factors. The above properties of the EPS are determined by the action of voltage/frequency governing effects of load, frequency characteristics of generators, as well as the inertia of rotating masses of rotors of synchronous and asynchronous machines, and the action of regulation and automation systems. Due to the presence of these properties, EPSs adapt to abrupt operation mode changes set within permissible limits, and when the operation mode parameters exceed permissible limits, the emergency control system comes into operation.

Electric power systems of the 21st century are undergoing significant changes in their properties not only due to the transformation of their structure but also due to the use of technology innovations in production, transport, storage, distribution, and consumption of the electric power. The factors internal to the EPS that significantly reduce the ability of systems to self-adaptation and self-stabilization are related to the mass use of power electronics and rectifier and inverter units for communication with the EPS of high-speed gas turbine and gas-reciprocating generators, wind turbines, photovoltaic units, electric energy storage, and frequency-controlled load motors.

The growth in the scale of the use of these technologies at the levels of super-systems and mini-systems significantly reduces the ability of the EPS to self-adapt and self-stabilize and, as a result, reduces the level of its flexibility. On the other hand, the growth of the share of randomly fluctuating generation on renewable energy resources (wind turbines,

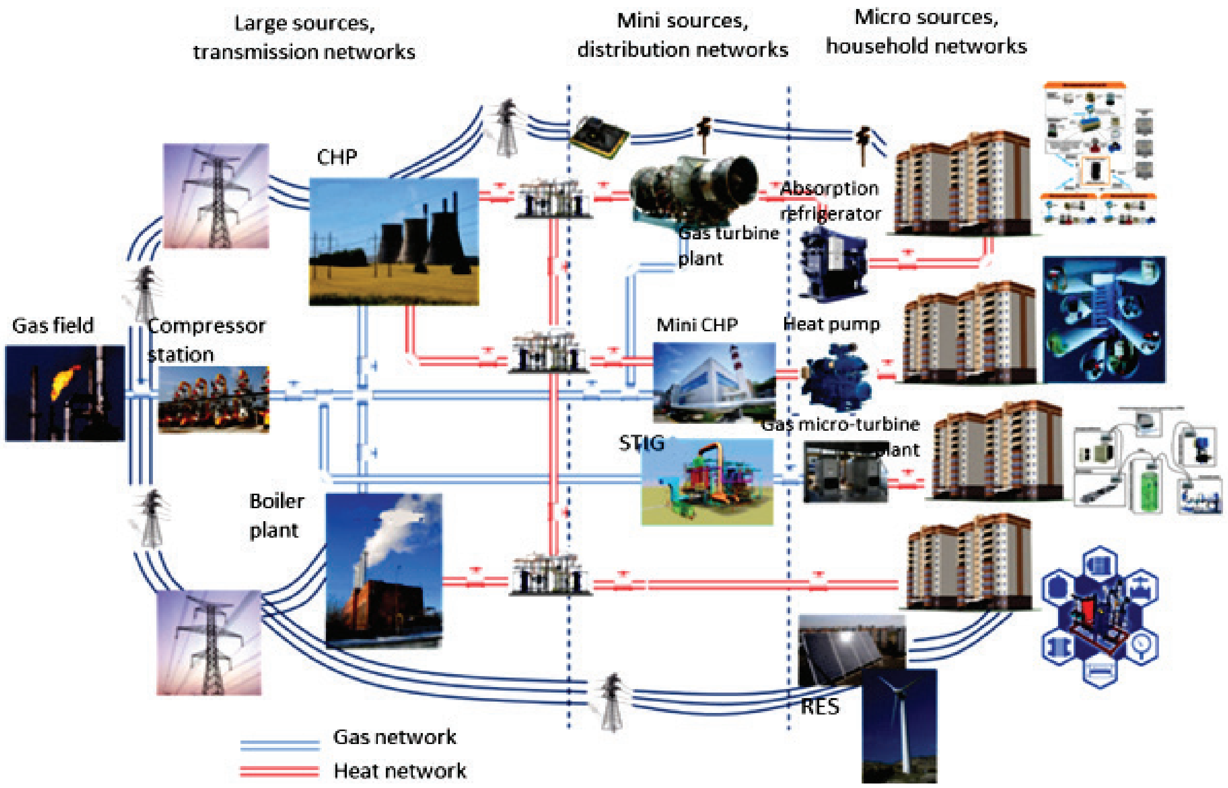

Fig. 8. Integrated energy systems.

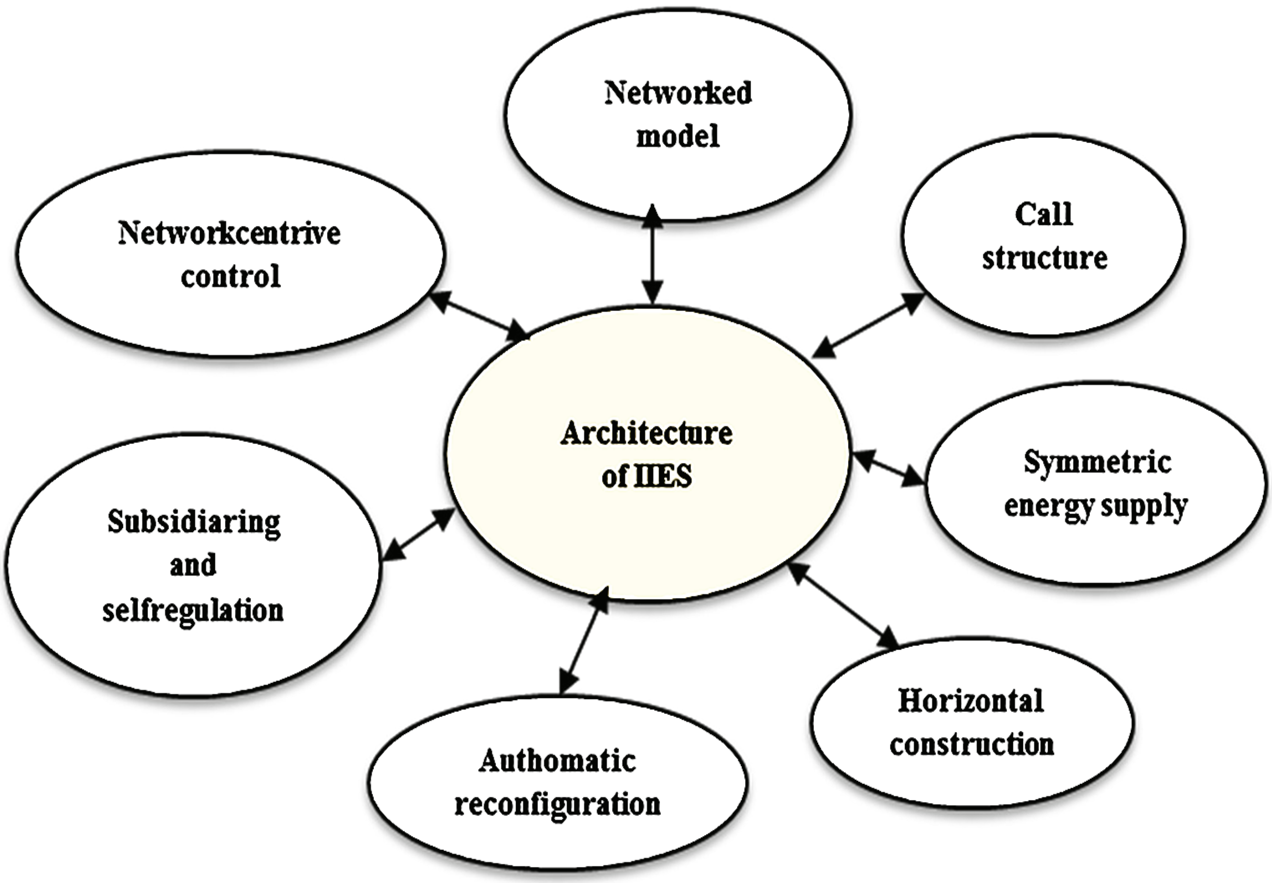

Fig. 9. Architecture of integrated intelligent energy systems.

photovoltaic panels, small HPPs) also leads to a decrease in the flexibility of the EPS. At the same time, the control systems of many devices using power electronics (FACTS, energy storage, DC lines and links) have high efficiency of control and stabilization. Their wide adoption in future EPSs will ensure a drastic increase in controllability and, consequently, in flexibility of these systems.

In general, there are numerous possibilities for future EPSs to ensure their flexibility and to choose reasonable means for this purpose: this is a far from easy problem than can be solved for standard conditions of operation and development of these systems [13]. At the same time, the relevance of studies of off-standard (extreme) conditions under the impact of corresponding external and internal factors that require careful consideration increases. These factors are associated with the notion of EPS survivability [13], and recently with the closely related property of resiliency, which is considered in relation to large-scale disturbances and cascade accidents in EPSs [14, etc.]. To counteract such complex emergencies, the emergency control and protection system is available and is being developed, including effective procedures for restoring EPSs. An important role is relegated to regular dispatcher training sessions, as well as analysis and generalization of the nature and mechanisms of occurrence and development of such unique accidents.

B. Heating systems

Heating systems starting from the end of the 19th century to the present day have undergone the transformation in four generations. Heating in Russia is now at the stage of the transition from second- to third-generation systems, although European countries are already at the stage of development of systems of the fourth generation.

In order for domestic heating systems to level up, it is necessary to move from a single-loop system to a two- or three-loop system with individual intelligent heat consumption systems.

This will allow changing the technology of systems operation by advancing to the regulation of heating to consumers in real-time, which will complement the energy-consuming centralized regulation with local and individual settings and will provide an opportunity to strengthen existing and implementing new properties such as flexibility (adaptation to the current level of energy consumption); customer-centricity (the ability of the system to respond to consumer demands); integration (integration into the urban infrastructure); efficiency (compliance with energy efficiency requirements); competitiveness (economic advantage); reliability (meeting the growing energy demand, resistance to accidents), interoperability (the ability of subsystems and their elements to exchange energy and information so as to attain the maximum gains), etc.

Technological transformations of HSs will allow implementing other properties listed above that are typical also of electric power and gas supply systems and various types of their structures.

An important change in the properties of the energy systems under consideration is the transition from a unidirectional (from the source down to the consumer) scheme of movement of energy flows to a multidirectional one (i.e., with flows in multiple directions). This increases the mobility of HSs, their maneuverability, implements the bilateral nature of supply to consumers, significantly enhancing the property of reliability of heating, but at the same time, it gets way more difficult to control their development and operation. The transition from systems with high inertia of the process to flexible information-and-energy structures controlled in real-time seems to be the key for HSs, which provides them with quality performance of their functions with respect to heating provided to consumers while reducing energy and financial costs (see Fig.7).

C. Gas supply systems

Under the influence of technology innovations, the properties of GSSs are transformed at all levels considered herein, from fields and facilities of sales gas production to the processes of its use.

Thus, the concept of the intelligent gas field as a system of automatic control of gas production operations, which provides for automatic optimization of all the most important technological processes in their direct interrelationships, is already beginning to be implemented in practice. The pros of the introduction of this concept are expressed in the emergence of a new property of facilities and the system as a whole, that of a possibility of remote control. It also provides opportunities to monitor energy consumption, improve the efficiency of equipment operation and deliverability of wells through the monitoring and regulation of well yields, the prediction parameters of well exhaustion based on machine learning methods, forecasting of the behavior of new wells, centralized control of a large number of wells through remote monitoring systems, rational personnel management, and transparency of information.

As for improving the reliability of the operation of the line pipe section of the GSS, the so-called "intelligent tie-ins" or remote monitoring system for the strain-stress state of pipelines are already being adopted at newly constructed and reconstructed gas trunklines. Such systems are tied into the gas pipeline and allow monitoring mechanical loads by comparing them against current strength characteristics of the pipe. Their use proves feasible both in the gas trunklines themselves and in the piping of compressor and gas distribution stations, etc. Incidentally, cathodic protection parameters of gas pipelines are also monitored.

Such a concept can be applied to the full extent, with consideration of the respective differences, at all levels of the GSS. As a result of all these innovations, individual elements of the system and the entire GSS system as a whole have significantly increased their reliability. It is achieved by means of receiving reliable information on the state of elements of the system, arriving at optimum parameters of their operation and systems of protection against negative influences (galvanic corrosion, etc.), and also the possibility of timely decision-making when it is required to take preventive measures on maintenance of the pre-defined level of operability of the GSS.

All that having been said, at the micro-level, novel technologies will also have a positive impact on the energy efficiency of consumer processes, incorporating them into a common friendly interface between gas suppliers and consumers, within the framework of intelligent energy consumption processes, both for process and domestic needs.

IV. Integrated cyber-physical energy systems of the future

A. Integrated intelligent energy systems

The current objectively observable trends in the development of energy infrastructural systems are characterized by their tighter integration at the levels of production and consumption of energy and energy resources (see Fig.8) [1, etc.]. The processes of integration of electric power, heating, and gas supply systems into a meta-system increase its level of integrity and organization while contributing to the higher volume and intensity of relationships and interactions between individual systems. As a result, a high level of comfort in residential, public, and production buildings is achieved, including quantitative and qualitative growth of the array of energy services (related to electric power, heating, and gas supply) at an affordable price; ensuring controllability, reliability, safety, and efficiency of energy systems; reducing their negative impact on the environment, including greenhouse gas emissions. Combining multiple energy systems into a single energy and process meta-system with a common coordinated control system yields a synergistic effect in many aspects.

An integral property of such an integrated meta-system is its intelligent nature. It is based on the agent-based paradigm: each consumer, receiving information through its intelligent agents about all other participants in the energy supply process, determines its own behavior.

The technology of intelligent meta-system operation is also getting new. Due to the complex structure, possible conflicts, and competition in this meta-system, the classic hierarchical principle of integrated energy systems control fails to deliver on the targets they share. The new system design should combine certain independence of multiple decision-making centers and their coordination in ensuring reliable energy supply to consumers. It should be based on the principles of subsidiarity (ability to delegate control functions to the system levels remote from the center) and self-regulation, according to which control is implemented from the inside instead of by acting on the controlled system from the outside. The implementation of this principle presupposes arranging the interaction of agents with each other, which results in the introduction of internal control factors. At the same time, the systems have their own control, goals, and tasks and operate relatively independently, coordinating themselves with other systems by pursuing a common target.

These provisions predetermine a network model of relationships, based on the principle of complementarity, where the actions of one participant in achieving their tasks simultaneously contribute to achieving certain tasks of other participants. The architecture of integrated intelligent energy systems is shown in Fig.9. The network organization is a principle of higher order in comparison with the existing hierarchical subordinate structure of energy systems control.

As a result of the integration of energy systems into a higher level meta-system, the old properties get enhanced, while the new ones manifest themselves, among which the most significant are: flexibility; intelligent nature; integration; efficiency; competitiveness; reliability; complementarity in the performance of a shared task; unity of principles of organization and operation, and independence in the implementation of local functions. This generates new tasks for the management and control of integrated intelligent infrastructure systems of the energy industry.

B. Cyber-physical energy systems of the future

Modern energy infrastructure systems (EPS, HS, and GSS) are the entities of utmost complexity in terms of their structure operation, with each of them being made up of two closely interconnected subsystems: physical (process) and information-and-communication (ICS) subsystems. Already at present, and even more so in the future, the process and information-and-communication subsystems are getting comparable in complexity and responsibility in terms of ensuring the normal operation of each of these subsystems.

Currently, the digitalization of the above integrated intelligent infrastructure systems of the energy sector is being actively carried out. It implies not only the acceleration of information processing in digital form but also an increase in the efficiency of technological processes in energy systems due to optimal intelligent control of processes. These, as well as the noted factors of ICS complexity and responsibility, predetermine the necessity to treat EPSs, HSs, and GSSs as complex cyber-physical systems [15, etc.].

Within such systems, the ICS can operate inadequately due to internal defects (errors in algorithms, etc.) and can also be exposed to unauthorized external impacts (cyber attacks) [16, etc.]. Taking into account internal and, especially, external factors (cyber attacks) the problem of cybersecurity becomes urgent [17, etc.].

Reliability of information on the current state of the energy system or its loss due to internal defects of digital devices or external cyber attacks on the ICS may be the reason for working out and implementing incorrect control actions and unfolding of the emergency process in the physical subsystem. In turn, a failure or accident of an element in a physical subsystem may not only cause an emergency in that subsystem but may also contribute to the failure of the ICS elements. Taking into account these interrelationships, the integration of physical and information-and-communication factors should be implemented at the level of substantiation of the development of cyber-physical energy systems, as well as in solving various problems of controlling their operation modes.

Thus, for the present, and even more so for the future, cyber-physical energy systems, the scope of factors that largely determine the transformation of the structure and properties of energy systems and form a list of relevant problems for research and ensuring the flexibility and survivability (resiliency) of these systems is drastically expanding.

V. Directions of control systems development for integrated energy systems

A. Electric power systems

The presented analysis of the transformation of the structure and properties of future EPSs testifies to the key role of control in ensuring the normal operation of these cyber-physical systems. Taking into account the growing complexity of processes that take place in EPSs, control systems should match them in their developments. Forecasts that deal with this direction indicate that future EPS control systems should have a hierarchical structure [18, etc.]. To counteract the development of cascade accidents, the need for coordinated hierarchical control is discussed. The important role of artificial intelligence methods in improving control efficiency is formulated. The ideology of Wide Area Monitoring, Protection, and Control Systems based on vector measurements with the prediction of state variables to ensure adaptive control is developed. It is typical for electricity storage devices, FACTS devices, etc. for control purposes.

In the above plan, the currently operating and developing highly efficient system of automatic emergency control of EPSs of Russia including the key hierarchical subsystem of adaptive emergency control automatics [19, etc.] should be represented. The lower level covers microprocessor-based automatic devices that implement specific control actions, which are cyclically adjusted at the upper level, thus providing adaptive control. The multi-tier principle of automatics operation is realized: if at the first stage automatics failed to ensure maintaining of stability of the EPS, the next group of automatic devices counteracting the cascade development of accident comes into operation.

The above tenets of the transformation of EPS control systems are mainly related to the level of super-systems and can be considered as a baseline for mini-systems. The ideology of control systems of micro-systems on a multi-agent basis with the aid of consensus control algorithms when using appropriate protocols of the interaction of agents in the process of control is actively developed [20, etc.].

B. Heating systems

The fundamental thesis for HSs that is implemented as a result of their technological transformation, is the transition from a qualitative method of regulation of heat supply to a quantitative method of its supply. This radically changes the organization of systems and the principles of control of their thermal and hydraulic modes. The availability of automatic equipment, intelligent systems, and the horizontally-organized control structure ensures the control of heating in accordance with the needs, increases the efficiency of HSs while improving the quality of performing their functions.

Consumers are increasingly beginning to exercise active load control functions. They assume a part of the tasks aimed at creating comfortable conditions delegated to them by centralized control structures. Active consumers not only manage their power consumption mode but also influence the operation of the HS as a whole. If they have their own heat source, they can provide heat not only to meet their own heat needs but also to meet the demand for heat by neighboring consumers. The presence of such consumers in the HS expands the functionality of the systems, creates the necessary conditions for controlling the reliability of their heating, and enhances resiliency.

For many years, computational and optimization computer models have been and continue to be used to control the development and operation of HSs, as well as other energy systems. With the development of information and hardware technologies as well as methods of computational mathematics, they were transformed into their digital doubles with a wider range of information and intellectual resources. They represent digital models of the interconnected elements of the HS and are used for remote information acquisition, its processing, and control of operation modes of heat sources, heating networks, and ensuring heat load profiles of consumers with automatic monitoring and maintenance of comfortable indoor temperature. At the same time, there are new opportunities emerging for controlling heating systems, improving efficiency, timely identification and localization of damage locations in visually unobservable heat networks distributed over a large area, assessment of causes of excess heat losses, prioritization within repair schedules, etc.

Many energy companies, such as Gazprom Energoholding, are already implementing services of online applications for contracts, exchange of billing documents, and online payment for consumed heat. The automated system of heat energy metering is being implemented, which allows automatic collecting and storing the readings coming from the metering units, as required for analysis and monitoring of heating parameters. Their processing, digital structural representation for integration into automated complexes of dispatching control of systems operation is being carried out.

C. Gas supply systems

Just like with electric power systems, in connection with the global intellectualization of the GSS, there are certain fears associated with the increased vulnerability of the system given the negative impact of the intellectual nature of cyber attacks. In this case, the task of reducing GSS vulnerability should be solved simultaneously with the growth of the system's intellectualization. This can be done from the standpoint of the developing information technology and administration of the corresponding systems, as well as from the perspective of improving the optimality of dispatch control in the event of emergencies of various nature. One should provide for the possibility of switching over individual process operations and logical chains thereof to the "manual" control mode with the return back to the mode of the interconnected intellectual operation following the elimination of possibilities of threat realization.

Intelligent dispatching control systems of the GSS should have a hierarchical structure with independent modules of individual facilities and subsystems, linked into a single control system. At the super-system level, dispatching of strategic processes in each element and the GSS as a whole is implemented, starting from the main compressor stations at the field outlets and down to the points of its delivery to gas distribution stations and units, natural gas liquefaction plants with the corresponding infrastructure, gas carriers, and regasification terminals.

The same control ideology should apply to the level of gas distribution systems (the level of mini-systems in the GSS). As for the operation of gas supply systems inside buildings, structures, industrial enterprises of different levels, the control systems of the micro-level GSS fit nicely into the ideology of intelligent systems of "smart" houses and enterprises that are nowadays being developed and put into operation. Gas supply control systems of this level of the GSS will be actively developed inseparably from the directions and rates of intellectualization of control of internal utility systems of buildings and structures in direct connection with unified dispatching centers of the mini-systems level.

Conclusion

The development of infrastructure energy systems on the basis of technology innovations in physical and information-and-communication subsystems under digitalization and intellectualization of operation processes will lead to the decisive transformation of the structure and properties of these systems. As a result, future energy systems will take the form of elaborate intelligent cyber-physical systems, radically different from the systems of today. This transformation will require a significant reconsideration of the existing principles and methods of modeling such systems, analysis of their new properties, justification of their development and control of their operation. The basis of new methods and models, along with the traditional ones, should become the proven-to-be-effective apparatus of artificial intelligence. The key role in ensuring the normal operation of the transforming energy systems will be played by future control systems, the ideology behind construction and operation of which should be ahead of the needs of the transforming cyber-physical systems.

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Prospective Electric Power Cooperation among Northeast Asian Countries in the Context of Carbon Tax

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***Abstract* — The paper addresses the prospects for power grid formation in Northeast Asia in terms of carbon dioxide emissions. Carbon dioxide tax is implemented as a tool to quantitatively engage environmental issues in the study. A survey of the studies on the prospective NEA power grid has been done. The research employs a methodology and a mathematical model for the optimization of power system expansion and economic dispatching of power plants. Environmentally friendly scenarios of the NEA power grid were built and studied.**

***Index Terms*: Northeast Asia, electric power cooperation, interstate electric tie and grid, interconnection, system effects, economic effectiveness.**

I. Introduction

Interstate electric power cooperation started as a process of creating interstate electric ties (ISETs) and shaping interstate power grids (ISPGs) at the beginning of the last century with the advent of the first ISETs in Western Europe and North America. Since then, this process has become a global trend covering all regions of the world and continents.

The driving forces of this trend are the benefits to be achieved as a result of electric power cooperation, such as a) reduction in the need for the installed generating capacities due to the time difference in load maxima (both daily and annual) in different countries and regions; b) improvement in the reliability of the interconnected electric power systems (EPSs); c) large-scale integration of renewable (hydraulic, wind, solar, tidal) energy sources in the interconnected EPSs of different countries; d) expansion of electricity markets and intensification of electricity trade between countries; e) income generation from extended electricity trade within the interstate electricity markets; and others. [1].

The trend has also been persistent in the Asian region, although to a varying extent in different subregions, including Central, South, Southeast, and Northeast Asia (NEA). The power grid of Central Asia was mainly formed as part of the Unified power system of the Soviet Union. Now it is functioning as a separate and independent entity expanding inner and outer ISETs. The Southeast power grid is extensively developing with the support of ASEAN (Association of Southeast Asian Nations) countries getting benefits from electric power cooperation. The countries involved in the South power grid (backed by SAARC – South Asian Association for Regional Cooperation) build ISETs facilitating electricity cooperation within the subregion for mutual benefits. NEA lags behind the process of power cooperation mainly for political reasons. The current electricity exchange in the NEA subregion is insignificant, but the studies prove considerable potential benefits from the ISETs and subregional grid formation [1-5, and others].

II. Studies of potential NEA power system interconnections

Initially, power system interconnection in NEA was considered and studied as bilateral, maximum, trilateral projects of ISETs connecting EPSs of two or three countries for a joint operation to gain the benefits of systems integration. These are the projects of ISETs 'Russia–Democratic People's Republic of Korea (DPRK)–Republic of Korea (RoK)', 'Russia–North China', and others [1,6,7, a.o.]. It is worth noting that until recently, none of the studies on the ISETs in NEA has considered the formation of a single Northeast Asian interstate power grid. Currently, the studies have advanced to the level of the interstate power interconnection of the entire NEA subregion. Some of those carried out to date are presented in [3,4,8-14]. The studies discussed in [3,4,8,13,14] are distinguished from

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those noted above by the extensive mathematical modeling and the application of optimization models to shape the prospective NEA-wide power grid. They will concisely be considered below.

A comprehensive assessment of the system effectiveness of the entire NEA interstate power grid was made in [3]. The study quantitatively investigated the economic viability of power grid interconnections in NEA and renewable energy developments in the Gobi Desert and Eastern Russia. The investigations focused on different Scenarios of the NEA power system interconnection for the target year 2030, including the absence of the interconnection and the Gobitec project. The Scenarios were found to be economically and environmentally feasible. The results show rather modest benefits in lowering the total cost because of the large investments needed to develop the renewables and the transmission lines.

A Scenario with the generation based solely on renewable energy sources (RES) in the NEA grid is studied in [4]. The study states that the existing RES technologies can generate enough energy to cover all electricity demand of NEA for the year 2030 at a lower price compared to non-renewable options. The high voltage direct current (HVDC) transmission infrastructure plays a key role since the established Super Grid enables a significant cost decrease within the renewable resource-based power system. The use of HVDC transmission lines will reduce the employment of energy storage systems and significantly curtail generation capacities.

Our studies presented in [8,13,14] differ from other studies by the following: a) all countries in NEA subregion are considered, b) consumer loads and generating capacities are examined for all nodes (representing EPSs of the countries or their territories) of NEA interstate grid, c) the system benefits resulting from the interstate power grid establishment in NEA are assessed in detail, d) all participating countries share the system benefits. These studies show that the integration of the national power systems of NEA countries makes it possible to obtain substantial system benefits. Ramified bulk power interstate transmission infrastructure is to be developed in the subregion to attain the noted benefits through intensive electricity trading. The findings indicate that all the countries involved receive benefits from joining the interstate power grid in NEA. Thus, the grid is economically feasible for each participating country.

III. The generalized methodology

The study relied on a special optimization mathematical model. It optimizes the expansion of installed generating and transmitting capacities and their economic dispatching within electric power systems and the interconnected grid. Technical features of EPSs are presented in the model in detail as a set of specific constraints and balance equations. The model was presented in [1,13] and elsewhere, which is why it is not described here in detail.

The methodology involves complex optimization studies for the no-ISPG Scenario (Scenario 1) and the ISPG Scenario (Scenario 2) using the above mathematical model. The objective function of the model is the annualized cost for all interconnected power systems, which is minimized for both Scenarios:

$$Z_{sep}(X) \to \min, \quad Z_{inter}(X) \to \min, \tag{1}$$

where $Z_{sep}(X)$ is the objective function of the model for Scenario 1; $Z_{inter}(X)$ is the objective function of the model for Scenario 2; X is a vector of the model variables, including actual hourly power and installed capacity of power plants of different types (thermal power plants (TPPs) based on steam turbine, gas turbine, combined cycle, including cogeneration; nuclear power plants; hydroelectric and pumped storage power plants) using different types of organic fuel (coal, gas, oil), transfer capabilities of electric tie lines and hourly power flow via them.

The resulting optimal values of the objective function from expression 1 are compared with each other: $Z_{sep}(X) \gtrless Z_{inter}(X)$. If the cost in Scenario 2 is lower than in Scenario 1: $Z_{sep}(X) > Z_{inter}(X)$, the ISPG is effective; otherwise, it is not. The economic effect of the power interconnection is defined as the difference in costs (values of the objective function) for Scenarios 1 and 2:

$$\pm \mathrm{E} = Z_{sep}(X) - Z_{inter}(X). \tag{2}$$

If the power system interconnection is effective, the effect will be positive, otherwise, it will be negative (i.e., there will be losses due to the formation of the power system interconnection). This effect is composite. It includes the system effects obtained through the ISPG formation, including capacity and fuel-saving effects.

IV. Assumptions and scenarios

The study presented in the paper is a continuation of our previous investigations [8,13,14]. It differs from the previous ones in the following:

a). a new target year was assumed;
b). Northwest China electric power system (EPS) was considered as a new node connected to the node of North-Central-East China EPS and through this node connected to other Chinese and NEA grids;
c). electric power and economic indices for calculations were adjusted according to the new target year, and
d). carbon dioxide (CO2) tax on electricity generation from fossil fuel thermal power plants was taken into account in the environmental Scenarios of the research.

The following Scenarios for the studied NEA power system interconnection were built considering the influencing factors and conditions: 1) without interstate NEA grid; 2) with interstate NEA grid; 3) without interstate NEA grid, with CO_2 tax 1; 4) with interstate NEA grid, with CO_2 tax 1; 5) without interstate NEA grid, with CO_2 tax 2; 6) with interstate NEA grid, with CO_2 tax 2. Tax 1 in

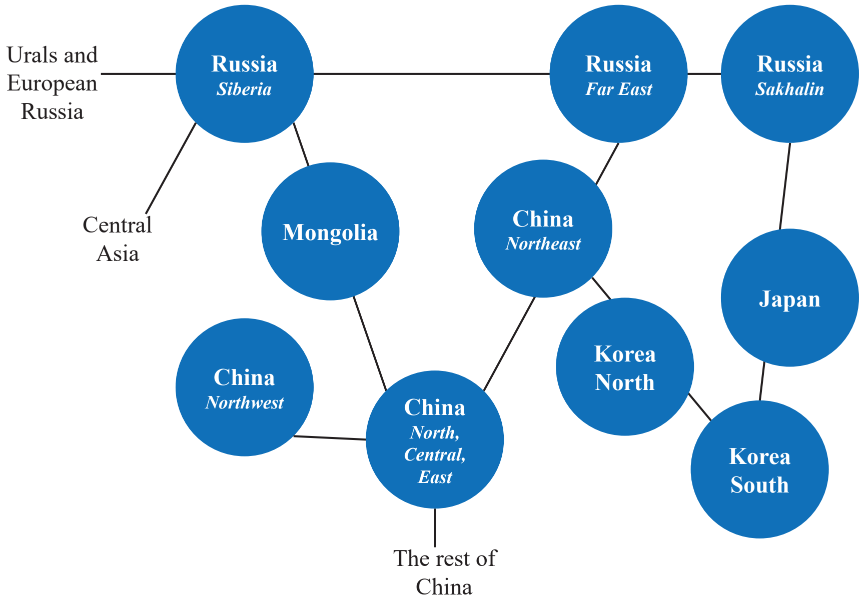

Fig. 1. Diagram of the interstate power grid in NEA.

Scenarios 3 and 4 differs from tax 2 in Scenarios 5 and 6 (see the next Section for detail).

The target year assumed for the study was 2040.

Figure 1 presents a diagram (a set of nodes standing for national or regional EPSs and electric ties) of the potential interstate power interconnection in NEA, which is represented by ten nodes, including three nodes in the territory of Russia (EPS of Siberia, EPS of the Far East and EPS of Sakhalin), and three more nodes in China (EPS of North-Central-East China, EPS of Northeast China and EPS of Northwest China). EPSs of other countries are represented by one node in the diagram.

V. Input data

Input data for the research were taken from the reports and studies made by international, governmental, and scientific organizations of the considered East Asian countries [14-17, and others]. Prospective demand for electricity in the NEA countries was assumed to grow according to business-as-usual national scenarios [16]. Main economic and some technical input data for the model are presented in Tables 1-3. Table 2 presents fuel costs given in ranges for different power plants located in various territories of a country or having different generating technologies but using the same fuel.

The ISETs to be installed are HVDC ±800 kV transmission lines and submarine cables. The cables are needed to cross the sea straits (between mainland and Japan, mainland and Sakhalin, Sakhalin and Hokkaido). The ISET costs in Table 3 were calculated considering a particular route length, transfer capability, and others.

Wind and solar renewable power facilities are assumed in the study for the target year according to the national power strategies and are not optimized in the model.

Table 1. Capital investment in power plants, usd/kw.

	Hydro	Pumped storage	Thermal			Nuclear
			Coal	Gas	Fuel oil	
Russia (Siberia, Far East, Sakhalin)	3000	-	2000	1200	-	2800
Mongolia	3200	1000	1300	-	-	-
China (North, Northeast, Northwest)	2500	1000	800	-	-	2500
RoK	2500	1200	1500	850	1900	2500
DPRK	2500	-	2000	1200	1500	-
Japan	6000	2400	2500	1250	1900	4000

Table 2. Fuel costs, usd/mwh.

	Thermal			Nuclear
	Coal	Gas	Fuel oil	
Russia (Siberia, Far East, Sakhalin)	15-23	16-35	-	5
Mongolia	22-24	-	-	-
China (North, Northeast, Northwest)	22-24	41	-	9
RoK	32-33	69-72	249	8
DPRK	25	52	110	-
Japan	32-33	71-73	249	9

Table 3. Technical and economic indices of electric ties.

Tie lines	Siberia – Mongolia	Mongolia – North-Central- East China	Russian Far East – Northeast China	Russian Far East – DPRK	DPRK – RoK	RoK – Japan	Northeast China – DPRK	Russian Far East (mainland) – Sakhalin	Sakhalin – Japan
Capital investment in ISETs [USD/kW of transfer capability]	420	260	270	480	180	950	180	550	900
Transmission losses [%]	5.0	5.6	4.9	7.1	1.0	3.7	1.8	3.4	4.6

In the context of the expected uncertainty, carbon tax was represented in the study by two options – USD 40 (tax 1) and USD 60 (tax 2) per ton [18, 19].

VI. The results and discussions

Figure 2 demonstrates the substantial benefits of Scenarios 2, 4, and 6 of the interstate grid in NEA (compared to Scenarios 1, 3, and 5 of separate operation of the national EPSs in NEA). The benefits indicate the feasibility of the interstate power grid in NEA. The estimations of the interstate power grid in NEA show a 60-64 GW reduction in the total number of generating capacities to be added in the NEA countries, with China being the major beneficiary. Annual cost saving is calculated to be USD 17-20 billion. Fuel cost saving is about USD 9-15 billion a year. Japan and RoK gain a greater share of this saving. A significant variation in the fuel benefit by Scenario is due to the consideration of CO_2 tax. As seen in Figure 2, the fuel benefit rises with tax growth. The highest fuel benefit (USD 14.9 billion) corresponds to the highest accepted tax value (USD 60/ton of CO2) because the tax was transformed to and included in the fuel cost. The investment benefit, however, decreases with the tax rise, which is due to the replacement of fossil fuel TPPs by capital-intensive nuclear and hydropower plants under the CO_2 emission tax imposed.

Figure 3 confirms and clarifies the above statement about the replacement of fossil fuel TPPs by carbon-free and low-carbon generation when CO2 tax is imposed. The Figure indicates that the considerable decrease in power generation by coal-fired TPPs in Scenario 4 (with the interstate NEA grid and USD 40 tax) versus Scenario 2 is offset by carbon-free generation and gas-fired generation with low-carbon emissions. The tax growth up to USD 60 (Scenario 6) further suppresses the coal-fired TPPs generation, but nuclear and renewable capacities do not

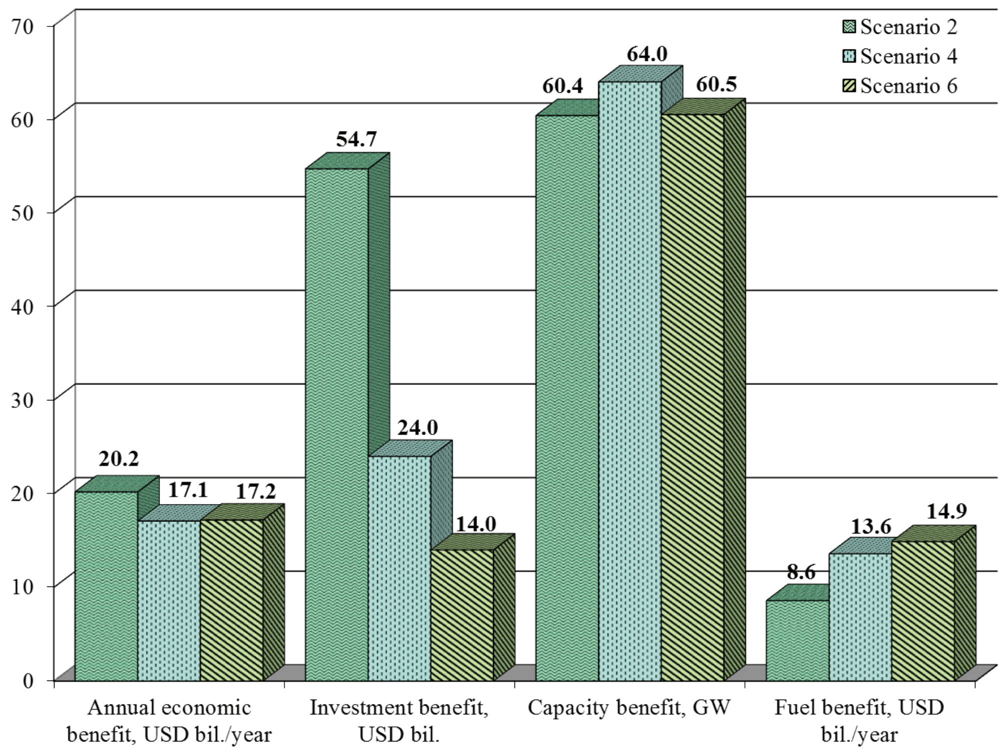

Fig. 2. System benefits of the interstate NEA grid.

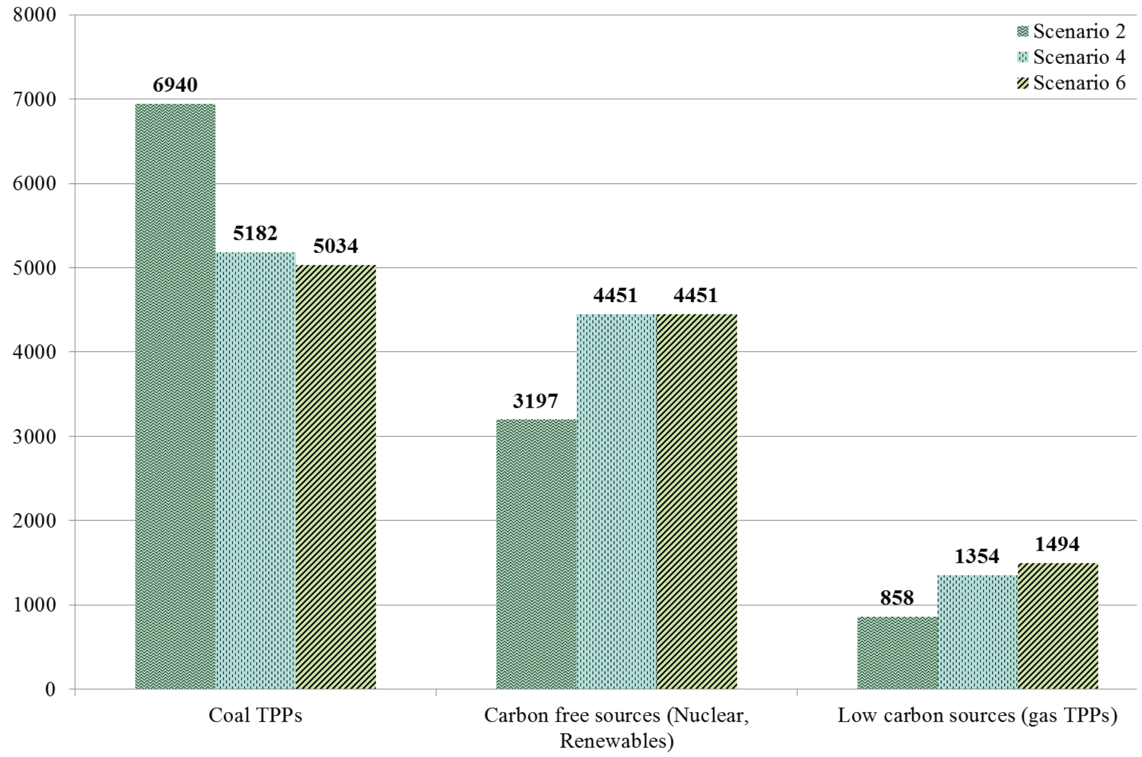

Fig. 3. Power generation by type of power plant [TWh/year].

respond because nuclear installed capacity reaches its expansion limits (constraints) and renewable installed capacity, as was noted, is assumed to be fixed. Instead, low-carbon sources such as gas-fired TPPs appear and increase their power output.

Power generation from coal-fired TPPs in Scenarios with CO_2 tax decreases mainly in China (up to about 40% in Scenario 6) and partly in RoK and Japan. The growth of power generation substitution is mostly provided by nuclear generation from China and partly from RoK and Russia. Following the noted change in the power generation mix, the prospective installed capacity mix and

capacity additions in the potential NEA grid and national EPSs also change. Thus, the coal-fired capacity additions in China in Scenario with the maximum tax are about half of those in Scenario with no CO_2 emission tax. Moreover, there is a concurrent six-fold increase in the nuclear capacity additions in this country.

The integration benefits in the NEA grid are accompanied by a considerable electricity exchange among all its participants. The potential power exchange (totally export and import) among NEA countries is estimated at nearly 700 TWh annually in the target year in Scenario 2 with no CO2 emission tax. In Scenario 6, with the maximum tax, power exchange varies insignificantly. Thus, the CO2 emission tax strongly affects mixes of power generation and capacity additions in contrast to power exchange among NEA countries.

There is a considerable power flow from China across the Korean peninsula to Japan, which is complemented by the flow along the northern route from the Russian Far East. The countries of the Korean peninsula play mainly the role of transmitters. Japan's energy security requirement in terms of the permissible power import is not violated. Russia and China (through Mongolia), and Russia and the countries of the Korean peninsula participate in the mutual power exchanges, thus gaining the system integration benefits from the interstate grid in NEA.

The total transfer capability of ISETs in the NEA interstate grid is maximum for Scenario 2 with no tax, and it is estimated to be about 83 GW. Although the transfer capability somewhat declines (by 6%) in Scenario 6 with the maximum tax, it remains considerable. The most powerful (14-15 GW) electric ties appear between North-Central-East China and Russian Siberia (through Mongolia), Northeast China and DPRK, DPRK and RoK, RoK and Japan.

Development of ISETs between national EPSs in the NEA countries, which have different mixes of generating capacities, daily and yearly load curves and load peaks, and renewable energy sources, results in their close relations and interdependence, and finally shapes the interstate NEA grid.

VII. Summary

The potential interconnection of power systems in the NEA subregion can be expected to bring about significant benefits for participant countries, including savings of installed capacity, investment, fuel cost, and total annual cost. To gain the benefits, it is necessary to establish a powerful transmission infrastructure in the NEA subregion.

The introduction of CO_2 emission tax in NEA countries can substantially change mixes of installed capacity and power generation in favor of carbon-free and low-carbon electricity sources. However, the imposition of the tax will have little impact on potential electricity exchanges among the NEA countries, although the transfer capabilities of prospective ISETs will somewhat change.

Acknowledgment

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The Geometry of Power Systems Steady-State Equations– Part I: Power Surface

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***Abstract* — Steady-state equations play a fundamental role in the theory of power systems and computation practice. These equations are directly or mediately used almost in all areas of the power system state theory, constituting its basis. This two-part study deals with a geometrical interpretation of steady-state solutions in a power space. Part I considers steady states of the power system as a surface in the power space. A power flow feasibility region is shown to be widely used in power system theories. This region is a projection of this surface along the axis of a slack bus active power onto a subspace of other buses power. The findings have revealed that the obtained power flow feasibility regions, as well as marginal states of the power system, depend on a slack bus location. Part II is devoted to an analytical study of the power surface of power system steady states.**

***Index Terms*: feasibility region, Jacobian, marginal state, power flow, power surface, power system, slack bus, steady state.**

I. Introduction

STEADY-state calculations play a crucial part in the analysis, planning, and control of power systems. The majority of research papers published thus far focus on the development of numerical methods, which are fairly completely reviewed in [1] and [2]. At the same time, an analytical investigation and understanding of the steady-state equations are essential since they provide qualitative insights [3].

Initially, a steady-state solution space was examined for lossless power systems with *PV*-buses only. The authors of [4] indicate that the steady-state solution space is bounded by the power flow feasibility region in the parametric space; and that a steady-state solution may be non-unique, i.e., there can be several solutions, in some of which power circulates in one or more loops of the network. Using Hamiltonian formulation, the authors of [5] show that stable power flows are not necessarily unique either. A study of topological properties of the stable region [6] reveals that in such cases, the stable region is disconnected. The author of [7] uses Hamiltonian formulation to investigate the number of steady-state solutions, topological properties of stationary points, and features of a stable region for a 3-bus radial system.

Explorations of steady-state solution space for lossy power systems were usually confined to computational studies. The author of [8] has studied a limit on the existence of a steady-state solution of the 3-bus radial power system with *PV*-buses only. The influence the parameters of the system lines have on the power flow feasibility region was investigated in [9]. A computational study of the power flow feasibility region for a 3-bus radial power system with *PV*-buses only is presented in [10]. The author of [11] proposes using *L*-functions to study the power flow feasibility region, analytically shows, and computationally confirms that the power flow feasibility region can have a hole through it. An analytical framework is developed in [12] to describe the convexity properties of the power flow feasibility boundary in parametric space. In [13], the researchers propose a contour approach to the global analysis of power system performance, and in [14], a monogram method is developed to explore a solution boundary of the power flow problem.

It is noteworthy that the cited scientific studies, as well as others, tend to use geometrical images only to represent

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numerical results [15] or to explain the proposed approaches [17], [18], [16]. At the same time, the development of the bifurcation theory [19], singularity theory [20], and catastrophe theory [21], [22] shows that the geometric consideration provides qualitatively new results.

The objective of the present paper is to propose a geometric interpretation of a set of all the solutions to steady-state equations in a power space. The rest of the paper is organized as follows. Section II presents an analysis of specific properties of steady-state equations. Section III proposes and considers the geometric interpretation of the steady-state solutions, i.e., a power surface, and reveals its relation to the feasibility regions of power flow and marginal states of power systems. Section IV discusses the causes of the hole inside a power flow feasibility region. Section V geometrically justifies the slack bus application in steady-state calculations. Section VI presents the conclusions.

II. Specific Properties of a Steady-State Model

There are several steady-state models, each of which is based on the Kirchhoff laws, has certain advantages and shortcomings, and can be obtained from another one by a mathematical transformation. Therefore, qualitative results and conclusions obtained for the model of interest remain valid for all other steady-state models. Consider the nodal steady-state equations in polar coordinates:

$$\begin{aligned}\Delta P_k &= P_k + \sum_m V_k V_m \left|Y_{km}\right| \sin(\delta_{km} - \alpha_{km}) = 0;\\ \Delta Q_k &= Q_k - \sum_m V_k V_m \left|Y_{km}\right| \cos(\delta_{km} - \alpha_{km}) = 0,\end{aligned} \tag{1}$$

where P_k, Q_k, δ_k, V_k are active and reactive power, the voltage angle and magnitude at bus k, respectively; $Y_{km} = G_{km} + jB_{km}$ is an element of the bus admittance matrix; $\alpha_{km} = -\operatorname{arctg}(G_{km}/B_{km})$ is a loss angle; $\delta_{km} = \delta_k - \delta_m$.

The steady-state calculation involves solving the set of nonlinear simultaneous equations (1), under the assumption that the system parameters, i.e., bus admittance matrix elements, are known, and a steady state at each bus is determined by four parameters (variables) – P_k, Q_k, δ_k, and V_k. According to (1), each bus has two balance equations for active and reactive power. Therefore, to obtain a solution, two of four variables P_k, Q_k, δ_k, V_k, are to be specified at each bus. Therefore, the system of nonlinear equations (1) can be summed up as follows:

$$\Delta F(X, Y) = 0, \tag{2}$$

where $\Delta F(X,Y)$, and X, Y, are the vector of power mismatches and the vectors of dependent and independent (given) variables, respectively. Mathematically, there is no special way to determine the dependent and independent variables. Only the number of the dependent variables is given. In terms of the steady-state solution, the independent variables are those that can be controlled [2], for example, power injections and voltage magnitudes at the generation buses with automatic excitation control. Buses voltage are dependent variables obtained by solving (2).

Solving the system of nonlinear equations (2) can be considered as mapping the independent variables into a space of dependent variables $X = X(Y)$ [23]. According to the implicit function theorem [20], the necessary condition for the existence of such a map (as well as the solution existence) is the non-singularity of a matrix of first partial derivatives of the nonlinear equations set with respect to dependent variables $[\partial\Delta F/\partial X]$.

Consider a full matrix of first partial derivatives (Jacobian) of the nodal steady states equations with respect to the voltage angles and magnitudes:

$$[J_{\mathrm{F}}] = \begin{vmatrix} \partial\Delta P/\partial\delta & \partial\Delta P/\partial V \\ \partial\Delta Q/\partial\delta & \partial\Delta Q/\partial V \end{vmatrix}, \tag{3}$$

where

$$\begin{aligned}
\left(\frac{\partial\Delta P}{\partial\delta}\right)_{km} &= \begin{cases} -V_k V_m \left|Y_{km}\right| \cos(\delta_{km} - \alpha_{km}), & k \ne m;\\ \sum\limits_{m \ne k} V_k V_m \left|Y_{km}\right| \cos(\delta_{km} - \alpha_{km}), & k = m;\end{cases}\\
\left(\frac{\partial\Delta P}{\partial V}\right)_{km} &= \begin{cases} V_k \left|Y_{km}\right| \sin(\delta_{km} - \alpha_{km}), & k \ne m;\\ 2V_k G_{kk} + \sum\limits_{m \ne k} V_m \left|Y_{km}\right| \sin(\delta_{km} - \alpha_{km}), & k = m;\end{cases}\\
\left(\frac{\partial\Delta Q}{\partial\delta}\right)_{km} &= \begin{cases} -V_k V_m \left|Y_{km}\right| \sin(\delta_{km} - \alpha_{km}), & k \ne m;\\ \sum\limits_{m \ne k} V_k V_m \left|Y_{km}\right| \sin(\delta_{km} - \alpha_{km}), & k = m;\end{cases}\\
\left(\frac{\partial\Delta Q}{\partial V}\right)_{km} &= \begin{cases} -V_k \left|Y_{km}\right| \cos(\delta_{km} - \alpha_{km}), & k \ne m;\\ 2V_k B_{kk} - \sum\limits_{m \ne k} V_m \left|Y_{km}\right| \cos(\delta_{km} - \alpha_{km}), & k = m.\end{cases}
\end{aligned} \tag{4}$$

Equations (3)-(4) show that the diagonal elements of $[\partial\Delta P/\partial\delta]$ and $[\partial\Delta Q/\partial\delta]$ are equal to the sum of the non-diagonal row elements with an opposite sign. Therefore $[\partial\Delta P/\partial\delta]\, e = 0$, $[\partial\Delta Q/\partial\delta]\, e = 0$, where e is the vector of all ones. Hence the full Jacobian $[J_F]$ will be singular since $[J_F]\,[e^{\mathrm{T}}, 0^{\mathrm{T}}]^{\mathrm{T}} = [0^{\mathrm{T}}, 0^{\mathrm{T}}]^{\mathrm{T}}$.

This property of the full Jacobian (3) is a direct consequence of (1). Changes in every voltage angle by the same value does not influence its left-hand and right-hand sides. Therefore, system (1) has an infinite number of solutions. To specify a solution, it is necessary to set a reference point, i.e., the voltage angle of a bus should be considered as known, i.e., this voltage angle must be moved from dependent variables to independent ones. Such a bus is called the angle reference bus. Since the number of dependent variables is reduced by one, mathematically, the initial number of dependent variables should be restored. Due to the power system-specific features, the active power of a bus is assigned as a new dependent variable. This bus balances active power in the whole power system and is called a slack bus. The reference bus may be chosen arbitrarily. The slack bus is chosen based on the specific features of a power system.

In general, two other sub-matrices $[\partial\Delta P/\partial V]$ and $[\partial\Delta Q/\partial V]$ of the full Jacobian are not singular. However, if there are no shunts, transformer tap ratios, and phase shifters, their diagonal elements at the point of "flat start" are also equal to the sum of non-diagonal row elements with opposite sign, i.e., $[\partial\Delta P/\partial V]\ e = 0$, $[\partial\Delta Q/\partial V]\ e = 0$. In this case, $[J_F]\ [0^T, e^T]^T = [0^T, 0^T]^T$ and a null-space dimension of the full Jacobian will be equal to two. The use of the reference and slack buses reduces the null-space dimension of the full Jacobian by one, but the Jacobian remains singular. In most cases, voltage magnitudes are not equal to the «flat start» values; therefore, sub-matrices $[\partial\Delta P/\partial V]$ and $[\partial\Delta Q/\partial V]$ are not singular. They are, however, ill-conditioned, and the resulting solution is very sensitive to reactive power variation. As a result, it is almost impossible to set the reactive power of buses so that the resulting steady states correspond to the power system operating condition [24]. Therefore, it is necessary to fix the voltage magnitude at one of the buses, i.e., to make it an independent variable. As in the case of fixing voltage angle, the reactive power at one of the buses is assigned as a new dependent variable. Therefore, this bus becomes the bus balancing reactive power. The slack bus balances both active and reactive power ($V\delta$-bus). Generator buses equipped with automated excitation control balance reactive power as well. These buses keep voltage magnitudes constant by regulating reactive power within given ranges (PV-buses).

With all the above things considered, the matrix of first partial derivatives of steady-state equations with respect to dependent variables can have the following form:

$$[J] = \begin{bmatrix} \multicolumn{2}{c}{J_{PF}} & 0 & 0 \\ \partial\Delta P_b/\partial\delta & \partial\Delta P_b/\partial V_{PQ} & 1 & 0 \\ \partial\Delta Q_{PV}/\partial\delta & \partial\Delta Q_{PV}/\partial V_{PQ} & 0 & E \end{bmatrix}, \qquad (5)$$

where

$$[J_{PF}] = \begin{bmatrix} \partial\Delta P/\partial\delta & \partial\Delta P/\partial V_{PQ} \\ \partial\Delta Q_{PQ}/\partial\delta & \partial\Delta Q_{PQ}/\partial V_{PQ} \end{bmatrix} \qquad (6)$$

is the standard power flow Jacobian; [E] and [0] are the identity and zero sub-matrices of respective sizes, and index b is used for the slack bus. According to (5) $det\ [J] = det\ [J_{PF}]$ and non-singularity of power flow Jacobian, (6) ensures non-singularity of matrix (5).

Formally, to solve the system of nonlinear equations (1) by the Newton method, the system of linearized equations with matrix (5) is to be solved. However, the linearized equations using $[J_{PF}]$ do not depend on other equations and are solved separately. All the other dependent variables, e.g., the power at slack bus and reactive power at PV-buses, are determined by (1) with ordinary substitution of voltage angles and magnitudes.

The active and reactive power of the corresponding buses is included in (1) additionally. Excluding technical limitations, system (1) will always be consistent with any voltage angles and magnitudes, if the power at buses is obtained directly using (1). Therefore, a marginal state of

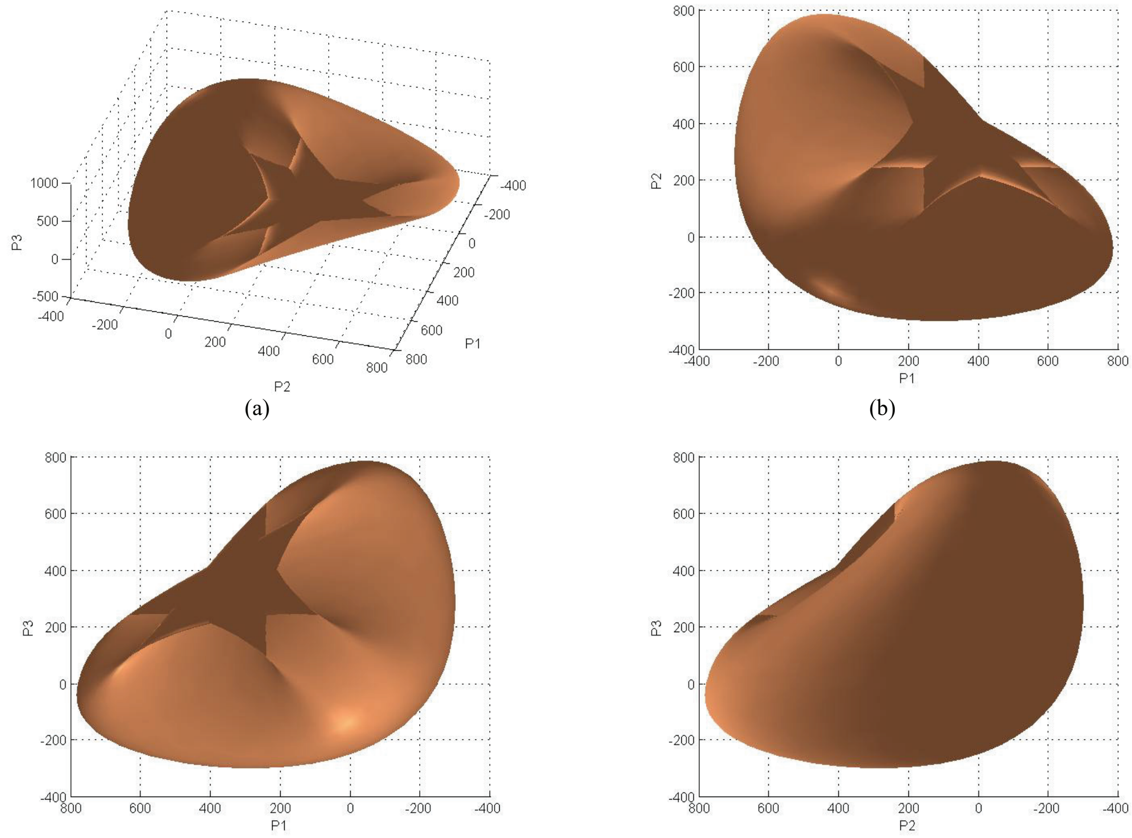


Fig. 1. Power surface of a 3-bus system (a) and its projections onto coordinate planes (b)-(d).

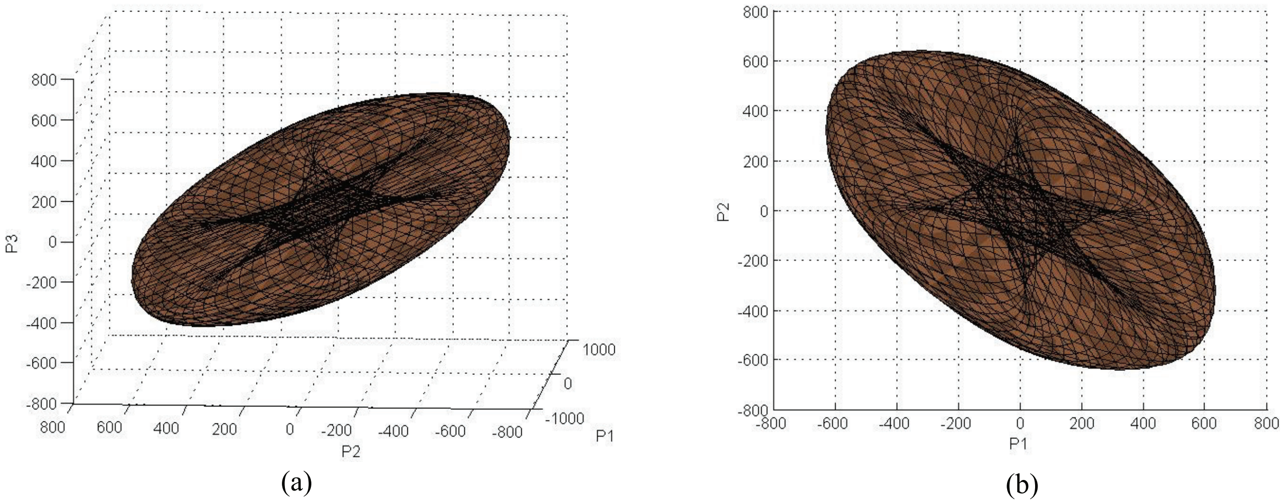


Fig. 2. Power surface (a) and power flow feasibility region (b) of 3-bus lossless system

a power system is a steady state where small deviations of independent variables in an unfavorable direction lead to inconsistency of system (1), i.e., it cannot be solved with respect to dependent variables. The implicit function theorem asserts that if Jacobian (5) at point X_0, Y_0 is not singular, then for each Y close enough to Y_0 there is only one solution $X = X(Y)$, which in turn is the solution to the nonlinear nodal steady-state equations $\Delta F(X(Y),Y) = 0$. Therefore, corollaries of the implicit function theorem are: firstly, a necessary condition (criterion) for the marginal states is the singularity of (5)-(6) [25]; secondly, another necessary condition is the existence of close alternative solutions nearby the marginal state [20]. According to (5)-(6), the Jacobian depends on the set of dependent and independent variables of the steady-state model. Therefore, slack bus location influences the power flow Jacobian and MS [26].

It is necessary to note an important property of the power flow Jacobian. According to the Sard theorem, a set of non-regular values of variables, i.e., when the Jacobian is singular, has measure zero [23]. In terms of the probability theory, it means that the probability of such events is equal to zero. The complement for every set of measure zero is dense everywhere, i.e., the set of regular values has a full measure. Therefore, each point in the space of variables is arbitrarily close to some regular value of the map. On the one hand, the Sard theorem guarantees the impossibility of the practical existence of a normal steady state having the singular Jacobian, i.e., makes the necessary condition of marginal state the sufficient one. On the other hand, it asserts that the obtained solutions are only approximations of actual marginal states. Mathematicians seldom apply the Sard theorem. However, it is a very powerful and useful mathematical tool for those who elaborate or apply computing models of power systems. For example, the theorem allows explaining the operability of the damped Newton method when the steady-state equations have no real solution. It is known that in this case, the iteration process of the damped Newton method converges to a marginal state with a «singular» Jacobian [27], [28]. Theoretically, it is impossible to solve a system of linear equations with a singular matrix. However, this is done by the damped Newton method [2]. It confirms that in computing models, the power flow Jacobian is not singular, although it may be ill-conditioned. In the damped Newton method, an optimal multiplier considerably improves the condition number of the problem to be solved.

III. Power Surface

Consideration of solving the steady-state equations as mapping of independent variables onto the space of dependent variables $Y \rightarrow X$ allows obtaining an interesting and important geometrical interpretation of steady-state equations. Since the slack bus active power P_b is a dependent variable, it is a function of the active power of all other buses and the reactive power of the *PQ*-buses. Its graph $P_b = P_b\,(P,Q)$ is a surface in the power space. The power surface defines the set of the power system steady states, including hypothetical unstable ones, for given system parameters [29]. There are no power system steady states outside the power surface for the specified system parameters and independent variables. Any point of the power surface corresponds to a steady state and its coordinates, i.e., the power at the buses in this steady state. As an example, Fig. 1 shows the power surface of a 3-bus power system with all *PV*-buses and its projections onto the corresponding coordinate planes. Parameters of this power system are as follows: $V_1 = V_2 = V_3 = 110$ kV; $Z_{12} = Z_{13} = Z_{23} = 20 + j40\ \Omega$.

The power system state analysis tends to use the concept of the power flow feasibility region. As the power surface determines all the power system steady states for the given system parameters, its projection along the axis of the slack bus active power onto a subspace of power of

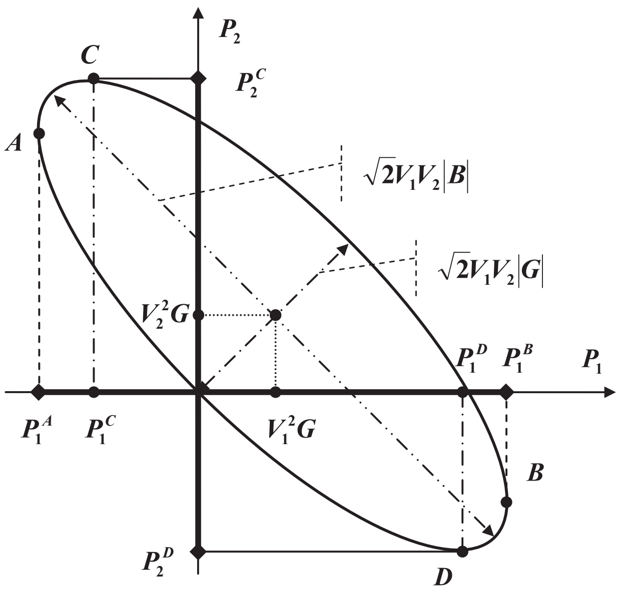


Fig. 3. Power ellipse of 2-bus power system

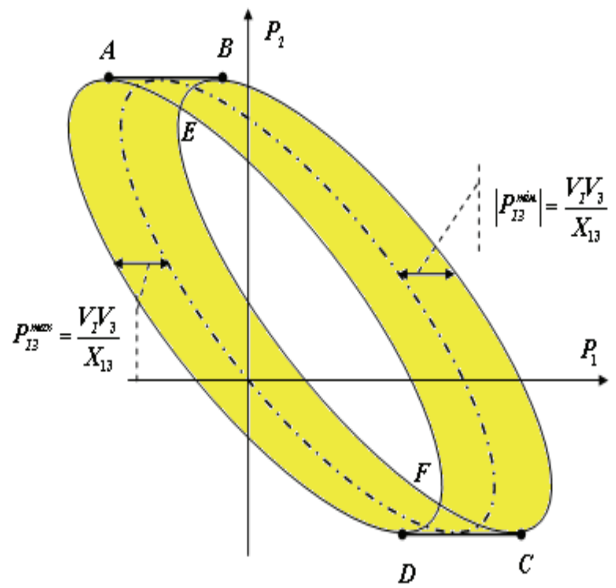


Fig. 4. Power flow feasibility region of 3-bus radial power system

all other buses is nothing else but the power flow feasibility region and boundary of this projection represents a marginal state surface in the power subspace of the buses. Thus, projections of the power surface presented in Fig. 1 (b), (c), or (d) are power flow feasibility regions when buses 3, 2, or 1 are used as slack buses, respectively. Since the power surface is normally not plane, its projection, i.e., the power flow feasibility region, and its boundary, i.e., the marginal state surface, will depend on the choice of the axis along which it is projected, i.e., they depend on the slack bus choice.

The power surface of a lossless power system is plane since there are no active power losses and power at buses satisfies the equation $\sum P_k = 0$. As an example, Fig. 2(a) shows the power surface of a 3-bus lossless power system ($Z_{12} = Z_{13} = Z_{23} = 40\ \Omega$) with *PV*-buses, and Fig. 2(b) indicates its projection onto the coordinate plane. This surface is a plane ellipsoid. The boundary of the plane surface corresponds to the marginal state, and only its projection along the axis of the active power of any slack bus onto the subspace of power at other buses is the boundary of the power flow feasibility region of the lossless power system. Therefore, the marginal states of lossless power systems do not depend on the choice of a slack bus.

It is known that the set of nonlinear steady-state equations for specified independent variables may have several solutions, some of which are stable while others are not. If the transmission lines of the power system are not purely inductive, then the number of solutions corresponds to the number of crossings of the power surface by the vector of the given buses' power directed in parallel to the axis of the slack bus active power. When there is purely inductive reactance, then even one power surface point may correspond to several solutions.

Thus, each point of the plane power surface of the 3-bus lossless power system represented in Fig. 2 corresponds to one solution on the boundary of the power surface; two solutions inside the surface but outside the region of triangles; and two additional solutions inside each triangle region, but only one of these solutions is stable. In the area of crossing triangles, each power surface point corresponds to six solutions, including the origin [4], i.e., when power injections of all the buses are equal to zero. Four solutions, including a stable one, correspond to zero active power flows in the lines. The other two solutions correspond to the circulation of active power around the loop (even when all the active power injections are zero), giving the sum of the branch-angles along the loop equal to $\pm 360^{\circ}$, rather than zero as in an ordinary solution. According to [5] and [6], interconnected power systems may have stable solutions, where active power circulates in one or more loops. In these cases, losses are much larger than those for ordinary solution.

IV. Power Flow Feasibility Region with a Hole

The geometrical consideration of the power system's steady states as the power surface allows highlighting the reasons why holes can occur inside the power flow feasibility region [11]. This can be done by considering the power surface of a 2-bus system with *PV*-buses presented in Fig. 3. This «surface» is a hollow ellipse in the two-dimensional space of bus power [32]

$$\left(\frac{P_1 - V_1^2 G + P_2 - V_2^2 G}{2V_1V_2\mathrm{G}}\right)^2 + \left(\frac{P_1 - V_1^2 G - P_2 + V_2^2 G}{2V_1V_2\mathrm{B}}\right)^2 = 1, \quad (7)$$

where $G + jB$ is the complex admittance of the line connecting these two buses.

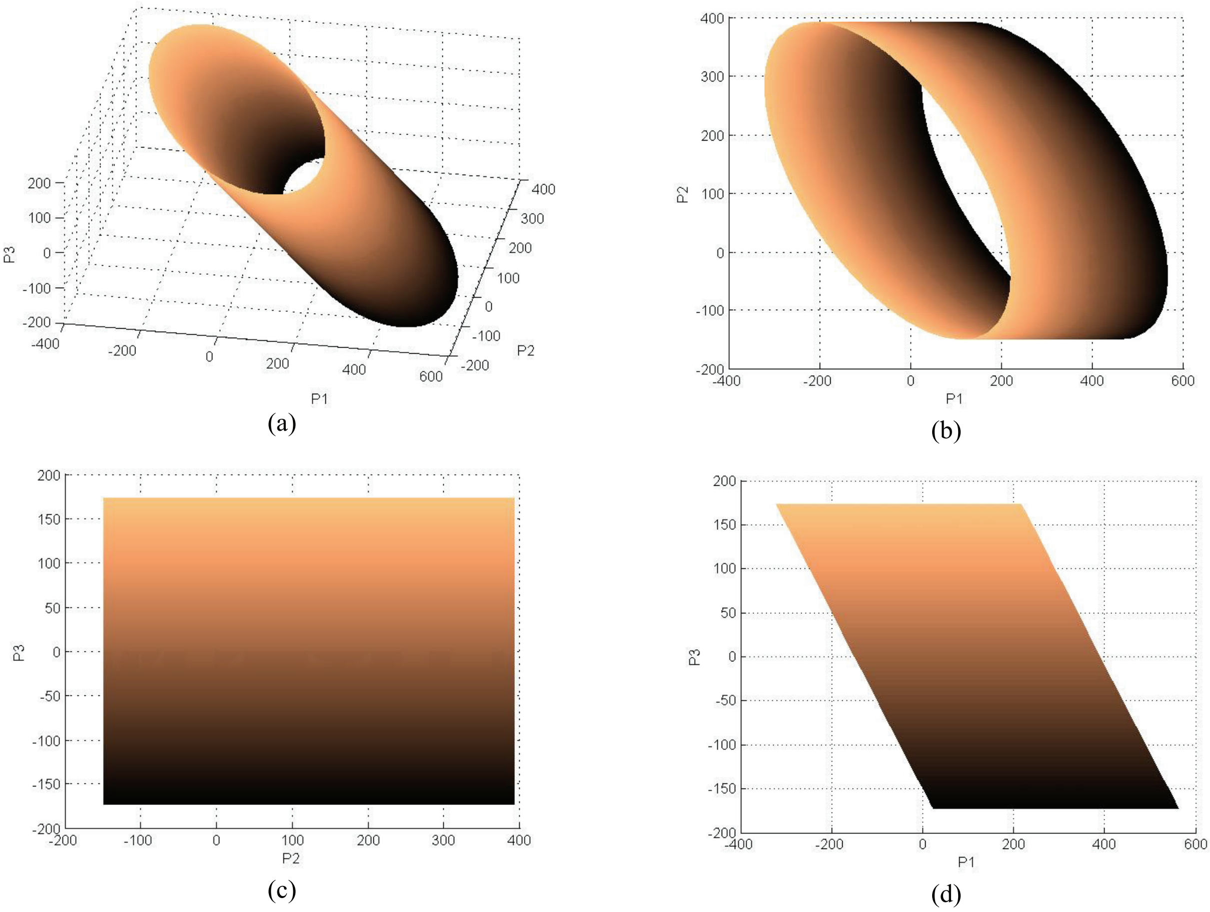


Fig. 5. Power surface of a 3-bus radial system (a) and power flow feasibility regions when the slack bus is bus 3 (b), bus 1 (c), or bus 2 (d).

The coordinates of the center of the power ellipse are (V_1^2G , V_2^2G) and its principal axes are rotated by an angle of 45º relative to the coordinate axes. The length of one of the principal axes is $\sqrt{2}V_1V_2|\mathrm{B}|$, the length of the other is $\sqrt{2}V_1V_2|\mathrm{G}|$. The power ellipse defines all the steady states of the given 2-bus system. Any ellipse point corresponds to a particular steady state, and its coordinates are steady-state power at the buses. Outside and inside this hollow ellipse, there are no steady states. Therefore, a set of feasible power of the buses for the 2-bus system is non-convex. It is one of the principal prerequisites for the holes to appear inside power flow feasibility regions.

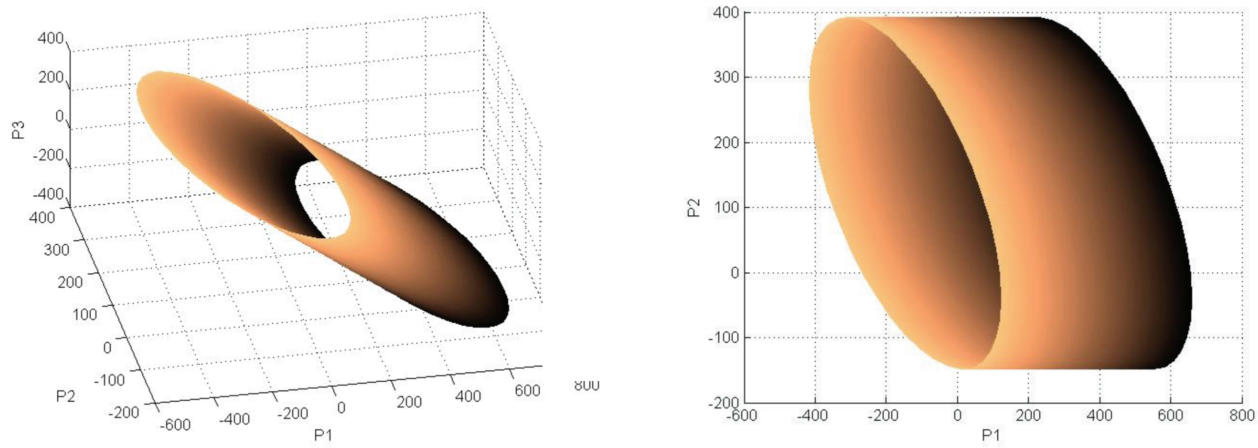
Note that power at all buses is equal in rights for the power surface, and a slack bus is not required. The need to use the slack bus arises in the case of steady-state calculation. If bus 2 is used as a slack bus to calculate the steady state for the 2-bus system, the thick line [P_1^A , P_1^B] in Fig. 3, which is the projection of the power ellipse onto the active power axis of bus 1, will be the power flow feasibility region. In this case, points A and B correspond to two marginal states. On the other hand, if bus 1 is a slack bus, the thick line [P_2^C , P_2^D] in Fig. 3, which is the projection of the power ellipse onto the active power axis of bus 2, will be another power flow feasibility region, where points C and D will correspond to two other marginal states.

The power flow feasibility region of the 2-bus power system is a straight-line segment and, therefore, has no holes. However, a hole in the power flow feasibility region may arise already in the case of a 3-bus system. To see it, add PV-bus 3 connecting the 2-bus system to bus 1, for example, by the inductive impedance $Z_{13} = jX_{13}$, and assign bus 3 as a slack bus. In this radial 3-bus power system, all buses are PV-buses, and the active power of bus 3 is directly transported to bus 1 without power losses. Therefore, using (7), the power surface of this system can be determined by

$$\left(\frac{P_1 + P_3 - V_1^2G + P_2 - V_2^2G}{2V_1V_2\mathrm{G}}\right)^2 + \\ + \left(\frac{P_1 + P_3 - V_1^2G - P_2 + V_2^2G}{2V_1V_2\mathrm{B}}\right)^2 = 1 \quad (8)$$

where $P_3 = P_{31} = (V_1V_3/X_{13}) \sin \delta_{31}$.

Expression (8) is the equation of a surface in a three-dimensional space, and its projection onto the coordinate plane $P_1{\times}P_2$ represents a power flow feasibility region for this power system when bus 3 is used as a slack bus (Fig. 4). Comparison of (8) with (7) reveals that the ellipse (8) for particular P_3 is the same ellipse (7) as in Fig. 3, but displaced horizontally to the left by the value of power P_3 in the case where bus 1 receives power from slack bus 3,



(a) (b)

Fig. 6. Power surface of a 3-bus radial system (a) and power flow feasibility region obtained by using slack bus 3 (b)

otherwise, to the right. Hence, (8) can be considered as an infinite set of ellipses on the coordinate plane $P_1 \times P_2$. Therefore, the power flow feasibility region of this power system is the area filled with ellipses (8). Its boundaries, i.e., marginal states, represent the envelopes of the infinite set of ellipses (8).

The maximum and minimum values of active power, which bus 1 can receive from slack bus 3, are determined by the expression $P_{13}^{\max} = V_1 V_3 / X_{13} = -P_{13}^{min}$. Therefore, the external boundary of the power flow feasibility region is the boundary of the convex hull of two outermost ellipses displaced horizontally to the left and to the right by the power value $P_{13}^{\max} = V_1 V_3 / X_{13}$ with respect to the central ellipse (7), i.e., the closed curve *A-B-C-D-A* in Fig. 4. The «hole» through the power flow feasibility region of this power system is the area of intersection of these two outermost ellipses, i.e., the region bounded by two arcs *EF* of these outermost ellipses. It is interesting to notice that the power flow feasibility region of this power system will not have a «hole» if any other bus is assigned as a slack bus. For example, Fig. 5 demonstrates a power surface of the 3-bus radial power system with parameters $V_1 = V_2 = V_3 = 110$ kV, $Z_{12} = 20 + j40$, $Z_{13} = j70$ (Ω) and its power flow feasibility regions for different assigned slack buses.

According to Fig. 5(a), the power surface of the power system represents a hollow ellipsoidal cylinder. The projection of the power surface along the active power axis of bus 3 onto the coordinate plane $P_1 \times P_2$, presented in Fig 5(b), has a form similar to that shown in Fig. 4 and represents a power flow feasibility region when bus 3 is used as a slack bus. If bus 1 is assigned as a slack bus, it corresponds to splitting the power system into two subsystems, whose steady states do not depend on each other. Steady states of the first subsystem are determined only by parameters of bus 2, of the second subsystem – by parameters of bus 3. It follows that the power flow feasibility region will be a filled rectangle, with the length of its sides determined by the maximum active power which bus 2 or bus 3, respectively, can withdraw from the network and inject into it, as shown in Fig. 5(c). If bus 2 is assigned as a slack bus, the power flow feasibility region will be a filled parallelogram, Fig. 5(d).

If to reduce the inductive impedance Z_{13}, for example, to set $Z_{13} = j45$ Ω, i.e., to increase the electric connection of bus 1 with slack bus 3, the power surface will also be represented as the hollow ellipsoidal cylinder (Fig. 6(a)), but projections of two outermost ellipses onto the coordinate plane $P_1 \times P_2$ will not be crossed and the «hole» inside the power flow feasibility region will disappear, as shown in Fig. 6(b). The use of other slack buses does not qualitatively change power flow feasibility regions, and they will be similar to those presented in Figs. 5(c), (d).

V. Slack Bus

The power surface allows a geometrical interpretation of the necessity of using the slack bus to calculate the steady state, i.e., the active power of the bus is not specified and regarded as unknown. Usually, such necessity is explained by the fact [30] that system losses are not known precisely before steady-state calculations. Therefore, it is impossible to specify power at all the buses precisely to provide consistency of the steady-state equations, i.e., their solvability. However, such consideration cannot explain the impossibility of calculating the steady state of a lossless power system with all *PV*-buses without using the slack bus. In a lossless power system, active power losses are equal to zero, therefore, it is not difficult to specify active power at all buses to provide consistency of the steady-state equations. However, even in this case, the steady-state calculation is impossible without assigning a slack bus. The power surface allows explaining such a need.

Each power system steady state corresponds to a certain point on the power surface and vice versa. The power surface is a map of the whole set of power system steady states, including all hypothetical (unstable) power system steady states, into the power space of buses. Outside and inside the power surface, there are no steady states. Like any surface, the power surface has a measure zero in the space of power at buses [31]. In terms of the probability theory, it means that a chance to specify the coordinates of a point on the power surface (the power of buses), disregarding their functional dependence so that they could satisfy the equation of the surface (steady state), is equal to zero. Hence, to obtain the coordinates of a point on the power surface (to solve the steady-state equations), it is necessary to use a coordinate of this point (active power of the slack bus) as a dependent variable. Therefore, all computational models that use steady-state equations always apply the slack bus explicitly or implicitly to calculate not only the steady state but also the optimal power flow, to estimate the power system state, and assess steady-state stability, and others [32]-[36].

VI. Conclusion

The study of steady-state equations reveals that a set of the power system steady states can be geometrically represented as a surface in the space of active power of buses and reactive power of *PQ* buses referred to as the power surface of the power system.

The findings indicate that the power flow feasibility region in the power space of buses, which is widely used in the theory and practice of power systems, is nothing but the projection of the power surface along the axis of the slack bus active power onto the subspace of all other specified power of buses, and the boundary of this projection is the surface of marginal states of the power system in the space of specified power of buses. Since the power surface is not plane, its projection, i.e., the power flow feasibility region, and its boundaries, i.e., the surface of marginal states, will depend on the choice of the axis along which it is projected, i.e., on the slack bus choice. The lossless power system power surface is plane, consequently, its power flow feasibility region and the surface of marginal states do not depend on the choice of slack bus.

The power surface allows visual interpretation of how «holes» through the power flow feasibility region appear and disappear in the case where the slack bus is changed.

Consideration of the set of all possible steady states of the power system as the power surface allows making use of the differential geometry and singularity theory for the further research of specificity and structure of power flow feasibility regions and marginal states.

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The Geometry of Power Systems Steady-State Equations– Part II: a Power Surface Study

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***Abstract* — Steady-state equations play an essential part in the theory of power systems and the practice of computations. These equations are directly or mediately used almost in all areas of the theory of power system states, constituting its basis. This two-part study deals with a geometrical interpretation of steady-state solutions in a power space. Part I has proposed considering the power system's steady states in terms of power surface. Part II is devoted to an analytical study of the power surface through its normal vectors. An interrelationship between the entries of the normal vector is obtained through incremental transmission loss coefficients. Analysis of the normal vector has revealed that in marginal states, its entry of the slack bus active power equals zero, and the incremental transmission loss coefficient of the slack bus equals one. Therefore, any attempts of the slack bus to maintain the system power balance in the marginal state are fully compensated by associated losses. In real-world power systems, a change in the slack bus location in the marginal state makes this steady state non-marginal. Only in the lossless power systems, the marginal states do not depend on a slack bus location.**

***Index Terms*: distributed slack bus, feasibility region, incremental transmission loss coefficient, Jacobian, marginal state, normal vector, power flow, power surface, power system, slack bus, steady state.**

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I. Introduction

Steady-state models play a crucial part in the analysis, planning, and control of power systems. Therefore, an analytical investigation and understanding of steady-state equations are essential since they provide qualitative insights and facilitate the evolution of power system theories and elaboration of faster and more efficient algorithms. At present, most publications tend to use an algebraic approach. Mathematical expressions and equations are efficient tools for a numerical solution but are complicated for the qualitative analysis in the case of multidimensional systems. At the same time, a geometrical consideration allows taking advantage of powerful tools of modern geometry and obtaining noteworthy results. Part I [1] of the two-part study suggests the geometrical interpretation of a set of all the steady-state solutions in terms of surface in a power space. Consideration of the whole set of power system steady states using power surface allows taking advantage of differential geometry tools to qualitatively study steady-state models.

The objective of the present paper is to analytically investigate the power surface. This work improves upon the early study [2] considering the steady- states equations with distributed slack bus. The rest of the paper is organized as follows. In Section II, equations of a tangent plane and a normal vector to the power surface are obtained. Section III investigates the entries of the normal vector to the power surface and their specific features in marginal states of a power system. It also examines an interrelationship between entries of the normal vector to the power surface and entries of the normal vector to the surface of marginal states. Section IV considers the influence of a slack bus location on the marginal states through the entries of the normal vector to the power surface by the example of a 4-bus power system. Section V analyzes the adequacy of the parameters of marginal states obtained when using a distributed slack bus to assess an actual steady-state stability reserve of the power system in terms of power. Section VI presents the conclusions.

II. Tangent Plane to Power Surface

One of the differential geometry tools is tangent planes to the surface and their normal vectors. An equation of a tangent plane to the power surface is conveniently obtained by using nodal steady-state equations in polar coordinates:

$$\Delta P(P,V,\delta)=0;\quad \Delta P_b(P_b,V,\delta)=0;\quad \Delta Q(Q,V,\delta)=0. \tag{1}$$

where P and Q are an injection power vector consisting of the active power for buses other than the slack bus and the reactive power for PQ-specified buses, respectively; δ and V are vectors defined by phase angles for buses other than the angle reference bus and voltage magnitude for PQ-specified buses, respectively; subscript b refers to the slack bus.

Linearization of (1) gives:

$$\begin{bmatrix} \frac{\partial \Delta P}{\partial \delta} & \frac{\partial \Delta P}{\partial V} \\ \frac{\partial \Delta P_b}{\partial \delta} & \frac{\partial \Delta P_b}{\partial V} \\ \frac{\partial \Delta Q}{\partial \delta} & \frac{\partial \Delta Q}{\partial V} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} + \begin{bmatrix} dP \\ dP_b \\ dQ \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}. \tag{2}$$

Unlike standard linearized equations, which are used for steady-state calculations, system (2) explicitly includes the linearized equation of active power balance at slack bus b. Hence, the augmented Jacobian in (2) is rectangular; its number of rows is greater than the number of columns by one. According to the theory of linear algebra, rows of such matrix are linearly dependent [3]. Consequently, there exists a non-zero vector $\lambda = \left[\lambda^{P^{\mathrm{T}}}, \lambda_b^P, \lambda^{Q^{\mathrm{T}}} \right]^{\mathrm{T}}$ satisfying the following equation:

$$\begin{bmatrix} \lambda^P \\ \lambda_b^P \\ \lambda^Q \end{bmatrix}^{\mathrm{T}} \begin{bmatrix} \frac{\partial \Delta P}{\partial \delta} & \frac{\partial \Delta P}{\partial V} \\ \frac{\partial \Delta P_b}{\partial \delta} & \frac{\partial \Delta P_b}{\partial V} \\ \frac{\partial \Delta Q}{\partial \delta} & \frac{\partial \Delta Q}{\partial V} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}. \tag{3}$$

Hence, multiplying the left-hand side of (2) by λ^{T}, we obtain the following equation:

$$\lambda^{P^{\mathrm{T}}} dP + \lambda_b^P dP_b + \lambda^{Q^{\mathrm{T}}} dQ = 0. \tag{4}$$

Expression (4) is the equation of the tangent plane to the power surface in the space of the active power of the buses and the reactive power of PQ-specified buses. Therefore, (4) determines the vector λ as a normal vector to the tangent plane, i.e., to the power surface. According to (3), the normal vector to the power surface can be obtained by specifying λ_b^P and solving the set of linear equations:

$$\begin{bmatrix} \frac{\partial \Delta P}{\partial \delta} & \frac{\partial \Delta P}{\partial V} \\ \frac{\partial \Delta Q}{\partial \delta} & \frac{\partial \Delta Q}{\partial V} \end{bmatrix}^{\mathrm{T}} \begin{bmatrix} \lambda^P \\ \lambda^Q \end{bmatrix} = -\lambda_b^P \begin{bmatrix} \frac{\partial \Delta P_b}{\partial \delta}^{\mathrm{T}} \\ \frac{\partial \Delta P_b}{\partial V}^{\mathrm{T}} \end{bmatrix}, \tag{5}$$

in which the coefficient matrix is the transposed power flow Jacobian.

III. Study on the Normal Vector to Power Surface

To determine an interrelationship between the entries of a normal vector to a power surface, it is convenient to use the system power balance equation

$$P_b + \sum_{\forall k \neq b} P_k - \pi = 0, \tag{6}$$

where π is a system power loss.

The active power of the slack bus and power loss are dependent variables. Therefore, differentiation of (6) with respect to independent variables (power at specified buses) yields:

$$\left[\frac{\partial P_b}{\partial P}\right] + e^{\mathrm{T}} - \left[\frac{\partial \pi}{\partial P}\right] = 0^{\mathrm{T}};\quad \left[\frac{\partial P_b}{\partial Q}\right] - \left[\frac{\partial \pi}{\partial Q}\right] = 0^{\mathrm{T}}, \tag{7}$$

where e is the vector of all ones; $\left[\frac{\partial \pi}{\partial P}\right]$ and $\left[\frac{\partial \pi}{\partial Q}\right]$ are vectors of incremental transmission loss coefficients (ITLs). In turn, differentiation of (1) with respect to independent variables yields:

$$\begin{vmatrix} \frac{\partial \Delta P}{\partial \delta} & \frac{\partial \Delta P}{\partial V} \\ \frac{\partial \Delta Q}{\partial \delta} & \frac{\partial \Delta Q}{\partial V} \end{vmatrix} \begin{bmatrix} \frac{\partial \delta}{\partial P} & \frac{\partial \delta}{\partial Q} \\ \frac{\partial V}{\partial P} & \frac{\partial V}{\partial Q} \end{bmatrix} + [\mathrm{E}] = [0]; \tag{8}$$

$$\begin{aligned} \left[\frac{\partial \Delta P_b}{\partial P}\right] &= \left[\frac{\partial P_b}{\partial P}\right] + \left[\frac{\partial \Delta P_b}{\partial \delta}\right]\left[\frac{\partial \delta}{\partial P}\right] + \left[\frac{\partial \Delta P_b}{\partial V}\right]\left[\frac{\partial V}{\partial P}\right] = 0^{\mathrm{T}}; \\ \left[\frac{\partial \Delta P_b}{\partial Q}\right] &= \left[\frac{\partial P_b}{\partial Q}\right] + \left[\frac{\partial \Delta P_b}{\partial \delta}\right]\left[\frac{\partial \delta}{\partial Q}\right] + \left[\frac{\partial \Delta P_b}{\partial V}\right]\left[\frac{\partial V}{\partial Q}\right] = 0^{\mathrm{T}}, \end{aligned} \tag{9}$$

where [E] and [0] are identity and zero matrices, respectively. In turn, the use of (8) in (9) yields:

$$\begin{bmatrix} \frac{\partial \Delta P}{\partial \delta} & \frac{\partial \Delta P}{\partial V} \\ \frac{\partial \Delta Q}{\partial \delta} & \frac{\partial \Delta Q}{\partial V} \end{bmatrix}^{\mathrm{T}} \begin{bmatrix} \frac{\partial P_b}{\partial P}^{\mathrm{T}} \\ \frac{\partial P_b}{\partial Q}^{\mathrm{T}} \end{bmatrix} = \begin{bmatrix} \frac{\partial \Delta P_b}{\partial \delta}^{\mathrm{T}} \\ \frac{\partial \Delta P_b}{\partial V}^{\mathrm{T}} \end{bmatrix}. \tag{10}$$

Comparison of (10) with (5) and use of (7) yield:

$$\lambda_m^P = \left(1 - \frac{\partial \pi}{\partial P_m}\right)\lambda_b^P; \tag{11}$$

$$\lambda_m^Q = -\frac{\partial \pi}{\partial Q_m}\lambda_b^P. \tag{12}$$

The normal vector to the power surface does not depend on a selection of the slack bus because an alteration of the slack bus does not change solution to (5) if the entry of the normal vector of a new slack bus to set is equal to a value of this entry obtained by solving (5) using the old slack bus. Thus, (11)-(12) allow revealing the interrelationship between the ITLs obtained by using the new slack bus and the old one:

$$\frac{\partial\pi_k}{\partial P_m}=\frac{\dfrac{\partial\pi_b}{\partial P_m}-\dfrac{\partial\pi_b}{\partial P_k}}{1-\dfrac{\partial\pi_b}{\partial P_k}};\quad \frac{\partial\pi_k}{\partial Q_m}=\frac{\dfrac{\partial\pi_b}{\partial Q_m}}{1-\dfrac{\partial\pi_b}{\partial P_k}},\qquad(13)$$

where $\frac{\partial\pi_b}{\partial P_m}$ and $\frac{\partial\pi_k}{\partial P_m}$ are ITLs obtained by using slack bus b and new slack bus k, respectively.

Consider specific features of the normal vector to the power surface in a marginal state. According to (5) and (11)-(12), the entries of the normal vector can have different values. Assume that the normal vector entry λ_k^P is zero at some point on the power surface. According to (11), this will only be when $1-\frac{\partial\pi}{\partial P_k}=0$, i.e.,

$$\lambda_k^P=0\ \Rightarrow\ \frac{\partial\pi}{\partial P_k}=1.\qquad(14)$$

Assume that bus k is assigned as a slack bus at this point. Then, the adjusted (5) can be represented as follows:

$$\begin{bmatrix}\dfrac{\partial\Delta P}{\partial\delta} & \dfrac{\partial\Delta P}{\partial V}\\ \dfrac{\partial\Delta Q}{\partial\delta} & \dfrac{\partial\Delta Q}{\partial V}\end{bmatrix}^{\mathrm{T}}\begin{bmatrix}\lambda^P\\ \lambda^Q\end{bmatrix}=-\lambda_k^P\begin{bmatrix}\dfrac{\partial\Delta P_k}{\partial\delta}^{\mathrm{T}}\\ \dfrac{\partial\Delta P_k}{\partial V}^{\mathrm{T}}\end{bmatrix}=\begin{bmatrix}0\\0\end{bmatrix}.\qquad(15)$$

The matrix in (15) is the transposed power flow Jacobian by using slack bus k, and condition (15) determines its singularity, i.e., a marginal state. According to (14), in the marginal state, the incremental transmission loss coefficient of the slack bus is equal to one, which is why any attempts of the slack bus to maintain the power system steady state are compensated by associated power loss. The inability of the slack bus to maintain the steady state even at some buses determines the power system marginal state. In the marginal state, the slack bus as if loses connection to a part or the whole of the power system; it corresponds to the absence of slack bus in the computational model of steady states with all consequences.

The interpretation of the marginal state surface in the subspace of power at specified buses as the boundary of the power surface projection along the axis of slack bus active power onto the subspace of power of all other buses allows obtaining an interesting interrelationship between the normal vector to the power surface in marginal state and the normal vector to the marginal state surface. According to (14), the slack bus entry of the normal vector to the power surface is equal to zero in the marginal state. Therefore, in the marginal state, the normal vector to the power surface is orthogonal to the axis of slack bus active power and will be projected onto the subspace of power at specified buses in full size. Consequently, the entries of the normal vector to the marginal state surface will be equal to the corresponding entries of the normal vector to the power surface.

Table 1. A 4-bus power system.

Bus	1	2	3	4
Base Case				
P	20	-50	50	-22.1951
λ^P	0.9259	0.9069	1.0231	1
Marginal states obtained by using slack bus 4				
P	20	-411.77	411.77	-465.27
λ^P	-1	-0.9794	0	0
Marginal states obtained by using slack bus 1				
P	-118.72	-171.51	171.51	-22.1951
λ^P	0	0	1	0.9775

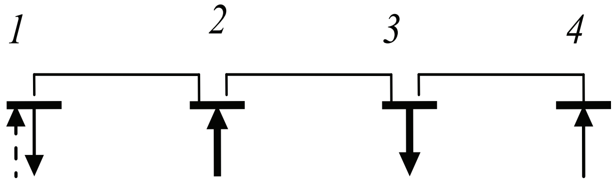

Fig. 1. A 4-bus power system.

IV. Influence of Slack Bus Location on Marginal state

In the marginal state, in the case of a changing slack bus, generally, condition (15) will not be satisfied, unless a new slack bus has zero entry of the normal vector to the power surface in (5). A simple system with 4 PV buses in Fig. 1 allows showing this.

Table 1 indicates the power at buses in MW (the minus sign corresponds to generation) and entries of the normal vector to the power surface for the base case and also for the marginal states obtained by using slack bus 4, and slack bus 1. These marginal states are the results of a generation increase at bus 2 and a load increase at bus 3. The line parameters are $Z_{12}=Z_{34}=5+j10\ \Omega$, $Z_{23}=20+j40\ \Omega$, and $V_1=V_2=V_3=V_4=110$ kV.

Consider the parameters of the marginal state obtained by using slack bus 4. Since the power transfer through line 2-3 is associated with loss, slack bus 4 supports the power transfer through line 3-4. The marginal state occurs when line 2-3 is overloaded. The steady state remains marginal if bus 3 is assigned as slack bus since its entry of the normal vector to the power surface is also equal to zero in this case. However, it will not remain marginal, if the slack bus is moved to bus l as its entry of the normal vector is not equal to zero and there is a possibility of continuing generation increase at bus 2 and load increase at bus 3. In the marginal state, the ITLs for bus 4, obtained by using slack bus 1 or 2, are equal to one.

The marginal state will be different if slack bus 1 is used because it maintains the power system steady state through line 1-2 in this case. The ITL for the slack bus increases with growth in the power transfer. As soon as it reaches one, the load increase at bus 3 becomes impossible. Slack bus 1 is unable to maintain the steady state of bus 3 and 4

TABLE 2. 4-BUS LOSSLESS POWER SYSTEM.

Bus	1	2	3	4
Base Case				
P	20	-50	50	-20
λ^P	1	1	1	1
Marginal states obtained by using slack bus 4				
P	20	-322.5	322.5	-20
λ^P	1	1	0	0
Marginal states obtained by using slack bus 1				
P	20	-322.5	322.5	-20
λ^P	0	0	1	1

in this marginal state. The marginal state remains marginal if bus 2 becomes slack bus, as its entry of the normal vector is equal to zero. This steady state will not be marginal if the slack bus is bus 4 or 3 since these buses have non-zero entries of the normal vector. The marginal values of power at buses and system loss in the marginal state obtained by using slack bus 1 are smaller than those obtained by using slack bus 4. At the same time, the marginal state obtained by using slack bus 4 and the steady states in its vicinity will be unstable if the dynamic Jacobian is used for the steady-state stability assessment [4].

The influence of the slack bus location on the marginal state can be explained by considering the power surface. Each power system steady state corresponds to a certain point on the power surface and vice versa. The projection of the power surface along the axis direction of the slack bus active power onto the subspace of power of all specified buses is the power flow feasibility region [1]. The boundary of this projection corresponds to a set of marginal states. Since the power surface is usually not plane, the points on the power surface, which correspond to the boundary of such a projection, i.e., marginal state, will be different for another slack bus. Therefore, the slack bus change in the marginal state makes the steady state non-marginal.

In the case of no resistances in the network in Fig. 1, the power system marginal states obtained by using slack bus 4 and slack bus 1 will be the same. The base case and marginal state parameters for the 4-bus lossless system with $Z_{12} = Z_{34} = j10\ \Omega$, $Z_{23} = j40\ \Omega$ are shown in Table II.

In any lossless power system, marginal states remain marginal regardless of the slack bus location. It can be shown if to consider the following. Firstly, if all the resistances are zero, the vector $\lambda = [e^{\mathrm{T}}, 1, 0^{\mathrm{T}}]$ will always correspond to (3), i.e., it will always be the normal vector to the power surface. Secondly, in the marginal state, the dimension of a null space of the transposed augmented Jacobian (3) is equal to two [5]. Therefore, in the marginal state, another normal vector $[\,{\lambda^{P}}^{\mathrm{T}}, 0, {\lambda^{Q}}^{\mathrm{T}}\,]$ to the power surface of the null space of transposed augmented Jacobian (3) will correspond to (14)-(15). Hence, in the marginal state, vector λ of a linear combination of vectors

$$\lambda = \beta\left[e^{\mathrm{T}}, 1, 0^{\mathrm{T}}\right]^{\mathrm{T}} + \left[{\lambda^{P}}^{\mathrm{T}}, 0, {\lambda^{Q}}^{\mathrm{T}}\right]^{\mathrm{T}} \tag{16}$$

will also be a normal vector to the power surface. Two cases are possible when new slack bus k is used. If $\lambda_k^P = 0$, then the entries of the normal vector remain unchanged in (14)-(15). Otherwise, the normal vector λ (16) with $\beta = -\lambda_k^P$ will also correspond to the power flow Jacobian (15) singularity.

The fact that the marginal state does not depend on the slack bus location can also be explained by considering the power surface of a lossless power system. This power surface is plane [1] since it also satisfies the equation $\sum_{\forall k} P_k = 0$. The points on the plane power surface that correspond to the boundaries of its projections along the active power axis direction of any slack bus onto the subspace of power of specified buses, i.e., the marginal states, are the same. Therefore, marginal states do not depend on the slack bus location. It is also noteworthy, that one side of this plane power surface corresponds to aperiodic stable steady states; while the other side is unstable ones, i.e., the same point on the power surface of the lossless power system corresponds to stable and unstable power system steady states [1].

V. DISTRIBUTED SLACK BUS

Several power flow programs use a so-called distributed slack bus, i.e., active power is balanced by several generators with specified participation factors [6]. Participation factors ϑ_k may be specified according to economic reasons, or based on requirements of the primary or secondary frequency control, and so on. In this case, a dependent variable P^S is used for the distributed slack bus, which is taken into consideration in steady-state equations as $\vartheta_k P^S$ with $\sum_k \vartheta_k = 1$, and the power flow Jacobian is represented as follows:

$$\begin{bmatrix} \dfrac{\partial \Delta P}{\partial \delta} & \dfrac{\partial \Delta P}{\partial V} & \vartheta \\ \dfrac{\partial \Delta P_b}{\partial \delta} & \dfrac{\partial \Delta P_b}{\partial V} & \vartheta_b \\ \dfrac{\partial \Delta Q}{\partial \delta} & \dfrac{\partial \Delta Q}{\partial V} & 0 \end{bmatrix}. \tag{17}$$

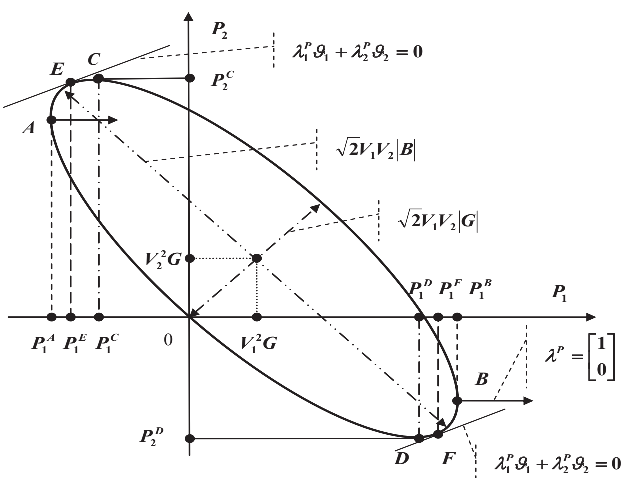

Fig. 2. Power ellipse of a 2-bus power system and marginal states

Matrix (17) includes partial derivatives of active power balance equations for all buses, and subscript b refers to a reference bus. In the marginal state, this matrix is singular. With the left-hand side eigenvector (corresponding to its zero eigenvalue) denoted by γ, singularity conditions of (17) can be represented as follows:

$$\vartheta^{\mathrm{T}}\gamma = \sum_{k\subset S}\vartheta_k\gamma_k^P = 0; \tag{18}$$

$$\begin{bmatrix}\gamma^P\\ \gamma_b^P\\ \gamma^Q\end{bmatrix}^{\mathrm{T}}\begin{bmatrix}\frac{\partial\Delta P}{\partial\delta} & \frac{\partial\Delta P}{\partial V}\\ \frac{\partial\Delta P_b}{\partial\delta} & \frac{\partial\Delta P_b}{\partial V}\\ \frac{\partial\Delta Q}{\partial\delta} & \frac{\partial\Delta Q}{\partial V}\end{bmatrix} = \begin{bmatrix}0\\0\end{bmatrix}^{\mathrm{T}}. \tag{19}$$

In turn, (19) can be rewritten as:

$$\begin{bmatrix}\frac{\partial\Delta P}{\partial\delta} & \frac{\partial\Delta P}{\partial V}\\ \frac{\partial\Delta Q}{\partial\delta} & \frac{\partial\Delta Q}{\partial V}\end{bmatrix}^{\mathrm{T}}\begin{bmatrix}\gamma^P\\ \gamma^Q\end{bmatrix} = -\gamma_b^P\begin{bmatrix}\frac{\partial\Delta P_b}{\partial\delta}^{\mathrm{T}}\\ \frac{\partial\Delta P_b}{\partial V}^{\mathrm{T}}\end{bmatrix}. \tag{20}$$

Comparison of (20) with (5) shows that vector γ is the normal vector λ to the power surface. Therefore, condition (18) can be represented as follows:

$$\vartheta^{\mathrm{T}}\lambda = \sum_{k\subset S}\vartheta_k\lambda_k^P = 0. \tag{21}$$

Thus, the marginal state determined by using the distributed slack bus corresponds to such points on the power surface at which their normal vectors to the power surface λ are orthogonal to the vector of bus participation factors for balancing active power ϑ. In the case of a 2-bus power system with PV-buses, two points E and F in Fig. 2 satisfy this condition.

Fig. 2 also shows the marginal states and power flow feasibility regions when the slack bus is bus 2 (the points A, B and the straight line [P_1^A , P_1^B]) or bus 1 (the points C, D and the straight line [P_2^C , P_2^D]). This means that when the distributed slack bus is used, the obtained marginal states are not on the boundary of the power flow feasibility region but inside the region. Therefore, the steady-state stability reserve in terms of power, obtained by using the distributed slack bus, can be less than the reserve obtained by using the single slack bus. Consider, for example, the marginal state at point E. Indeed, when the marginal state is determined by changing load at bus 1 and using the distributed slack bus then, according to the arc OAE of the ellipse, at the beginning of the process, the power of bus 1 will gradually increase to P_1^A and then decrease to P_1^E . This means that the marginal state E obtained by using the distributed slack bus will be farther in an angle space than the marginal state A obtained by using single slack bus 2 but nearer in the power space. Usually, the steady-state stability reserve of a power system is determined in terms of power. Therefore, the steady-state stability reserve will be assessed more correctly if we use parameters of the steady state corresponding to point A, i.e., the parameters of the marginal state obtained by using single slack bus 2.

Consideration of the system power balance equation

$$P^S + \sum_{\forall k} P_k - \pi = 0, \tag{22}$$

and use of an approach similar to (7)-(12) allow obtaining the following relationship between the entries of the normal vector to the power surface determined by using the distributed slack bus [5]:

$$\lambda_m^P = \left(1 - \frac{\partial\pi^S}{\partial P_m}\right)\lambda^S; \tag{23}$$

$$\lambda_m^Q = -\frac{\partial\pi^S}{\partial Q_m}\lambda^S, \tag{24}$$

where $\frac{\partial\pi^S}{\partial P_m}$ is ITL for bus m determined by using the distributed slack bus s, and

$$\lambda^S = \vartheta^{\mathrm{T}}\lambda = \sum_{k\subset S}\vartheta_k\lambda_k^P. \tag{25}$$

Any changes in the distributed slack bus, even in marginal state when

$$\lambda^S = 0, \tag{26}$$

do not change the entries of the normal vector to the power surface as they correspond to (3). Therefore, if in the marginal state, the use of (25) gives $\lambda^{Snew} \neq 0$ for new distributed slack bus s_{new}, then according to (23)

$$\lambda_m^P = \left(1 - \frac{\partial\pi^{Snew}}{\partial P_m}\right)\lambda^{Snew}, \tag{27}$$

substitution of which into (25) and considering (26) yield:

$$\frac{\partial\pi^{Snew}}{\partial P^S} = \sum_m \frac{\partial\pi^{Snew}}{\partial P_m}\vartheta_m = 1. \tag{28}$$

Thus, in the marginal state, the incremental transmission loss coefficient of the distributed slack bus is equal to unity, which is why any manipulations of the distributed slack bus to balance active power are compensated by power loss caused by such manipulations. It means that the distributed slack bus is unable to maintain such a steady state. Any random insignificant power changes at buses in an unfavorable direction cannot be balanced by the distributed slack bus.

As in the case of the single slack bus, a change in the distributed slack bus (for example, an alteration in participation factors) in the marginal state makes this steady state non-marginal. Exceptions are the cases either where condition (21) is also satisfied in this steady state for a new structure of the distributed slack bus or where the lossless power system model is used. In the latter case, the normal vector (16) with $\beta = -\sum_k \vartheta_k\lambda_k^P$ corresponds to (18)-(21), i.e., the power flow Jacobian remains singular.

VI. Conclusion

Part II of the two-part study investigates the power surface proposed in Part I. The findings have revealed that the entries of the normal vector to the power surface are interrelated through incremental transmission loss coefficients. Analysis of the normal vector to the power surface has shown that in marginal states of the power system the entry of the normal vector corresponding to the slack bus active power equals zero, and the incremental transmission loss coefficient of the slack bus is equal to one. Therefore, in marginal states, any attempts of the slack bus to balance active power in the power system are completely compensated by active power loss caused by such manipulations. The inability of the slack bus to maintain the steady state even of some buses determines the power system marginal state. In marginal states, the slack bus as if loses connection to a part or the whole of the power system; it corresponds to the absence of the slack bus in the computational steady-state model with all consequences. In real-world power systems, a change in the slack bus location in a marginal state makes this steady state non-marginal. Only in the lossless power systems, marginal states do not depend on the slack bus location. The study has also revealed that parameters of marginal states obtained by using the distributed slack bus may give an underestimation of the real steady-state stability reserve of the power system in terms of power.

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Knowledge Mapping of Energy Systems Research in 1970-2020

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***Abstract*—This study presents a brief bibliometric overview of large scientific literature data related to issues of energy systems research from 1970 to 2020 in the Scopus database. The six periods depending on different publication activity rates were analyzed to observe the evolution of research topics of energy systems. VOSviewer software was used to construct scientific knowledge maps and to discover valuable main topics for each period. Proposed visualization of the energy knowledge domain can be considered as a necessary step for a holistic understanding of complex development pathways towards the future sustainable energy systems.**

***Index Terms*—energy systems, power systems, knowledge mapping, big data, research trends, bibliometric analysis, scientometric analysis, visual analysis, VOSviewer.**

I. INTRODUCTION

Energy systems are the most complex technical systems people invented. The world's energy systems implement integrated and continuously working technologies for the production, transmission, distribution, and consumption of energy. In the 21st century, we should expect drastic changes in the energy sector. This new energy transition is related not only to the intensive development of energy technologies, in particular, renewable energy sources, a qualitative shift in the scale of adoption of intelligent information and communication technologies and means of control of energy facilities and systems, but also to a fundamental change in the paradigm of development of energy systems as client-oriented infrastructure systems that provide reliable and efficient services to industries and the community [1].

The transition to future energy systems requires a comprehensive understanding of the respective knowledge development. However, this is a complicated task because a lot of various interrelated topics, subject categories, technologies, and actors are involved in consideration of the energy systems knowledge domain. Multidisciplinary studies that include and integrate different fields are necessary to identify and understand feedbacks and interactions between energy systems components and hold the promise for advancing holistic system-level knowledge of energy systems.

There are a lot of publications implementing scientometric or bibliometric approaches to review various aspects of the energy sector. For example, the evolution of research on multi-energy systems such as smart grids and microgrids is considered in [2]. The work [3] assesses the global scientific research on low-carbon electricity both quantitatively and qualitatively over a large number of publications from the Science Citation Index Expanded (SCI-Expanded). Comprehensive review and scientometric analysis of prosumer flexibility as an important property of modern power systems is a good example of a holistic viewpoint providing the hotspot knowledge map of the topic [4]. Nevertheless, there is no scientometric assessment of energy research in the context of systems semantics.

This study addresses a scientometric review of the scientific literature related to the historical development of energy systems research. Opposite to the aforementioned studies this article mainly focuses on:

- summarizing the past and recent existing international research efforts in the field of energy systems;
- understanding main research directions and their transformation over the past 50 years based on the recovered topic clusters;
- knowledge mapping with keywords' co-occurrence network.

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II. Data and tools

The methodology of the study is a scientometric analysis joint with supporting visualization to provide an in-depth understanding of the research structure and trending topics in the field of energy systems. The scientometric analysis is a well-established technique to construct a knowledge map of the specific area over a large massive dataset of scientific literature. An example of a scientometric review of global research on sustainability and sustainable development can be found in [5].

General workflow of scientometric analysis includes several sequential steps:

1. Publications data retrieval related to a specific problem or knowledge area.
2. Data cleaning manually or automatically to remove irrelevant publications.
3. Scientometric quantitative analysis applying various metrics like betweenness centrality to construct different co-occurrence networks. The network examples are co-authorship network, co-word network, co-terms network, co-citations network, and others. Further clustering analysis over the constructed networks is also an important part of the scientometric approach.
4. Knowledge domain visualization and in-depth analysis to obtain status-quo of research, discover emerging trends, hidden interrelations, and other valuable outputs.

In this study, the Scopus database was selected as the most comprehensive and easy-to-use international data source. A search in the database was carried out using the base phrases "energy system*" and "power system*". Symbol "*" is inserted instead of the end of the words to satisfy a fuzzy search of both plural and single word forms. The publications with the language "English" and document type as "Article" and "Review" from reviewed and trusted journals were selected. We consider the long period 1970–2020 when the different rates of publications growth are observed.

The final query text inserted in the bar of "Advanced search" of the Scopus search engine is presented below.

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TITLE-ABS-KEY ( "energy system*" OR "power system*" ) AND ( PUBYEAR > 1969 ) AND PUBYEAR < 2021 AND ( LIMIT-TO ( DOCTYPE , "ar" ) OR LIMIT-TO ( DOCTYPE , "re" ) ) AND ( EXCLUDE ( SUBJAREA , "BIOC" ) OR EXCLUDE ( SUBJAREA , "MEDI" ) OR EXCLUDE ( SUBJAREA , "ARTS" ) OR EXCLUDE ( SUBJAREA , "HEAL" ) OR EXCLUDE ( SUBJAREA , "PSYC" ) OR EXCLUDE ( SUBJAREA , "NEUR" ) OR EXCLUDE ( SUBJAREA , "PHAR" ) OR EXCLUDE ( SUBJAREA , "NURS" ) OR EXCLUDE ( SUBJAREA , "IMMU" ) OR EXCLUDE ( SUBJAREA , "VETE" ) OR EXCLUDE ( SUBJAREA , "DENT" ) OR EXCLUDE ( SUBJAREA , "Undefined" ) ) AND ( LIMIT-TO ( LANGUAGE , "English" ) )
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To avoid including irrelevant documents, for example from medical science, the search results were filtered to remove the subject areas far from "Energy" like "Medicine", "Nursery", "Computer Science", "Arts and Humanities", etc. On the other hand, since "energy" is a multidisciplinary topic, such subject categories as "Engineering", "Chemistry", "Environmental Science", "Social Science", "Material Science", etc. remain under consideration.

The query search on September 25, 2020, gives 111 260 documents including 106 124 research articles and 5 136 reviews. Fig. 1 presents the documents' growth statistics by years. Fig. 2 shows the distribution by countries, and by most productive sources like "IEEE Transactions on Power Systems", "International Journal of Electrical Power and

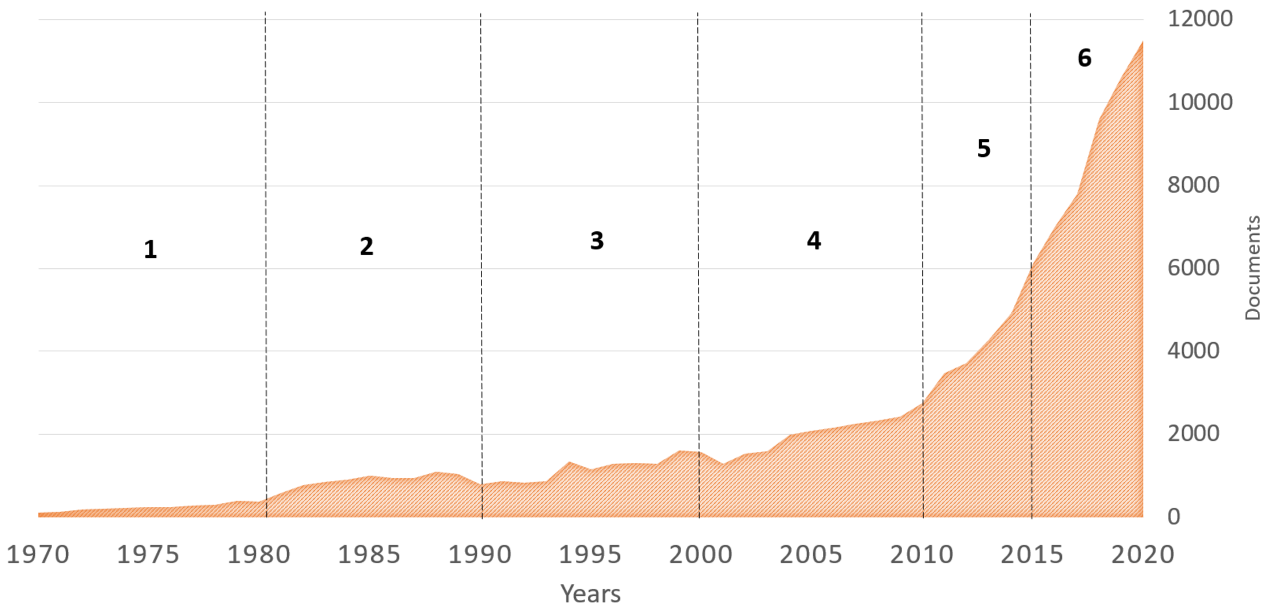

Fig. 1. Published documents growth on the field of energy systems research in the Scopus database within 1970-2020 divided into six periods.

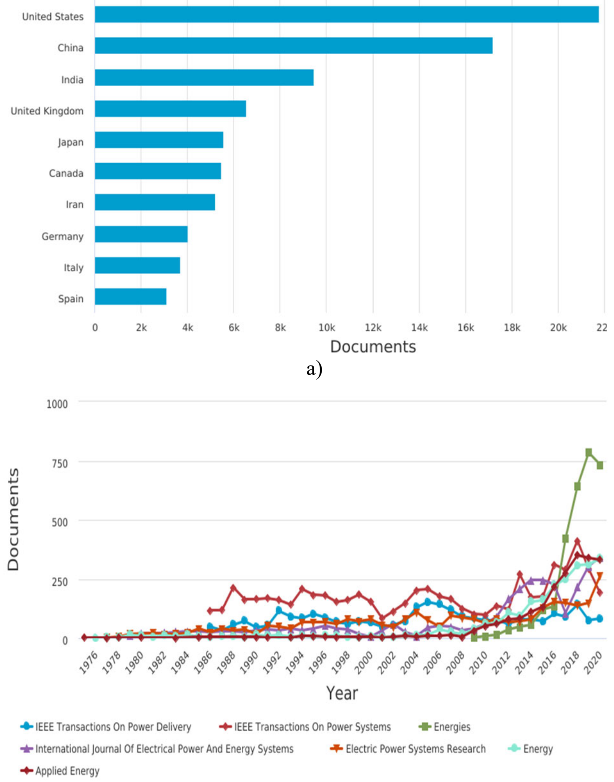

Fig. 2. The number of documents on energy systems research in the Scopus database during 1970–2020 (a) country distribution, (b) most productive journals with more than 2000 documents over the entire period. The figures are received with the standard Scopus analyzer tool.

Energy Systems", "Energies, Electric Power Systems Research", "IEEE Transactions on Power Delivery", "Energy" and "Applied Energy".

To track topic changes in the knowledge domain, it is necessary to divide the entire period under consideration into characteristic time intervals. Analyzing the publication activity growth in Fig 1 we can roughly divide 50 years' interval into decades. Due to expansive publication growth, the last decade should be subdivided into two 5 years' periods in such a way as presented in Table 1. The research history of energy systems in the past 50 years can be divided into four stages: the early period 1970s with low publication activity, the foundation period (1980-2000) with light publication growth, mature stage (2001-2010), and big data era after 2010, when explosive publication growth is observed.

To investigate key topics and their corresponding interrelations the study uses a scientometric technique, namely, co-term analysis. We employ keywords co-occurrence analysis, which is one of the basic capabilities of VOSviewer open software developed by N.J. Van Eck and L. Waltman [6] from Leiden University for scientometric analysis. VOSViewer software is widely used by researchers as a powerful analytical tool in scientometrics [7].

There are many applications of VOSviewer in the energy field, for example, to assess global research and trends in renewable energy [8, 9], in bioenergy and biomass utilization [10, 11]. VOSviewer software is used to obtain results of co-word and cluster analysis of keywords of the papers published in the journal *Renewable Energy* to track 5 major clusters during 20 years' timeline 1990-2010 [12].

The perfect investigation of worldwide scientific production can be found in [13], where hot research topics of renewable energy technologies such as solar, wind, geothermal, hydro, and biomass are considered along temporal dimension for 1992-2011.

The article [14] describes a bibliometric overview of the several periods of academic research on the multidisciplinary field as knowledge management.

Advanced features are available in VOSviewer such as co-authorship, keyword co-occurrence, bibliographic linkage, and a co-citation network to represent bibliometric

Table 1. Statistics of data used for network visualization by periods.

#	Years	Documents	Period	Term (keywords)	Terms (keywords) with occurrences > 5	Links between keywords
1	1970 - 1979	2246	Early-stage. Low publication activity	2749	180	922
2	1980 - 1989	8445	Foundation stage. Small publications growth	20490	1026	14415
3	1990 - 1999	11313		34262	2216	34262*
4	2000 - 2010	19201	Mature period. Sustainable publication growth	65703	5780	117359*
5	2010 - 2015	25233	Big Data Era. Explosive publications growth	92143	11746	153382*
6	2016 - 2020	46491		134236	18360	205000*

* Total number of links between 1000 "hottest" keywords.

relationships between authors and between document terms. The main algorithms built-in into VOSviewer include a unified approach to mapping and bibliometric network clustering. VOSviewer software pays special attention to displaying large science maps in an easy-to-interpret way.

Besides, VOSviewer allows the use of a thesaurus file, which allows the user to clean the irrelevant data or unify the synonymic terms. In our study, the general terms like “article”, “review”, “journal”, “study”, geographical names, and so on were excluded from the total keywords list. The various forms of the term related to keywords with the same meanings were merged into a single term to resolve the issues caused by synonyms, singular/plural, hyphenated or unhyphenated descriptors, etc.

III. Mapping and visual analysis of energy systems research

All keywords were extracted from the bibliographic dataset of collected articles and reviews. Keywords provided by authors of the paper and occurred more than 5 times were enrolled for the final analysis. For each keyword, the total strength of the co-occurrence links with other keywords was calculated.

Figures 3-8 presents the keyword network maps generated separately for the periods from Table 1. In the maps, the sizes of the label font and the sizes of the circles are depending on the number of documents associated with each keyword. The maps display the most prominent 1000 terms to avoid overlap and unappropriated mixing. The term "electric power system" is hidden from all maps as the basic search term which is not informative and of too much weight in comparison with other keywords. The term "renewable energy" is hidden from the maps of periods 2010-2020 (see Figs. 7-8) so as not to conceal the underlying knowledge structures of renewable energy sources.

After that, the clustering analysis was applied to evaluate the main topic clusters. Color of labels and circles are used to distinguish the different clusters. All maps on the figures were constructed using VOSviewer software [6].

The map of co-occurrence keywords for the 1970s period (see Fig. 3) shows us several recognizable clusters related to most considered issues such as “system stability”, “electric power transmission”, “solar energy” and “mathematical modeling” and “oil hydraulic”.

The second map reflecting energy systems research of the 1980s (see Fig. 4) is much denser than the previous. All main topics of the 1970s remain, but it’s observed the new semantically closest terms are grown. For example, “transient stability” is one of the forms of “system stability”. The terms “computer programming” and “computer simulation” correspond to “mathematical modeling” in the cluster of research approaches. The cluster of renewable energy sources “solar energy” and “wind energy” is identified more clearly on the right side of the keyword cloud, but as shown in Fig. 4 the all clustered themes are intersected and quite mixed.

One of the "hottest" keywords that appeared in the 1990s is "optimization". Researchers focus on optimal economic management and power flow dispatch control using non-linear programming, stochastic programming, genetic algorithms, and other approaches to attain a high system efficiency of electric power generation, transmission, distribution in electric power systems.

The topic map of the 1990s on Fig. 5 outlines four main clusters related to different domains of knowledge:

(A) research methodology and tools (blue and violet colors) in the top part of the keyword network;

(B) electric power systems control issues as the yellow cluster on the left side of the map;

(C) terms of renewable energy sources as the green cluster on the right side;

(D) the intermediate red cluster of the keywords describing electric power equipment properties.

As seen further these four clusters are still paid to the attention of researchers now.

The knowledge map of the 2000s keeps the semantic core of general research methodology based on common “mathematical models”, “computer simulation” and “optimization” terms as shown in Fig. 6. Additionally, the “artificial neural network” approach is a newcomer, which is used to solve problems such as fault detection on transmission lines and distribution, fast power harmonic identification, the prediction of electric loads and wind power generation, etc. The renewable energy green cluster includes a new area addressed to “energy utilization/efficiency” and “energy policy” topics challenged by carbon dioxide emission and climate change.

The trends of the first half of the 2010s illustrate a significant expansion of the renewable energy field as shown in Fig. 7. One of the central themes is “wind energy” linked with “photovoltaic system”, “energy storage” (or batteries), “fuel cells”. Such semantic interrelation leads later to the conception of “hybrid energy systems” appearing on the next map of 2016-2020. Of course, the renewable energy concepts have strong linkages to the conventional issues: system stability, electric power transmission and generation, computer simulation, optimization, stochastic system, and others.

Fig. 8 presents a state-of-arts or research frontier summarizing all recent main hot topics. “Optimization”, “stochastic system”, “uncertainty analysis”, “electric power system control”, “electric power transmission”, “electric load flow”, “power system stability”, “power quality”, “smart grid” as a newcomer, and wind/solar energy sources, energy storage with the respective components are a set of most popular keywords.

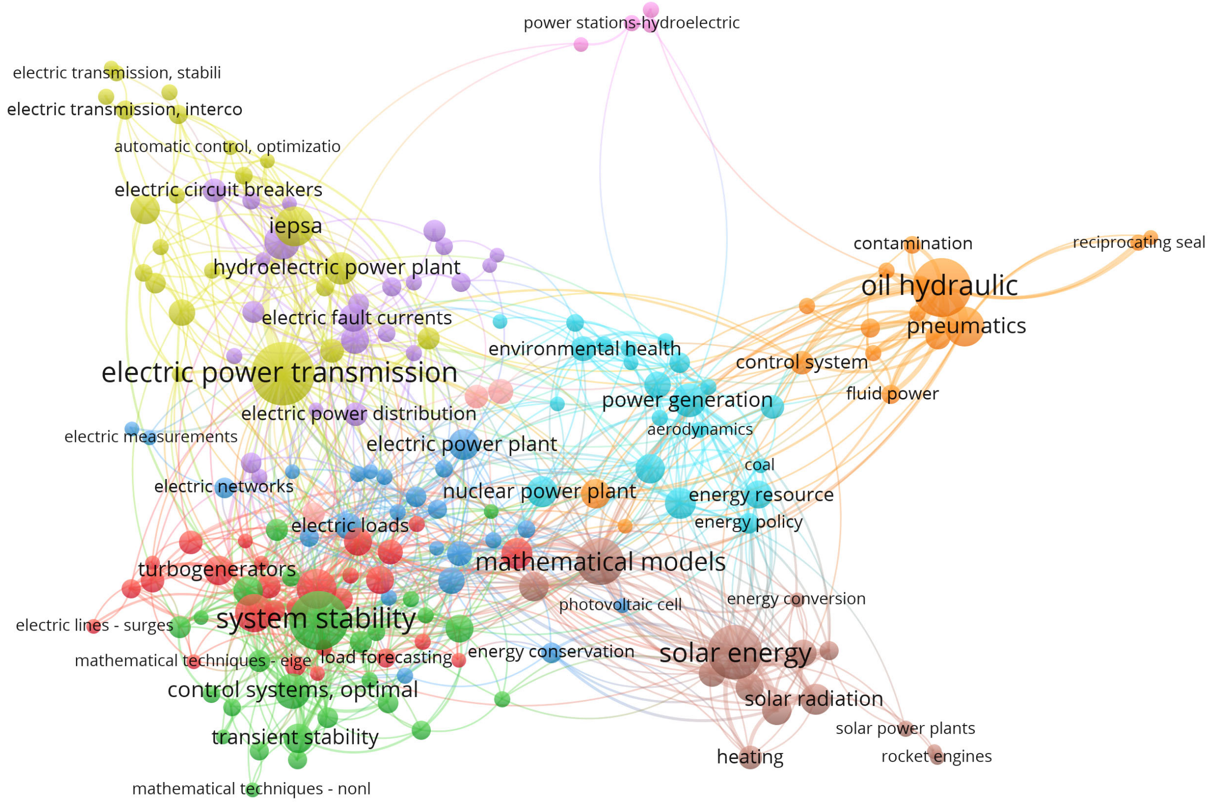

Fig. 3. Knowledge mapping of energy systems research for the 1970s.

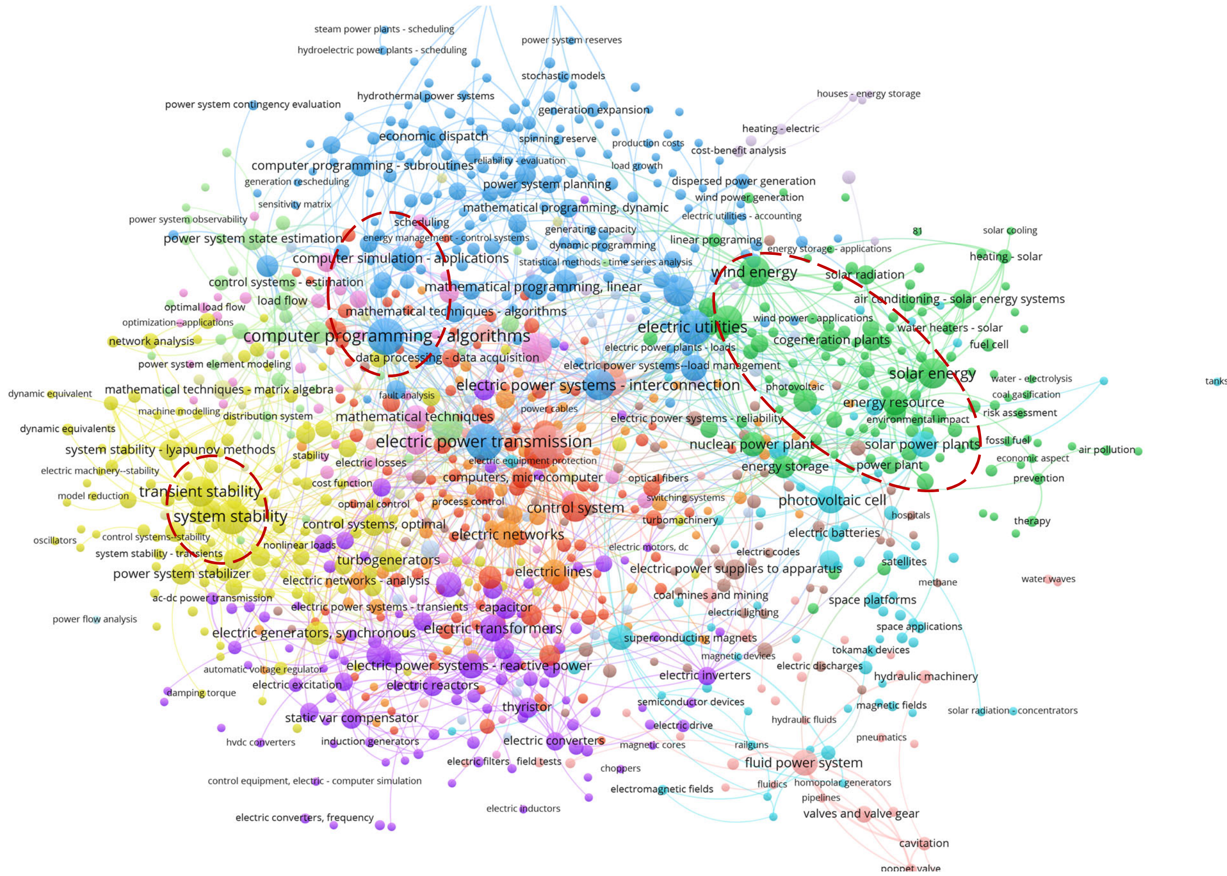

Fig. 4. Knowledge mapping of energy systems research for the 1980s.

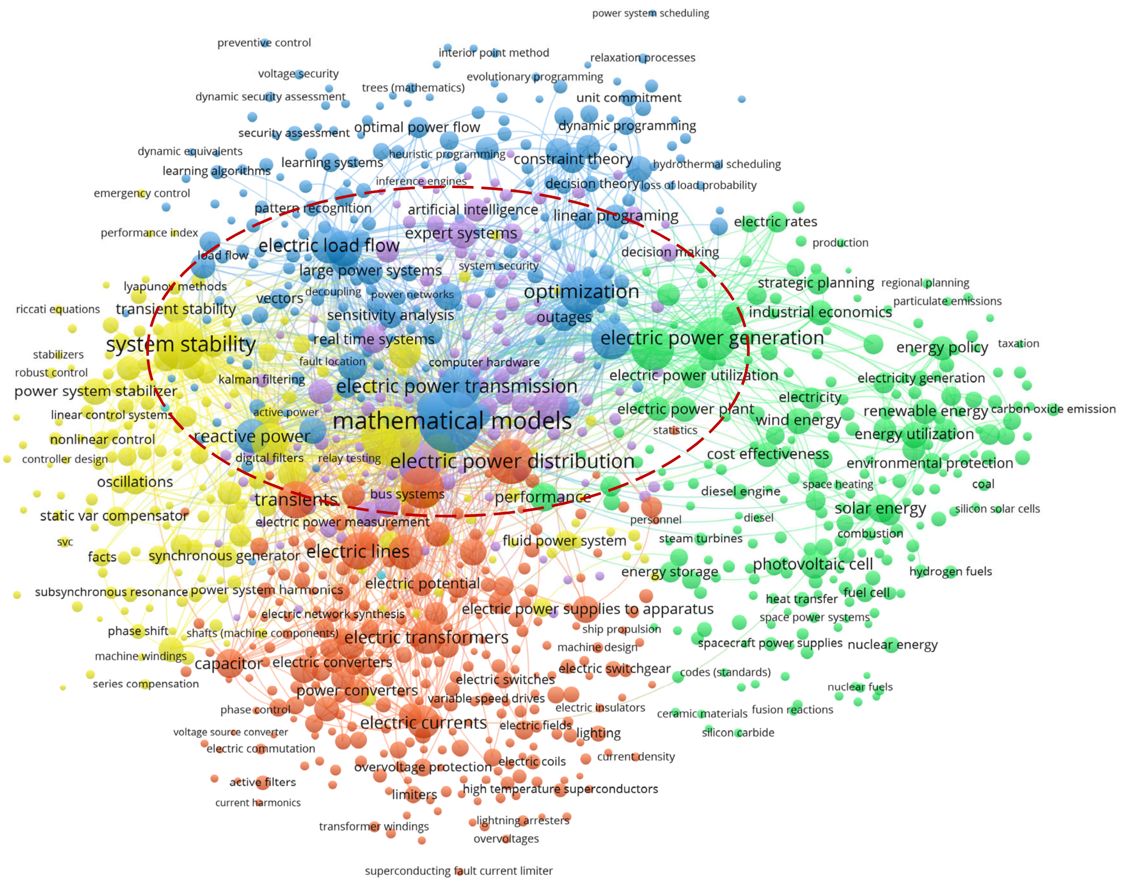

Fig. 5. Knowledge mapping of energy systems research for the 1990s.

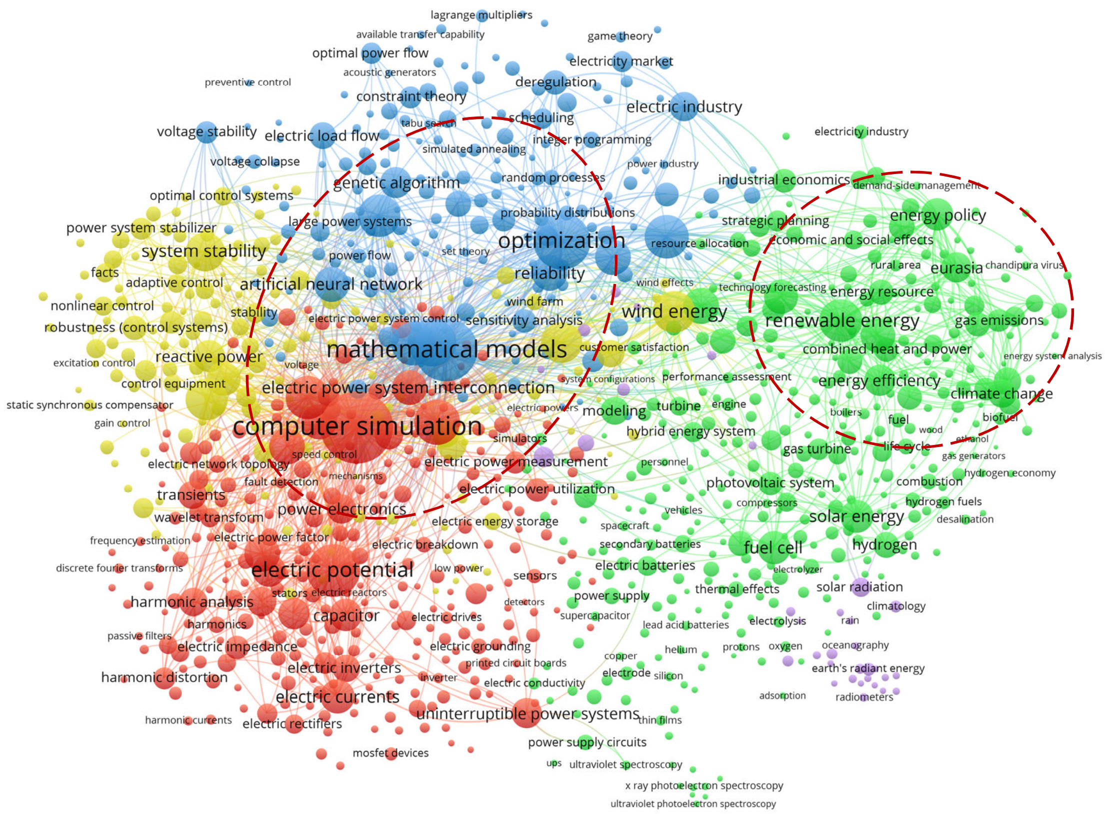

Fig. 6. Knowledge mapping of energy systems research for the 2000s.

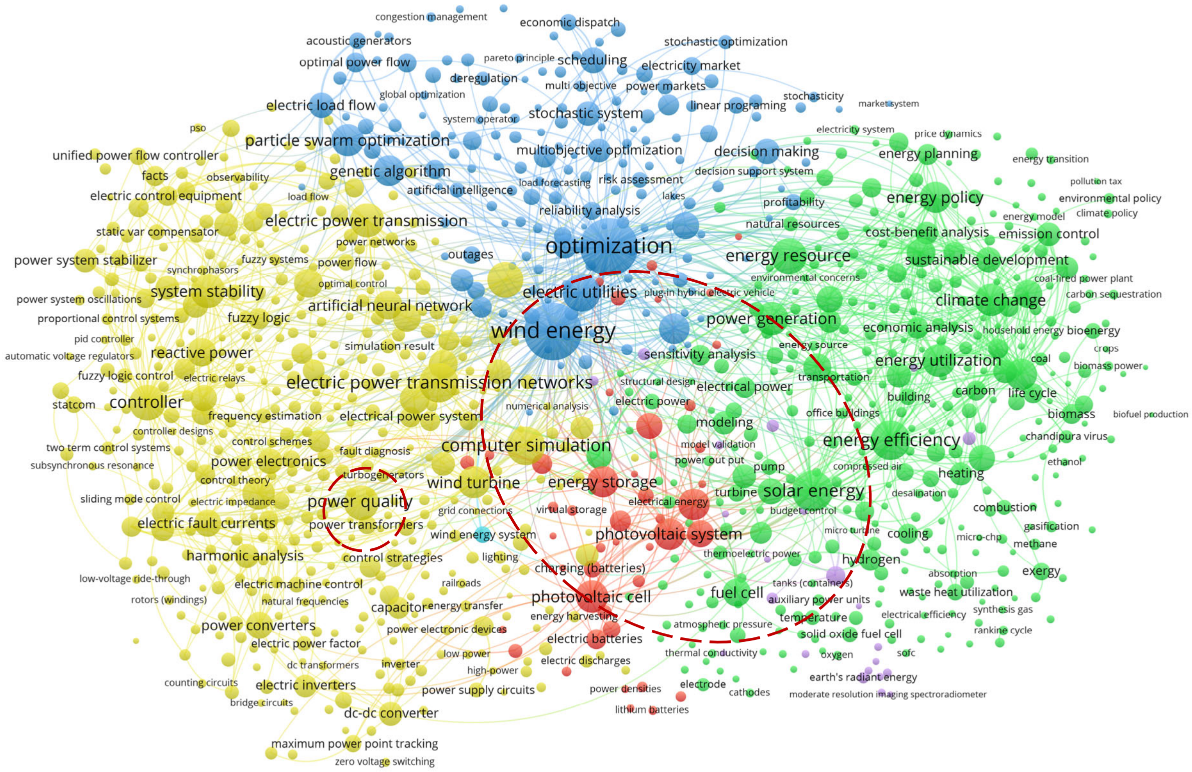

Fig. 7. Knowledge mapping of energy systems research for 2010-2015.

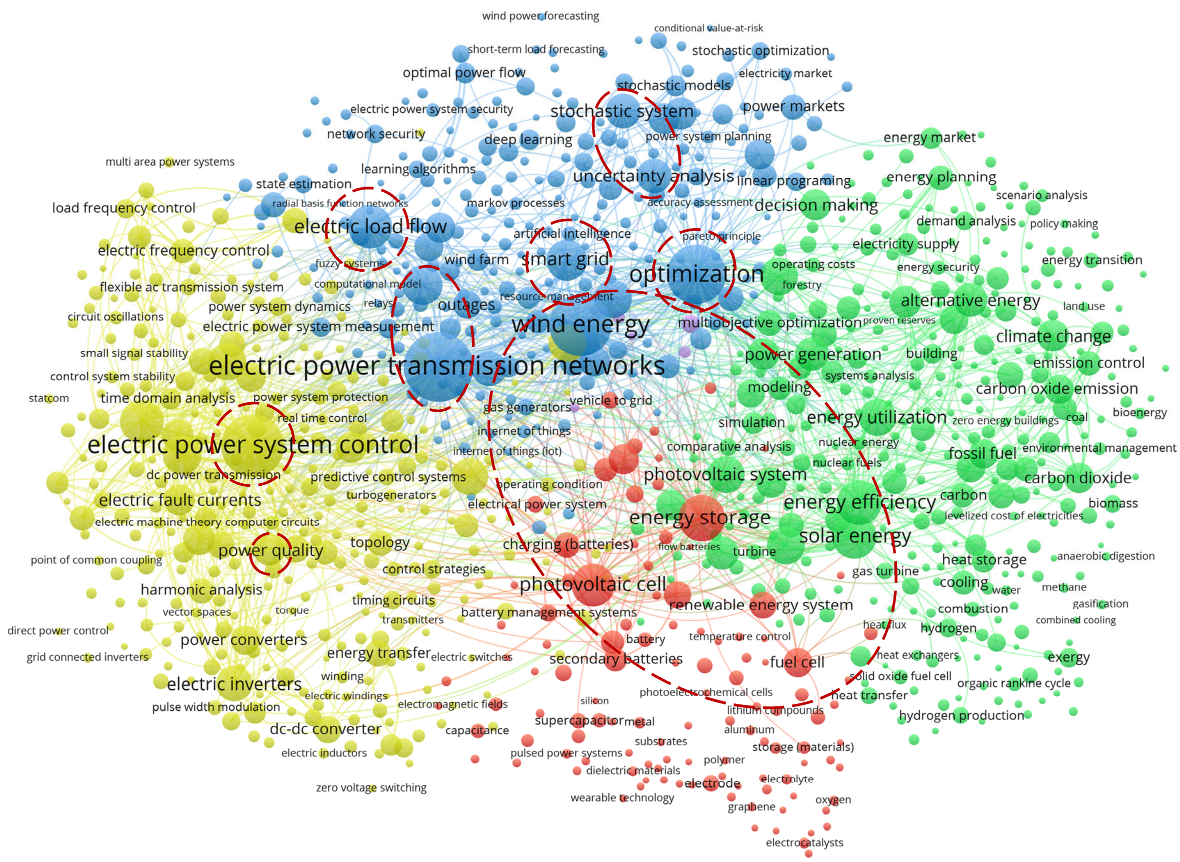

Fig. 8. Frontier of key research topics on energy systems for 2016-2020.

IV. Conclusions

This work presents an overview of energy systems research for the last 50 years through an exhaustive bibliometric analysis of scientific literature including more than 100,000 articles and reviews from the Scopus database. The science mapping approach is used as the main bibliometric method with further visual analysis using the co-citation technique and co-occurrences of keywords. This analysis was conducted using the VOSviewer software.

In opposite to the other bibliometric studies in energy this analysis mainly focuses on the transformation of the conceptual structure of the "energy systems/power systems" theme over a long period. Thus, the general topic hotspots and development trends in the research of energy systems were evaluated and visualized. It should be noted since the semantic meaning of basic terms the study concerns mainly electric power systems, but not energy systems in general. Energy systems related to heat supply and different kinds of perspective fuel supply (natural gas, hydrogen, methanol, etc.) were poorly considered in the study.

The study represents dynamics of most common topics of the knowledge domain, but more deep semantic structures and their interrelations have remained outside of the consideration yet. The quantification and classification of the multidisciplinary and complex field of energy systems are not simple. Future work implies the use of pre-designed hierarchical ontology to overcome the existing gaps and to build an adaptive semantic model of developing the knowledge domain of energy systems.

The results of the study were presented and discussed at the conference "Energy-21: Sustainable Development & Smart Management", September 7-11, 2020, Irkutsk, Russia.

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