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The Linear Programming Problem of Regional Energy System Optimization

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ABSTRACT

The paper contributes to the literature by developing a linear programming (LP) model for optimization of the development of the regional energy system according to environmental and economic criteria by involving various types of renewable energy sources in the energy balance. The environmental criteria are taken into account throughout the entire life cycle of each energy product. Validation of the model was carried out on the example of a large southern region of Russia - Krasnodar Territory. This region was chosen for testing for several reasons: firstly, the region has significant potential for the development of various types of renewable energy sources, including solar and wind energy, hydro- and geothermal energy, rich biological resources, as well as a large number of bio-waste that can be considered as resources for bioenergy. Secondly, the Krasnodar Territory is currently one of the most densely populated and dynamically developing regions of Russia, experiencing a serious energy shortage and problems with air quality in large cities. The solution of the LP problem shows that when optimizing the development of the regional energy system of the Krasnodar Territory in terms of economic parameters, it is advisable to include bio-waste and municipal solid waste as priority energy sources. Solar power generation is involved in development on a leftover basis in order to make up the difference between the already used renewable energy sources and the required heat and electricity demand. When optimizing the energy balance according to environmental criteria, the involvement of biogas in the energy balance becomes impractical, therefore, after the complete use of the potential for processing solid waste and wind energy, the gap between the used potential of renewable energy sources and the required volume of generation can be replenished through the development of photovoltaics.

Keywords: Regional Energy System, Energy Balance, Environmental Footprint, Product Life Cycle Analysis, Linear Programming, Simplex Method, Shadow Prices
JEL Classifications: O44, Q01

1. INTRODUCTION

Nowadays many countries around the world are seeking to optimize their energy systems to achieve their stated national climate policy goals. Various opportunities for increasing renewable electricity and heat generation, transferring transport to alternative fuels are considered as directions for possible optimization (Song et al., 2012; Daraei et al., 2019; Siala et al., 2019; Li et al, 2020; Haikarainen et al., 2020; Ratner et al., 2020). At the same time, when choosing possible directions for development, the main optimization criteria are most often considered the cost of energy, technological accessibility and environmental impact that arise in the process of generation and consumption of energy (Karlsson et al., 2009; Zhang et al., 2018; Titova and Ratner, 2019; Siala et al., 2019; Daraei et al., 2019). Given the heterogeneity of the spatial distribution of energy resources available for use by the energy system, first, the heterogeneity of the distribution of renewable energy sources, such optimization problems must be solved at the local level, considering all possible options for involving renewable energy resources in the energy balance. For regions with a wide variety of renewable energy sources that are potentially available for involvement in the energy balance, such a task may become too complex to be solved with simple decision making methods, without involving mathematical modeling (Zhou et al., 2015; Larin et al., 2019). In addition, the optimization problem becomes significantly more complicated when the environmental parameters of each potential renewable energy source are taken into account throughout the entire life cycle “from cradle to grave” and not only in terms of influence on the climate, but also in categories (Turconi et al., 2013). Well-known examples of such important environmental categories that often have trade-off in energy technologies are water use and land use (Hoang et al., 2018; Ratner, and Lychev, 2019; Iosifov and Ratner, 2018; Zhen et al., 2020).

The purpose of this study is to develop an economic and mathematical model that allows optimizing the development of the regional energy system according to environmental and economic criteria by involving various types of renewable energy sources in the energy balance. In this case, environmental criteria are taken into account throughout the entire life cycle of the production of an energy product. This is the main difference between our work and other studies, which solve the problem of optimizing the energy balance in any territory.

To assess the environmental impact of the involvement of renewable energy sources in the energy balance, the life cycle analysis methodology was used in accordance with international standards ISO 14000 (Amponsah et al., 2014; Aitor and Rodriguez, 2016). To assess the economic impact, the input-output method was used (Ratner and Nizhegorodtsev, 2018; Liu et al., 2020; Ratner and Zaretskaya, 2020; O’Mahony, 2021). The energy balance was optimized by solving the linear programming problem using the simplex method. The main advantage of this approach to solving the problem of selecting renewable energy sources for subsequent involvement in the energy balance is the ability to analyze shadow prices.

Validation of the proposed linear programming model was carried out on the example of a large southern region of Russia - Krasnodar Territory. This region was chosen for testing for several reasons: firstly, the region has significant potential for the development of various types of renewable energy sources, including solar and wind energy, hydro- and geothermal energy, rich biological resources, as well as a large number of biowaste that can be considered as resources for bioenergy (Ratner et al., 2018; Ratner et al., 2020). Secondly, the Krasnodar Territory is currently one of the most densely populated and dynamically developing regions of Russia, experiencing a serious energy shortage and problems with air quality in large cities (Ratner and Zaretskaya, 2018). Therefore, solving the problem of optimizing the energy balance of a given region is an urgent practical task.

The rest of the paper is organized as follows: in Section 2 we describe basic methodology approaches and formulate LP problem; Section 3 gives an overview of the research background, in particular, main trends and status-quo of renewable energy technologies development in in the region under the study; in Section 4 presents the results of LP problem for Krasnodar region and discusses some policy recommendations; final Section concludes the study and discusses its added value for academic literature.

2. METHODOLOGY

In order to identify the optimization problem of the regional energy system, first of all, we will formulate optimization criteria, namely, the objective function for the cost of energy for the consumer and the objective function for the negative environmental impact of the regional energy system which would take into account the negative effects of all stages of the life cycle of an energy product: form the stages of extraction, production and transportation to the stages of direct consumption and disposal.

We represent the objective function of the total cost of all consumed energy products as:

$$\sum_{i=1}^{K}\alpha_i V_i^H + \sum_{i=1}^{M}\beta_i V_i^E + \sum_{i=1}^{L}\gamma_i V_i^F \rightarrow \min \quad ,$$

Where

α_i is the cost of heat energy produced by the *i*-th method (RUB/Gcal);

β_i is the cost of electricity generated by the *i*-th method (RUB/kWh);

γ_i is the cost of motor fuel produced by the *i*-th method (RUB/l).

V_i^H, V_i^e, V_i^f are the volumes of heat, electric energy and fuel produced by the *i*-th method, respectively; *K, M, L* - the number of available technologies for the production of heat, electrical energy and motor fuel, respectively.

Let us present the target function of the cumulative negative environmental impact (in a simplified version, the carbon footprint) of the production and consumption of all energy products as:

$$\sum_{i=1}^{K}(\tilde{n}h_i^{prod} + ch_i^{cons})V_i^H + \sum_{i=1}^{M}(ce_i^{prod} + ce_i^{cons})V_i^e$$
$$+\sum_{i=1}^{L}(cf_i^{prod} + cf_i^{cons})V_i^F \rightarrow \min \quad ,$$

where

ch_i^{prod} is a carbon footprint of production of a unit of thermal energy by the *i*-th technology (kg CO_2/kcal);

ch_i^{cons} is a carbon footprint of consumption of a unit of thermal energy produced by the *i*-th technology (kg CO_2/kcal);

ce_i^{prod} is a carbon footprint of production of a unit of electrical energy by the *i*-th technology (kg CO_2/kWh);

ce_i^{cons} is a carbon footprint of consumption of a unit of electrical energy produced by the *i*-th technology (kg CO_2/kWh);

cf_i^{prod} is a carbon footprint of production of a unit of motor fuel by the *i*-th technology (kg CO_2/l);

cf_i^{cons} is the carbon footprint of consumption of a unit of motor fuel produced by the *i*-th technology(kg CO_2/l).

For a more complex version of the formulation of the optimization problem, taking into account not only greenhouse gas emissions, but also other categories of environmental impact, the objective function will have the following form:

$$\sum_{i=1}^{K}(\sum_{j} imh_{ij}^{prod} + \sum_{j} imh_{ij}^{cons})V_i^H + \sum_{i=1}^{M}(\sum_{j} ime_{ij}^{prod}$$
$$+\sum_{j} ime_{ij}^{cons})V_i^e + \sum_{i=1}^{L}(\sum_{j} imf_{ij}^{prod} + \sum_{j} imf_{ij}^{cons})V_i^F \to \min$$

where imh_{ij}^{prod} is the amount of the *j*-th negative environmental impact from the production of a unit of thermal energy by the *i*-th technology. According to the ReCiPe method used by the international organization EcoInvent, all negative environmental impacts can be measured in unified eco-points, which allows to summarize them;

imh_{ij}^{cons} is a carbon footprint of consumption of a unit of thermal energy produced by the *i*-th technology (kg CO_2/kcal);

ime_{ij}^{prod} is a carbon footprint of production of a unit of electrical energy by the *i*-th technology (kg CO_2/kWh);

ime_{ij}^{cons} is a carbon footprint of consumption of a unit of electrical energy produced by the *i*-th method (kg CO_2/kWh);

imf_{ij}^{prod} is a carbon footprint of production of a unit of motor fuel by the *i*-th method (kg CO_2/l);

imf_{ij}^{cons} is the carbon footprint of consumption of a unit of motor fuel produced by the *i*-th method (kg CO_2/l).

We will formulate the balance between the production of energy products and the demand for them using the following constrains (restrictions on functionality):

$\sum_{i=1}^{K} V_i^H \geq V_T^{HP}$ the total volume of heat production from all potential sources is not less than the volume of consumption in year *T*;

$\sum_{i=1}^{M} V_i^e \geq V_T^{EP}$ the total volume of electricity production from all potential sources is not less than the volume of consumption in year *T*;

$\sum_{i=1}^{L} V_i^F \geq V_T^{FP}$ the total volume of fuel production from all potential sources is not less than the volume of consumption in the year *T*.

Year *T* can be considered the year for which the latest statistics for the region are available. Note that such a formulation of restrictive conditions imposes only the requirement to produce each of the main types of energy products (electrical energy, thermal energy and motor fuel) in volumes no less than real demand. Surplus production is possible; in this case, it is assumed that the surplus of manufactured products is sold outside the region, and financial receipts from the sale of energy products are taken into account in the GRP. In the event of an increase in the energy efficiency of the regional economy and, as a result, a decrease in the consumption of heat, electric energy and motor fuel (which is unlikely given the rebound effects), excess volumes of produced energy products can also be sold on foreign markets.

Let us now formulate a set of constrains for the productivity of the regional energy system. Taking into account the studied spectrum of potential industrially mature renewable energy technologies (solar, wind, waste-to-energy, biogas production from animal waste, biofuel production from crop and fish farming waste), these restrictive conditions can be formulated as follows:

$S^{PV}+S^{SC}\leq S^{cit}$ the area for installing solar panels S^{PV} and the area for installing solar collectors S^{SC} is not more than the building area (it is assumed that the use of agricultural and forest land, as well as lands of specially protected natural areas for the construction of solar power plants is unacceptable);

$S^{Wand}\leq S^{Class}$ the area for the installation of wind generators is not more than the area of territories with a suitable wind class;

$V_{garb}^{e} \leq k_{garb}^{el} V_{garb}$ the volume of electricity production at waste incineration plants is not more than the product of the plant productivity factor k_{garb}^{el} by the volume of solid domestic waste generation V_{garb} in the region;

$V_{LW}^{e} \leq k_{LW}^{el} V_{LW}$ the volume of electricity production at biogas plants is not more than the product of the plant productivity factor k_{LW}^{el} by the volume of livestock waste V_{LW} generated in the region;

$V_{PW}^{f} \leq k_{PW}^{f} V_{PW}$ the volume of biofuel production is not more than the product of the plant productivity factor k_{PW}^{f} by the volume of crop waste in the region V_{PW}.

Considering that constrains on the area for installation of solar panels and collectors, as well as wind turbines, are ultimately restrictions on the potential volume of heat and electricity production, we rewrite them in the following form:

$$\frac{1}{\tau}V^{PV} + \frac{1}{\mu}V^{SC} \leq S^{city},$$

$$\frac{1}{l}V^{Wind} \leq S^{class},$$

where τ is the average annual productivity of solar panels per unit area (Wh/m^2); μ is the average annual productivity of solar collectors per unit area (cal/m^2); l - average annual productivity of wind turbines per unit area (Wh/m^2).

Thus, we have the following linear programming problem in general form:

$$\sum_{i=1}^{K}\alpha_i(\sum_{j} imh_{ij}^{prod} + \sum_{j} imh_{ij}^{cons})V_i^H + \sum_{i=1}^{M}\beta_i(\sum_{j} ime_{ij}^{prod}$$
$$+\sum_{j} ime_{ij}^{cons})V_i^e + +\sum_{i=1}^{L}\gamma_i(\sum_{j} imf_{ij}^{prod} + \sum_{j} imf_{ij}^{cons})V_i^F \to \min(1)$$

Subject to

$$\sum_{i=1}^{K} V_i^H \geq V_T^{HP};\quad \sum_{i=1}^{M} V_i^e \geq V_T^{EP};\quad \sum_{i=1}^{L} V_i^F \geq V_T^{FP}; \tag{2}$$

$$\frac{1}{\tau}V^{PV} + \frac{1}{\mu}V^{SC} \leq S^{city};\quad \frac{1}{l}V^{Wind} \leq S^{class};$$

$$V_{garb}^{e} \leq k_{garb}^{el} V_{garb};\quad V_{LW}^{el} \leq k_{LW}^{el} V_{LW};\quad V_{PW}^{f} \leq k_{PW}^{f} V_{PW};$$

$$V_i^H \geq 0,\quad V_i^e \geq 0,\quad V_i^f \geq 0.$$

3. THE FORMULATION OF LP PROBLEM FOR KRASNODAR REGION

In order to concretize the constrains and the objective functions of the linear programming problem, let us consider in more detail the status and development prospects of the energy system of the Krasnodar Territory.

The Krasnodar Territory is considered the most attractive region in Russia in terms of its climatic characteristics for the development of renewable energy, which can replace up to 22 GWh of thermal energy and 13 GWh of electric energy currently produced from hydrocarbon fuel. However, the total installed capacity of renewable energy facilities in the Krasnodar Territory currently stands at about 220 MWh (Iosifov et al., 2020).

On the territory of the region, heat supply to the population and social facilities is provided by 2801 boiler houses and 3320 km of heating networks. The installed capacity of boiler houses of heat supply enterprises is 6076 Gcal/h (7066 MW), the connected load is 4911 Gcal/h (5711 MW). The average utilization rate of the installed capacity of boiler houses in the region is 80%. The volume of sales (productive supply) of heat energy per year by all heat supply enterprises is 7.2 million Gcal.

The consumption of motor fuel in the region (according to 2015 data) is 2.3 million tons. At the same time, it is mainly consumed fuel produced directly in the region. Thus, five large oil refineries in the region (Krasnodar Refinery, Afipsky Refinery, Tuapse Refinery, Slavyansky Refinery, Ilsk Refinery), according to 2018 data, reached 25,414.8 thousand tons of annual refining volume. Oil refineries produce gasoline, winter and summer diesel fuel, jet fuel, marine fuel, fuel oil, gas condensate distillate, malonaft, bitumen. According to the data presented on the official websites of these refineries, the average refining depth ranges from 77% to 85%, which makes it possible to estimate the volume of produced motor fuel of various types and environmental classes at about 19.57 million tons. Such production volumes fully satisfy even the growing local demand for motor fuel and other types of petroleum products and allow exporting products outside the region, including abroad.

Thus, the Krasnodar Territory is experiencing the greatest shortage of electricity (fig. 1), and not motor fuel (which is produced much more than consumed) or thermal energy. Therefore, to simplify the formulated linear programming problem, we can restrict ourselves to modeling the optimal option to compensate for the deficiency in electricity production. Then, in a simplified formulation, the linear programming problem will take the form:

$$\sum_{i=1}^{M} \beta_i \Big(\sum_j ime_{ij}^{prod} + \sum_j ime_{ij}^{cons}\Big) V_i^e \rightarrow \min \tag{3}$$

Subject to

$$\sum_{i=1}^{M} V_i^e \geq V_T^{EP}; \tag{4}$$

$$\frac{1}{\tau}V^{PV} + \frac{1}{\mu}V^{SC} \leq S^{city};\quad \frac{1}{l}V^{Wind} \leq S^{class};$$

$$V_{garb}^{e} \leq k_{garb}^{el} V_{garb};\quad V_{LW}^{el} \leq k_{LW}^{el} V_{LW};\quad V_i^e \geq 0.$$

We estimate the cost of generating electricity from renewable sources (RES) based on data on the potential productivity (*prod*) of the generating source (in particular, the installed capacity utilization factor (*ICUF*) for photovoltaic panels and wind turbines), capital (*CapCost*) and operational (*ExpCost*) costs and expenses for the transportation of electricity through the grid (*trans*) according to the formula:

$$COST = \frac{Cap\,\mathrm{Cos}\,t + Exp\,\mathrm{Cos}\,t * year}{prod * year} + trans$$

Where *year* is the minimum service life of the generating equipment.

Discounting was not used in the calculations. The data on capital costs and operating solar and wind projects were estimated based on the official information of JSC "Administrator of the Wholesale Electricity Market Trading System" on the results of the competitive selection of renewable energy projects, which are supported within the framework of Government Decree 449 of May 28, 2013 (https://www.atsenergo.ru). Data on the capital and operating costs of projects for biogas generation and generation through the processing of municipal solid waste (MSW) are obtained from the literature.

Data on the negative environmental effects of energy production were assessed in accordance with the Life Cycle Analysis methodology, which involves the identification, measurement and aggregation of all negative impacts of production processes (including all redistributions), transportation, operation and disposal of products, starting as usually from the stages of extraction of raw materials.

In this study, the methodology of life cycle analysis and assessment is applied in accordance with the requirements of the international standard ISO 14040-14042. The information base of the study was the data presented in the EcoInvent aggregator. EcoInvent is currently the world's leading Life Cycle Assessment (LCA) framework in accordance with ISO 14040-14043 standards and contains lifecycle datasets of more than 12,800 products and services. In an expanded form, data on the negative environmental effects of the product life cycle are presented in the EcoInvent aggregator by seven categories of environmental impact: (1) Oxidation, (2) climate change, (3) freshwater and marine eco-toxicity, (4) human toxicity, (5) ionizing radiation, (6) land use (withdrawal of their turnover of productive lands, reduction of forest area, loss of biodiversity), (7) stratospheric thinning of the ozone layer. In a simplified version, the negative impact on the environment can be assessed (and in most literary sources it is assessed) only in the category of "climate change," since it is the climatic effects of various technologies that are currently regulated by numerous international standards.

The results of the conducted meta-analysis of data from literary and statistical sources on the technical, economic and environmental parameters of modern renewable energy sources in Russia are shown in Table 1.

Taking into account the obtained estimates, it is possible to formulate the restrictive conditions for optimization problems (3) and (4) as follows:

$$V_{garb}^{e} \leq 1152000$$
$$V^{PV} \leq 5800000$$
$$V^{wind} \leq 1060000000$$
$$V_{LW}^{e} \leq 218000000$$

Taking into account the formulated constraints, problems (3) and (4) are classical linear programming (LP) problems in which the decision variables are the volumes of electricity generation. We solve this LP by well-known simplex method, used in standard Microsoft Excel (Solver).

4. RESULTS AND DISCUSSION

According to the Ministry of Energy of the Krasnodar Territory, the strategic goal of the development of the region's energy system is to gradually increase its own power generation by maximizing the involvement of available renewable energy sources in the energy system. Let us find the optimal share of each of the available RES in the following cases: (1) If the optimization is performed only by cost parameters (simplified formulation of the problem); (2) if optimization is carried out only according to environmental parameters (simplified formulation of the problem); (3) in the case of simultaneous optimization in terms of environmental and economic parameters (complete statement of the problem). Let us assume that at the first stage of the development of the power system, the goal is to increase generation by 3 billion kWh per year. Under this assumption, the constraint conditions for the optimization problem will change as follows:

Table 1: Literature and statistical data on technical, economic and ecological characteristics of modern renewable energy technologies

Parameter	Value	Source
Incinerator capacity	With a capacity of 150 thousand of solid wastes per year, the useful supply of electricity (excluding consumption for own needs) is 19.2 MWh	Russian Ministry of Energy
Carbon footprint (CO_2 emissions) in the production of electricity from solid waste	0.0056248 kg CO_2-equivalent per 1 kWh of generated energy	EcoInvent
Cost of electricity production from solid waste	0.1 euros (in 2005 prices) or 4.0 rubles/kWh	EcoInvent
Potential for generating electricity from solid waste	Assuming an available volumes of solid waste for processing 9 million tons annually, gives the estimated value of electricity 1.152 million kWh per year	Authors' calculations
Solar power plant performance	Assuming the available area for solar panels installations 100 hectares, capacity of 40 MW, the average capacity factor is 17%.	Orksakaya solar plant (Russia) Balashova et al., 2020
Expected cost of solar energy	Based on capital costs 59,000-122,000 rubles/kW, operating cost - 10% of capital costs, minimum service life (without degradation) 15 years, energy transportation cost 30% of the generation cost. The estimate is 5.96 rubles/kWh	Russian Ministry of Energy
Carbon footprint (CO_2 emissions) in the production and operation of photovoltaic panels	0.07 kg v-equivalent per 1 kWh of generated energy	EcoInvent
The potential for generating electricity through the use of photovoltaics	Assuming the use of 5% of the total building area in the region (200 thousand hectares)	Authors' calculations
Wind farm performance	The permissible capacity of wind power plants in the regions of the Bugaz Spit, the Taman Peninsula, the Chushka Spit, Temryuk, Anapa, Primorsko-Akhtarsk, Yeisk and the coast at the Novorossiysk-Gelendzhik section is estimated at 800-1150 MW. It is assumed that only 50% of the potential is used. Average capacity factor is 25-30%	IRENA, 2012.

(*Contd...*)

Table 1: (*Continued*)

Parameter	Value	Source
Expected cost of wind energy	Assuming capital expenditures RUB 93,000/kW, operating costs 20% of capital costs, capacity factor 15%, energy transportation costs 30% of generation costs. The estimate is 4.54 rubles/kWh	Russian Ministry of Energy
Carbon footprint (CO_2 emissions) in the production and operation of photovoltaic panels	0.016 kg CO_2-equivalent per 1 kWh of generated energy	EcoInvent
Biogas plant performance	The potential volume of biogas produced from available materials (animal waste) per year is 1010 (million cubic meters), which corresponds to the generation of electricity 100 million kWh and heat energy (additionally) 118 million kWh	Authors' own calculations
Expected cost of electricity production from biogas	Based on capital expenditures 32 million rubles for the unit with a processing capacity of 44.5 tons of waste per day, operating costs 20% of capital and the cost of waste disposal 5 thousand RUB per ton. The estimate is 1 RUB kWh. The costs of electricity transportation are not taken into account, assuming the use of generated energy near the source of generation	Authors' own calculations Titova and Ratner, 2019
Carbon footprint (CO_2 emissions) in the production and operation of biogas plants	0.298 kg CO_2-equivalent per 1 kWh of energy produced	EcoInvent

Source: Authoring

$$\begin{aligned} &V^{e}_{garb} \le 1152000 \\ &V^{PV} \le 5800000 \\ &V^{wind} \le 1060000000 \\ &V^{e}_{LW} \le 218000000 \\ &V^{e}_{garb} + V^{PV} + V^{wind} + V^{e}_{LW} = 3000000000 \end{aligned} \quad (6)$$

The results of solving the linear programming problem (3), (6) are shown in Table 2.

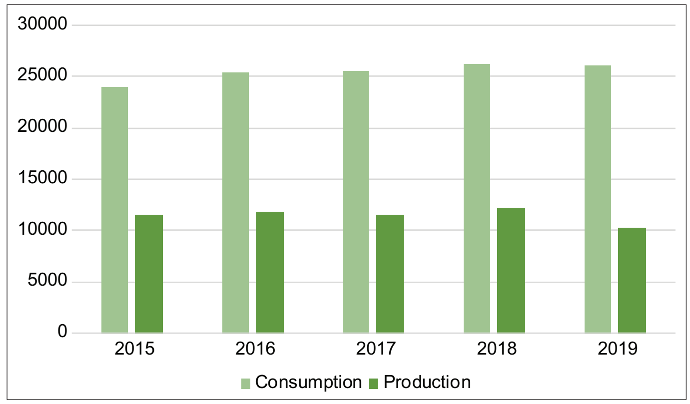
The analysis of the obtained results shows that when optimizing the development of the regional energy system of the Krasnodar Territory only in terms of economic parameters (the cost of electricity produced), it is advisable to involve in the development, first of all, in full, biowaste and municipal solid waste as energy sources, as well as to fully use the potential of the wind farm. energy. The values of the optimal volumes of use of these types of resources are equal to the maximum. Solar power generation is involved in development on a leftover basis in order to make up the difference between the already used RES potential and the required generation volume.

Table 2: Results of solving optimization problems

RES type	Optimal value (economic criteria)	Optimal value (ecology criteria)	Optimal value (complex criteria)
Waste – to - energy	1,152,000	1,152,000	1,152,000
Solar PV	1,720,848,000	1,938,848,000	1,720,848,000
Wind	1,060,000,000	1,060,000,000	1,060,000,000
Biogas	218,000,000	0	218,000,000

Source: Authoring

Figure 1: Electricity production and consumption in Krasnodar region in 2015–2019 (millions of kWh).



Source: authoring based on data from https://mintekgkh.krasnodar.ru/activity/elektroenergetika

When optimizing the energy balance according to environmental criteria (volumes of greenhouse gas emissions throughout the entire life cycle), a different picture emerges: the involvement of biogas generation in the energy balance becomes impractical, therefore, after the full use of the potential for processing solid waste and wind energy, the difference between the used potential of renewable energy sources and the required volume of generation may be replenished due to the development of photovoltaics.

With the simultaneous optimization of the development trajectory of the regional energy system in terms of economic and environmental parameters, the volumes of involvement in the energy balance of all types of renewable energy sources coincide with the volumes that were obtained when solving the optimization problem only according to economic criteria.

The results obtained are in good agreement with the results of studies by other authors on economic (Reichelstei and Yorston, 2013; Dubey et al., 2013; Comello et al, 2018) and ecological characteristics of various RES (Kim et al., 2012; Hsu et al., 2012), which allows us to conclude that the proposed approach to the choice of strategy and development of the regional energy system of the Krasnodar Territory is correct. Note that the main advantage of the proposed approach is its scalability, i.e. the possibility of taking into account a larger number of alternatives for the development of the regional energy system, including the inclusion of small hydropower, geothermal energy and other types of renewable energy sources as alternatives for the development of the energy system, as well as traditional power generation using natural gas as a fuel and innovative technologies of gas power generation using combined cycle (Combined Cycle Technology). Taking into account in the optimization models not only the electric power sector, but also the motor fuel and thermal energy sectors, while maintaining the general structure of the model, it can be transformed into a multi-sectoral one and the possible influence of the sectors of the regional energy system on each other can be traced. The development of the proposed approach in this direction is a priority for further research by the authors.

At the same time, it should be noted that even in a simplified formulation of the optimization problem, the proposed approach to choosing the optimal direction for the development of the regional energy system allows us to come to an important practical conclusion about the priority of involving waste from the housing and household sector in the energy balance of the Krasnodar Territory (through the construction and commissioning of modern waste incineration plants). factories) and the livestock sector (through the use of biogas plants).

5. CONCLUSIONS

The analysis of the results obtained shows that when optimizing the development of the regional energy system of the Krasnodar Territory in terms of economic parameters, it is advisable to involve in the development, first, bio-waste and municipal solid waste as energy sources, as well as to fully use the potential of wind energy. Solar power generation is involved in development on a leftover basis in order to make up the difference between the already used RES potential and the required generation volume. When optimizing the energy balance according to environmental criteria, the involvement of biogas generation in the energy balance becomes impractical, therefore, after the full use of the potential for processing solid waste and wind energy, the difference between the used potential of renewable energy sources and the required volume of generation can be replenished through the development of photovoltaics.

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