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MODELING ENVIRONMENTAL AND ECONOMIC FACTORS IN REGIONAL ENERGY OPTIMIZATION

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ABSTRACT: This article addresses the contemporary environmental challenges stemming from rapid economic growth, surging energy consumption, urban expansion, and mounting waste issues. The study explores the optimisation of a regional energy system, considering not only the electric energy sector but also the fuel and thermal energy sectors for the selected geographical destination. In this study, the application of the Linprog optimisation function in MATLAB programming tool to solve Regional Energy System Optimization with renewable resources is explained. The primary objective is to develop a mathematical model that identifies the optimal energy balance structure, allowing for the partial replacement of hydrocarbon sources with bioresources and waste in heat and electricity generation, as well as in vehicle fuel consumption. The modelling approach involves linear programming and integrates two key criteria: economic (cost of energy for consumers) and environmental (carbon footprint). The novelty of this approach lies in applying life cycle analysis to assess potential environmental consequences. Results reveal optimal generation volumes based on economic and environmental considerations. When optimising solely for economic criteria, municipal solid waste, along with wind energy, emerges as the preferred source. In contrast, the simultaneous optimisation of economic and environmental parameters aligns with the economic calculation, demonstrating a balanced approach to sustainable development.

KEYWORDS: regional energy system, environmental footprint, renewable energy, linear programming

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Introduction

The available literature emphasises that rapid economic growth, surges in energy consumption, urban sprawl, and mounting waste issues have led to inevitable environmental challenges (Rehman et al., 2022; Zhironkin & Cehlár, 2022). The resolution of these problems necessitates a shift in regional energy systems toward more eco-friendly technologies (Siala & Mahfouz, 2019). The persistent rise in the public's use of vehicles and heightened emissions of pollutants into the atmosphere due to congested traffic in nearly all major cities, coupled with inadequate solid household waste and sewage processing systems, contributes to environmental degradation (Cuce & Ugur, 2021; Güzel & Alp, 2020). This accumulation of waste poses additional environmental risks and leads to the deterioration of natural ecosystems and the decline in the quality of life for residents.

It is important to emphasise that, in many regions, emissions from mobile sources, particularly road transport, account for more than half of total atmospheric pollutant emissions in recent years (Turkish Statistical Institute, 2022). Municipalities produce solid waste and this volume is constantly growing in parallel with the population growth of the region. For example, Turkey has significant natural and climatic potential for widespread adoption of "clean" energy sources such as wind, solar, and hydropower in its energy mix (Ozgur, 2008). It also offers significant opportunities for the production of various biofuels and biogas, including through innovative waste and agricultural waste processing technologies. Renewable energy production has, indeed, a key role in reducing the environmental impact of small and large communities (Minelli et al., 2024).

The key research problem is to develop a mathematical model capable of identifying the optimal energy balance structure for a region, allowing for the partial replacement of hydrocarbon sources with bioresources (agricultural and processing waste) and waste (wastewater and animal husbandry waste) in heat and electricity generation processes, as well as in fuel consumption for vehicles. Previous studies (Iosifov et al., 2020; Ratner et al., 2018; Semin et al., 2019) have been conducted on regional energy system optimisation and feasibility, but the difference between this study and others is that it uses the so-called interior-point-legacy method and the "linprog" function in the MATLAB programming tool.

The primary modelling approach employed here is linear programming, underpinned by the assumption of equilibrium between energy supply and demand within the particular region. It also considers the possibility of importing and exporting energy products beyond the particular region. The optimisation process revolves around two primary criteria: environmental (in a simplified form, focusing solely on greenhouse gas emissions) and economic (the cost of energy for consumers). The novelty of this approach to modelling the optimal regional energy balance structure lies in the use of life cycle analysis methodology to evaluate the potential environmental consequences of alterations in the region's energy balance.

The scientific goal of the work is to develop a mathematical model for optimising regional energy systems in the face of environmental challenges caused by factors such as rapid economic growth, increased energy consumption, urbanisation, and waste accumulation. The subject of the research was to obtain answers to the following research questions:

1) How can regional energy systems be optimally designed to address environmental challenges arising from rapid economic growth, increased energy consumption, urbanisation, and waste accumulation?
2) How can a mathematical model, utilising linear programming and life cycle analysis, be employed to identify the optimal energy balance structure for a region, with a focus on integrating bioresources and waste to partially replace hydrocarbon sources in heat and electricity generation, as well as fuel consumption for vehicles?

This study extends existing research in the field of analyses of the need to transition regional energy systems to more environmentally friendly technologies.

The remainder of the paper is organised as follows: in Section 2, basic methodology approaches are described, and a linear programming problem is formulated; Section 3 gives the results of the linear programming problem for the selected destination, i.e. city; the final Section concludes the study, discusses its added value for academic literature and presents further directions for research in this area.

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Research methods

Definition of the Optimization Problem

In order to define the optimisation problem for the regional energy system, our initial step is to establish the optimisation criteria. Specifically, the authors outline two target functions: the cost of energy for consumers and the environmental impact of the regional energy system. The latter considers the adverse effects across all phases of the energy product's life cycle, spanning from production, manufacturing, and transportation to direct consumption and disposal. The objective function of the total cost of all energy products consumed is expressed as follows:

$$\underset{cost}{minimize}\left\{\sum_{i=1}^{G} ct_i + \sum_{i=1}^{E} cel_i + \sum_{i=1}^{F} cf_i\right\}, \tag{1}$$

where:
ct_i – the cost of generated thermal energy,
cel_i – the cost of generated electricity,
cf_i – the cost of the produced fuel,
G – the number of available facilities for the generation of thermal energy,
E – the number of available facilities for the generation of electricity,
F – the number of available facilities for the production of fuel.

A function was proposed for the collective adverse environmental impact, in other words, the carbon footprint, arising from both the generation and consumption of all energy products. The objective function of the decision model takes the following form:

$$\underset{cost}{minimize}\left\{\sum_{i=1}^{G} tcf_i^{gen} + tcf_i^{cons} + \sum_{i=1}^{E} elcf_i^{gen} + elcf_i^{cons} + \sum_{i=1}^{F} fcf_i^{pro} + fcf_i^{cons}\right\} \tag{2}$$

where:
tcf_i^{gen} – the greenhouse gas footprint of thermal energy generation units,
tcf_i^{cons} – the greenhouse gas footprint of thermal energy consumption units,
$elcf_i^{gen}$ – the greenhouse gas footprint of the electrical energy generation units,
$elcf_i^{cons}$ – the greenhouse gas footprint of the electrical energy consumption units,
fcf_i^{pro} – the greenhouse gas footprint of the fuel production units,
fcf_i^{cons} – the greenhouse gas footprint of the fuel consumption units.

At the next stage, it is important to formulate restrictive conditions regarding the efficiency of the regional energy system. Considering potential directions for the development of renewable energy in the selected region, these restrictive conditions can be expressed as follows:

- the area for installing solar panels (A_{pv}) is not more than the building area (A_{tot}). It is considered unacceptable to utilize forested and agricultural lands, as well as natural areas, for the construction of solar power facilities:

$$A_{pv} \le A_{tot}, \tag{3}$$

The area for wind generator installation (A_{wind}) is limited to the extent of territories (A_{tot}) having a suitable wind class.

$$A_{wind} \le A_{tot}, \tag{4}$$

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The volume of generated electricity (gen_{el}) at waste incineration plants does not exceed the volume of solid waste (V_{sw}) generated multiplied by the plant's productivity coefficient (φ_{el}) in the region.

$$gen_{el} \leq V_{sw} \cdot \varphi_{el}, \tag{5}$$

$$0 \leq gen_{el}. \tag{6}$$

To resolve the formulated optimisation problem concerning the production quantities of diverse energy products, it is imperative to ascertain the anticipated cost of emerging energy products that could be cultivated within the region, along with their associated carbon footprint.

In this study, it is assumed that the electricity supply of the facility with an annual 10,000 solid waste incineration capacity is 1.3 MW. Furthermore, in Turkey, 375 grams of CO_2 are emitted for every kWh of electricity, which is below the G20 average (426.8 grams) (Climate Transparency, 2021). It is fundamental to point out that the overall emissions intensity has decreased over the last five years, with a 12.55% reduction from 2015 to 2020. This reduction can be attributed primarily to the significant year-on-year increase in renewable energy generation in 2019, which displaced other sources, such as natural gas. Before that, there was a substantial increase in fossil fuel-based generation. Retail rates in Turkey fluctuate depending on the state, time of day, and demand. Generally, rates span from 0,18 EURO¢/kWh to 0.64 EURO¢/kWh for the largest industrial customers, while retail consumers typically encounter rates ranging from 0.74 EURO/kWh to 0.10 EURO¢/kWh or higher. In this study, the cost of electricity production from solid waste is assumed to be 1.18 EURO¢/kWh. In this study, it is assumed that the potential to generate electricity from solid waste is 1 million tons of solid waste to be processed per year, and the estimated electricity value is 130 MWh per year. In this study, fuel consumption in the region selected for the case study was assumed to be 300,000 tons (Cizre district population 143,124). It is important to note that Turkey has an important solar energy potential due to its geographical location. According to the Turkey Solar Energy Potential Atlas report, the average annual total sunshine duration is 2,741 hours, and the average annual total radiation value is calculated as 1,527.46 kWh/m^2 (Republic of Türkiye Ministry of Energy and Natural Resources, 2023). In this study, it is assumed that the cost of solar energy is between 0.83 EURO and 1, 38 EURO per watt for material, 25% additional cost for labour, 10% of operating cost capital cost, minimum lifetime of 20 years, energy transportation cost of 20% of generation cost. The global wind markets have been disrupted by various factors, including the Covid-19 pandemic, a global supply chain crisis, and the conflict in Ukraine. As a result, the price of a wind turbine has surged by 38% over the past two years (Ferris, 2023). In this study, assuming that the cost of wind energy is 918,95 EURO /kW, the operating cost is 20% of the capital costs, the capacity factor is 15%, and the energy transportation costs are 20% of the generation costs.

The comprehensive cost analysis of generating electricity from renewable sources took into account data related to the potential productivity of the energy source, capital investment, operational expenses, and the expenses associated with electricity distribution through the network. Data analysis was performed using the following equation:

$$\sum COST = \frac{cap_{cost} + OM_{cost} \cdot lf}{pp_{ren} \cdot lf} + grid_{cost} \tag{7}$$

where:
cap_{cost} – the capital cost,
OM_{cost} – the operation and maintenance costs,
lf – the lifetime of equipment,
pp_{ren} – the potential productivity from renewable sources,
$grid_{cost}$ – the cost of distance energy transmission.

A 4% discount rate was applied during the calculations. Data on capital costs and operational performance of wind and solar projects were obtained from reports by the IEA (IEA, 2020, 2022) and NREL (Ramasamy et al., 2022; Stehly & Duffy, 2021). The negative environmental impacts of energy production were evaluated following the methodology of product life cycle analysis. This method entails the identification, measurement, and aggregation of all adverse effects resulting from the processes of product production, transportation, operation, and disposal, typically commencing from the stages of raw material extraction.

Considering the stipulated constraints and research questions posed, (1) and (2) constitute linear programming challenges in which the sought-after variables pertain to electricity generation volumes. The simplex method, a widely recognised technique in the field, can be utilised to address these identified issues. The existing constraints were taken into account, and the linearised problem was solved using the 'linprog' function of the MATLAB programming tool. This approach to mathematical modelling is based on linear relationships and is one of the methods for solving complex problems. At the same time, they indicate a linear relationship between variables and input and output data.

Results of solving the optimization problem

To assume that the strategic objective for the development of the energy system is the gradual augmentation of its own electricity generation by maximising the incorporation of available renewable energy sources into the energy system. The optimal allocation of each available renewable source can be determined under the following scenarios: when optimisation is exclusively based on cost parameters, when optimisation is solely guided by environmental considerations, and in the case of a simultaneous comprehensive resolution of optimisation problems (1) and (2). Assuming that, in the initial stage of energy system development, the aim is to increase generation by 35.000 MWh/year, Table 1 presents the results of solving problems (1), (2).

Table 1. The results of energy optimisation (MWh)

Type of generation sources	Optimal volume according to environmental criteria (emissions)	Optimal volume according to economic criteria (cost)	Optimal volume considering a combination of environmental and economic criteria
Generation from municipal solid waste	130	130	130
Thermal generation	0	13.800	13.860
Wind generation	10.800	6.600	6.800
Solar generation	23.888	14.208	14.210

The analysis of the presented data indicates that the optimisation of the energy system of the selected region based on economic criteria should, as a priority, be based on obtaining energy entirely from solid municipal rainfall. Additionally, in order to achieve the synergy effect, it is recommended that wind energy be used to its full potential. It should be emphasised that the optimal amounts of use of renewable resources in this case were determined at their maximum values. However, obtaining energy from photovoltaics is included only as an additional source aimed at filling the gap between the already used potential of renewable sources and the necessary production volume.

When simultaneously optimising the developmental path of the energy system based on both environmental and economic factors, the levels of engagement of all forms of renewable energy sources in the energy balance align with the levels obtained when addressing the optimisation problem solely from economic aspects.

The results we obtained lead us to assert that the proposed approach for selecting and developing the energy system strategy for the selected region is sound. The main advantage of this approach is that it has the capacity to accommodate a wider range of alternatives for the development of the regional energy system. These alternatives encompass thermal energy, wind energy, and other types of renewable sources, as well as conventional electricity generation technologies employing a combined cycle simultaneously, achieving the desired synergy effect.

By incorporating not just the electric power sector but also the thermal energy and fuel sectors into the optimisation models (1) and (2) while preserving the model's overall structure, it becomes

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feasible to transform it into a multi-sector model. This adaptation enables the study of potential interactions between various energy sectors within the regional energy system.

Conclusions

In response to contemporary environmental challenges resulting from rapid economic growth, increased energy demand, urbanisation, and waste accumulation, this study has developed a mathematical model for optimising regional energy systems. The assumption is that the aim of the model is to improve environmental sustainability by partially replacing hydrocarbon-based energy sources with energy obtained from renewable energy sources and municipal waste in the processes of energy production and consumption.

Utilising linear programming and considering environmental and economic criteria, the model revealed key insights. When optimising solely for economic factors, prioritising biowaste, municipal solid waste, and wind energy proved prudent. These observations have not changed while taking into account the optimisation of economic and environmental parameters in the model. Demonstrate an effective approach to the idea of sustainable energy development. Considering that achieving the Sustainable Development Goals requires sustainable and inclusive regional development, with particular emphasis on the green economy (Hsieh & Yeh, 2024).

Furthermore, the model's scalability allows for the exploration of various alternatives, including applying thermal energy, wind power, and other renewable sources, as well as innovative conventional electricity generation technologies. The area of energy from the fossil fuels and thermal energy sectors should be included in the model. Thus, it offers a multi-sectoral perspective, facilitating the assessment of the effects of using energy from several sources within regional energy systems. It should be noted that a full assessment of economic aspects may be significantly difficult considering the dynamically changing socio-economic conditions. In summary, this approach holds promise for regions facing similar challenges, offering a pathway to environmentally responsible and sustainable energy systems (Coban & Lewicki, 2022).

While this study provides valuable insights into the optimisation of regional energy systems with a focus on environmental sustainability and the integration of renewable energy sources, several avenues for future research and development emerge. Future research should focus on exploring the integration of new and advanced technologies in energy production and consumption. Embracing the potential of energy storage solutions, smart grid technologies, and advanced control systems. To investigate the performance and reliability of regional energy systems based on the energy mix. From a scientific point of view, it seems important to adopt an approach based on dynamic modelling in order to identify temporal changes in energy demand in terms of the availability of individual energy sources (Coban & Lewicki, 2023). Scenario analysis under different future conditions, such as changes in population dynamics, economic growth, and technological advancements, could provide a more robust understanding of the resilience and adaptability of the proposed energy optimisation model. Considering that, in the authors' opinion, investigating the impact of existing policy and regulatory frameworks, as well as proposing new policy measures, could be crucial for successful implementation of the idea of green energy transformation and the fit for 55 package. Also, important issues will be changes in the field of automotive transportation after 2030, i.e. phasing out conventionally powered vehicles. Further implementation of assumptions related to Agenda 2030, or the obligation of a company to clearly report its ESG and zero waste activities (Liu et al., 2024). Understanding how governmental policies influence the adoption of renewable energy sources and sustainable practices would contribute to the practicality and feasibility of the proposed energy optimisation of selected cities and geographical areas, taking into account a combination of both environmental and economic criteria.

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The contribution of the authors

Conception, H.H.C. and W.L.; literature review, H.H.C. and W.L.; acquisition of data, H.H.C., W.L. and A.B.; analysis and interpretation of data, H.H.C., W.L. and A.B.

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MODELOWANIE CZYNNIKÓW ŚRODOWISKOWYCH I EKONOMICZNYCH W REGIONALNEJ OPTYMALIZACJI ENERGETYCZNEJ

STRESZCZENIE: W artykule omówiono współczesne wyzwania środowiskowe wynikające z szybkiego wzrostu gospodarczego, rosnącego zużycia energii, ekspansji miast i narastających problemów z odpadami. W opracowaniu podjęto próbę optymalizacji regionalnego systemu energetycznego, uwzględniając nie tylko sektor energii elektrycznej, ale także sektor paliwowy i energetyki cieplnej dla wybranej lokalizacji geograficznej. W tym opracowaniu wyjaśniono zastosowanie funkcji optymalizacyjnej Linprog w narzędziu programistycznym MATLAB do rozwiązywania problemów z optymalizacją regionalnego systemu energetycznego przy użyciu zasobów odnawialnych. Podstawowym celem jest opracowanie modelu matematycznego identyfikującego optymalną strukturę bilansu energetycznego, pozwalającą na częściowe zastąpienie źródeł węglowodorów biosurowcami i odpadami w procesie wytwarzania ciepła i energii elektrycznej, a także w zużyciu paliwa przez pojazdy. Podejście modelowe obejmuje programowanie liniowe i integruje dwa kluczowe kryteria: ekonomiczne (koszt energii dla konsumentów) i środowiskowe (ślad węglowy). Nowatorstwo tego podejścia polega na zastosowaniu analizy cyklu życia do oceny potencjalnych konsekwencji dla środowiska. Wyniki ujawniają optymalne wielkości produkcji w oparciu o względy ekonomiczne i środowiskowe. W przypadku optymalizacji wyłącznie pod kątem kryteriów ekonomicznych, preferowanym źródłem są stałe odpady komunalne oraz energia wiatrowa. Natomiast jednoczesna optymalizacja parametrów ekonomicznych i środowiskowych pokrywa się z kalkulacją ekonomiczną, wykazując zrównoważone podejście do zrównoważonego rozwoju.

SŁOWA KLUCZOWE: regionalny system energetyczny, ślad środowiskowy, energia odnawialna, programowanie liniowe

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