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Estonian Energy Roadmap to carbon neutrality

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ABSTRACT

The aim of this study is to demonstrante Estonian Energy Roadmap 2040 modelling process, taking into account energy consumption in accordance with the expectation and improvement of the living standard. In the frame of this study, the evaluation of the possibility for Estonian Energy sector to become carbon neutral by 2040 have been presented.

The methodology employed in this study consist of two main phases. Firstly, data collection and inputs from a number of experts and stakeholders who is working in Estonian energy sector. Secondly, technical and economic analyses using mathematical excel model. Additionally, energyPRO is used generate hour by hour computer simulations to assess the electricity grid's ability to supply Estonia's hourly energy demand

The roadmap to climate neutrality models three sectors: electricity, heating / cooling and transport together, aiming at reducing overall energy consumption, sustainability, security of national supply and the implementation of balanced economic principles. Balanced economic principles in this case mean high resource efficiency and reduced amount of subsidies. Results of modelling show energy demand, energy mix and carbon emissions for these sectors in 2030 and 2040 and are compared with these indicators in 2021. The study estimates the amount of investment required to achieve carbon neutrality of Estonian energy sector.

In assessing the future economy, the total environmental impact of activities, the preservation of the well-being of the Estonian population and economic reasonableness are examined in parallel with traditional economic indicators.

Keywords

Energy roadmaps;
Carbon footprint;
Energy modelling;
Climate change

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1. Introduction

Global warming and climate change has evolved into a major concern worldwide. Energy sector plays an important role in improving the quality of environment. The carbon emission from energy sector reached 36.8 Gt in 2022, indicating a 0.9% growth than previous year [1]. At the same time, access to energy and its consumption per capita are considered as an important metric for human development. On these lines, the World Energy Council (WEC) has proposed the term "energy trilemma" which states that future energy systems must be capable of providing environmental sustainability and energy security, as well as ensuring reasonable energy prices [2]. The main goal of an energy roadmap is that it would offer a realistic and feasible way to solve the energy trilemma; however, this can only be accomplished through a sensible, informed, and intentional collaboration between society, government, and business sector [3].

The EU has set a goal of reaching carbon neutrality by 2050 [3]. This may be feasible if the 2021 climate

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package measures are implemented on time. All EU member states are obliged to develop their own strategies that are in line with EU's decarbonisation goals. Estonia's goals are consistent with those of the EU, and the Estonia 2035 document outlines the goals for the next 15 years. The energy sector of Estonia is in transition phase, with aim to become carbon neutral by 2050. During the time of COP27, Estonia's net carbon emission lowered by 65% when compared with 1990 levels [4]. One one hand, the renewable energy utilisation is increasing in Estonian energy sector. On the other hand, domestically mined oil shale provided 56% of the total energy in 2020 [5]. Estonia has set an ambitious goal of avoiding fossil fuel energy by 2040. Achieving this goal simultaneously is challenging and requires new energy sources, new energy production and conservation technologies, and new economic policy approaches. Solving the energy trilemma necessitates changes in behavioural habits, particularly consumer habits. In such complex scenarios, development of roadmap becomes relevant.

Energy roadmaps can be developed for different territorial regions (cities/ county / country) as well as single or multiple sectors. One of the most well-known sector-specific energy roadmaps can be mentioned Head Roadmaps. Many countries have developed national energy roadmaps, which have been initiated by various organisations. A detailed review of various energy roadmaps is provided in Section 2. The Estonian energy roadmaps were first developed in 2021. This study was initiated by the Economic Committee of the Estonian Interdisciplinary Cooperation Platform Green Tiger (Rohetiiger). Green Tiger aims to develop a balanced economic model for Estonia and the rest of the world based on feedbacks from entrepreneurs, individuals, and representatives from the public and the civic sector. The Economic Committee of Green Tiger has launched the Green Energy Roadmap to gather proposals from entrepreneurs and experts aimed at achieving carbon neutrality in Estonia [6]. In 2022, they were updated to reflect significant geopolitical and economic changes. By the end of 2021, the energy trilemma's focus had shifted to energy price issues. and the environmental aspect of the trilemma is overlooked. The roadmap update takes these new circumstances into account and demonstrates the possibility of reaching a balance point in the background system without making unreasonable compromises on any aspect of the trilemma in the long run.

To the best of knowledge, energy roadmaps specific to Baltic region is not available in scientific literatures. The main objective of this study is to develop a comprehensive energy roadmap for Estonia to achieve carbon neutrality by 2040. The development of a robust roadmap for Estonia's energy sector is expected to be benefical to the decision makers, energy professionals and project developers. A country specific roadmap aid in achieveing carbon neutrality goals. An overview of energy roadmaps is provided in Section 2. Section 3 describes the methodology employed for development of energy roadmaps. Section 4 reveals the key findings of the analysis in Estonian context. Important conclusions and recommendations of study are provided in Section 5.

2. Review on energy roadmaps

Energy consumption in any region can be classified based on its purposes or consumers or sources. Transportation, industrial, electricity, residential, commercial are the major global users of energy (as given in Annual Energy Outlook 2022 [7]). The main purposes of energy include electric power, transportation, heating/ cooling, etc [7]. The source of energy generation can be fossil fuels, solar, wind, geothermal, biomass, tidal etc [8]. Deployment of clean energy technologies such as renewables, electric vehicles, and heat pumps avoided 550 Mt carbon emissions in 2022 [1]. In this regard, adoption of Clean Energy Technologies (CETs) and energy efficient measures played important role in energy roadmaps. Energy roadmaps that cover one or more sectors are reported in literatures. Generally, all sector energy roadmaps are focussed on transforming existing to energy system with CETs. In such roadmaps, energy generation is from wind, water, and sunlight (WWS) for meeting all purposes (electric power, transportation, heating/cooling, etc.).

As far as all sector energy roadmaps are concerned, the scientific contribution by Jacobson and Delucchi is remarkable [9]. These authors developed 100% WWS all-sector roadmaps in the context of different geographical scope such as California, USA [9], New-York, USA [10], 50 states of USA [11], 53 towns & cities of North America [12] and 139 countries of the world [13]. The methodology used in these studies can be broken down into three main parts. At first, annually averaged energy demand is assessed for the year 2050 based on Business-as- Usual scenario. Secondly, the required capacity and numbers of renewable generators is estimated for each sector. Thirdly, a comparative analysis is carried out between different scenarios using parameters such as energy cost, climate cost, job creation etc. It was reported that 100% clean energy generation is feasible both technically and economically worldwide. Social and political landscape are expected to be the major barriers towards the implementation [14]. It is worth noting that wind and solar systems have significant share in all-sector clean energy solutions.

The common outcomes in the studied all-sector roadmaps are employment generation, climate cost reduction and lower air-pollution deaths & costs. Significant reduction in energy demand and stabilization of energy costs are the added advantages. In fully RE powered energy scenario, additional capacity of renewables are needed for grid stability and peak load management [11]. Further, several researchers reported stable operation of electric grid at 100% or near 100% RE penetration [15]. Cantarero Maria [16] considered various technical aspects and associated socio-political dimensions in the just energy transition roadmap for developing countries. Geographic information system (GIS) software's are beneficial in the development and planning phase of energy roadmaps [17].

IRENA's Renewable Energy Roadmap (REmap 2030) is an initiative towards doubling the RE share in energy production worldwide, thereby getting closer to carbon neutrality [18]. REmap considered energy demand for different purposes such as electric power, heating, cooling and transport. The project outcome includes an accomplishment as well as warning. The positive news is that the existing technology is enough to meet the aspirational goal by 2030. However, the current pace of transition to CETs is slower in such a way that there is only 3% rise in RE share by 2030 [19]. The economic burden of energy transition is nullified when the socio-economic benefits are considered. The Heat Roadmap Europe recommended more than 50% of heat requirement to be met through district heating (DH) systems by 2050. Odgaard and Djørup [20] suggested the development of a model that combines tariff and ownership for tackling the socioeconomic barriers in the implementation of DH systems.

The energy roadmaps can be studied further by assessing its consequences in socioeconomic aspects. Mauleón Ignacio [21] analysed different aspects of the PV and wind roadmaps by international energy organizations. It was reported that the LCOE in 2050 will be remarkably lower than prevailing electricity cost. The impacts of the implementation of energy roadmaps on electricity sector can be detrimental. Gómez et al. [22] assessed the consequences of Spanish energy roadmap in terms of different socioeconomic parameters. Substantial rise in electricity cost, initial investment and land requirement are predicted with the accomplishment of energy targets.

Babonneau et al. [23] analysed the decarbonisation roadmap in European Union (EU) using complex statistical models. A fair burden-sharing formula was put forward that equalizes welfare losses between countries in terms of their discounted household consumption. Hansen et al., assessed the significance of heat savings and heat supply from an economic perspective. It was suggested to focus on sustainable heat supply over heat saving investments for meeting the 50%-70% of the projected heat demand [24]. Connolly et al., developed a new methodology to identify the decarbonisation pathway for energy sector and applied it in the context of European Union (EU) energy system. It was observed that EU's decarbonisation goals can be achieved at a lower cost when district heating is given higher importance in the energy mix [25].

Generally, energy roadmaps are associated with a timeline to reach the decarbonisation goals by considering single/different scenarios. In the decarbonisation roadmap for all the prominent energy sectors of Taiwan, Lau & Tsai [26] proposed the renewable electricity growth at an average annual growth rate of 7% until 2050. In another study, Lau et al., [26] developed a carbon neutrality roadmap for Singapore based on energy landscape analysis and technology mapping exercise. In this roadmap, the main highlight is the centralized post-combustion carbon capture technology. In a roadmap case study for Spain, Borge-Diez [27] reported that a reduction of 8.43% in total emissions is achiveable in the existing buildings using renewable energy driven heat pumps. In the energy conservation and carbon emission reduction (ECER) roadmap proposed by Cao et al., [28] it was reported that enourmous amount of energy (201.5 Mtce by 2030) can be saved by adopting ECER technologies in chosen energy-intensive industries of China. A summary of studied energy roadmaps is shown in Table 1.

In the frame of the current study the Energy Roadmap model represents three energy sectors on the path to climate neutrality: electricity, heating/cooling, and transportation, with the goal of reducing overall energy consumption, improving environmental sustainability and

Table 1: Selected studies on energy roadmaps

Authors	Studied Region	Theme of roadmap	Energy Sector	Timeline	Tools/Approach
Jacobson et al., [11]	50 States, USA	100% clean energy	All-purpose energy systems*	2050	Analytical
Jacobson et al., [12]	53 Towns and cities in North America		All-purpose energy systems*	2050	Analytical
Jacobson et al., [13]	139 Countries of the world		All-purpose energy systems*	2050	Analytical
Lau & Tsai [29]	Country wide - Taiwan	Net Zero carbon emission	Power, transport, industry	2050	Energy scenario analysis and technology mapping exercise
Lau et al., [26]	Country wide - Singapore	Net Zero carbon emission	All-purpose energy systems*	2100	Energy scenario analysis and technology mapping exercise
Li et al., [30]	Country wide - China	Carbon neutrality	Energy and chemical sectors	2060	Analytical
Borge-Diez et al., [27]	Country wide- Spain	Carbon emission reduction	Heating/cooling for residential buildings	2050	Spatial analysis supported by EnergyPLAN software
Cao et al., [28]	Country wide - China	Energy conservation and carbon emission reduction	Six energy-intensive industries	2030	Conservation supply curve (CSC) method, bottom-up approach
Heidari et al., [31]	Ontario & Vancouver Canada	Net Zero energy	Typical residential house	2030	Building's energy model (eQuest), Embodied carbon assessment using Athena Impact Estimator, Flexible life cycle costing analysis (Ms Excel)
Heo et al., [32]	DIP industrial complexes, South Korea	Net Zero carbon emission	Industry	2050	Explainable AI-driven prediction model
Lund & Mathiesen [33]	Country wide- Denmark	100% Renewable energy	All-purpose energy systems*	2050	Analytical method supported by EnergyPLAN and Expert's input
Heyne et al., [34]	Baltic ja Nordic countries	Colloboration on Clean Energy Advancement	All-purpose energy systems*	2050	Analytical
Paardekooper et. al, [35]	14 EU nations	De-carbonisation	Heating and cooling sector	2050	Detailed spatial analysis, energy system analysis

*All-purpose energy systems includes electricity, transportation, heating/cooling, and industry

domestic energy security, and implementing balanced economy principles (improving the efficiency of natural resource use along with minimal subsidies).

3. Background

As the energy roadmap is focused on three sectors (electricity, heating/cooling and transport), it is important to provide background regarding current status of these sectors in Estonia.

Electricity sector has historically had the greatest environmental impact in Estonia due to its dependence on oil shale for electricity production [36]. As of now, it can be said that Estonia is on the brink of major energy transformation. Clean energy technologies could drastically reduce the impact of electricity generation on the environment. According to the logic of the energy trilemma, an uninterrupted supply of electricity at a reasonable price must be ensured while minimising environmental impact [37]. Electricity price flexibility and transparency allow consumers to both win and lose in this market. The addition of fuel-free and uncontrolled renewable energy sources will increase the use of both large and small energy storage technologies, reducing price fluctuations.

Electricity is also becoming more widely used in the transportation and heating sectors, which increases the demand for it. In the near future, all electricity generation for Estonia's needs must be replaced by cleaner and smarter technologies. Furthermore, the utilisation of biomass from the forest (round timber as well as logging residues) for direct combustion in energy production must be reduced in order to improve the use of wood. In 2021, the volume of gross electricity consumption increased by almost 7% compared to 2020 [38]. Despite extremely high prices, electricity consumption in 2022 remained the same as the year before. Since the cessation of Russian electricity imports to the Baltic States and Finland, the entire region is in short supply of electricity. The launch of Finland's Olkiluoto 3 nuclear reactor has been particularly difficult. The Baltic region's electricity prices have risen as a result of Latvia's and especially Lithuania's reliance on high gas prices. The rising price trend is encouraging consumers to enter into fixed-price electricity contracts, limiting their ability to control consumption (consumption management).

High electricity prices in Estonia boosted solar panel investments, and solar parks received the lion's share of floor price support during the renewable electricity auction [39]. As a result, it is expected that the capacity of solar panels in Estonia will exceed 1000 MW by 2026. At the same time, both onshore and offshore wind farm development has been rather minimal, with larger investments in onshore wind farms made in Lithuania and Finland, where support mechanisms are no longer in place.

As regards *heating* sector district heating plays a key role in heating buildings in Estonia; over 60% of Estonian residents use district heating [40]. Most of Estonia's 200+ district heating zones have switched to local renewable wood-based biofuel [41]. The efficiency of the heating sector has increased as a result of considerable investments in heat pipes, boiler houses, and modern cogeneration plants [42]. These measures contributed to heating price stabilisation in large district heating districts. The price has decreased even for smaller districts and is now competitive with other types of heating. Pieper et al, showed the signifance of utilising waste heat in district cooling systems using absorption chillers [43]. The development of district cooling in Tartu, Pärnu, and now Tallinn is certainly a success story. In a feasibility study, Volkova et al., reported that more than 50% of annual cooling demand can be met using free cooling with seawater in the context of Tallinn, Estonia [44].

Building renovation has also significantly contributed to making the heat supply more energy efficient [45]. The government has helped to modernise the heating sector through assistance programmes, but it must be acknowledged that the driving force for investment is sometimes not free-will but the pressure of European directives or the high price of imported gas.

Despite significant changes in the economics of heating, nearly 40% of the heat consumed is still based on fossil fuels. There are far too few large-scale applications of fuelless technologies, even though burning low-value wood has been a good renewable energy solution in the past and has helped Estonia meet its climate pledges. The most efficient way to use wood fuel is to use low-value wood in highly efficient district heating systems and cogeneration plants. However, in the long term, this is not always a sustainable solution. Wood, as one of the most important carbon binders, should be used primarily to make long-lasting products. Heat pump technology and the wider use of excess heat provide additional opportunities for environmentally friendly heat management and consumption load distribution [46]. Furthermore, a large number of heat accumulators are planned to be built in Tallinn and other major cities in the near future. The most important trend in heat consumption is a decrease in the amount of energy used to produce heat over time.

Transport is a large source of CO_2 emissions in Estonia. Specifically passenger cars have the highest average CO_2 emission levels in the European Union, [47]. CO_2 emissions from transport sector in Estonia continue to rise. However, the transportation sector is undergoing major changes this decade, including a shift away from internal combustion engines and/or a search for cleaner fuels to burn; the popularisation of public transportation and railroads as alternatives to car ownership; and the sharing economy, which has created new ways for people to get around [48]. At the moment the share of electric transport in Estonia is low and electric vehicles account only for 3% of car sale, but this amount continue to rise. According to the EU climate package, stricter emission standards for cars and vans will facilitate the transition to zero-emission transportation. According to Eurostat 3.3.% of energy used for transportation is renewable energy. According to the proposed climate package, average emissions from new cars should be reduced by 55% by 2030 and 100% by 2035 compared to 2021. As a result, all new cars registered after 2035 will be zero-emission vehicles. As per the proposal to develop alternative fuel infrastructure, Member States should increase the number of charging stations in line with zero-emission vehicle sales and install charging and refuelling points on major highways at regular intervals: every 60 kilometres for charging electric vehicles and every 150 kilometres for refuelling hydrogen vehicles.

4. Approach and methodology

The analysis approach consists of the following stages: collecting input data and defining assumptions; calculating using an Excel-based analytical input/output model; and analysing the results.

The numerical values used in the analysis are based on the IEA's 2021 Net Zero by 2050 report, as well as the EU climate package (introduced in July 2021) and the 2021 UN climate report. For numerical values pertaining to Estonia, data from Statistics Estonia [38] was used. Furthermore, the roadmap was developed using a bottom-up data collection approach with the largest stakeholders, including power operators, district heating and cooling operators, transportation companies, fuel companies, and professional associations. Inside information on specific planned actions for the installation/closure of power/heat generation, transmission, and storage facilities, as well as other operations, was provided by stakeholders. The idea behind this approach is to obtain data on planned activities at a lower level (companies and subsectors) and thus aggregate data at a higher level (national). The collected data covered 95% of the analysed sectors because, in addition to stakeholders participating in the Green Tiger interdisciplinary collaboration platform. Additionally, feedback from stakeholders who are not users of this platform was taken into account.

The Excel-based input/output analytical model included structured datasheets for each sector from 2021 to 2040. Each datasheet consists of the following modules: energy consumption, energy generation, and energy loss, as well as an economic module that includes value added, investments, and taxes. If information on planned energy generation, storage, or transition unit/component was available, the starting year of this activity was entered as input, and the summarised parameter was updated beginning with the planned year. For example, knowing that a hydro-pumped energy storage station will be installed in 2027, from the data on available storage facilities has been added to the roadmap beginning in 2027.

Each sector's reduction/increase coefficient was calculated using historical data as well as national energy strategy targets for 2030 [49] and the discussed goals for 2035 [50]. Additionally, the results of the heat consumption indicators in the building sector were determined based on the Building Renovation Long-Term Strategy [44].

Datasheet for *electricity* has been built based on principles, introduced below. Electricity consumption and production will increase over time, but the structure of production will change dramatically and consumer behaviour will change to some extent. Another statement, regarding electricity sector in Estonia is that there will be no new energy-intensive industries in Estonia, and the end of oil shale mining and processing will reduce demand for electricity in this sector. Taking into account that heat pumps, electric vehicles, and rail transportation become more popular, many former consumers of heat and traditional transportation fuels will switch to electricity. This will lead to an increase in overall electricity consumption. Consumers will increasingly generate electricity by installing solar panels on buildings during renovations and establishing solar parks, storing energy in local electric batteries, and optimising the sale of energy storage units based on the market price of electricity across the region. As regards onshore wind farms its capacity will increase by at least four times by 2035 and by 5.6 times by 2040, due to both the replacement of existing wind turbines and the use of new wind sites. There is no need for additional increase in capacity. One of the primary goals of offshore wind farms is to generate the electricity required to produce hydrogen for long-distance transportation and various industries. By 2040, electricity generated by offshore wind farms is expected to be less expensive than electricity generated by onshore wind farms. Special attention is dedicated to hydropower pump stations (two stations are planned in Paldiski and Ida-Virumaa), because they will play an important role in balancing large wind farms. Stations can also provide the necessary electricity in cold weather along with consumer electric and thermal batteries. Two operating large-scale fossil-fuel CHPs (Narva CHP and Auvere CHP) will begin operating on wood waste in 2030. Gas turbines powered by biogas or biomethane, CHPs, hydropower stations, and consumer accumulators (with total capacity of 1000 MW), as well as an additional strategic reserve such as a 1000 MW turbine powered by biomethane, natural gas, or hydrogen, can be used as reserve capacity in 2040.

Datasheet for *heating* sector has been filled based on following statements. As district heating is phased in and heat pumps are introduced, the proportion of fossil fuels in heat production will decrease. A decrease in demand for thermal energy is associated with building renovations and a reduction in heat production and transmission losses. Heat pipe investments and warmer weather can reduce network water temperatures and increase the efficiency of district heating systems. This, in turn, allows for the use of more waste heat and heat pumps. Heat pumps will replace natural gas, oil, and wood in local heat production. Beginning in 2031, the use of locally produced biomethane and biogas for heat generation will be taken into account. Four new CHP units (in Haapsalu, Kiviõli, Jõhvi, and Kohtla-Järve) will be installed resulting available biomass CHP capacity of 250 MW in 2040. During this time, shale oil production will cease, and as a result, the use of shale gas byproducts for heat production will decrease and eventually cease as well.

Datasheet for *transport* has been built based on statements, presented below. The use of traditional fossil fuel vehicles will decrease over time, but some vehicles will continue to use liquid fuels in 2040. By 2031, the share of passenger electric vehicles will be 12%, rising to 45% by 2040. The use of LPG and CNG in transportation will keep rising until 2031, then drop, with consumption shifting to heavy goods vehicles. The popularisation and development of public and rail transport, as well as future trends such as ridesharing, autonomous vehicles, micromobility, and so on, are slowing the rise in car ownership. Car ownership will increase at an average rate of 1% per year until 2031, when it will plateau due to changes in consumer behaviour and regulations. The average car mileage will continue to increase until 2025, then begin to dwindle; the mileage of light commercial vehicles will rise while heavy goods vehicle mileage will drop. The most important factor in reducing mileage is increasing the use of public and rail transportation. The fuel consumption of internal combustion engines is rapidly decreasing due to vehicle fleet renewal, where old cars with high fuel consumption are being replaced by fuel-efficient cars. The vehicle fleet's average fuel consumption is reduced by 2-3% per year for both gasoline and diesel. Diesel will dominate the heavy goods vehicle segment with a nearly 67% share in 2031, but by 2040, diesel vehicles will account for only 25%. Diesel is mainly being replaced by (bio)methane and hydrogen. Biomethane will dominate the bus segment until 2031, then decline. By 2040, buses will primarily be powered by electricity and hydrogen. Rail transport will be converted to electric power, and Rail Baltic will be implemented. Ferries will use electricity instead of diesel fuel (one ferry will continue to use hydrogen as an option). Every year, 470 GWh of biomethane production capacity will be added between 2022 and 2025, with an additional 370 GWh added between 2026 and 2031.

Based on these statement shown above generation and consumption of energy in electricity, heating and transport sector for each year for periood from 2021 to 2040 has been assumed.

In the frame of analysis taking into account CO_2 emission factors for diferent technologies and fuels carbon intensity of each sector has been calculated. The same approach as in [37] has been used.

Regarding electricity sector additional modelling was required in the preparation of energy roadmaps to predict future electricity consumption and production. The simulation began with the goal of balancing Estonia's annual electricity production and consumption with cost-effective renewable energy solutions. To test electricity grid's ability to supply Estonia's hourly consumption energyPRO was used for simulation electricity consumption and produciton. This software can be used both for detailed simulation of technical behaviour in the energy system as far as business economic consequences [51]. This model is used for analysis of DH systems, coupling of heating and electricity grids and analysis of power grid. The scale of the modelling can range from a single home to national level. The energyPRO software was used for simulation of electricity grid in Hungary. Electricity and heat generation simulation on national level of Estonia has been done in [52].

The operation of the system with given production capacities and recorders was simulated using the energyPRO model for 2031 and 2040. The model examined the market's and producers' probabilistic behaviour in accounting for energy consumption in the Estonia, as well as the use of energy meters for both storage and production. The model assumed the possibility of hourly

Table 2: Definition of the main components considered in calculation of value addition

Direct value added	The direct value added from the production of a specific product was calculated. The model is used to visualise the processes of energy and fuel production (production volumes, income, and costs). Value added is calculated as the sum of labour costs, depreciation, net production taxes, and operating income.
Indirect value added	Indirect value added is created as a result of intermediate consumption associated with the production process. The assumption is that as the manufacturing volume of the product in question increases (or decreases), so does intermediate consumption, i.e., consumption of the products and services used to manufacture said product. To calculate indirect value added, a methodology based on national economy input-output tables was used, with the latter displaying the links between various fields of activity and value-added creation.
Associated value added	Associated value added is the result of a change in final consumption caused by changes in direct and indirect production and a corresponding increase in income or revenue. When calculating value added, the impact of changes in the final consumption of households (wages), the public sector (tax revenue), and businesses (investment activity) was considered. Indirect value added was also calculated using the methodology based on the national economy's input-output tables and the structure of final consumption derived from said tables.

imports and focused solely on meeting the demand of the Estonian market. Data regarding existing and planned electricity generation units have been used for the model input. Although the possibility of export was not separately modelled, it was possible to estimate potential export volumes through an assessment of producers' generation potential. Such modelling cannot account for all potential market aspects (for example, the impact of regulatory and political changes, changes in consumer behaviour, the impact of the regional market, and so on), but is based on a limited set of assumptions. In this case, the goal was to assess the probability of these Estonian electricity producers to meet the forecasted electricity demand.

In the frame of the model calculations, value added and potential investments for each sector has been done. Value added is a national accounting indicator that expresses production in monetary terms (net of subsidies) after subtracting intermediate consumption, i.e., production costs minus personnel costs, depreciation, and production taxes. Value added is a parameter that is primarily used to track the growth of a national economy or activity and to compare the economies of different countries or regions. In this study, the value added of energy savings was determined based on three components, shown in Table 2.

Thus, the value added is related to the volume of production in the corresponding year, taking into account the price forecasts for the associated energy carrier. The input-output method can account for the complex interdependence of various activities (supply and consumption chains) as well as the structure of value added and final consumption, allowing us to estimate the expected impact of changes on the entire economy (direct, indirect, concomitant, and import). The value-added ratios of individual sectors are shown in the Table 3 above, including both direct and indirect value added. As a basis of the impact calculations, latest macroeconomic input-output table (no RAT00002) of Statistics Estonia was used. Based on this input-output table the full cost coefficients, which captured both direct and indirect costs, were estimated by the experts involved in the research. For this, first the supply coefficients matrix (A) was estimated and then the inverse matrix based on subtracting of A from unit matrixes (I) i.e. I-A, provided the full cost coefficients for impact analysis. The coefficient shows how many value-added euros are generated by selling a specific product in the relevant field of activity for one euro. These coeficients have been calculated based on "Symmetric product by input-output table at Basic prices" [38], taking into account direct and indirect effects.

Table 3: Value-added coefficients of various fields of activity in Estonian context

Field of activity	Coefficient
Biofuel: wood chips	0.751
Biofuel: biomethane	0.540
Natural gas	0.266
Other fossil fuels (import)	0.030
Gasoline and diesel	0.044
Thermal energy	0.717
Electricity	0.648
Other raw materials, products, and supplies	0.611
Construction	0.661

The smaller the coefficient, the greater the expected share of imports in production resources. For example, the natural gas coefficient only includes costs associated with its sale and transportation in Estonia. In this analysis, the energy production processes (electricity and heat) were slightly adjusted to account for the increased share of renewable energy as well as the change in the share of imports in the electricity sector. The disadvantage of the input-output model is that it takes into account the economy's former structure. Because structural changes are expected to be gradual, the Department of Statistics compiles input-output tables every five years. This is due to the table's complexity; it takes three years to compile (for example, a new table for 2020 will not be published until 2023). This coeficients have been used for added value calculation across sectors. Assumption regarding energy price index increase by 2% has been taken into account.

Investments have been calculated, taking into account only investments in new production (storage) capacities; replacement investments were not taken into account. In addition to investments in energy production, investments in building renovation were calculated. The projected production volumes for various technologies served as the starting point; if the production volume increased, the required production capacity and the need for investment were calculated using unit prices. Investment costs were indexed at 2% per year, with the exception of new technologies, which had a growth rate of -0.5% to account for the learning effect. In addition to unit costs, the optimal operating hours (per year) of various technologies were considered when looking for investments in electricity generation (Table 4). Table 5 contains assumptions for calculating investments in heat production.

The most money was invested in building renovations, with the variables being the size of the renovation (m^2) and the cost (EUR/m^2). Table 6 provides an overview of the input data. The estimation of the volume and cost of building renovation was based on technical report titled as Building renovation long-term strategy [53].

The developers of Estonian biomethane production estimate that the investment in biomethane production will begin at EUR 11 million per unit of production, with an annual production capacity of 3 million m^3 (about 28 GWh). The investment's value is expected to rise by 2% per year. The number of biomethane plants will continue to increase until the expected optimal production volume is reached, which is 108 million m^3 or 1000 GWh per year [54]. Replacement investments for biomethane production were not considered. Because the expected lifespan of biomethane units is ten years, they will need to be replaced between 2021 and 2040. When replacing a working production unit, the investment required is slightly lower. It is estimated at EUR 6-7 million per unit.

With an annual production of 500 tonnes, the cost of investment in hydrogen production is estimated to be EUR 6.7 million per unit [55]. The change in investment value over time takes the so-called learning curve into account and thus grows slightly slower than the overall price increase. The number of hydrogen production units

Table 4: Assumptions for estimating electricity generation investments

Technology	Cost	Operational hours
	1000 EUR/MW	h/year
Onshore wind farms	1190	3066
Offshore wind farms	1785	4380
Photovoltaic	680	1000
PHEJ	1200	2400
Electric batteries for small consumers	792	2000

Table 5: Assumptions for estimating heat production

Type of energy generation	Particulars	Cost (1000 EUR /MW)	Operational duration (hours/year)
Centralised generation	Conversion of oil shale gas boilers	200	5 000
	CHP	700	6 500
	Heat pumps	650	5 000
	District cooling	800	1 100
	Other – storage	1 000	500
Local generation	Heat pumps	900	5 000
	Solar collectors	1 000	1 000

Table 6: Assumptions for building renovation investment

Particulars	Cost	Size of the renovation	
	(EUR/m²)	Usual (million m²)	Effective (million m²)
Private houses	400	1.9	2.7
Apartment buildings	300	10.8	12.5
Offices, accommodation	500	2.0	2.5
Trade, service, industry and other non-residential building	250	5.2	6.3
Education and health care	1 100	1.9	2.3
Warehouses/transport buildings	150	1.6	1.9

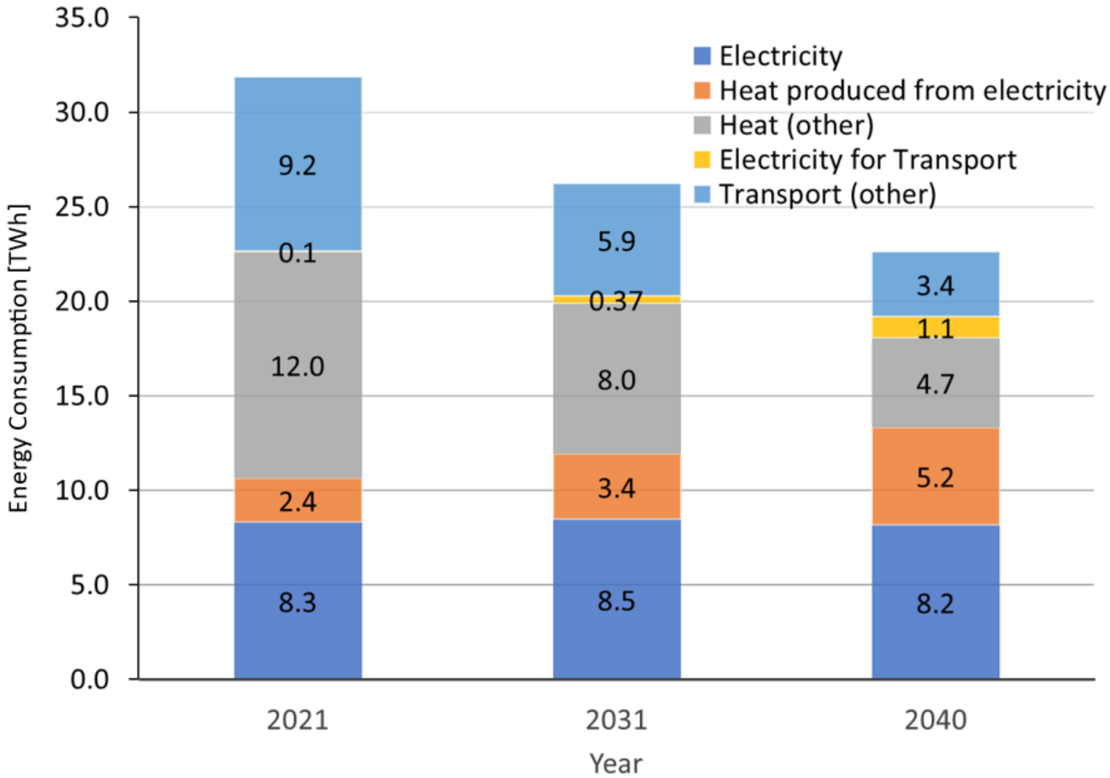

Figure 1: Estimated energy consumption in Estonia for studied years

in this model has been increased to correspond with the expected hydrogen consumption in the Estonia. The model only takes into account hydrogen consumption for transportation.

5. Results

At first, the energy consumption for each sector in Estonia for three years (2021, 2031, 2040) are presented. It is anticipated that the total energy consumption for heating/cooling, electricity, and transportation will drop from 32 TWh in 2021, to around 26 TWh in 2031 and then 22 TWh in 2040 (as shown in Figure 1). This reduction in energy consumption can be attributed to electrification of heating and transport sector. Between 2021 and 2040, the electricity for transportation is expected to increase 10 times, reaching 1.1 TWh. Drastic reduction in heat consumption is observed over the years. This can be correlated with increased in power-to-heat consumption. The variation in electricity consumption remained almost the same, at around 8 TWh.

The graph clearly shows that electrification of both heat supply and transportation is critical. Imported electricity is also important to ensure that the hourly consumption of consumers can be covered. As it was mentioned, an analysis was performed using EnergyPro to determine the ability of such an electricity supply system to cover Estonia's hourly consumption. The blue line on the graphs represents the anticipated electricity consumption as well as the energy required to charge the batteries. When total generation by producers does not reach the consumption line, the size of the deficit, which must be covered by imported electricity, becomes clearly visible. The majority of these incidents occur in January and June. Figure 2 and Figure 3 depict simulated load curves for January and June 2040, respectively. These figures are screenshots of simulation in energyPRO.

The simulation results provided important insights into the operation of such a novel electrical system. Wind farms' production capacity is expected to significantly exceed Estonia's domestic consumption in both 2031 and 2040. Their export potential in windy weather is estimated to be approximately 2.5 TWh in 2031 and nearly 5 TWh in 2040. The greatest average hourly electricity deficit in winter is expected to be 750 MW in 2031 and 1500 MW in 2040. According to the model, there were approximately 3,400 hours of supply shortage 2031, with a total import of approximately 0.5 TWh, and approximately 3,700 hours in supply shortage in 2040, with a total import of approximately 0.6 TWh. On windy winter days, the price of fuel-free electricity may be so low that it forces CHP plants out of the electricity market, pushing them to produce heat rather than operating in the usual cogeneration mode to cover the heat load. Because cogeneration plants are the base load plants in the heat production of district heating networks, their total energy production does not decrease. Thermal energy is produced in greater volumes than electricity during hours when electricity prices are low or negative. To utilise their full potential, storage facilities (both pumping stations and household electric

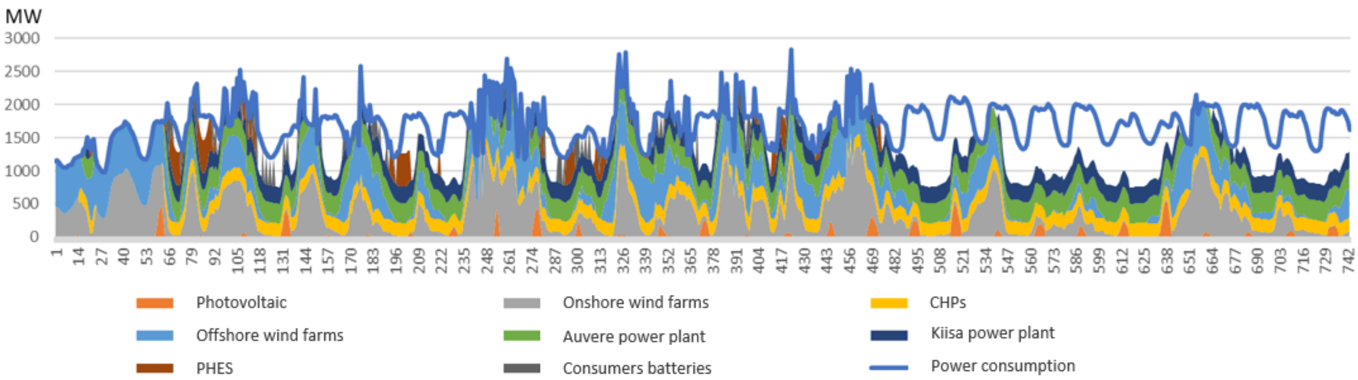

Figure 2: Estimated hourly electricity demand in January 2040

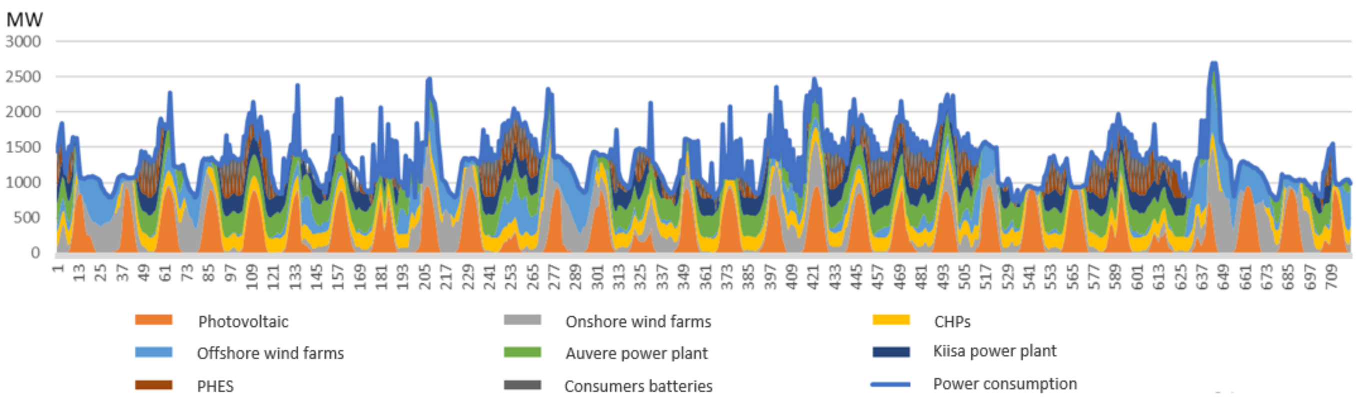

Figure 3: Estimated hourly electricity demand in June 2040

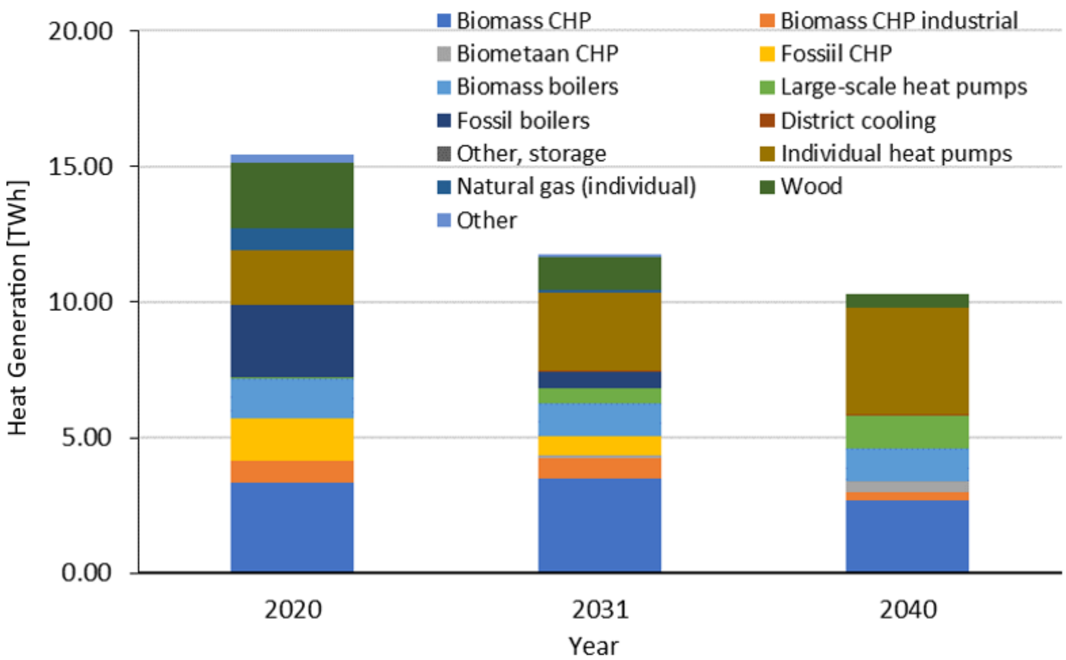

Figure 4: Heat generation estimated for the studied year in Estonian context

storage units) must be able to function as regional market system service providers in the regional market. Their potential will be underutilised if they continue serving only the Estonian market. It is possible to compensate for the lack of controlled capacities during the shortage hours by purchasing electricity from neighbouring countries. Due to oversupply, electricity prices in the region are likely to be very low on sunny and/or windy days in summer and very high on windy days (especially in winter). Smart consumers will be able to optimise their consumption with the help of various accumulators as well as shift consumption times.

As a result of this analysis, it turned out that the proposed electricity generation portfolio produces more electricity than the annual consumption in Estonia. At the same time, in the absence of electricity import options, there may be a total deficit of up to 0.5 TWh in the winter months of 2031, with a maximum hourly deficit of up to 750 MW, and a total deficit of up to 0.6 TWh with a maximum hourly deficit of up to 1500 MW in the winter months of 2040. Because the modelling did not account for import opportunities, consumption optimisation, offshore wind farms' superior production capacity compared to onshore wind farms, the flexibility and full potential of accumulator production, and the possibility of producing solar panels in clear cold weather, it is very likely that these opportunities will cover the entire estimated deficit. As shown in Figure 4, heat generation can be significantly reduced over the years. Power-to-heat share will be increased significantly, both by individual heat pumps and by large-scale heat pumps integration into district heating system.

The role of biomass combustion in CHP and boiler use will be significantly reduced. In the future, all biomass should be used efficiently as per the principles of energy and resource conservation in a balanced economy. For the transportation sector, initially, two scenarios were modelled. According to the first scenario, achieving zero carbon emissions in the transportation sector by 2040 is required in any case. However, there is extremely low likelihood of achieving the conditions required for the implementation of this scenario. A second scenario named as the main energy roadmap scenario was developed, which takes into account a more probable and realistic situation. Both the impact of legislation and changes in consumer behaviour and driving style were considered when modelling the scenario (Figure 5).

Figure 6 depicts the dynamics of change in CO_2 emissions for the energy roadmap scenario. It can be

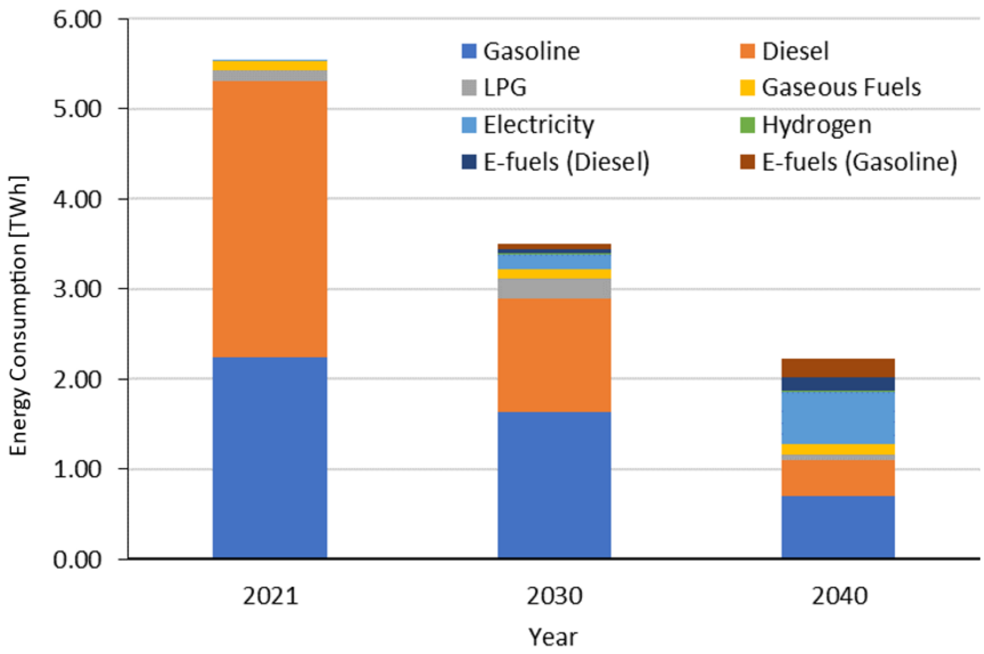

Figure 5: Energy consumption estimated for transport sector in Estonia

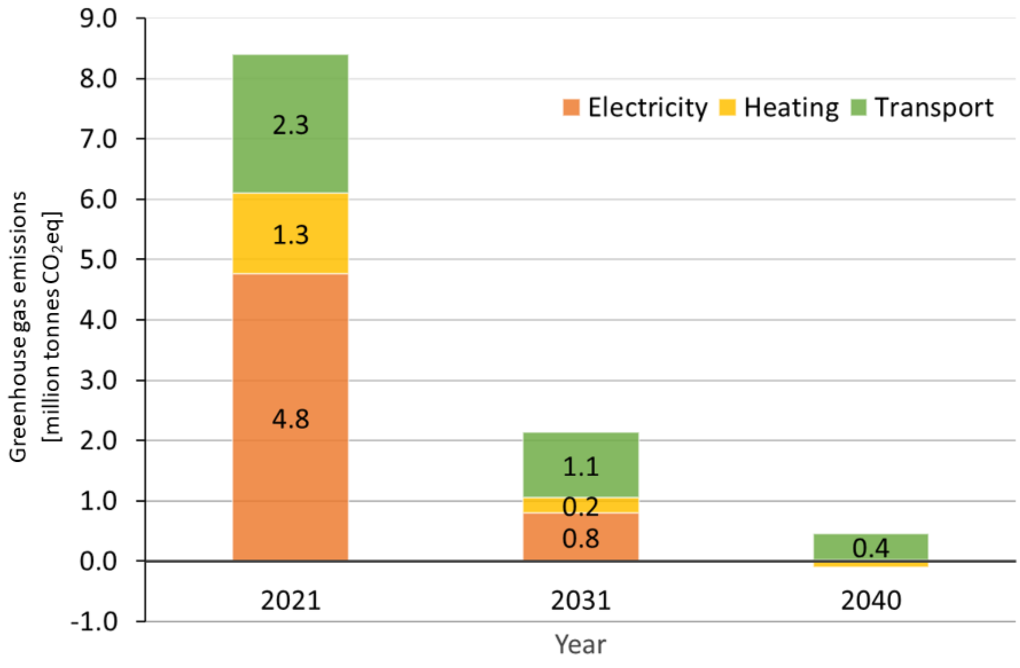

Figure 6: Variation of carbon emission in Estonian context for the study period

seen that carbon neutrality of energy sector will not be achieved, due to CO_2 emissions from transportation sector. This figure shows, that electricity generation can become carbon neutral, but heating generation will have negative CO_2 emissions. It is related to the negative emission factor for biomethane consumption. Results regarding value added calculations are shown in Table 7.

The numbers are nominal, which means they account for inflation. Bearing this in mind, the value added of

Table 7: Added value across different fields of energy for various scenarios, million EUR

Energy Field	Usual			Energy roadmap	
	2021	2031	2040	2031	2040
Electricity	277	417	352	775	1 042
Heat	796	953	979	921	911
Biomethane	0,2	109	156	109	156
Hydrogen	0	6	50	17	57
TOTAL	1 073	1 484	1 537	1 821	2 166
Estonian added value (%)	4.4%	4.1%	3.1%	5.0%	4.4%

Table 8: Summary of the most important investments for studied years (million EUR)

Particulars	2022-2025	2026-2030	2031-2035	2036-2040	TOTAL
Electricity management	2 692	3 930	423	335	7 380
incl. solar parks	183	320	79	62	644
offshore wind farms	1 732	2 425	0	0	4 156
onshore wind farms	271	706	44	32	1 054
other (incl. PHEJ)	505	479	301	241	1 526
Heat management	1 711	2 814	3 355	3 455	11 335
incl. heat production	146	118	140	76	480
renovation of buildings	1 565	2 696	3 215	3 379	10 854
Production of fuels	194	206	33	18	450
incl. biomethane	175	175	0	0	351
hydrogen	18	30	33	18	99
TOTAL	4 596	6 950	3 811	3 808	19 165

heat production, for example, will actually decrease compared to today; heat consumption in energy units will also decrease by approximately 29% under normal conditions. In real terms, under the energy roadmap scenario, value added is about 17% higher than in 2021, primarily due to increase in electricity production, hydrogen, and biomethane production. As overall economic growth outpaces this, the energy sector's share in the country's value added decreases slightly. Table 7 shows the value of the investment in terms of the current purchasing power of money (2021). The need to cover basic domestic consumption of electricity from renewable energy sources is in such a way that the amount of electricity produced domestically equals or exceeds consumption was agreed upon during the energy roadmap preparation process in order to define and specify the objective and goal of the roadmap. Imports are only permitted when the country lacks sufficient renewable energy or storage capacity. The demand for heating/cooling is always fully covered by self-production and stored energy. Table 8 presents the estimated investment costs required to cover the domestic consumption described in the roadmap, based on current knowledge and prices in 2021, in order to achieve the desired goals of reducing environmental impact, ensuring supply security, and optimising value added.

There are certain limitations to this study. Since some sectors have not been thoroughly analysed (e.g., industry, agriculture, and services), roadmaps represent only a subset of a larger economy-wide integrated strategy for decarbonisation by 2040. Another limitation is that roadmaps were developed for 2040 rather than 2050. This is due to Estonia's ambition to achieve carbon neutrality early before 2050 and the availability of information on stakeholders' planned investments for the next 20 years.

6. Conclusions

In this paper, a brief overview of development of energy roadmaps in different countries is provided. Based on this knowledge, an energy roadmap is presented for Estonian energy sector considering different fields such as heating/cooling, electricity, transport. The main objective was to define a set of measures and actions required for Estonia to achieve carbon neutrality by 2040. The following conclusions are drawn.

- The analysis revealed that while carbon neutrality is achievable in the heat and electricity generation sectors, it is not achievable in the transportation sector, even with significant investment. Most of the carbon emission in 2040 will occur from this sector.
- The electrification rate of heat/cooling sector & the transportation sector is observed to be critical in the proposed decaronisation pathway. Based on this, the model predicted that electricity consumption would skyrocket. A simulation in energyPRO revealed that it is possible to cover domestic electricity consumption with local renewable sources.
- It is anticipated that the total energy consumption for heating/cooling, electricity, and transportation will drop from 32 TWh to 22 TWh in 2040. This reduction in energy consumption can be mainly attributed to electrification of heating and transport sector
- It is aniticipated that heat demand will reduce by around 33% in 2040 due to possible adoption of heat pumps (individual & large-scale)
- About 60% of the total investment is required between 2022 -2030, catering to the needs of electricity and heating sector. The investment for electricity will be quite low between 2030-40 as only operational expense is expected.

It is recommended to continue (or increase) compensation for building's renovation. Also, energy conservation must be further promoted in residential sector. Energy subsidies must be paid to only those who really need it. Otherwise, it may hamper energy conservation goals. When setting goals, it is important to understand, that national goals will be achieved and implemented not only by the state alone but also by the private sector in collaboration with the state. Though the correctness of an energy roadmap is subjective, it will definetly contribute to the current actions in decarbonising Estonia's energy sector. This roadmap can serve as a template for plans in other states and countries. The future scope of study includes modelling of different decarbonisation scenarios within the framework of energy roadmaps. National energy strategical plans could be more ambitious and prioritise nature conservation and climate neutrality. In the energy sector, the private sector's ambitions and goals can be progressive and innovative than the states, and their achievement necessitates a clear strategy from the state as well as support to prevent market distortions.

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