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Jānis Kramens

TECHNOLOGIES FOR ENERGY SECURITY: STIRLING ENGINE

Summary of the Doctoral Thesis

RTU Press
Riga 2024

RIGA TECHNICAL UNIVERSITY
Faculty of Natural Sciences and Technologies
Institute of Energy Systems and Environment

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TECHNOLOGIES FOR ENERGY SECURITY: STIRLING ENGINE

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for defence at the open meeting of RTU Promotion Council on May 2st, 2024 at 14:00 the Faculty of Natural Sciences and Technology of Riga Technical University, Azenes 12/1 Street, Room 116.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for review to Riga Technical University for promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for the promotion to a scientific degree.

Name Surname ……………………………. (signature)
Date: ………………………

The Doctoral Thesis has been written in Latvian. It consists of an Introduction, 4 chapters, Conclusions, 59 figures, and 13 tables; the total number of pages is 130. The Bibliography contains 263 titles.

CONTENTS

GENERAL CHARACTERISTICS OF THE THESIS

Actuality of the topic

The war in Ukraine and the military actions in Israel and the Gaza Sector have transformed the world and are forcing it to change. Special attention is paid to the energy sector in each member state of the European Union separately and in the entire European Union together. Special attention was also paid to this issue at the Climate Conference COP28 in Dubai.

One of the most important goals of the development of the energy sector is not only to fulfil the tasks of the European Green Course but also to pay more attention to the security and independence of energy supply at the same time.

Security of energy supply in specific crisis situations differs from peacetime situations and has a dual dimension:

1. The dimension of the technological solution, starting with microgeneration and ending with large cogeneration plants for simultaneous or separate production of heat and electricity.
2. Energy demand ranges from an individual single-family home, a single apartment building, a small municipal power system to energy communities, large businesses, and large city municipal and national power systems.

It is important to understand that in times of crisis there is a shift in emphasis and key weighting points. The importance of economic and climate issues is also changing in energy supply.

The purpose and tasks of the study

To define special conditions and carry out scientific research on the security of energy supply in cases of various potential crisis conditions.

In order to fulfil the set goal, it is necessary to perform the following tasks:

1. To carry out scientific research of technological solutions of electricity sources, applying them to special crisis situations in energy supply.
2. A special evaluation should be made for a historically well-developed technological solution – the Stirling engine (SE). The relevance of its use grows in direct proportion to the possibilities of military threats and other crises intensifying. Therefore, it is important to understand the direction of development of the Stirling engine today.
3. To finalize the performance of the Stirling engine under real experimental conditions in the firebox of a water-heated boiler.
4. To compare the energy source of an individual energy user and the facilities of a municipality-level energy producer.
5. To assess the impact of the Stirling engine on climate change through life cycle analysis.

The proposed hypothesis

Latvia's energy supply security in the conditions of military threat and crisis depends on the diversification of technological solutions and the innovative use of different approaches.

Scientific novelty of the Thesis

Several scientific innovations were created during the development of the Doctoral Thesis, which are based on the innovative integration of historically recognizable technological solutions in the energy sector in the conditions of military threats and other crisis situations. Scientific research and analysis of technological solutions with an innovative point of view, different from the traditional development of energy supply, was carried out in the Thesis.

Several methodologies are applied in the Doctoral Thesis:

- bibliographic;
- experimental research for the creation of an empirical model of the energy source;
- comparative analysis of multi-criteria decision-making;
- modelling of the operational balance of the energy supply system;
- analysis and evaluation of the impact on climate change.

The methodologies use the role and possible use of various technological solutions in energy supply systems for small energy users in various conditions of economic development:

1) analyse the revival of a century-old technological solution: the development of scientific research, the spread of the use of the Stirling engine in Europe and the world;
2) potential integration of different small energy sources into small energy supply systems, comparing technological, economic, socioeconomic, environmental and climate change aspects.

Practical significance of the Phesis

The study of the use of various technological solutions makes us think about their place in energy sources for increasing the security of energy supply.

The results of the study suggest not to wait for a crisis situation when restructuring of the energy supply system might already be necessary.

The study encourages thinking that in a crisis situation, economic and climate change issues could recede into the background.

Structure of the Thesis

The Thesis is based on six thematically related scientific articles published in scientific journals and available for citation in several databases of scientific works and publications. In each of the publications, attention is paid to the analysis of energy supply technological solutions through the prism of different perspectives and evaluations of scientific research.

The Thesis consists of an introduction and four chapters:

1. Literature review
2. Methodologhy of the research
3. Results
4. Discussion

The introduction examines the topicality of the topic, indicates the purpose of the work and tasks to achieve the goal, puts forward a hypothesis, and describes the scientific novelty and practical significance of the Doctoral Thesis.

Chapter 1 provides an insight into the field of research, i.e., the study of technological solutions for energy supply security. Chapter 2 analyses research methodologies used to evaluate a small energy source for the analysis of technological solutions. Chapters 3 and 4 analyse the research results obtained using the aforementioned methodologies and draw conclusions.

The structure of the Thesis is shown in Fig. 1. The distribution of the most essential and important methods used is summarized using a triple helix approach.

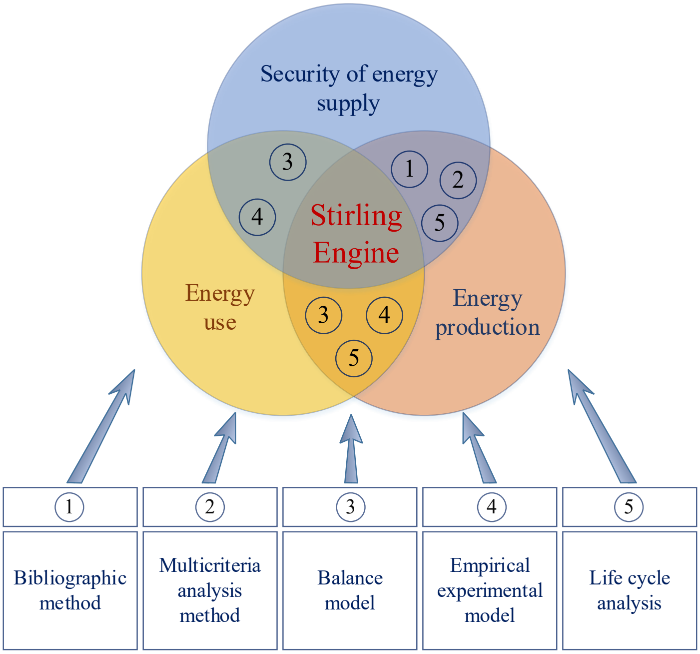


Fig. 1. Structure of the Thesis.

An illustration of the use of the triple helix approach includes all the methods used in the research, showing the analysis of the interrelationships between the means of the various measures:

- energy supply security and energy users;
- energy supply security and energy producers;
- energy producers and energy users;
- simultaneous overlapping of all three levels of measures, which resulted in the use of the Stirling engine.

The five methods illustrated in Fig. 1 are discussed in the following publications:

1. Bibliographic method

Kubule, A., **Kramens, J.,** Bimbere, M., Pedišius, N., Blumberga, D. Trends for Stirling engines in households: A systematic literature review. Energies 2024:2024, 17(2), 383. doi: 10.3390/en17020383

2. Multi-criteria analysis method

   Kramens, J., Valtere, M., Krigers, G., Kirsanovs, V., Blumberga, D. Ranking of Independent Small-Scale Electricity Generation Systems. *Clean Technologies* 2024:6(1), 140-151. doi: /10.3390/cleantechnol6010009

3. Balance model

   Kramens, J., Švedovs, O., Sturmane, A., Vīgants, E., Kirsanovs, V., Blumberga, D. Exploring Energy Security and Independence for Small Energy Users: A Latvian Case Study on Unleashing Stirling Engine Potential. *Sustainability* 2024: 16(3). doi: 10.3390/su16031224

4. Empirical experimental model

   Kramens, J., Vīgants, E., Liepiņš, I., Vērnieks, L., Terjaņika, V. Research of a Biomass Boiler with Stirling Engine Microgeneration Unit. *Environmental and Climate Technologies* 2021: 25(1): 587–599. doi: 10.2478/rtuect-2021-0043

   Kramens, J., Vīgants, E., Liepiņš, I., Terjaņika, V. Research of Biomass Micro-Cogeneration System Integration with a Solar PV Panels in Zero-Energy Family Building. *Environment. Technology. Resources. Proceedings of the 13th International Scientific and Practical Conference* 2021:1:132–138. doi: 10.17770/etr2021vol1.6568.

5. Life Cycle Analysis

   Kramens J., Feofilovs M., Vīgants E. Environmental Impact Analysis of Residential Energy Solutions in Latvian Single-Family House: A Life Cycle Perspective. *Smart Cities* 2023: 6(6): 3319–3336. doi: 10.3390/smartcities6060147

Approbation of the Thesis

Approbation at scientific conferences

1. International Scientific Conference of Riga Technical University on Power and Electrical Engineering, CONECT, May 12–14, 2021, Riga, Latvia.
2. International Conference of Young Scientists on Energy and natural Science Issues, CYSENI, May 24–28, 2021, Kaunas, Lithuania.
3. 13th International Scientific Practical Conference "Environment. Technology. Resources", June 17–18, 2021, Rezekne, Latvia.
4. 22nd International Scientific Conference on Engineering for Rural Development, May 24–26, 2023, Jelgava, Latvia.
5. 14th International Scientific Practical Conference "Environment. Technology. Resources", June 15–16, Rezekne, Latvia.

1. METHODOLOGY

This chapter discusses the methodology of the conducted research and experiments. This methodology ensured the reliability and safety of the obtained data.

1.1. Bibliographic analysis

As the information availability and open-access knowledge repositories continue to expand and the size of their stocks increases, more efficient and systematic literature review methods have become indispensable. This research adopts the Structured Literature Review (SLR) methodology. In the SLR process, first, the literature review protocol has to be developed, and one of its initial steps is formulation of research questions (RQs). For structured literature review, the following RQs are elaborated:

RQ1: How has the research on Stirling engine evolved over time?

RQ2: What is the focus and latest tendencies in small-scale (residential) renewable energy studies based on Stirling engine, with particular focus on biomass?

RQ3: What are the implications of Stirling engine within the energy supply, energy security and environmental research field?

The developed research protocol (see Fig. 1.1) describes the process that will be applied and includes the methods used to choose information sources (database), selects the particular studies for analysis, explores and summarizes them.

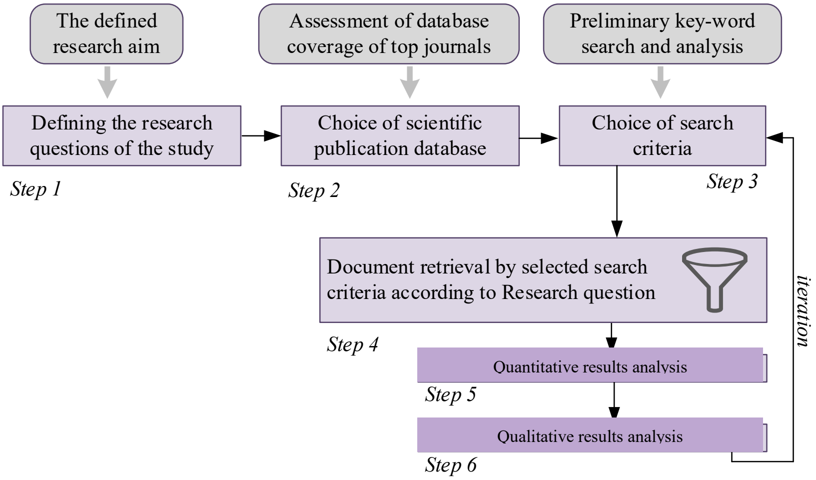


Fig. 1.1. Applied research methodology.

According to the database evaluation approach, Step 2 is to compare the coverage of Scopus and Web of Science, two most popular scientific publications indexes. The top 100 journals in 2022 (latest available data) for the subject area “Energy” and subject category “Energy Engineering and Power Technology’ were identified from Scimago journal rankings. Then it was identified, which of those journals are available in each of two databases. As a result, Scopus coverage in this context is determined to be 100 %, as all 100 top journals were indexed in Scopus. For Web of Science, only 84 of the top 100 journals were represented in this database, thus the coverage of 84 % can be assumed. There were no journals in the selection that were included in Web of Science database and were not available in Scopus index.

Step 3 is the selection of search criteria to filter the whole literature basis. The following approach was adopted: first, the initial keyword generation and analysis and the literature in the respective research area is analyzed, then, the backward and forward searching is used to improve the search criteria. The most general keyword “Stirling engine” was used for the preliminary search.

1.2. Multi-criteria decision analysis

This study used two methods: literature review and MCDA. The literature review was based on scientific literature. MCDA was chosen based on the reviewed paper.

Initially, decisions were made on which renewable electricity generation systems could be compared. Four systems were selected: proton-exchange membrane fuel cell with photovoltaic panels (PEMFC/PV), photovoltaic panels (PV), biomass-fueled Stirling engine (SE/BM), and solar dish Stirling engine (SE/SD). After choosing the alternatives to compare, the next step was to select the criteria. The criteria were determined based on their relevance to the study's objective and available data. Six criteria were identified from environmental, technical, and economic standpoints to evaluate energy generation systems. Table 1.1 shows the selected criteria

Table 1.1

Criteria for Multi-Criteria Decision Analysis

Criteria category	Criteria	Ideal value
Economic aspect	LCOE – levelized cost of energy of the system (€/kWh)	–
Technical aspect	Efficiency – electrical efficiency of the system (%)	+
	Reliability – full-load working hours of the system (h/year)	+
Environmental aspect	GWP – global warming potential of the system (kgCO_2eq/kWh)	–
	Lifetime – technical lifetime of the technology (years)	+

1.3. Energy supply balance

The complex methodology is designed to assess scenarios for increasing energy security. Data availability (user data or from energy audit) plays an important role in creating the right preconception and further developing appropriate scenarios for development. If, after an assessment of the current situation, it was found that the alternative scenario is not necessary or transition to new technologies is not possible, then the proposed solution may contain recommendations to improve the existing technology.

All defined scenarios are compared with each other and with the base scenario, which describes the current situation. The user can choose the criteria by which the analysed scenarios will be compared. The mandatory criterion is the possibility of providing 100 % self-sufficiency with a chosen scenario and technological solution. If this criterion is met, then further analysis of the scenario using other criteria may follow.

The research is based on the case study of Ādaži Municipality. Only local municipal buildings were considered as part of the study (Table 1.2).

Table 1.2

Technical Parameters of Selected Municipal Buildings

Municipal building	**Sign**	**Heating area, m^2**	***E****** **(average), MWh/month**	***Q******* **(average), MWh/month**	**Specific annual *E*, kWh/m^2**	**Specific annual *Q*, kWh/m^2**	**Renov. state**	**Available roof area, m^2**
Office building	A	333	3.8	15.6 * 1.1 **	131	328	Partly renov.	423
Primary school	B	8724	17.0	54.1 * 1.5 **	23	51	New	472
Council building	C	729	1.9	12.8 * 2.3 **	32	163	Partly renov.	81
Cultural centre	D	6285	19.3	113.0 * 12.8 **	37	164	New	910
Secondary school	E	16 186	38.0	267.2 * 44.4 **	28	140	Partly renov.	1761
Kinder-garten	F	4138	8.6	109.6 * 21.6 **	25	238	Renov.	480
Police department	G	194	1.1	7.8 * 1.4 **	66	323	Partly renov.	57

* heating season, ** off-heating season, *** electricity consumption, **** heat consumption

1.4. Empirical experimental analysis

Experiment 1: Working principle of Stirling engine

One of the technologies powered by solid biomass fuel is the Stirling engine-based mCHP system. Stirling engines are external combustion engines which, in combination with an electric generator and a boiler, form a closed micro-cogeneration system. An experimental test unit was developed and set up to evaluate the application of household's self-consumption scale Stirling engine-based mCHP. The following experimental tasks were set by the research group(authors):

1) To assess the impact of the cogeneration regime on the total heat production of the biomass boiler heating installation;
2) to determine the quality of fuel combustion of a heating installation by measuring CO_2 and O_2 emissions in flue gases at the beginning, middle and end of the operation cycle;

3) to determine the changes in the productivity of the Stirling engine mCHP system depending on the firewood quality, moisture level, the amount and fraction of fuel loaded in the boiler furnace;
4) to determine the gasification and combustion chamber temperatures at the stable operation of the system in cogeneration mode.

Experiment 2: Combination of Stirling engine and PV

The system for investigation consists of a micro-cogeneration unit based on external combustion Stirling engine, a solid biomass gasification boiler, and solar photovoltage panels (PV). A prototype of a solid biomass micro-cogeneration unit was used for the experiments. An "A" class solid biomass heating boiler *Magasro* 31 kW was used to create the prototype. For the research, a solar PV panel system was created on the roof of the building 14º in relation to the horizon with a south-facing position, the installed total panel power is 1200 W. The study is performed on a system connected to an external public electricity grid, Fig. 2.19.

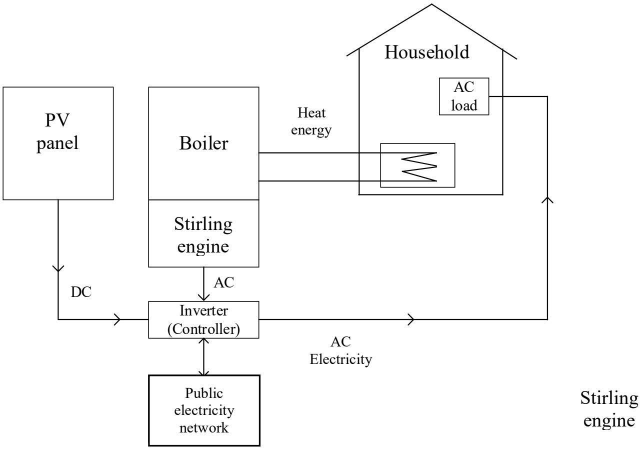


Fig. 2.19. System connection diagram.

The system is controlled by a control unit with a current inverter, which regulates the flow of electricity when transmitting or receiving it from the grid.

1.5. Life Cycle Analysis

This study undertakes the LCA methodology according to common reference framework ISO 14040:2006 to compare the environmental impact of different single family residential building energy supply scenarios. The study aims to find which is the optimal solution for energy supply at local level for the case of Latvia, taking into consideration multiple criteria and life cycle of technology for describing environmental burden. A single family residential house in Latvia with living area of 200 square meters is selected as the object of the study.

The comparative LCA is performed for the single family residential house in Latvia for following scenarios:

- Scenario 1: Heat supply from boiler and electricity supply from the grid.
- Scenario 2: Heat supply from boiler and electricity supply from PV panels.
- Scenario 3: Heat and electricity supply from mCHP.

The objective of this study is to clarify which of the defined scenarios has the lowest environmental impact associated with the selected technologies from their cradle to use in energy production, including raw material extraction, transportation, processing, manufacturing, and fuel consumption among the compared scenarios. The end of life stage referring to disposal of technologies is not included in this study.

2. RESULTS

This chapter observes the results of the research described in the previous chapter.

2.1. Bibliographic analysis

The summary of the quantitative results for all three research questions are shown in Table 2.1.

Table 2.1

Search Criteria for Each of the Defined Research Questions

RQ	Retrieved records	Retrieved full papers	Time series range	Document type in selection
RQ1	3997	n/a	1960–2023	1978 articles, 1948 conference papers, 71 reviews
RQ2	41	29	2001–2022	24 articles, 14 conference papers
RQ3	8	8	2009–2017	5 articles, 2 conference papers, 1 review

In the retrieved articles, various terms are used as keywords relating to solar technologies. However, the highest increase in total in the last decade is seen for the use of keywords related to “efficiency”. Regarding the geographic coverage of analysed publications, the work summarizes the countries that most frequently publish Stirling engine related studies. Geographic coverage can be can be visualized using bibliometric data analysis programs, for example, *VOS viewer*. *VOS viewer* visualization possibilities are used also to analyse the timely dynamics of keywords used in the retrieved articles. The minimum number of keyword mentions was set to 50, in order to acquire a representable set of keyword clusters, and close duplicates were combined by providing replacement thesaurus. Hence, 84 keywords were mentioned at least in 50 publications which are grouped in three main clusters (Fig. 2.1).

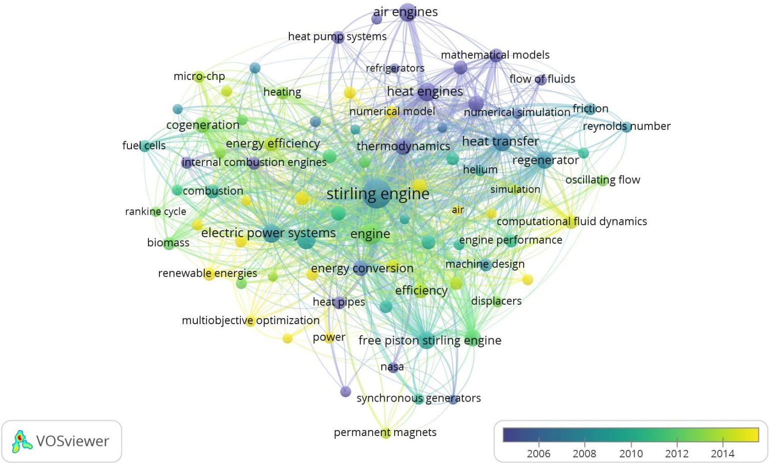


Fig. 2.1. Overlay visualization of the most common keywords in RQ1 sample.

In order to answer RQ2, another iteration of document retrieval based on a dedicated set of search criteria was performed. The aim was to select the particular set or Stirling engine related literature that also addresses residential level applications and biomass as a fuel. To achieve an even better coverage of household-scale technologies, six most popular variations of micro cogeneration related keywords were obtained from RQ1 keyword statistics and added to the research string with the logical "OR" function.

Hereafter, the statistics of publications selected to answer RQ2 are summarized. The earliest of the retrieved publications have been published in 2001, however 95 % of publications on this topic have been published between 2010 and 2023. An increase is seen in years 2014 and 2015 (with 4 publications annually) and 2021 and 2022 (with 5 publications annually). 24 of the publications were journal articles and 14 were conference papers; there were no reviews in the selected set. In addition to environmental and climate change concerns, the current and future energy security challenges will also further encourage the Stirling engine research. Therefore, Q3 is dedicated to the implications of Stirling engine within the energy supply, energy security and environmental research field. The dedicated search string returned 8 documents that have been published between 2009 and 2017. It is a very small set of documents, but it indicates the recent topicality of the subject.

As the Stirling engine historical development trend identified, the topicality and popularity of the technology has fluctuated throughout the years. One of the promising recent development directions, identified through the content analysis of the papers selected by the structured literature analysis approach, is the research regarding biomass fuelled technology and Stirling engine integration.

As indicated during the preliminary research and keyword analysis, Stirling engine use in combination with micro-CHP is an emerging technology that is especially interesting for decentralized generation. The application of renewable energy sources in micro-CHP and Stirling engine system is increasingly topical; however, there are still practical challenges.

For off-grid RES systems, a significant challenge can be the production-demand management. While biomass based micro-CHP can provide a generation stability at a larger degree and is more controllable than other renewables (like PV and wind power) in terms of production intermittency, the main challenges are related to the lack of significant heat demand in summer, which leads to reduced overall efficiency of the system. Due to high heat to power ratio and dependence on heat demand, Striling engines can only run intermittently during summer. Another upcoming trend is the application of integrated systems of PV and Stirling engine hybrid cogeneration.

Regarding RQ3, though the gathered set that fits the query is small most of the articles directly indicate that the Stirling engine technology aids ensuring energy security exactly by diversifying electrical energy production. Overall, these studies acknowledge the advantages that cogeneration in general and Stirling engine use, in particular, provide for energy source and production, e.g., diversification and decentralization of energy production, but no in-depth analysis has yet been done on this sub-direction.

2.2. Multi-criteria decision analysis

Quantitative data were available for each criterion and alternative. These are listed in Table 2.2.

Table 2.2

Multi-Criteria Decision Analysis Decision Matrix

Criteria	**PEMFC/PV**	**PV**	**SE/BM**	**SE/SD**
LCOE, EUR/kWh	0.46	0.13	0.11	0.17
Efficiency, %	48	18	47	31
Reliability, h/year	1691	1314	7000	2400
GWP, kgCO$_2$eq/kWh	0.24	0.60	0.12	0.30
Lifetime, years	5	25	20	20

The electrical efficiency of different types of fuel cells ranges from 20 % to 70 %. However, when looking at the efficiency of the systems in which they operate, it can be seen that they are typically in the range of 10 % to 60 %. PEMFC has an electrical efficiency of between 50 % and 60 %, while the system in which it operates has an efficiency of between 30 % and 50 %. For the greenhouse system modelled, the PEMFC had an electrical efficiency of 48 %, which falls within the limits defined above and was, therefore, used for the analysis. The efficiency of PV panels has improved in recent years. In 2006, the average efficiency was 13 % for multicrystalline PV panels and 15 % for monocrystalline PV panels, compared with 17 % and 18 %, respectively, in 2018.

After the data has been compiled, TOPSIS calculations were performed (Fig. 2.2).

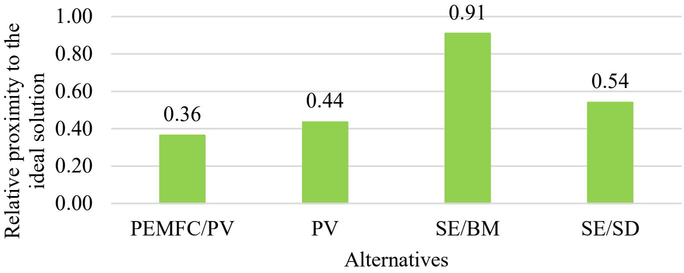


Fig. 2.2. Results from TOPSIS analysis.

The sensitivity analysis shows that the biomass-fuelled Stirling engine score remains relatively stable even when altering the criteria weights, except for the lifetime criterion, which shows a slight drop in score (Fig. 2.3).

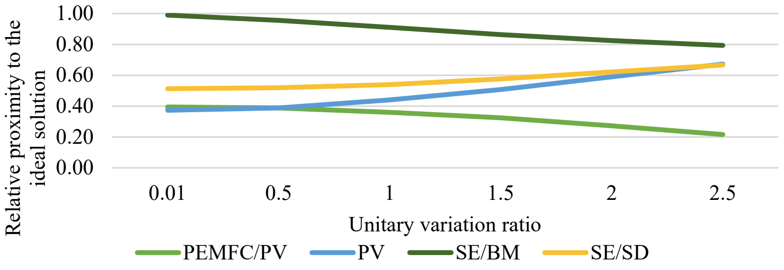


Fig. 2.3. Results of sensitivity analysis of lifetime criteria.

In all cases where the criterion has a reduced impact, meaning a unitary variation ratio is 0.01, the solar powered Stirling engine remains the second-best alternative. In such a case, PV and fuel cell systems swap places in the LCOE and lifetime criteria analysis, i.e., PV drops to the last and PEMFC/PV moves to the third place. The results of the LCOE criterion analysis are shown in Fig. 2.4.

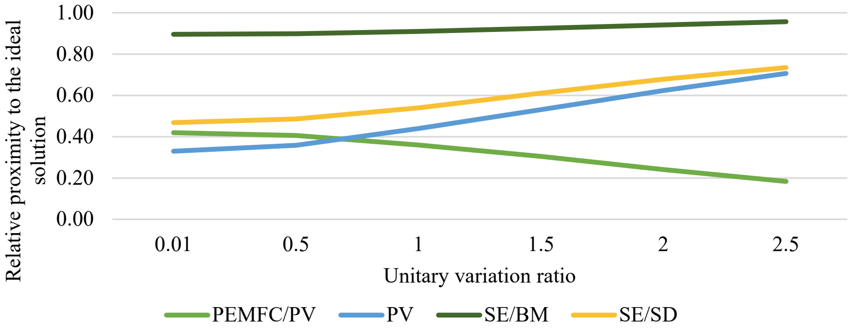


Fig. 2.4. Results of sensitivity analysis of levelized costs of energy criteria.

When the criterion is given a high impact (unitary variation ratio is 2.5), all alternatives except the biomass-fuelled Stirling engine have a changing rank.

2.3. Energy supply balance

Based on the analysis of thermal energy (*Q*) consumption, options for reducing it were identified for the selected buildings. Considering the correlation between *Q* consumption and outdoor air temperature, a heat load diagram has been created (Fig. 2.5). The heat load diagram shows the difference between the *Q* demand of different buildings, but the common trend is that the heat load peaks are relatively short in comparison to all heating season. At the same time, the influence of these peaks on the heating system is significant. The capacity of energy technologies is typically chosen to fully cover the peak hours of short-term *Q* consumption. As a result, energy technologies work with reduced heat load during most of the heating season. In addition, the power selection of energy technologies according to the peak heat load contributes to increased capital costs during installation. Some buildings have *Q* consumption in the summer period for hot water preparation. The heat load in the summer period is very low in relation to the peak heat load in the winter period. Such differences in heat load create an additional challenge for the creation of a sustainable heating system. Therefore, the reduction of *Q* consumption has significant benefits for the creation of an efficient energy supply system.

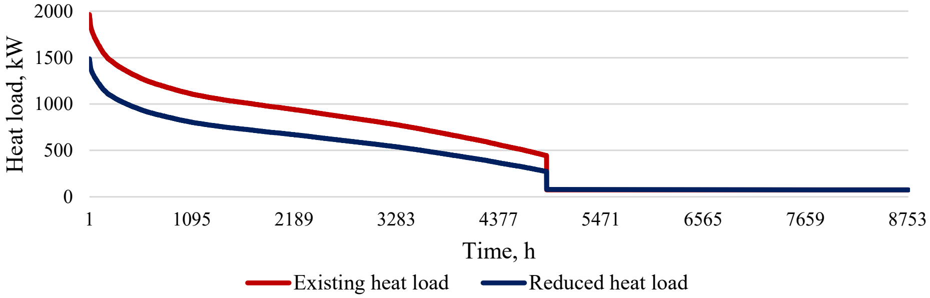


Fig. 2.5. Annual total heat load of selected municipal buildings.

In the case of electricity (*E*), a benchmark for reducing *E* consumption is also applied. Monthly *E* consumption was used as a benchmark for each building, which may not be higher than the average annual *E* consumption. This limits maximum *E* consumption and peak electrical loads. There is also a decrease in average annual *E* consumption. The biggest drop in *E* consumption is seen in the winter months. The maximum reduction is in December, which amounts to 34.7 MWh.

Applying the established benchmarks reduces both total *Q* and *E* consumption and maximum heat and electrical loads. Figure 2.6 shows the relative decrease between the current situation and the benchmarks. The decrease observed varies significantly between buildings. This means that there are consumers for whom heat or electrical loads are already balanced. The largest reduction can be achieved in *Q* consumption (by 26.0 % in total) and the lowest reduction in *E* consumption (by 13.4 % in total). The reduction in peak loads is significantly higher both in terms of heat load (31.3 % on average) and in terms of electrical load (28.4 % on average). This is an important aspect both in the context of increasing energy security and in establishing an efficient energy system, as it reduces the necessary installation capacity of energy technologies. In addition, the efficiency of energy technologies increases.

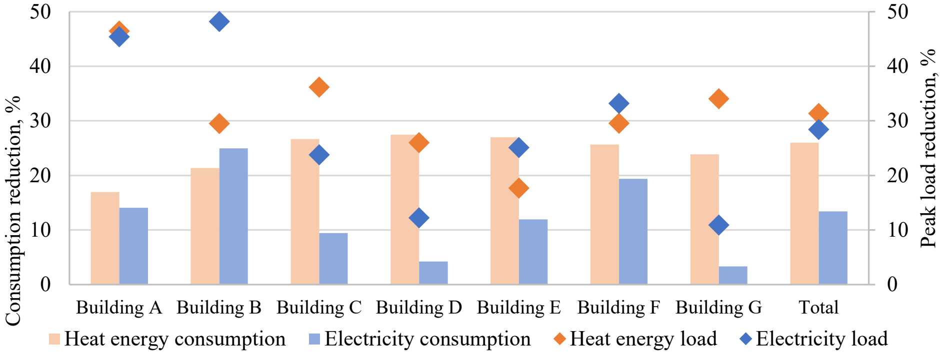


Fig. 2.6. Thermal energy and electricity consumption and maximal load reduction possibilities.

A specific energy cost was calculated for each scenario included in the study. The results show that in each alternative scenario (S1, S2 and S3), this indicator is lower than in the current situation (Scenario BS). In Fig. 2.7, the dispersion of specific energy cost is reflected between all selected buildings considered in all scenarios. Scenario S1 with SE has the highest dispersion, suggesting that this technology can be suitable and reach high results under certain preconditions (smoothed *Q* and *E* consumption without peaks, summer heat load) and appropriate *Q* and *E* consumption ratios. Scenario *BS* is the most disadvantageous option (the median indicator is 241 EUR/MWh at base load and 245 EUR/MWh at reduced load). The most advantageous alternative is Scenario S2: by introducing the technologies proposed in this scenario, the specific energy cost will decrease on average to 101 EUR/MWh at base load and 108 EUR/MWh at reduced load. The reduction in load makes it possible to reduce energy consumption, but this leads to an increase in specific costs.

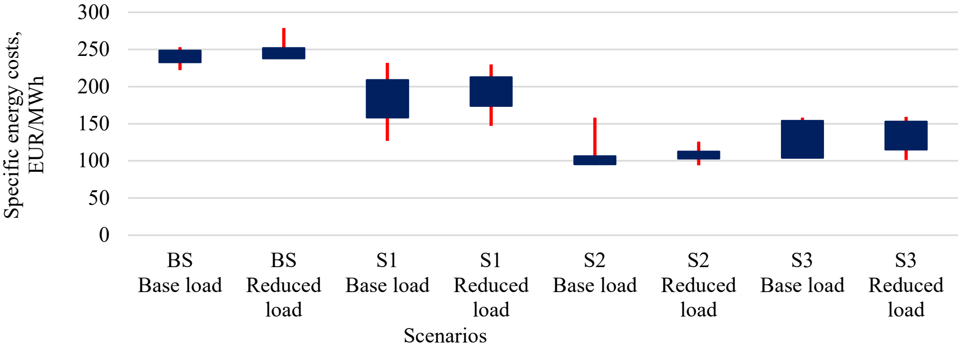


Fig. 2.7. Specific energy cost of selected scenarios.

Scenarios S1, S2 and S3 require new energy technologies that require investments. Scenario *BS* is based on the current situation and energy technologies used, so no additional investments are necessary. Figure 2.8 shows cumulative investments – the sum of the values for each selected building in each scenario. The lowest indicator is for Scenario S1 as it expects to use only one hybrid technology – a pellet boiler with an SE. There are significantly more investments in Scenarios S2 and S3, as in addition the solar technologies are used – solar PV with HP in the Scenario S2 and solar collectors with TES in the Scenario S3. The highest cumulative investments are predicted for Scenario S3.

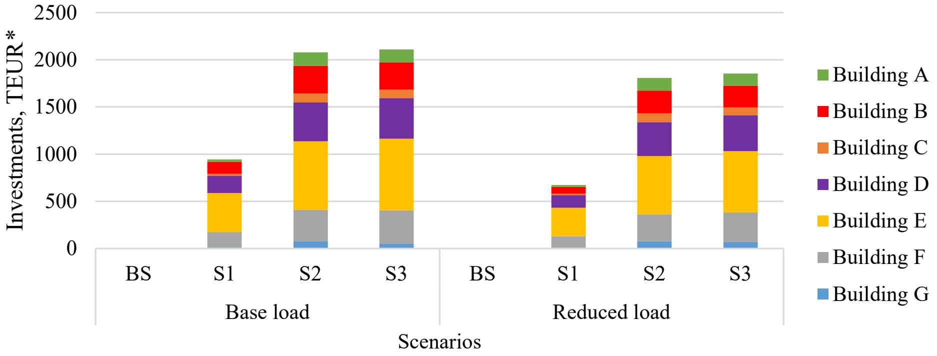


Fig. 2.8. Total investment for scenario implementation (* TEUR – EUR in units of thousands).

Given the amount of the investments, on average, the shortest payback period, considering all municipal buildings, is for Scenario S1, which is equal to 3 and 4 calendar years at base and reduced load, respectively. This is due to lower investments as the cost of producing energy for Scenarios S1 is higher than for Scenarios S2 and S3. For different buildings, the introduction of Scenario S1 will pay back in 9 years. The longest payback period is for Scenario S3, with average values at base and reduced load accounting for 5 and 6 calendar years, respectively. For Scenario S2, the indicator is between 4 and 5 calendar years at base and reduced load, respectively. In scenarios with reduced load, the payback period is slightly higher than in scenarios with base load. This is due to slightly higher specific energy cost.

The study assessed each scenario not only based on technical preconditions and economic factors but also analyses the environmental impact. When comparing emissions from biomass and natural gas, it can be concluded that burning of natural gas produces less CO and NO_x emissions per energy unit, however, the amount of CO_2 is significant. On the other hand, biomass is considered as a carbon-neutral fuel. It is important to note that the emission factors set out in Table 2.3 refer to the total amount of energy produced, which includes both Q and E in a certain proportion. Given that, in the case of biomass, this energy resource is used at the same time, it was decided not to separate emission factors for each type of energy but to attribute them to the total amount of energy.

Table 2.3

Emission Factors Depending on Scenarios

Scenarios		CO, g/MWh	NO_x, g/MWh	PM, g/MWh	CO_2, kg/MWh
Base load	BS	117	142	0	224
	S1	521	456	391	0
	S2	378	331	283	0
	S3	416	364	312	0
Reduced load	BS	119	144	0	229
	S1	536	469	402	0
	S2	362	317	271	0
	S3	434	380	326	0

The overall environmental impact of the scenarios depends on the type of energy resource used and the amount of energy resource used. The emission factor values given in Table 2.3 were used to calculate the total amount of emissions, knowing the total energy consumption for each scenario. Scenarios with reduced load have lower energy consumption, so the total amount of emissions produced is also lower. The use of natural gas in Scenario BS results in quantity of CO and NO_x is 691 kg and 534 kg per year at base load and 841 kg and 649 kg at reduced load. Compared to biomass (Scenario S1), natural gas CO emissions are about 4 times less, while NO_x emissions are about 3 times less. In addition, biomass also produces a significant amount of particulate matter (PM) emissions. It should be considered that high amounts of CO_2 are released during the burning of natural gas. At base load in Scenario BS, 1326 tons of CO_2 emissions are produced and 1026 tons of CO_2 emissions at the reduced load. In Scenarios S2 and S3, the use of solar technologies reduces biomass consumption, which also reduces the air pollution. The lowest total amount of CO, NO_x and PM is produced in Scenario S2 among alternatives: 2222 kg of CO emissions, 1944 kg of NO_x emissions and 1667 kg of PM emissions at base load, and 1644 kg of CO emissions, 1438 kg of NO_x emissions and 1233 kg of PM emissions at reduced load.

2.4. Empirical experiment analysis

Experiment 1: Working principle of Stirling engine

To detect the cogeneration mode effect on boiler, thermal efficiency experiments are performed in thermal and CHP mode using fuel with the same parameters. Three experiments (1–3) were performed only in the heat energy production mode, while the experiments (4–9) were performed in the cogeneration mode. The calculations of thermal and electrical efficiency were done in each of the experiment. A comparison between input energy (firewood) and measured output of thermal and electrical energy was performed (Fig. 2.9). From experiment results presented in Fig. 2.9, calculations of system thermal and summary (thermal + electrical) efficiency expressed in % were calculated. In addition, it was calculated how much an average thermal and electrical energy experimental unit is able to produce from 1 kg of wood.

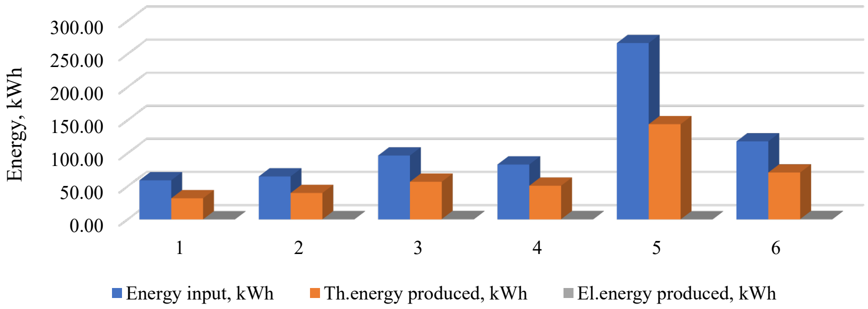


Fig. 2.9. Produced thermal and electrical energy from input energy.

Evaluating the results of the experiments, no influence of electricity production in CHP mode was found on the thermal productivity of the boiler. Those findings could be possible because of specific construction of the boiler, because part of the heat energy was recovered from the Stirling engine cooling circuit, so it gives extra heat collecting surface. No markable loss of thermal capacity was found in Experiments 4–9. The above leads to the conclusion that the operation of the plant in the cogeneration mode increases the overall efficiency of the plant (Fig. 2.9) compared to the identical boilers, which operate only in the heat energy production mode.

Evaluating the emissions from the heating system, measurements of CO_2 and O_2 in flue gases were taken every 15 min during all experiment with flue gas analyser *Testo 340*. Qualitative combustion process was observed, in stable combustion process from 30–180 min. of the experiment (Fig. 2.10), which complies with the "A" class boiler standards.

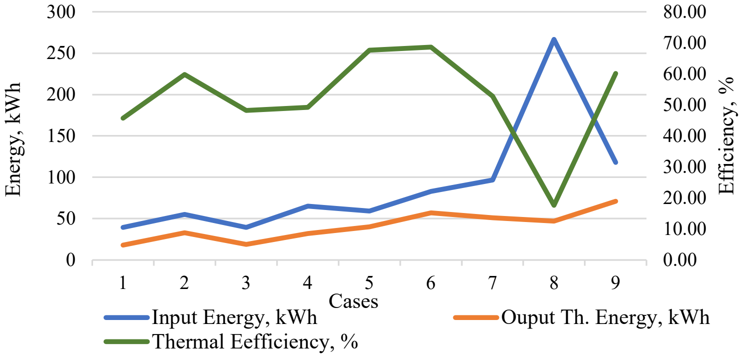


Fig. 2.10. Thermal efficiency of the boiler.

The productivity of the Stirling engine was measured with *Stirling Engine Data Viewer* software, by logging data every 15 min. According to the plan set, different types of fuel and moisture content were used in the experiments. Additionally, firewood and sawdust briquette combinations were tested. In the course of the experiment, a correlation was found between the temperature of the Stirling engine head and the electricity produced by the generator in each of Experiments 4–9 (Fig. 2.9). One of the most representative experiment results are shown in Fig.

2.11 – experimental minutes 90 and 150. It was also found that electricity production drops down sharply with relatively smooth temperature drop and then rises up with a little temperature increase. Measurements were taken 13 times, every 15 minutes; fuel was injected only before the boiler was ignited and was not replenished during the experiment, which explains the nature of the slowly dropping temperature curve.

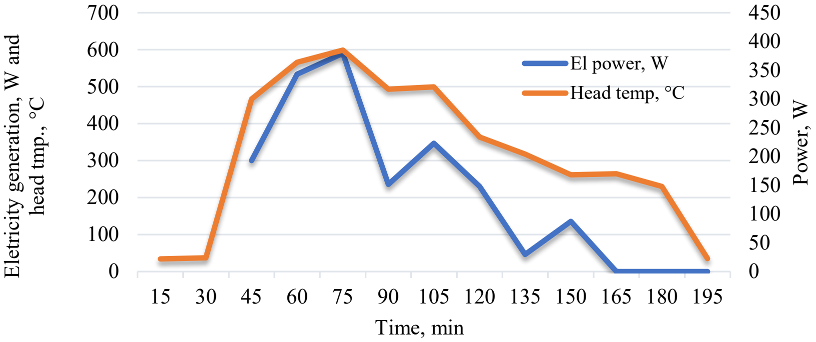


Fig. 2.11. The power of the mCHP electric generator (blue line) depending on the engine head temperature (red line) from the most representative Experiment 7.

Experiment 2: Combination of Stirling engine and PV

The electricity generation of the mCHP plant used in the study is directly related to the thermal energy production of the boiler. In the course of the study, 9 experiments were performed, the aim of which was to find out how much heat and electricity the mCHP unit is able to produce in cogeneration mode.

Experiment series were done to determinate the mCHP system electricity production (Fig. 2.13) and thermal energy (Fig. 2.12) from burning 1 kg of wood. Experiments 1–3 were done running an experimental unit in thermal mode, Experiments 4–9 – in cogeneration mode.

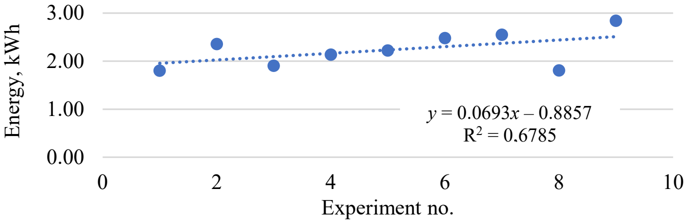


Fig. 2.12. Produced thermal energy from 1 kg of wood.

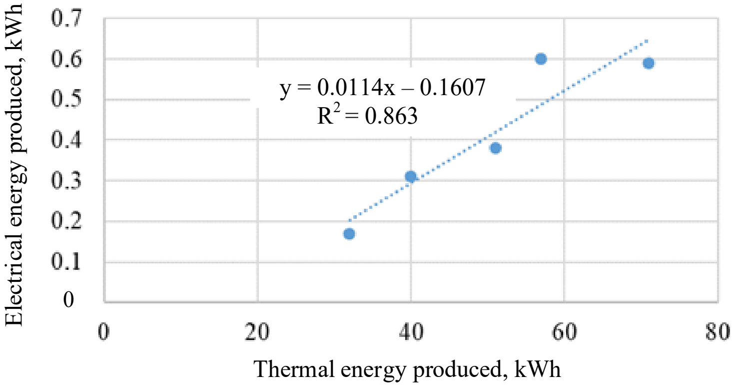


Fig. 2.13. Produced electrical energy from 1 kg of wood.

To determine the actual amount of electricity produced by PV panels, data was collected from the experimentally installed 1.2 kW solar panel system. Given that the experimental PV system was installed off-grid, it does not count the electricity produced without consumption, or if the battery system is fully charged. Based on the above, data on other solar panel systems installed in Latvia and Northern Europe, which are connected to the grid and all electricity generated is accounted for and transferred to the grid, were analysed. Data from grid tied systems were used for further calculations. According to the experimental results in Fig. 2.13 and further calculation, it can be concluded that when the plant is operating in cogeneration mode, 1014 kWh of electricity would be produced per year.

The electricity generation of the mCHP system directly depends on the heat energy of the boiler, as result total annual electricity produced with mCHP system is tightly depending on household heat energy demand. During the recalculation, it was determined that on average 0.026 kWh electricity (Fig. 2.13) and 2.53 $\mathrm{kWh_{th}}$ (thermal energy) was obtained from burning 1 kg of wood. A household with these parameters consumes 39 MWh of thermal energy per year. Correspondingly recalculating the capacity of the mCHP unit to produce electricity from the mentioned annual heat energy demand, it is obtained that 1014 kWh of electricity would be produced.

From 1 kW of installed solar panels annual production is around 800 kWh. The experiment installation is 1.2 kW, so it could produce 960 kWh electricity per year.

Monthly electricity demand on average household is 293 kWh, 3 516 kWh per year.

From mCHP annual electricity production would be1014 kWh.

To cover annual electricity demand, increase of PV panels installed power compared to experimental installation is necessary. To cover the total demand of 3 516 kWh, of which 1014 kWh could be covered by mCHP system, 2 412 kWh have to be covered by installed PV panels. To cover annual electricity demand of the household, 3 015 W of installed PV power is necessary, it means 10 solar panels of 300 W.

Experimental based calculations were done to define household annual electricity supply of consumption (SOC) by using the combination of PV systems with mCHP to reach NET Zero balance. In order to determine how much electricity a PV panel system is able to produce during a calendar year, an inventory was made, as well as a review of the literature on the operation of a similar PV systems in Latvia. Three scenarios from Net Zero point were observed (Fig. 2.14).

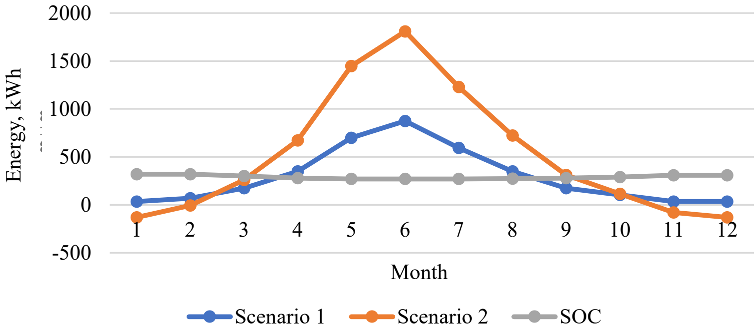


Fig. 2.14. NET Zero energy balance with public grid.

2.5. Life Cycle Analysis

The results of the model created within *SimaPro* software for single family residential building energy supply scenarios are analysed in several perspectives, including the single scenario network tree and single scenario impacts per specific emission type, specific process contribution to overall impacts, impacts at midpoint and damage (endpoint) categories, and comparative analysis among different scenarios in the aforementioned perspectives. The multidimensionality of assessment criteria allows for the identification of where the consequences of environmental loads occur among the given scenarios. All of the data are reported per functional unit (FU) and accurately represent the differences between technologies in the analysed scenarios.

The structure of the model is presented with a model network tree, which allows to track the links between the processes involved in the system and identify the main contributing processes to the environmental impacts. The figures of model network trees are presented for all scenarios by including only top three layers of processes and applying the cut-off of 4 %, because large number of links are created within the database processes for each scenario under study, and it is not possible to show all the processes that have contribution to the impact less than 4 % in one figure.

The model network tree for Scenario 1 shows the contribution in the total heat production in boiler (70.9 %) and electricity consumption form the public network (29.1 %). Taking a look at the causes of the contribution within Scenario 1, within the heat production the largest share of impact is caused by preparation of wood logs (16.9 %). The network tree diagram for Scenario 2 shows that the share of impact for the heat production in boiler is up to 84.7 %, electricity production with solar PV is added to the system and contributes to 4.2 % of the total impact. The impacts related electricity consumption from public network in Scenario B are 11.1 %. The network tree for Scenario 3 shows environmental impacts share for heat production equal to 74.4 %, for electricity consumption from public network 21.8 %, and 3.85 % for Stirling engine.

Impact category scores

The results presented at midpoint level are given for 14 impact categories. For most of impact categories at midpoint level the highest environmental impact score is for Scenario 1, followed by Scenario 3 and the lowest for Scenario 2, with the exception of the freshwater eutrophication, freshwater ecotoxicity and marine ecotoxicity, human non-carcinogenic toxicity, and mineral resource scarcity impact categories. Freshwater eutrophication is constant at around 0.614 kgPeq. in Scenarios 1 and 3 and is the lowest in Scenario 2, equal to 0.512 kgPeq.

Damage category score

The information on damages to environment caused by the environmental impacts described above according to the selected impact assessment methods are determined for three categories: damage to human health, damage to ecosystem and damage to resource availability. The impacts related to the damage to human health measured in DALY are reported in Fig. 2.15. Damage to human health is the highest in Scenario 1 and the lowest in Scenario 2. Fine particulate matter formation has the highest damage to human health among the impact categories in analysed scenarios. The second highest impact is for the global warming category. The rest of the impact categories have a relatively small damage to human health.

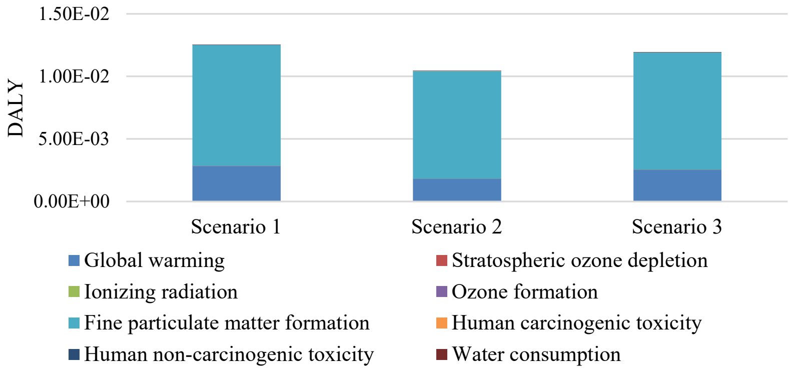
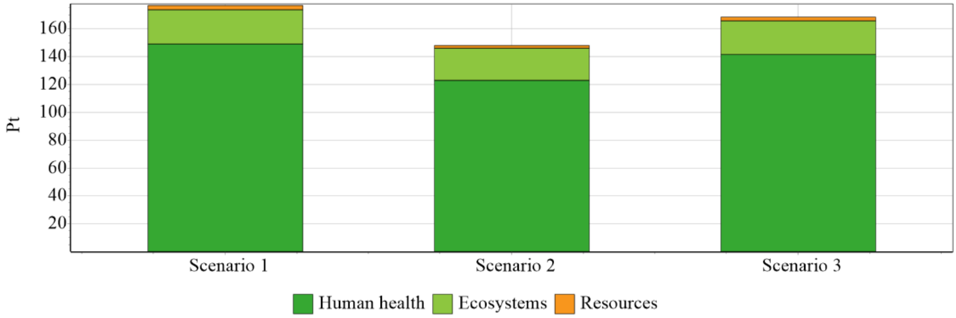


Fig. 2.15. Damage to human health measured in DALY across the three scenarios.

The damage to ecosystem has the same distribution among scenarios as the damage to human health. The highest damage is found in Scenario 1 and the lowest in Scenario 3. The highest contribution to the damage is coming from the land use indicator in all scenarios, followed by global warming, ozone formation and terrestrial acidification. The results for damage to resource availability show the same trend as observed with the highest damage for

Scenario 1 and the lowest damage for Scenario 2. The fossil resource scarcity is a much more significant contributor to the damage on resource availability in comparison to mineral resource extraction in all analysed scenarios.

Final results of comparative LCA at single score level account for the damage category scores together and are shown in Fig. 2.16 in Ecopoint units. Scenario 1 is the most impactful scenario in all damage categories. Scenario 2 has the lowest damage and Scenario 3 ranks in the second place. The highest impact is caused in human health damage category in all scenarios, followed by ecosystem quality, and then climate change and resources categories.



Method: ReCiPe 2016 Endpoint (H) V1.08 / World (2010) H/H / Single score
Comparing 1 p 'Scenario 1', 1 p 'Scenario 2' and 1 p 'Scenario 3';

Fig. 2.16. Single score results for the defined scenarios.

Sensitivity analysis

The sensitivity analysis for global warming potential in kg of CO_2eq. is reported in Fig. 2.17. For all scenarios under analysis, the sensitivity trend shows that the global warming potential impact increases with the increase in electricity consumption. The most sensitive to changes in electricity consumption is the Scenario 1 and the least sensitive is Scenario 2. Assuming that Scenarios 1 and 3 have similar impact on electricity consumption decrease by 50 %, it can be concluded that the change in Scenario 1 increases almost two times, from 1783 $kgCO_2$eq. to 3685 $kgCO_2$eq, while in Scenario 3 it increases only from 1722 $kgCO_2$eq to 3074 $kgCO_2$eq.

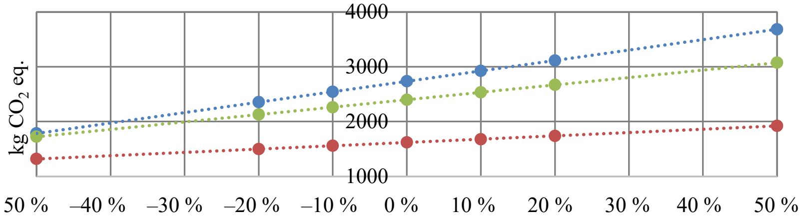


Fig. 2.17. Sensitivity analysis of electricity consumption for global warming potential, $kgCO_2$eq.

Similarly, the sensitivity analysis is made for changes in electricity for environmental impacts at the single score level. Also, here the highest impact increase can be observed for

Scenario 1 and the lowest for Scenario 2. The changes in the single score have smaller range than for global warming potential. Hence it can be concluded that no significant burden transfer occurs among scenarios and also the impact categories. The results of sensitivity analysis show that the model outputs are affected based on changes in input variables in a recognizable and meaningful pattern corresponding to the model structure. Thus, the model is valid and results are representative for the selected case of energy supply technologies for an average household in Latvia.

3. DISCUSSION

Chapter 3 is devoted to the discussion of the results obtained in the previous chapter. In the context of the previous chapter, where the systematized results of the research were presented, the purpose of this part is to supplement the analysis with the interpretation of the obtained results and to summarize the work done.

3.1. Bibliographic analysis

The answer to RQ1 “How has the research on Stirling engine evolved over time?” was investigated by analysing the statistics of the samples of documents retrieved according to the described research protocol. It was identified that for more than six decades, articles mentioning Stirling engines have been published in internationally indexed journals and conference proceedings. The key-word dynamics showed that, initially, such keywords as heat engine, air engine and thermodynamics were most frequently used. However, in the last two decades, the publications have evolved to include much wider sub-directions, including the very topical in the context of the Green Deal subjects of renewable energy resources, i.e. solar energy and biomass technologies, increasing of energy transformation and use of micro-CHP technologies. Research on Stirling engine technologies is evolving, and nowadays increased number of scientists are publishing new studies with the aim to find a feasible application for this technology in modern conditions.

The defined RQ2 was “What is the focus and latest tendencies in small scale (residential) renewable energy-based Stirling engine research, with particular focus on biomass?”. The quantitative bibliographic and qualitative content analysis results corroborate the progress towards the use of renewable resources where solar-based power generation systems have already been widely covered by scientists for many decades, but also the number of research articles related to biomass-based Stirling engines are increasing lately. Even more, for household or residential level, the use hybrid systems including micro-CHP, PV and Stirling engine combinations are increasingly investigated, indicating this as a future trend in implementation. Energy efficiency increase is a topical question as well, because the keyword and overlay analysis showed more frequent publishing in this and former mentioned areas. The content analysis on two more specific sub-directions of interest, i.e. biomass fuelled Stirling engine use in households and Stirling engine implications on energy security, showed that though research activity in these directions has increased lately, more profound research is needed, especially on energy security and independence aspects.

3.2. Multi-criteria decision analysis

Transition to renewable energy in the EU will include small-scale household energy production solutions. Therefore, this study compared four renewable energy systems using MCDA: proton-exchange membrane fuel cell with photovoltaic panels, photovoltaic panels, biomass-fuelled Stirling engine, and solar powered Stirling engine. The aim was to identify the most suitable energy system for household electricity generation in the EU, up to 50 kW.

In the literature review, data for each energy system was summarized. Five criteria were selected for TOPSIS, considering environmental, economic, and technical aspects. The results show that the biomass-fuelled Stirling engine system is the most favourable for household electricity generation (0.91). This is mainly because it is the cheapest, most reliable, and has a low environmental impact. The sensitivity analysis revealed that this system is not affected by weight changes and would remain the best alternative if the criteria weights were not the same.

Fuel cell is the best technological solution for small-scale heat and power generation, while the Stirling engine is more suitable for households because it is cheaper. The study concludes that the fuel cell has the lowest environmental impact, but it takes into account direct emissions instead of the whole life cycle environmental impact. The present study confirms that the Stirling engine is the best alternative for households.

3.3. Energy supply balance

The aim of the study was to evaluate the possibilities of increasing energy security in municipal buildings in the event of an energy crisis. For this purpose, a complex methodology was developed, which includes several interrelated steps: 1) evaluation of the current situation; 2) reduction of current energy consumption; 3) selection of energy technologies and definition of alternative scenarios; and 4) assessment of selected scenarios.

The study includes three main alternative scenarios and a baseline or reference scenario for comparison of benefits. Scenarios are divided into two levels depending on the load. Two loads are used – base and reduced. All scenarios were compared using predefined criteria. In all alternative scenarios, 100 % self-sufficiency was achieved using the biomass boiler and Stirling engine and in combination with solar technologies and a heat pump. The development of excess electricity tends to depend on consumer consumption profiles and technology characteristicshe development of excess electricity tends to depend on consumer consumption profiles and technology characteristics. This electricity cannot be used immediately and can, therefore, be sold on the grid.

Specific costs of energy production differ significantly depending on the technologies used. The lowest costs are in scenarios with solar PV and heating pump. The highest cost for energy production is in the base scenario where natural gas is used. The costs are relatively high in scenario with the use of pellet boiler with Stirling engine. Reducing energy consumption, a slight/small increase in specific costs of energy production can be observed for each of the technologies.

The specific energy cost is significantly influenced by the choice of technologies to be used or expected. The lowest costs are in scenarios which expect using solar PV and heat pumps. On the other hand, the highest specific energy cost is in the current situation, where the natural gas plays the main role.

The results for total investments in technology deployment clearly indicate that in Scenarios S2 and S3 the investments are approximately 2 times higher than in Scenario S1. This is because Scenarios S2 and S3 use more than one hybrid technology solution. Reducing energy consumption reduces technology-required installation capacity, and consequently reduces the investments required.

The scenarios considered in the study were also compared based on the amount of emissions produced. Air pollutant emissions CO, NO_x, and PM, as well as greenhouse gas CO_2 were calculated. In Scenario BS, where natural gas boiler is used, significantly less CO and NO_x emissions are produced; however, there are significant CO_2 emissions. By applying solar technologies in Scenarios S2 and S3, it is possible to reduce air pollutant emissions compared to Scenario S1. Reducing energy consumption also reduces the amount of emissions produced in all scenarios.

The results of the study clearly indicate that it is possible to create a sustainable energy supply system for municipal buildings, which is based on renewable energy resources obtained locally, thus increasing the energy security of both the municipal and the national energy system, achieving energy independence. The results also show that before the implementation of new energy technologies, it is important to ensure the reduction of energy consumption. It is an important aspect for creating an energy-efficient and energy-secure thermal energy and electricity supply.

3.4. Empirical experiment analysis

Experiment 1: Working principle of Stirling engine

The experiment results show that it is possible to achieve a higher electrical power for the experimental equipment. Taking into account what has been proved in the experimental part of the study, the result of the measurement shows temperature around 600 °C only, so it can be predicted that the maximum electric power of a particular Stirling engine together with a solid biomass boiler can reach 800–900 W. The observations made in the experimental part of the study indicate that the maximum engine power could also be increased by varying the boiler max. coolant temperatures as well as engine cooling system inlet/outlet temperatures. Using higher calorific fuel, such as very dry, less than 10 % moisture, or very dense wood like oak firewood would increase the temperature in boiler combust.

Experiment 2: Combination of Stirling engine and PV

The system is composed of an External Combustion Microgen Stirling Engine micro-CHP unit and PV panels. Reverse interpolation was done to set up minimum PV panels installed power to achieve annual NET Zero energy balance.

As the test results shows, mCHP can produce only about ¼ of the total annual electricity demand and fully meet the heat energy demand. It can be concluded that during the heating season there is still need to receive electricity from grid, therefore it is necessary to install solar panels with much bigger capacity as it was thought before. The capacity 1.2 kW of installed PV panels is not enough. Calculations show that about 3 kW of installed PV panels capacity should be installed to reach zero NET balance.

Optimum calculation software method was used to find the NET balance between the household heat energy supply, electricity production from mCHP+PV (Scenario 1) and PV panels only with heat from conventional biomass boiler. It was detected that it would be possible to decrease grid disbalance if mCHP would be used also during summer period, for example, for hot water preparation. It has been concluded also that by installing a heat energy storage tank, lower public grid disbalance could be reached, but for detailed results additional research is necessary.

The calculation shows that CO_2 neutrality could be reached by using the PV and mCHP systems combination for household energy supply..

3.5. Life Cycle Analysis

The examination of impact category scores revealed that Scenario 1 has the greatest environmental impact scores in most of impact categories, followed by Scenario 3, while Scenario 2 has the lowest environmental impact. Notably, most impact categories have consistent scores across all scenarios. The categories, such as freshwater and marine ecotoxicity, non-carcinogenic toxicity, and mineral resource scarcity exhibit different performance among scenarios, showing burden transfers between effect categories. Across all three scenarios the highest contribution to the environmental impact is made by fine particulate matter formation. This finding corresponds also to results of other studies mentioned in literature and should be addressed more seriously in local policy planning. Considering that the damage of the fine particulate matter formation is mainly for human health, this factor should receive more increased attention in specifically densely populated areas like cities, towns, and suburbian areas.

The study investigated three endpoint categories, including damage to human health, damage to ecosystems, and damage to resource availability. Scenario 1 consistently showed the highest damage in all three categories, while Scenario 2 the lowest damage. According to the obtained results, the main causes of ecosystem damage are land use and global warming. At the single score human health damage is most significant among the analysed scenarios, which again shows that particular attention should be addressed to dealing with the source of emissions – combustion furnaces, which is a popular technology for heating of residential sector. In order to decrease the potential threats to human health, local decision-makers and police-planners should more strongly address the preventive measures enabling decrease of the fine particulate matter formation. This can be achieved through forcing in power the regulations for residential sector that foresee various filtering technologies for pollution sources. The sensitivity analysis results confirm the model's validity and the representative character of the outputs. The patterns revealed in the sensitivity analysis match the structure of the model, strengthening the assessment's credibility. In the sensitivity analysis, Scenario 1 was found to be the most sensitive to changes in electricity usage, with a large increase in impact. Scenario 3 also exhibits sensitivity, although the changes in impact are much lower than in Scenario 1. Scenario 2 is the least susceptible in this aspect, indicating that its environmental effect profile is more stable under the changes in electricity demand. However, it is still an open question how to address the environmental impact specifically related to the heat production from local renewable sources for residential buildings. This aspect should be addressed more in-depth in the future research on the topic of residential sector energy technologies.

CONCLUSIONS

1. Security of energy supply depends on both social and technological aspects. The research of social aspects is more a branch of social sciences, but it is not ignored in exact studies either, because the change of people's habits and behaviour in crisis conditions can have a significant impact on both safety and environmental impact factors, which are widely discussed in the Doctoral Thesis. The crisis energy supply model is significantly different from everyday situations, and even small disruptions in energy supply can create a domino effect causing much deeper crises, including ecological disasters, so safety aspects must be given a very high priority.
2. Looking at energy supply security from a technological aspect, the preliminary discussion in the Thesis is about the centralized or decentralized energy supply model, which is more resistant to unpredictable crisis situations. Each of the models has its own advantages and disadvantages. As the main benefits of the centralized energy supply model they mention energy efficiency and the possibility of more effectively attracting investments for the modernization process, equipment replacement, and network construction. It is the construction of heat supply networks that is the critical issue in whether the model will be economically viable, and it is connected with technological challenges in densely populated areas and disproportionate costs in sparsely populated areas. The decentralized energy supply model shows higher resilience in crisis situations, but the biggest challenges are achieving high energy efficiency in small-scale boilers, attracting investments for the installation of modern equipment, and attracting qualified specialists for the maintenance and repair of equipment.
3. The hybrid energy supply model has shown higher resilience and suitability in crisis energy supply situations. The simultaneous use of several technologies makes it possible to show less dependence on external energy supply networks in seasonal and day-changing conditions, cogeneration equipment is able to fully provide the heat supply of buildings and partially also the electricity supply demand, in combination with solar PV panels and storage equipment, they can also operate autonomously under certain conditions. The creation of a hybrid model requires more investment at the initial stage, but in the long term the economic aspects balance out compared to the centralized energy supply model, for which the economic investment is lower at the initial stage, but the cost of energy is higher when it is purchased from external suppliers.
4. After studying the most suitable technology for the creation of an autonomous energy supply model, the use of a Stirling engine and a biomass heating boiler was determined as the most suitable. During the bibliographic research, it was concluded that in the last decade, the number of studies related to the use of the Stirling engine in the creation of cogeneration systems, the use of biomass and the creation of autonomous energy supply systems is increasing. During the experiments, an empirical equation was created, which indicates the relationship between the produced heat and electricity, as the production of heat energy increases, the production of electrical energy also increases, but for the operation of the Stirling engine, it is necessary to reach no less than 350 °C, which indicates the need to operate the boiler at nominal capacity in the mode when the working temperature of the boiler furnace is within 700 °C. Compliance with the temperature regime indicates the need to use a heat storage system that ensures a stable

demand for heat energy and reduces the need for the boiler to operate at a reduced capacity.

5. The analysis of the technology life cycle of the Stirling engine indicates the greatest impact on the environment in the stage of fuel preparation and combustion, the impact of the engine itself on the environment is significantly lower. The impact of the combustion cycle on human health is related to the emissions of solid particles from the burning of biomass, which indicates the need to increase the energy efficiency of the boiler and invites us to think about flue gas cleaning, as one of the solutions would be the wet cleaning of flue gases, or the use of the so-called scrubber.
6. Energy supply solutions are investment-intensive, technology replacement takes time. Individual devices and connections can be designed individually, which takes time. It can be concluded that crisis situations should be prepared in time by investing immediately, without waiting for the crisis to occur, because then it may already be too late. In addition, it should be taken into account that it is not permissible to turn off the heating system during the heating season, which requires additional planning processes and time for the preparation of the reconstruction. By investing initially, it will be easier to overcome crises and the risks of energy supply interruptions will decrease.

Jānis Kramens was born in 1972 in Liepāja. In 1995, he obtained a qualification in automation engineering from Riga Technical University. After several years of work in the field of medical technology, he resumed his academic studies in the master's programme at the Institute of Environmental Protection and Heating Systems of Riga Technical University in 2011, researching the possibilities of autonomous energy supply systems and the use of renewable energy resources in Latvia. During his master's studies, he developed practical solutions for energetically autonomous households, with a particular emphasis on the use of solar, wind, and biomass microcogeneration technologies. He obtained a master's degree in 2014 from Riga Technical University. During doctoral studies, he delved into the possibilities of biomass utilization for heat and electricity production in small-scale heating boilers. However, geopolitical processes in recent years have led to increased attention to energy security, thus adding a new dimension to his ongoing research. His Doctoral Thesis explores Stirling engine technology and comprehensively examines the issues related to energy security. During his Doctoral Studies, he authored ten scientific publications, nine of which was the primary author.