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ANALYSIS OF EXPERIMENTAL DATA FROM HOUSEHOLD OFF-GRID SYSTEM IN LATVIA

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Autonomous off-grid systems might be seen as a favourable option when it comes to high grid connection fees and for a sustainable electric system in transition to a low-carbon, renewable-based decentralized system. To ensure such a system, accurate analysis of different scenarios is required to determine the optimal energy source mix and sizing of the off-grid system. Software computing techniques or mathematical models can help solve this task, but, unfortunately, it is unpredictable how actually such systems will perform in real life. There are not so many publications, where the real data and off-grid systems are analysed and compared to simulation results. Thus, this paper examines an experimental stand-alone electrical off-grid solution in Latvia. The operational data of real autonomous off-grid system are obtained for the off-grid system performance and control strategy analysis, which is highly relevant for the planning and dimensioning of affordable renewable off-grid systems.

Keywords: *Equipment sizing, experimental off-grid system, power flow control based on battery voltage level.*

1. INTRODUCTION

In scientific literature, self-sustaining microgrid systems that are built for different consumers are analysed. For example, [1] examines the technical feasibility (including system dimensioning) for a single-family house off-grid energy system in Finland's northern climate with short-term battery and seasonal hydrogen storage. While in [2] comparative analysis between an off-grid hybrid power supply for different consumption levels (1825, 3650 and 5475 kWh) and a newly built grid connection for domestic consumers was performed in different regions of Estonia. In another paper [3], the configuration of off-grid systems in Estonia, which includes photovoltaics, wind turbines, a diesel generator, and batteries, is studied.

The validity of the results presented in literature, however, degrade the further to the south, to Latvia, for example, due to increased PV power generation, or less windy days which depend on specific climatic conditions. Moreover, according to the location, in scientific literature there is little information about real autonomous off-grid systems implemented in life, their technical characteristics, data acquisition and monitoring, as well as data analysis of such electrical systems in general.

In this article, an autonomous off-grid system is assumed as a set of interconnected controllable and uncontrollable rural household loads, decentralized energy sources, and energy storage that is not connected to the power grid. This means the cluster of equipment, which operates in the independent environment, island mode. Overall, there are several benefits for such an autonomous off-grid system:

1. useful development of project is possible in places where there are relatively high investments needed for the grid connection to the distribution networks [4];
2. due to reduced costs of new renewable energy technologies and fluctuating fossil fuel prices, a simplified off-grid system for household electricity supply in remote regions may be an efficient and cost-effective electrification way to the fight against climate change and to reach the European Union (EU) decarbonization targets [5]–[7];
3. to protect against electricity supply quality problems and overall reliability due to increased variable generation or decreasing conventional generation in the grid [8].

Considering the mentioned benefits, such an experimental system was implemented for rural household located 30 km away from Jelgava city in Latvia. The autonomous off-grid system is capable to operate with 16–25 amps (A) within single phase connection at a voltage of 230 volts (V) and frequency of 50 hertz (Hz).

By installing electricity generation devices, batteries, and system control equipment, the analysis is planned for the off-grid performance and possibilities to increase the availability of such electricity supply in Latvia and expand the use of local renewable and zero-emission energy resources. It will be useful to find out the possible costs of an optimized solution, commercialization possibilities, their contributing factors, problems, as well as the efficiency of the use of the overall and individual elements of the off-grid solution.

Initially, a special mathematical model was created to select energy sources, to size equipment and to further test the operation of this off-grid system in the Latvian climatic conditions. Thus, in this article not only we focus on evaluation of this real autonomous off-grid system performance, but also discuss aspects related to software computing techniques and mathematical models versus a real operational off-grid system.

As it is stated in [9], to ensure optimal design and that such renewable systems are affordable, careful planning preferably with high-resolution data on electricity generation and consumption is necessary. As it is one of research gaps identified in literature, and not delivered in a clear way, the objective of the article is to further increase knowledge of such system performance, planning and dimensioning in climatic conditions like it is in Latvia. It is expected to validate approaches which could be used in future and easily replicated for configurations that are more complex.

The study provides a reference for interested parties, including policy makers, foreseeing the landscape for off-grid energy system development.

2. MATERIALS AND METHODS

2.1. Setup of Off-grid System

An electric off-grid system (see Fig. 1) is installed for autonomous power supply of the individual household located near Jelgava city in Latvia. Electric off-grid system consists of:

1. micro wind turbines and solar panels;
2. diesel generator;
3. battery electric storage system;
4. all of it is set up in or around a standard sea container (3.0 x 2.5 m, 2.5 m high) with other necessary equipment (sensors, cables, etc.) for the operation of the off-grid system.

The off-grid system is modular and can be moved relatively easily. It is designed for installation with minimal compliance requirements.

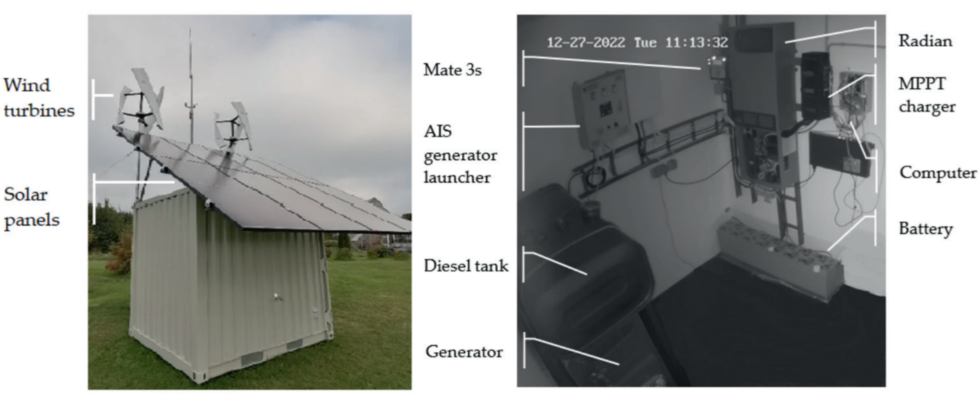


Fig. 1. Experimental autonomous off-grid system.

The basis of the off-grid system is a set of equipment manufactured by OutBack Power for microgrid implementation. System includes Radian GS7048E inverter/charger, system control equipment, panel MATE3, battery monitoring equipment FlexNetDC and solar panel (3.6 kW) charging controller FlexMax80. Separate charge controllers are used to transfer the electricity produced by micro wind turbines (2 x 1.1 kW) to the off-grid network, which are connected with the help of power relays depending on the battery charge level. In case of unavailability of renewable resources, a backup diesel generator is provided with automatic start-up according to the battery charge level. A LiFePO4 battery with a nominal voltage of 52.8 V (3.3 V per cell) is used to store electricity, with a total capacity of 160 Ah (7 kWh). The container, which hosts batteries, invertors and other electronic devices sensible to temperature, was insulated and equipped with devices for maintaining necessary microclimate: heater, conditioner and ventilation. The conceptual diagram of the off-grid system is given in Fig. 2.

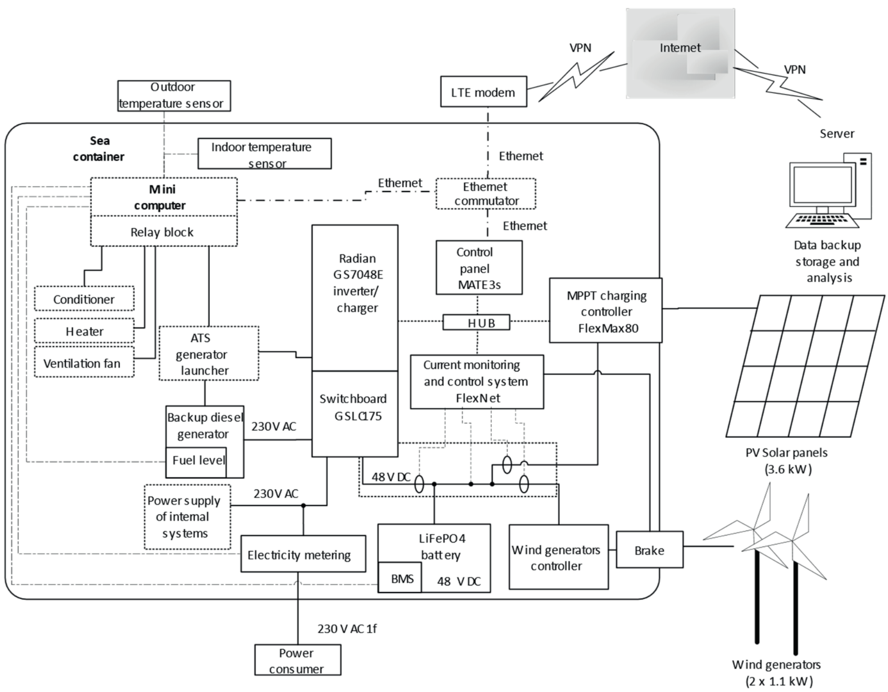


Fig. 2. Conceptual diagram of the installed off-grid system.

After the implementation of the off-grid system, it is expected that the quality of the electricity supplied to the household will meet the Latvian distribution system operator network connection requirements according to LVS EN 50160 standard. For research in the future, it is planned to upgrade the experimental system also with a fuel cell system.

Before installing the new off-grid system, the household owner was surveyed about their electricity consumption and existing electrical appliances, as well as any potential changes after the implementation of the off-grid system in order to create the necessary system configuration. Household load data were collected using a power network analyser, and average load projection for the entire year was created and used as an input in the Homer Pro software to evaluate the optimal energy source mix and sizing of the off-grid system. The equipment survey results are summarised in Table 1.

Table 1. The Current and Planned Electricity Equipment in Household

Consumer	Approximate electrical power, W	Number of units	Duration of use per day, h
Before off-grid system implementation			
LED bulbs	5	10	4 (depending on the season)
Refrigerator	200	1	2 (compressor activation depending on temperature)
Kettle	2000	1	0.5
Water Pump	400	1	0.5
Phone charger	7	2	4
Portable computer	100	1	3
TV	200	1	5
Electric tools	300-1000	3	0.5
After off-grid system implementation			
LED bulbs	5	15	4
Refrigerator	200	1	2 (compressor activation depending on temperature)
Kettle	2000	1	0.5
Water Pump	400	1	0.5
Water Pump	7	2	8
Portable computer	100	1	4
Washing machine	200–1500	1	2
Dishwasher	300	1	2.5
TV	200	1	6
Vacuum cleaner	1500	1	0.1
Fan	200	1	5
Conditioner	1000	1	5
Electric tools	300–1000	3	0.5

As it can be seen in Table 1, before the creation of the off-grid system, household electricity was mainly used for lighting, powering computers, and for other household equipment. The average daily electricity demand for the household was 4 kWh, totalling 1,460 MWh per year before the construction of the off-grid system. Consumer relied on a diesel-powered generator, connection with a capacity of up to 1 kW from the neighbour and a couple of solar panels; however, there were periods when the household had limited access to electricity.

After the construction of the off-grid system, the household owner was able to increase their power consumption, for example, by using an air conditioner as desired. Electricity consumption was forecast to be 12 kWh per day, considering the use of an air conditioner during the summer season. This would result in a total annual consumption of 4,380 MWh, which would be provided by the created off-grid system.

2.2. Setup of the Off-grid System

The operational modes and quantitative setting values are selected in such a way as to control the charging of the battery pack and ensure the supply of electricity to the load. The main parameter, according to which the control takes place, is the charge level of the batteries.

Fig. *3* shows the off-grid system control principle, which is summarised based on the above configuration.

The principle of power flow control in the off-grid system is based on voltage levels of the battery. Battery is charged from three sources using a two-phase charging method. During the first stage, constant current bulk charge is up to 0.5 C-rate or limited by resource availability, terminated at 58.4 V; and constant voltage absorption charge is terminated at return amps 0.03 C-rate. PV charger and AC charger using diesel generator are managed by a central system controller and obey rules descripted before. Wind turbine controller is a discrete device and, therefore, needs to be connected to DC bus if necessary, using power relay. If the voltage of the battery reduces below 52.0 V and solar energy is available, bulk constant current charging is started. In case solar energy is not available and voltage drops down to 57.6 V, wind turbines start to generate by connecting wind chargers to DC bus. If both wind and solar sources are insufficient or unavailable and voltage is below 52.8 V, a diesel generator shall take over the control and charge battery in that way avoiding power supply interruption. The operation of the diesel generator is set at 50 V.

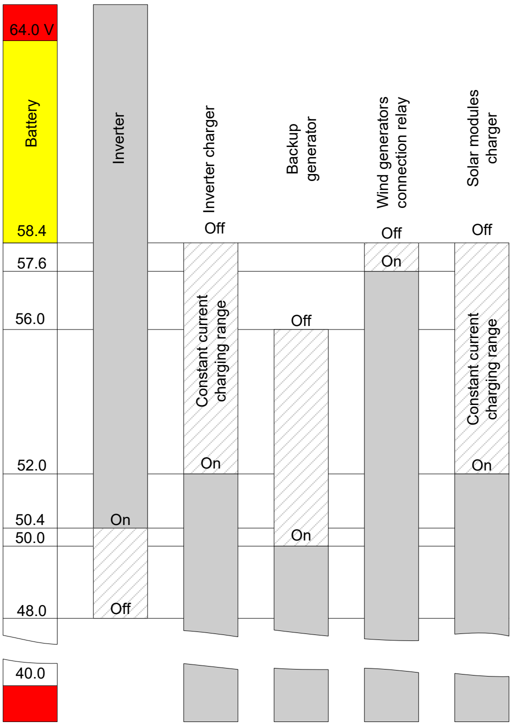


Fig. 3. Principle of power flow control based on a battery voltage level, source and power converter operating voltage ranges: red – voltage when battery damage occurs; yellow – charged battery voltage; grey – the device is working; dashed grey – switch-on or special charging mode.

When multiple sources are running simultaneously, priority is given to the source with the highest resource availability, i.e., for a charge controller that has a higher voltage and a proportionally larger amount of energy available from the renewable source. For example, if it is sunny with moderate wind, then due to higher installed capacity of the solar panels, charging will take place from them, the wind charge controllers will give a minimum current. In darker and windier weather, the situation will be the opposite. If the backup diesel generator is running, it will be able to charge battery at all times.

2.3. Data Collection

Accumulation of the off-grid operation data is organised both in a local database in a minicomputer installed in a container (Rapsberry PI), and remotely as a backup copy. The main monitoring data sources are listed below (see Fig. 2).

1. OutBack power MATE3 control panel – collects data from devices connected to OutBack Hub - FlexMax80, FlexNetDC and Radian GS7048E. Connected to a minicomputer via an Ethernet network.
2. The battery management system (BMS) has its own output data flow through the serial port to the minicomputer.
3. Power network analyser EM21 – Modbus RTU device connected to a minicomputer via RS485 network.
4. Minicomputer – collects information from connected sensors and analogue and digital inputs and outputs.

2.4. Data Analysis Method

Data analysis is made by using Python language in Jupyter notebook, which is a web-based interactive computing platform. The graph codes were written in Python using libraries like pandas, numpy, matplotlib, seaborn. A 31-day dataset from an off-grid system was collected between 18 October and 21 November 2022, with a minute-by-minute sampling frequency. The analysed dataset includes 37 input signals and high granularity data with a total of 48,301 data points.

The obtained dataset reflects only one time of the year. To create a more accurate analysis, it is desirable to use historical data to estimate the change taking into account the change of all seasons.

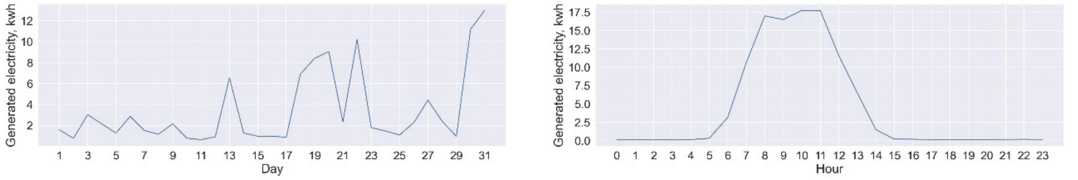
Various statistical methods are used in the present research – time series analysis, cumulative columns, and histograms.

3. RESULTS

The data analysis of the off-grid system was performed according to the previous sections. The off-grid system operating data are important and necessary to detect failures or faults of the system, especially in the initial stage of such off-grid system implementation. The results provide an insight for further studies and an indication of the importance of data availability and resolution.

3.1. Data Analysis Method

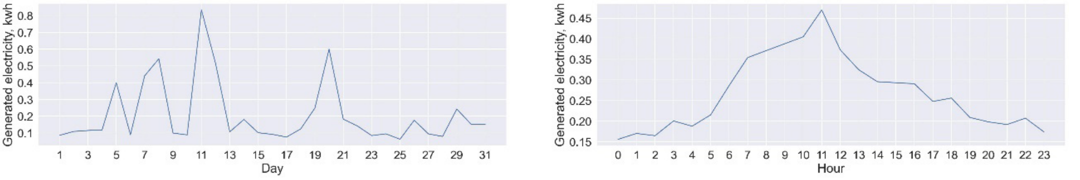
Figures 4–6 present daily and hourly production data curves of the off-grid system electricity between October 2022 and November 2022. The cumulative generation of electricity from solar, wind and diesel generator is covered.



(a) (b)

Fig. 4. Generation of electricity from solar modules: (a) daily cross section profile; (b) cumulative hourly profile.

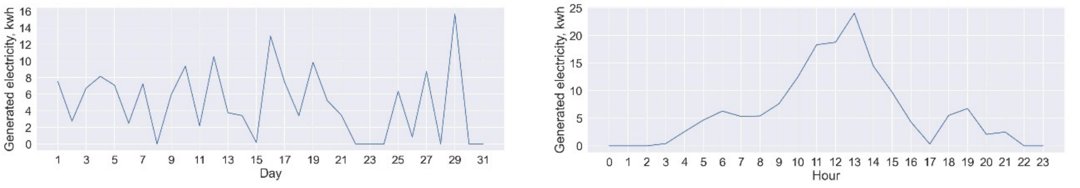
Figure 4 shows that solar power is generated on a relatively large scale and with a distinct tendency to take place from 6 a.m. to 3 p.m. Solar kilowatt hours (kWh) are calculated using data obtained from FlexnetDC.



(a) **(b)**

Fig. 5. Generation of electricity from wind generators: (a) daily cross section profile; (b) cumulative hourly profile.

Figure 5 shows that wind power is generated on a relatively small scale and with no distinct tendency during the days. Also, wind kilowatt hours (kWh) are calculated using data obtained from FlexnetDC.

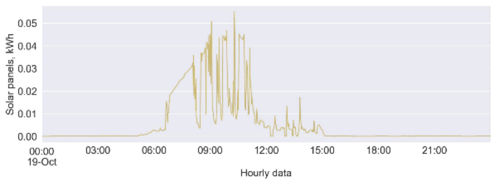


(a) **(b)**

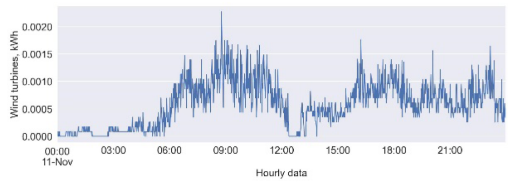
Fig. 6. Generation of electricity from diesel generator: (a) daily cross section profile; (b) cumulative hourly profile.

Figure 6 shows that diesel generator power is generated almost every day – roughly the same amount (7–12 kWh). In comparison with solar and wind, the generator operates also in the early morning and late evening hours. Diesel generator kilowatt hours (kWh) are calculated using data obtained from inverter RadianGS.

Looking at the minute-by-minute data, Fig. 7 shows how electricity generation profiles differ from sources.



(a)



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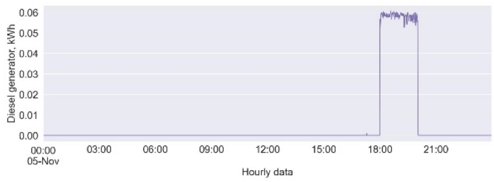


(c)

Fig. 7. Electricity generation profiles: (a) from solar source; (b) from wind and (c) from diesel source.

The data were taken on 19 October 19, 5 and 11 November. Thanks to the high granularity of the data, trend of each generation source can be seen in Fig. 7. It can be seen that renewable sources in these days show a lot of variability, while the diesel generator has been working for a specific period with a certain capacity.

3.2. Amount of Generated Electricity by Source Type

During 31 days of observation (see Fig. 8), most electricity was generated by the diesel generator (152 kWh), followed by solar (104 kWh) and wind generation (7 kWh). Later on, it was discovered that low output of wind generation was associated not only with insignificant wind velocity during the investigation period, but also due to inadequate operation of wind charger control logics. This is the challenge to be addressed during the course of experimental activity.

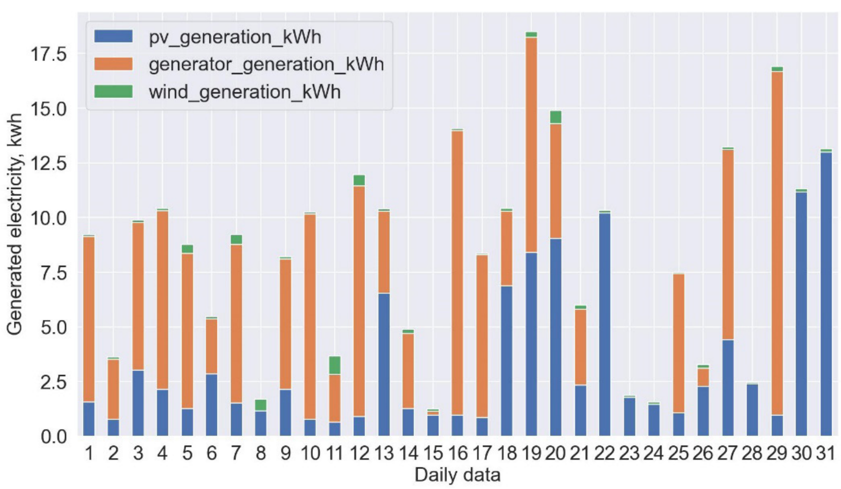


Fig. 8. Cumulative electricity generation by source type.

The analysis of the off-grid system operation throughout the experiment indicated that the off-grid system works sufficiently during this time. However, during some period of time, missing data were observed.

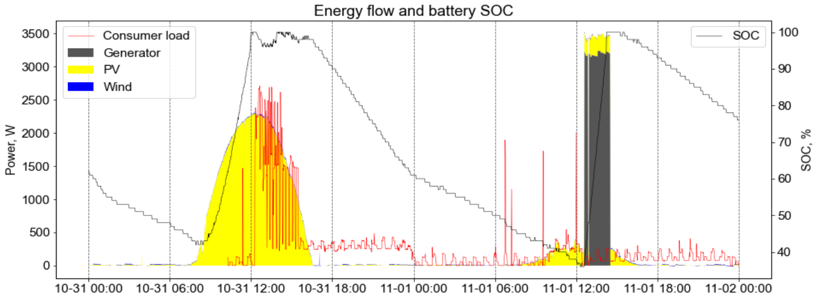


Fig. 9. Off-grid system characteristics during a sunny day at the end of October.

For example, Fig. 9 shows two sunny days at the end of October and at the beginning of November. During this time, the demand consumption was not logged in the beginning, indicating that the acquisition of data should be checked to ensure data continuity.

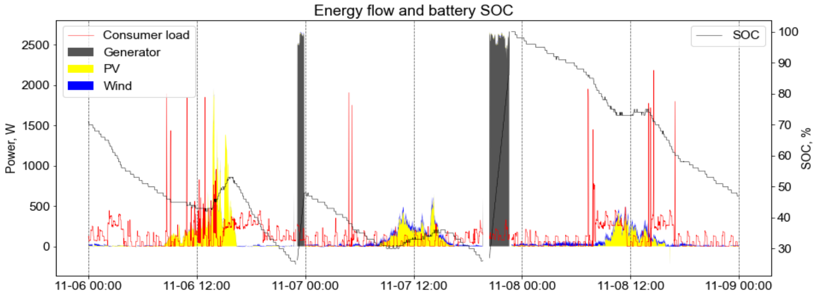
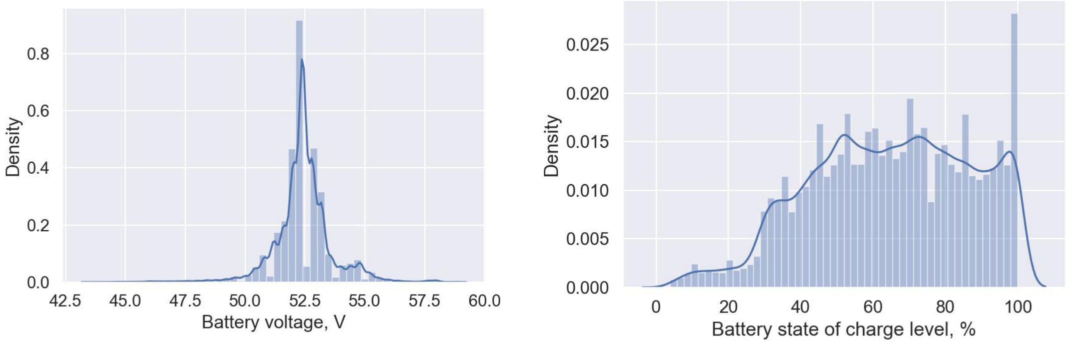


Fig. 10. Off-grid system characteristics during a sunny day at the beginning of November.

In Fig. 9 and Fig. 10, one can see the total contribution from each source. If the load capacity is greater than the total source contribution, the state of charge (SOC) of the battery falls, if less – battery charging occurs. When the generator is on, the SOC level climbs rapidly.

3.3. Electrotechnical Data: Voltage, SOC, Frequency

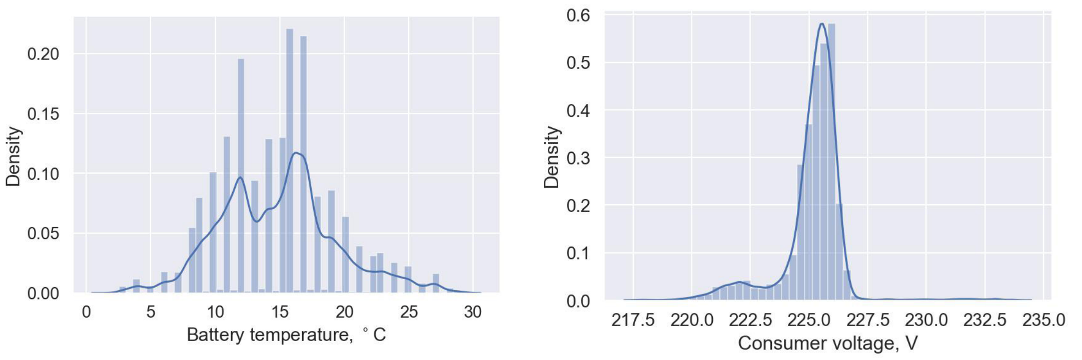
It was also important to observe electrotechnical data in the experiment. Figures 11 and 12 show the four histograms. A histogram divides the variable into bins, counts the data points in each bin, and shows the bins on the x-axis and the counts on the y-axis. In our case, we used Python library seaborn, which turns the y-axis as a density plot, which is the probability density function for the kernel density estimation. Density plot is a value only for relative comparisons. The y-axis is in terms of density, and the histogram is normalized by default, so that it has the same y-scale as the density plot [10].



(**a**) (**b**)

Fig. 11. Electrotechnical data analyses: (a) for battery voltage; (b) battery SOC level.

According to the electrotechnical data shown in Fig. 11, it can be noticed whether the battery has any overvoltage or the battery is operated in the most efficient way to reduce the risks of degradation.



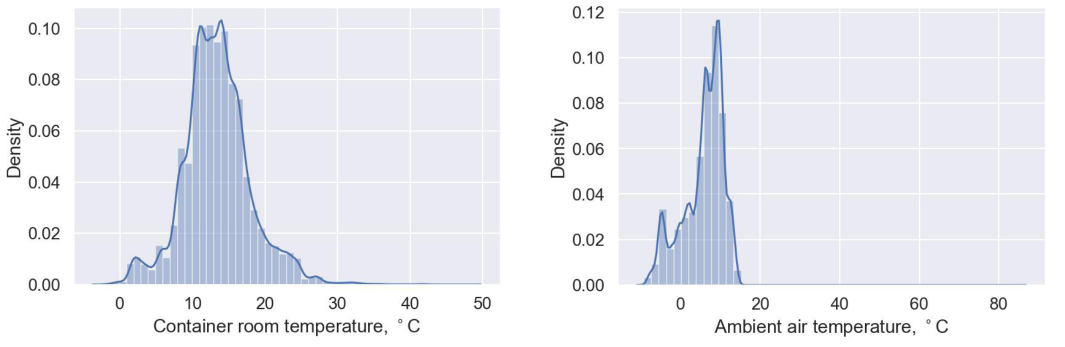
(**a**) (**b**)

Fig. 12. Electrotechnical data analyses: (a) for battery temperature; (b) for consumer frequency.

It is important to monitor what happens to the battery temperature and whether the electricity consumer is provided with the appropriate voltage quality of electricity supply (see Fig. 12). Battery voltage data were obtained from inverter RadianGS, SOC and battery temperature data from system monitoring – FlexnetDC device, while consumer voltage from power network analyser – Carlo Gavazzi EM21.

3.4. Analysis of Climatic Data (Wind Speed, Temperature)

During observations, the internal temperature of the off-grid container and the outside air temperature are monitored. Sensor DS1280 is used to determine both parameters. Results are shown in Fig. 13.

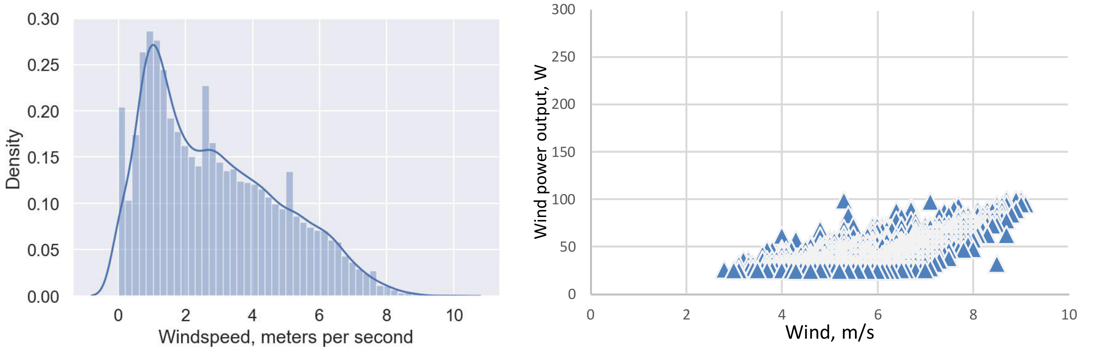


(a) **(b)**

Fig. 13. Air temperature analyses: (a) for container room temperature; (b) for ambient air temperature.

In the climatic conditions of the country of Latvia, it is important that the container is warm enough during the winter period (from November to December), while in the summer period (from June to August) it is the opposite, so that the container room does not overheat. During the observation period, container room temperatures were observed above 0 °C, despite the fact that the outside air temperature dropped below zero degrees Celsius.

In parallel, much attention is paid to the wind speed observations. Wind generation during the off-grid observation is not as originally planned. This is also shown in the data (see), which shows that the wind speed is not particularly high, but it does not explain why wind generator output is so low. Correlation between wind power output and wind speed can be seen in *b*.



(a) **(b)**

Fig. 14. Wind speed data: (a) using histogram; (b) using time scatter analysis. It should be admitted that wind data were obtained for only half of observation time.

All the previous weather conditions were measured every minute at the site. Wind speed data were obtained from the anemometer above the sea container.

4. MODELLING TOOLS VERSUS REALITY

To understand accuracy and validate off-grid modelling tools and mathematical models, initially a comparison analysis for this study was planned. The idea was to compare results from modelling tools and mathematical models versus real experimental off-grid system. The aim was to determine how applicable the selected energy source mix and equipment sizing are in real life regarding what was proposed by modelling tools and models. However, it was later concluded that it was not clear how to do it due to the following reasons:

1. to obtain life data it would be required to test experimental off-grid system for at least 1-year period;
2. the off-grid system operation should be tested using more than one dispatch strategy (longer analysis than a 1-year period would be needed);
3. to obtain data to be later used in computer tools and mathematical models more measuring devices as planned before would be required, for example, regarding solar radiation;
4. as the off-grid project is still implemented, its true costs can only be clarified after a longer time period than now.

Having a data array for a comparatively short period, it is difficult to make reasonable conclusions about the adequacy operation of the off-grid system. Nevertheless, from the available data it was possible to draw the conclusion that simulation results in certain aspects deviated from the real operation of the off-grid system.

The authors of this publication consider to obtain data for a longer period and to carry out a more comprehensive comparison of simulation data versus real measurements.

5. DISCUSSION AND CONCLUSIONS

The publication presents an experimental stand-alone electrical off-grid solution in Latvia. For the off-grid system discussed in this publication, the most important goals are the maximum use of all local renewable energy sources and reliability of electricity supply. The experimental system in Latvia showed that it was not feasible to power an off-grid system solely with renewable sources. A backup generator, such as a diesel or fuel cell system, is necessary to meet off-grid consumer demand. Theoretically, this might only be achieved by incorporating oversized solar, wind, and battery systems.

Real autonomous off-grid system operational data were analysed, and the following was concluded:

1. more attention should be paid to improve the operation of the off-grid wind turbines. The electricity from the wind is relatively small part from total consumption. On the other hand, the data show that the wind speed in the site is not high;
2. attention could be paid to setting the SOC level of the battery. For the battery to be able to accommodate the rapidly changing renewable generation, the battery should not be charged fully, but to a cer-

tain level. Also, in order not to degrade the battery, it should not be completely discharged;
3. the high granularity operating data (in minutes resolution) from the off-grid system are essential for troubleshooting and assessing the performance of such a system;
4. Such an analysis showed that it was important to gather data on off-grid performance in a timely manner in order to later analyse the results obtained from the operating system.

High-quality power supply off-grid and microgrid systems will have to solve the same main tasks that are solved by large energy systems. The project developers must always have a complete understanding of the probable consumers' load values and appropriate combination of the energy generating sources. It is necessary to ensure protection of systems from accidents, short circuits, overvoltage and other factors of environmental impact on energy equipment, as well as that batteries and electronic devices operate at their appropriate preferable temperature (microclimate). The safe and efficient operation of the system must be ensured both when connected to the public power grid if there is such a connection and when it operates autonomously. The integration of different power conversion equipment, often supplied by different standards and different times, must be achieved, ensuring a continuous power supply of electric system for all time equipment that operates in all provided regimes.

In the future, the authors plan to continue evaluating the performance of the autonomous off-grid system, considering a longer observation period, adding a comprehensive comparison of simulation data versus real measurements, as well as adding a fuel cell system to maintain system operation in a more environmentally sustainable manner.

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AGRICULTURE ELECTRIFICATION, EMERGING TECHNOLOGIES, TRENDS AND BARRIERS: A COMPREHENSIVE LITERATURE REVIEW

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On a global scale, the agriculture sector is a major contributor to greenhouse gas emissions, and this holds true for the European Union as well. While a shift to renewable energy sources could reduce reliance on fossil fuels and enable electrified agriculture, there are significant challenges to overcome. These include the high initial costs and inconsistent energy output of renewable sources, as well as issues with acceptance and cost related to electric tractor technology and load-balancing batteries. To explore potential solutions and future prospects for electrifying agriculture, a literature review is conducted to identify emerging technologies and research trends in areas such as agrovoltaics, semi-transparent photovoltaic panels, energy storage systems and electric tractors. The review conducted will provide a valuable insight into future research and the implementation of emerging technologies, thus addressing the challenges faced by the agriculture sector during its transition to electrification based on renewable energy sources.

Keywords: Agriculture, battery technology, electrification, electric tractors, hydrogen, literature review, renewable energy sources (RES), semi-transparent photovoltaics.

1. INTRODUCTION

Agriculture electrification, the process of introducing a wider use of electricity to rural environments, has the potential to revolutionise the way we produce food and manage our natural resources, thus becoming an increasingly important area of research as the world looks to decarbonise the sector and reduce greenhouse gas (GHG) emissions. According to the United Nations Framework Convention on Climate Change [1], in 2018, the agricultural sector contributed to around 24 % of the world's GHG emissions, but a study made in 2021 [2] determined that the emission level was much higher than expected, reaching up to 34 %. With this in mind, the European Union (EU) has implemented several acts of legislation to support the decarbonisation of the farming sector, which includes the EU Green Deal [3] and the Farm to Fork Strategy [4].

These policies aim at reducing emissions not only in food production, waste management and in the use of artificial fertiliser, but also increasing the use of renewable energy, promoting sustainable energy production and electrification of machinery practices. However, application of electrification activities is not without its challenges and barriers.

Implementation of renewable energy sources (RES) in agriculture is highly dependent on the initial cost of energy supply and RES energy generation patterns. Furthermore, placing renewable energy generation infrastructure on a plot of land may result in a reduction of the cultivated area, which could subsequently lead to a decrease in crop yield. Alternative installation and operation strategies for renewable energy systems should be explored.

Moreover, integrating RES could be challenging due to seasonal load fluctuations within the system. The integration of efficient battery systems has the potential to enhance the utilisation of renewable energy, promote self-consumption and minimise the impact of load fluctuations on the energy supply system [5].

Electrification of agricultural machinery (mainly tractors) faces considerable development challenges regarding battery efficiency and charging possibilities in a rural environment. From the acceptance point-of-view, farmers' willingness-to-buy is heavily influenced by the cost of the equipment. Since the expense of lithium is high, the battery system accounts for approximately 30 % to 50 % of the overall cost of electric tractors, which can result in the initial cost of electric tractors being up to three times more expensive than comparably capable diesel-powered internal combustion engine vehicles [6]. Thereby, it is necessary to identify the factors that could impact the farmers' inclination to opt for an electric tractor, despite the high costs associated with the current technology.

It is important to understand the current state of knowledge on existing technologies and practices, as well as the ongoing research in this area. A literature review could provide an overview of the subject matter, and enable farmers to make evidence-based decisions regarding the implementation of electrification activities. With this in mind, the aim of the paper is to provide a comprehensive literature review of the current state of agriculture electrification with emphasis on wider use of RES, energy storage and electric tractors. Furthermore, throughout literature review the authors would seek answers to barriers related to agriculture and give better understanding about current bottlenecks from an energy point of view, thus identifying key areas for future research and development.

The paper is organised as follows: Section II describes literature selection methodology, Section III includes literature review and Section IV contains results and conclusions.

2. METHODOLOGY

In order to conduct a structured literature analysis, aspects of literature selection methods described by [7], [8] were used. The methodology used for this review is presented in next paragraphs.

The main sources of information were gathered through academic journal publications, therefore providing review of the literature related to agricultural electrification from different analysis and research perspectives.

The initial step that was established involved selecting the most suitable scientific publication databases. To evaluate relevant publications, IEEE Xplore, Scopus, and Web of Science databases were chosen. Scientific publications filtering process consisted of two aspects: publication period and keywords. Publication period of 2018–2023 was used, thereby content of the scientific literature would reflect the latest research and electrification development trends. Publication search using review related keywords ("agriculture electrification", "agriculture electrification challenges" "renewable energy sources in agriculture", "electric machinery in agriculture", "electric tractors", "agriculture battery technologies") on the chosen databases was performed in January–February 2023. Keywords were determined to reflect the main aim of this review – trends, challenges, barriers and solutions for wider use of RES and electric machinery in agriculture.

By using specified publication databases, period and keywords, 59 publications were retrieved. Following a full-text analysis, 28 publications were excluded due to the non-compliance with the agriculture electrification and publication duplications between the aforementioned databases. Thirty-one papers remained, which formed the basis for this review.

To compare the progress of electrification in the agricultural sector with that in other industries, as well as to gain additional insights on legislation and development priorities beyond agriculture electrification, supplementary information was collected by using documents and reports cited in the reviewed publications and other studies.

Starting with the next section and its subsections, analysis and results of literature review are presented and possible solutions for the aforementioned challenges are sought.

3. LITERATURE REVIEW: SEEKING SOLUTIONS TO AGRICULTURE ELECTRIFICATION CHALLENGES AND BARRIERS

3.1. Innovative RES Installations and Emerging Technologies

Due to energy intensive loads and physical nature of RES elements, traditional electricity generation element installations and operations in agriculture can be difficult to implement. First of all, energy consumption can be variable, irresolute and non-definable; thus, agriculture-customised power generation and storage solutions are needed. Second, due to the high power consumption, RES elements can occupy large-scale territories, which could be used for crop fields and livestock pastures, thus decreasing the value of the land [9]. Therefore, innovative solutions to aforementioned problems have been developed, using new technologies, modelling skills and power system operations. This subsection will be devoted to review of these solutions.

3.1.1. Agrovoltaics

One of the most promising options for RES integration in the agricultural complex is using a synergy between PV panels and farmlands – a method of installation called "agrovoltaics". For the first time, this idea was put forward in the 1982 publication

[10], in which authors suggested that PV panels could be installed on the cultivated land above the crops (see Fig. 1). Since then, this method has gained popularity.

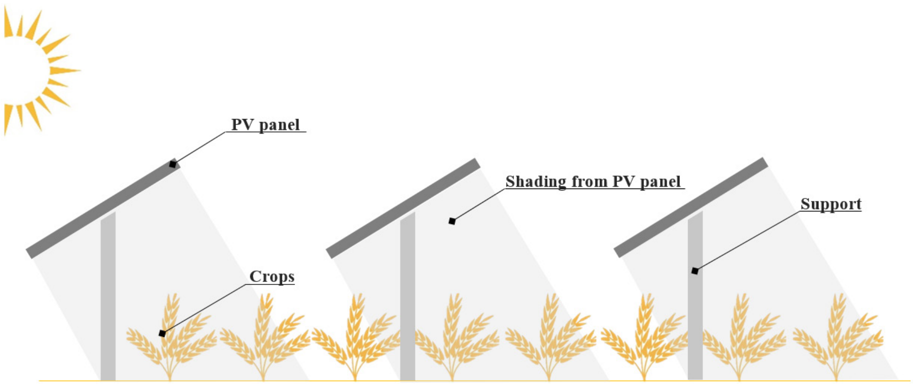

Fig. 1. Example of agrovoltaics installation method [5].

Its effectiveness is indicated in [11], where authors analysed United Nations Sustainable Development Goals (SDGs) and opportunities to reach them with the help of agrovoltaics. Additionally, the study compared it to roof PV panel and rooftop farming applications.

The authors determined that agrovoltaics can contribute to at least 10 of the overall 17 SDGs and, in comparison, gives greater contribution than rooftop PV and rooftop farming in the following activities:

- Agrivoltaics enables food and energy double income;
- It produces food locally;
- It brings more green view and offers a place to be with nature;
- Roof and agrovoltaics related farming work is not physically intensive and can create more jobs for females;
- Water used for PV panel cleaning can be used for crops underneath;
- It generates clean energy (less than rooftop PV);
- It is an emerging urban industry with economic potential;
- It reduces a heat island effect in cities;
- Partially it creates habitat space for animals, thus enriching urban biodiversity.

The main directions of agrovoltaics research are discussed and covered in [12], where authors summarised and analysed projects, technologies, field management implications and shading affect to crop growth using scientific publications done in the time frame from the 1980s until 2018. Since 2018, the ideas mentioned in the publication have been further developed by introducing innovative operational and technical solutions. For example, authors of [13] investigated agrovoltaics design features, which influenced microclimate under PV panels and temperature of PV modules by changing the panel height over the soil. The study concluded that the height of the installations and the microclimate under PV panels affected the efficiency of the panels themselves – when installing them at a height of 4 metres above the soybeans, the average temperature of the surface of the PV panels decreased by 10 °C. Agrovoltaics installation technique for growing individual plant groups can be effective from the point of the cooling of the modules due to the water vapour underneath them, which increases PV panel efficiency indicators and extends PV module lifespan. Although several authors point to the positive effects of agrovoltaics, publication [14] describes agrovoltaics techno-economic analysis using a neoclassical economic theory to determine PV panel negative effect of shading on crops, their growing efficiency and changes in land worth by using agrovoltaics installation. The method developed in the paper allows calculating not only the extent of crop yield reduction but also the ratio between profits from electricity generation and economic losses of crop yields.

Nevertheless, the reviewed concept is seen as a promising option for renewable energy integration in the agricultural sector. Agrovoltaics can contribute to at least 10 of the 17 United Nations SDGs and offer benefits, such as food and energy double income, local food production, job creation, clean energy generation, and reduction of a heat island effect in cities. However, the impact of shading from PV panels on crop yield and the overall economic viability of agrovoltaics are also important considerations that have been addressed in the above-mentioned studies.

3.1.2. Transparent and Semi-transparent PV Panel Modules

In order to avoid the negative effects of shading, at the same time to cover as little area as possible for RES installations, innovative semi-transparent and transparent PV panel modules can be used.

First fully transparent PV panel module was made in 2014 at the Michigan State University. Due to low efficiency, this technology has to be further developed to reach its efficiency from initial 0.4 % to potential 5 % and to find the possibility to be used in real agriculture conditions [15], [16].

More widely implemented technology is semi-transparent PV panels, the development of which began in the 1970s by creating the first thin-film solar technology. Nowadays, a wide transparency and efficiency range of semi-transparent PV panel technologies (see Table 1) are available to be used for agricultural purposes.

Table 1. Semi-transparent Solar Cell Technologies [15], [17]

Solar PV technology	Light transparency (%)	Efficiency (%)
Screen printing dye synthesised cell	60 %	9.2 %
Near-infrared heterojunction organic cell	55 %	1.7 %
Polymer cell	66 %	4.02 %
Perovskite cell	27 %	13 %
Electrophoretic technique cell	55 %	7.1 %
Dip-coater cell	70 %	8.22 %
Quantum dot cell	24 %	5.4 %

The authors of [18] and [19] identified the use of semi-transparent PV cells on greenhouse roofs as the main application of the technology. Paper [18] provides the development of an energy balance model to determine the impact of heat, air, and moisture flow and circulations in greenhouses with these PV panels. The study concluded that the roof design and placement of the panels were significant factors affecting the circulation. Another publication [19] conducted a pilot project using semi-transparent PV panels (47 % transparency and 8.25 % efficiency) on a tomato greenhouse roof. The results showed the following:

- There was no negative impact on tomato yield from PV panels;

- The shading from the PV panels resulted in a 1–3°C decrease in air temperature on clear days, due to the 35–40 % reduction of solar irradiation under the panels. In addition, the panels had no effect on greenhouse humidity level.
- PV panels were composed of three modules with a peak power of 170 Wp each, the annual generated electric energy of the panels was 637 kWh and payback period for the panels was calculated to be 9 years.

Considering all the above, semi-transparent PV panel technology has shown promising results. Pilot projects suggested that the panels have no significant impact on yield and provide only a slight decrease in air temperature. The efficiency and transparency of semi-transparent PV panels have a wide range, making them readily available for use in agricultural conditions. Nevertheless, further research is needed to improve the efficiency of fully transparent PV panel technology and reach its potential efficiency. In addition, further pilot projects using semi-transparent PV panels in different geographical conditions would provide additional valuable information for their integration potential.

3.1.3. Battery Systems

RES variability such as fluctuating solar radiation or wind speed can pose challenges for electricity supply stability. Energy storage systems, including batteries, are crucial components in maximising RES self-consumption level. They store surplus energy, ensuring a steady power supply during low energy generation periods. This enhances reliability of energy supply, as well as promotes effective and efficient energy utilisation. To better understand current and future battery technologies and address challenges and solutions for their implementation in agriculture, this paragraph conducts a comprehensive literature review on battery technologies.

At the onset, it is crucial to acknowledge the existence of a multitude of energy storage technologies, each possessing its own qualities and benefits. Selection of battery technology for agriculture electrification is dependent upon a number of factors, including but not limited to the electricity consumption profile and character, as well as the economic viability and efficiency of the technology [20]. The most widely used battery technologies, along with their benefits, drawbacks, and practical applications, are presented in Table 2.

Table 2. Overview of Existing Battery Technologies [20]

Technology	Life cycles	Advantages	Limitations	Main applications	Applicability in agriculture*
Li-ion	~3000	High energy density and efficiency, fast response time, no memory effect	Expensive and safety issues depending on the type	Portable devices and electric vehicles (EVs)	+++
Flow batteries	<20000	Nearly unlimited longevity	High maintenance, complex monitoring and control	UPS, EVs, load balancing	++
$LiFePO_4$	<2000	Safe and stable voltage discharge	Due to low capacity, it is used as preliminary energy storage	High load current devices	++

$LiMn_2O_4$	<700	High power output level and safer than LiCoO2	Low energy capacity	Power tools	+
Lead-acid	<3000	Cheap and freely available	Low-energy density and high environmental impact	Emergency lighting and electric motors	+
NaS	~4500	High efficiency and life cycle	High operating costs and temperature	Load balancing, EVs	+
$NaNiCl_2$	<3000	Long life cycle and high energy density	High maintenance costs and temperature	Load balancing and EVs	+
Double-layer capacitor	~1000000	High power density, long life cycle and fast response time	Complex water and thermal control, high initial cost and low efficiency	EVs, backup power applications and load balancing	+

**Rating was developed by the authors of the review from the analysis of existing battery technologies*

Battery technologies have undergone significant advancements, thanks to massive investments in financial resources. Despite their progress, all battery technologies face a common challenge – scarcity of raw materials. Lithium-ion batteries are currently the leading energy storage technology, but their main component material, lithium, presents a potential concern for the future. It is projected that the global lithium supply will only suffice market demand until 2100. To overcome this challenge, sodium-ion batteries are emerging as a promising alternative by using more available raw materials – sodium salts. Sodium-ion sources are abundant in nature, derived from sea water or salt deposits, and are cheaper than lithium.

Moreover, the energy capacity of a sodium-ion battery is heavily reliant on the size of its sodium-based solution, thus limiting its applicability to portable smart devices. Despite being larger and heavier than lithium-ion batteries, a sodium-ion battery could still be utilised as a cheaper option for large-scale renewable energy storage in the agricultural complex, where equipment size and weight are not significant limiting factors. Efforts are underway to enhance the capacity, stability, and rate performance of sodium-ion technology through research and experiments. The goal is to make this technology commercially viable in the near future [21].

A significant progress in calculating economic assessments for RES and battery configurations has been done in recent years, using general consumption and generation data, as evidenced by the numerous publications in this area (as listed in [22]). However, the economic feasibility of incorporating RES and related technologies into agriculture energy consumption remains poorly understood due to a shortage of research and data. This was highlighted in a questionnaire of Swedish farmers conducted as part of publication [23], which found that technical and economic risks, including potential deterioration of battery performance and uncertainty around investment aid and the size of investment required, represented major barriers to battery integration in agriculture.

As a result, there is a pressing need for more extensive and wide-ranging studies on the techno-economic viability of these elements in agricultural environments. This includes evaluating the economic synergies that can be achieved through the combined use of conventional energy elements, such as photovoltaic panels, wind generators, and lithium-ion batteries, with emerging technologies and installations, such as agrovoltaics, semi-transparent photovoltaic panels, next-generation battery technologies and electric tractors.

3.2. Electric Tractors

Electric tractors have the capability to revolutionise the transport and agriculture industries by reducing the reliance on fossil fuels and improving the use of locally available renewable energy resources. However, the effective implementation of this technology requires a thorough understanding of the current state of development, thus identifying electric tractor acceptance potential. The next paragraphs will be devoted to comprehensive literature review of the availability and efficiency analysis of electric tractors.

Broadly speaking, these tractors can be classified into three major categories [24]:

- Battery electric tractors: operated by an electric engine and energy stored in batteries;
- Hybrid electric tractors: a combination of internal combustion engine and electric engine with a battery system;
- Fuel cell electric tractors: operated by an internal combustion engine, which uses hydrogen as the main source of fuel.

Electric tractors are a subject of discussion in the field of agriculture and agricultural technology, with many experts examining their various capabilities and limitations. Each of the named types of electric tractors has their own advantages and disadvantages regarding power capacity, efficiency and other aspects (see Table 3).

Table 3. Advantages and Disadvantages of Battery Electric and Hybrid Electric Tractors [6], [24]–[26]

Battery electric tractors		Hybrid electric tractors		Fuel cell electric tractors	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**	**Advantages**	**Disadvantages**
Zero emissions	Limited battery life and long recharge time	Long continuous working hours	Release of emissions	High fuel consumption efficiency	Limited lifetime
High torque	High initial cost	High fuel efficiency	High complexity	Zero emissions	High initial and maintenance costs
Low running costs	High energy consumption during heavy loads	Energy generation during regenerative braking	High initial cost	Existing tractors can be modified to use hydrogen instead of diesel	Hydrogen production and storage issues
Long lifetime	Negative effect of hot climate on the battery				

Economic arguments at this point do not allow making a decision in favour of electric tractors. Hence, alternative approaches must be explored to encourage farmers to shift from diesel-based tractors to environmentally friendly machinery. To gain insight into the extent of demand for electric tractors and the underlying motivations for their adoption, the authors of the publication [27] carried out a comprehensive questionnaire of farmers to elicit information regarding their willingness and preferences for purchasing an electric tractor. They concluded that the demand for electric tractors was influenced by costs, the size of the farming area, farmers' age and technical skills, engine characteristics, and other preferences. In particular, lower initial and maintenance costs were found to be a motivator for farmers to purchase electric tractors.

Additionally, farmers with prior experience with electric tractors demonstrated a positive willingness-to-pay.

The trend towards sustainable and environmentally friendly agricultural practices has been driving the growth of the electric tractor market. According to [28], the global tractor market is expected to grow by 5.7 % each year by 2026. Furthermore, this growth is driven by increasing demand and the adoption of electric tractors. With increasing demand, manufacturers of electric tractors are contributing to market growth with supply of this environmentally friendly technology. The state of the market has been addressed by [24], [28] and [29], in which the authors identified the state of the market for electric tractors as well as the current assortment of them. Although the tractor market offers conventional tractors with electric engines, the market is limited to only low power engine technologies (40–50 horsepower electric tractors), despite their positive impact on energy costs and climate impact [30]. As [31] points out, <50 horsepower tractors are able to perform light ploughing and bailing, but are unable to perform heavy duty tasks like equipment transportation, harvesting, cultivation, hard ground ploughing and other activities.

Moreover, a significant part of the electric tractor market consists of autonomous tractors, which requires the farmers' relatively high technical, planning and programming skills [32]. While bearing in mind that electric tractor willingness-to-buy is influenced by farmers' age and skills factor, an excessively high supply of autonomous electric tractors can potentially slow down their acceptance rate and use by consumers simply because their operating principle would be drastically different from the use of conventional tractors.

Additionally, the lack of charging infrastructure and distance between charging stations and tractors in the field pose significant challenges in the aforementioned publications. One possible conceptual solution to this challenge could be the use of on-board battery packs or trailers with spare batteries and mobile charging option [33].

As a result, the agriculture industry has the potential to be transformed by the introduction of electric tractors, which would reduce dependence on fossil fuels and increase efficiency. Although the reviewed publications cover valuable insights into the capabilities and demand for electric tractors from a consumer perspective, lack of comprehensive examination of the connection between RES and the use of electric tractors can be seen.

Future research should investigate the feasibility of utilising renewable energy as a reliable and efficient power source for electric tractor charging infrastructure. By applying different business models, one of the ways could be to develop a comprehensive, commercialised and techno-economically compatible renewable energy system package (RES elements, battery system and power flow control system) for charging specific types of electric tractors and related equipment. It would greatly facilitate the determination, planning, and implementation of RES for electric tractor charging purposes. Furthermore, it would be advisable to examine how a wider range of electric tractors in the market could influence farmers' willingness to purchase them.

3.3. Initial Cost and Economic Assessment of RES

Due to the global economy's rapid movement towards greater use of RES and overall decarbonisation, the agricultural sector sooner or later will become a climate-neutral industry. But based on currently available solutions and technologies –

at what price? By reviewing scientific literature, this paragraph will examine the economic analysis of the use of different RES and will find out whether the current solutions economically justify the introduction of them to the farming sector.

Authors of publication [34] proposed a simple solution to the diesel powered irrigation system by replacing the existing water pumping system to water storage, distribution and control system by using PV panels as a source of electricity. Economic analysis showed that the system had a payback period of just 3 years on 100 % capital expenditure investments, additionally creating a nearly carbon free environment.

Another publication [35] focused on determining optimal configuration of energy generation elements using diesel generators, PV panels, inertia storage (flywheel) and electrochemical storage (battery). Taking into account electricity consumption profile of the site, a solar irradiation level in the studied region (Tunisia), equipment costs and other aspects, the results of the study clearly showed that PV-Diesel-Battery-Flywheel configuration had lower operating costs and cost of energy than in other configurations (PV-Diesel-Flywheel and Diesel-Battery-Flywheel). In PV-Diesel-Battery-Flywheel configuration, initial and maintenance costs were approximately two times lower than 100 % RES system, but in most optimal configuration 16.2% of overall costs consisted of diesel fuel purchases (at the contemporary unprecedentedly low price of 0.52 €/litre). Similar approach was made in [36], where authors modelled a Pakistan off-grid agricultural site in HOMER software using hydro, biogas and solar energy elements. By using determined load profiles, solar irradiation levels, biomass availability graph and generation element specifications and restrictions, a solar-biogas-hydro system showed the lowest cost of energy as well as net present costs related to other system configurations ("biogas-hydro", "solar-biogas", "solar-hydro" and "biogas only").

Although the above reviewed publications offered optimisation solutions, as well as discussed the comparison of different results from an economic point of view, regional economic and climatic conditions play a major role in RES efficiency and economic justification in those publications. It means that results cannot be applied in different regions outside their research directions. In the course of collecting scientific publications related to RES economic assessment, lack of specific literature was observed regarding impact of individual energy generation elements. Instead, authors offer a universal type of solutions, in which the economic assessment is calculated using not for agriculture suitable energy consumption or energy generation characteristics, but offering calculations that can be used for universal consumption and electricity generation profiles (publications in detail can be found in [8]). It is unclear whether a universal approach to economic assessment of RES implementation and business models can be suitable for this sector due to the rural and possibly off-grid conditions, along with energy intensive variable loads.

4. RESULTS AND CONCLUSIONS

In this paper, a literature review has been performed that summarised agriculture electrification related to economic assessment of RES and emerging technologies in the following categories: agrovoltaics, transparent and semi-transparent PV panel modules, energy storage systems and electric tractors. In each category, the current state, recent research developments, and the author's vision to enhance existing technologies have been reflected, as well as future research activities aimed at achieving full electrification of the sector through synergy between the wider use of RES and the afore-mentioned technologies.

Regarding agrovoltaics, the literature suggests that this approach to installing PV panels is effective in mitigating the adverse effects of inefficient use of agricultural land for PV panel installation. Studies indicate that irrigation below PV panels has a positive effect on the cooling of the PV panels, thus increasing their efficiency and lifespan. On the other hand, authors point out that such an installation can drastically shade the plants below and it is debatable whether the value of the energy produced by the PV panels is higher than the reduction in yield of the plants below.

Considering transparent and semi-transparent PV panels, results from pilot projects have shown that by installing them on the roofs of the greenhouses, PV panel light absorption has no significant impact on yield and provides only a slight decrease in air temperature inside a greenhouse. Nevertheless, authors insist that further research is needed to improve the efficiency of this technology, thus making it possible to apply it for other agriculture-related purposes.

The review summarised the advantages, disadvantages and applications for existing battery technologies and indicated that the selection of battery technology is mainly dependent upon the following factors: electricity consumption profile, economic viability and efficiency of the technology. The analysis shows that significant progress in calculating economic assessments for RES and battery configurations has been made, using general consumption and generation data; however, the economic feasibility of incorporating RES and related technologies into agriculture energy consumption remains poorly understood due to a shortage of research and data. As a result, there is a pressing need for more extensive and wide-ranging studies on the techno-economic viability of these elements in agricultural environments. In addition, new battery technologies are predicted to replace commonly used lithium-ion batteries with more accessible and cheaper battery technologies.

According to the reviewed literature, there is a significant potential for sodium-ion battery technology to replace the use of lithium-ion batteries in the agriculture sector. This can be justified by the fact that sodium sources are more abundant in nature than lithium and cheaper to acquire and process. Moreover, the energy capacity of a sodium-ion battery is heavily reliant on the size of its sodium-based solution. Nevertheless, it could still be utilised as a cheaper option for large-scale renewable energy storage in the agricultural complex, where equipment size and weight are not significant limiting factors.

As a result of this review, the advantages and disadvantages of the three main types of electric tractors (battery electric, hybrid electric and fuel cell electric) have been summarised. Moreover, according to the reviewed questionnaire, farmers' willingness to replace diesel-based tractors with electric tractors was mainly affected by the following factors: costs of the tractor, the size of the farming area, farmers' age and technical skills, engine characteristics, prior experience with electric tractors and other preferences. After analysing publications describing the current electric tractor market, it has been determined that the market is limited to low-power engine technologies that are only capable of performing light tasks. Heavy-duty tasks such as equipment transportation, harvesting, cultivation, hard ground ploughing, and other activities cannot be carried out by these tractors.

Additionally, a significant portion of the electric tractor market consists of autonomous tractors, which require farmers to have high technical skills. However, an oversupply of autonomous electric tractors can potentially slow down their adoption and use by consumers, as their operating principles are drastically different from those of conventional tractors. The lack of charging infrastructure and distance between charging stations and tractors in the field pose significant challenges in the reviewed publications, but these can be overcome with the help of on-board battery packs or trailers with spare batteries and mobile charging. While the reviewed publications provide a valuable insight into the capabilities and demand for electric tractors from a consumer perspective, there is a lack of comprehensive examination of the connection between RES and the use of electric tractors. Further research should focus on exploring how RES can be used as a reliable and efficient source of electricity for tractor charging infrastructure. Additionally, research should examine how changes to the current electric tractor market can affect farmers' willingness-to-buy more environmentally friendly solutions.

Looking at the literature related to the initial cost and economic assessment of RES, publications address the evaluation of different energy sources and their overall performance in various operating configurations. Nevertheless, a shortage of publications that offer a reliable direction for the development of agriculture can be observed, and most of the analysis in the available literature is heavily reliant on regional economic and climatic conditions. As a result, the solutions of the reviewed publications would be challenging to apply and justify in different economic and climatic environments. Instead, the authors offer a universal type of solutions, in which economic assessment is performed using not for agriculture suitable energy consumption or generation characteristics, but offering calculations that can be used for universal consumption and electricity generation profiles. It is unclear whether a universal approach to economic assessment of RES implementation and existing business models can be suitable for successful agriculture electrification.

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A COMPREHENSIVE OVERVIEW OF THE EUROPEN AND BALTIC LANDSCAPE FOR HYDROGEN APPLICATIONS AND INNOVATIONS

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Hydrogen has been widely recognised as a versatile and environmentally-friendly energy carrier, with a broad range of potential applications across various sectors. The abundance of hydrogen in the universe and its high energy content makes it an attractive alternative to conventional fossil fuels. Moreover, the utilization of hydrogen does not produce greenhouse gases or other pollutants that contribute to air pollution and climate change. In recent years, there has been a growing interest in developing and deploying hydrogen technologies for a sustainable energy future. This paper provides an in-depth exploration of the potential of hydrogen as a clean energy source in different sectors, such as transportation, energy storage, power generation, industry, buildings, maritime transport, and aviation. The aim of the paper is to provide an overview of the current state of hydrogen applications in Europe and the Baltic States, including examples of ongoing projects and initiatives, and to assess the advantages and disadvantages of hydrogen technologies in different sectors. The main results of the paper highlight that hydrogen has the potential to significantly reduce greenhouse gas emissions and achieve carbon neutrality targets. However, the deployment of hydrogen technologies also faces various challenges such as high production costs, lack of infrastructure, and safety concerns. The tasks of the paper are to provide an insight into the potential of hydrogen, identify the challenges and limitations, and highlight ongoing research and development efforts in this field. The paper concludes that the widespread adoption of hydrogen technologies is a long-term goal that requires the cooperation of various stakeholders and the development of innovative and cost-effective solutions. Despite the challenges, the current state of hydrogen applications and ongoing projects in Europe and the Baltic States demonstrate that hydrogen has the potential to play a significant role in the transition to a sustainable and low-carbon future.

Keywords: *Aviation, buildings, clean energy, energy storage, hydrogen, industry, marine, power generation, transportation.*

1. INTRODUCTION

Hydrogen, a colourless and odourless gas, is the most abundant element in the universe. It has a high energy content and can be produced from a variety of sources, including natural gas, coal, biomass, and renewable energy sources (hereinafter – RES). Hydrogen has been recognised as a promising alternative energy carrier that can contribute to a sustainable and low-carbon energy future. Its diverse range of applications across various sectors, including transportation, industry, and power generation, has garnered significant interest from governments, industry, and academia in recent years [1]–[5].

Hydrogen has emerged as a crucial element for the European market, as the region aims to transition, with the goal of achieving net-zero greenhouse gas emissions (hereinafter – GHG) by 2050. The European Union (EU) has recognised hydrogen as a key enabler of its energy and climate goals. One of the main reasons why hydrogen is so important for the European energy market is its potential to decarbonize sectors that are difficult to electrify, such as heavy industry, long-distance transport and aviation. The EU has set ambitious targets to reduce GHG by at least 55 % by 2030, and hydrogen can play a crucial role in achieving these targets. Moreover, hydrogen has the potential to reduce the EU's dependence on fossil fuels, improve energy security, and stimulate economic growth by creating new jobs and markets [2], [4]. The European Commission has identified hydrogen as a key priority and has proposed a strategy to support the development of a clean hydrogen economy in Europe. To achieve these goals, the EU has set a target of producing at least 40 gigawatts of renewable hydrogen by 2030, and has allocated significant funding to support research, development, and deployment of hydrogen technologies. The EU is also promoting the development of a hydrogen infrastructure network, including pipelines and refuelling stations, to support the widespread use of hydrogen in transportation and industry. In addition, the EU is collaborating with international partners, like Japan, South Korea, and the United States, to develop a blueprint of the global hydrogen market.

This collaboration aims at accelerating the development and deployment of hydrogen technologies, improving the cost-effectiveness of hydrogen production and storage, and establishing common standards and regulations for safe handling and usage of hydrogen. The EU's commitment to the development of a clean hydrogen economy presents significant opportunities for the region, including reduced GHG, improved energy security, and enhanced economic growth [5]–[8].

Hydrogen can play a crucial role in helping countries to reach their neutrality targets by providing a versatile, low-carbon energy carrier that can be produced from a variety of sources, including renewable energy. Hydrogen has the potential to decarbonize various sectors that are difficult to electrify, such as heavy industry, long-distance transportation, and heating and cooling of buildings. One of the main ways how hydrogen can help reach neutrality targets is by replacing fossil fuels in transportation. Fuel cell electric vehicles powered by hydrogen fuel cells emit only water vapor as a by-product, making them a zero-emissions alternative to conventional gasoline and diesel vehicles. In addition, hydrogen can be used to power heavy-duty trucks, buses, and trains, which are difficult to electrify due to their energy demands. Hydrogen can also be used as a feedstock for the production of chemicals, such as ammonia and methanol, which are used in the production of fertilizers and other industrial products. By replacing fossil fuels with hydrogen in these sectors, significant reductions in GHG can be achieved. Furthermore, hydrogen can be used in power generation, either through combustion or in fuel cells. When combined with RES such as wind and solar power, hydrogen can help store excess energy and provide a reliable source of electricity during times of low RES availability.

In order to reach neutrality targets, significant investments are needed to develop and deploy hydrogen technologies. This includes investments in the production, storage, and distribution of hydrogen, as well as the development of supporting infrastructure such as refuelling stations, adapting existing natural gas pipelines to hydrogen transportation and building special hydrogen pipelines. Governments, industry, and other stakeholders will need to work together to establish common standards and regulations to ensure the safe handling and usage of hydrogen. Hydrogen can help countries reach their neutrality targets by providing a versatile, low-carbon energy carrier that can be used across various sectors. By replacing fossil fuels with hydrogen, significant reductions in GHG can be achieved, while also supporting the transition to a sustainable, low-carbon energy future [9]–[13].

The Baltic States, which include Estonia, Latvia, and Lithuania, have been exploring the potential of hydrogen to help achieve their climate and energy goals. The region has recognised hydrogen as a key enabler of this complex process. One of the main areas of focus for hydrogen in the Baltic States is transportation. The region has set ambitious targets to reduce GHG in transport, and hydrogen can play a crucial role in achieving these targets. For example, Estonia has developed a national hydrogen roadmap, which outlines the potential for hydrogen fuel cell vehicles and the necessary infrastructure to support them.

Moreover, the Baltic States have significant potential for RES such as wind and solar power, which can be used to produce renewable hydrogen through electrolysis. The region is already a leader in renewable energy, with Estonia and Latvia ranking in the top five in the EU in terms of the share of renewable energy in their total energy consumption.

In addition to transportation, the Baltic States are exploring the potential of hydrogen in other sectors such as industry and power generation. For example, Lithuania is developing a green hydrogen production project, which aims at using renewable energy to produce hydrogen for industry. To support the development of a hydrogen economy in the Baltic States, significant investments are needed in research and development (hereinafter – R&D), as well as in the production, storage, and distribution of hydrogen. The region will also need to develop supporting infrastructure such as refuelling stations and pipelines [1], [2], [4], [8].

Latvia is exploring the potential of hydrogen to help achieve its climate and energy goals, and the main focus area for hydrogen in Latvia is transportation. The country has identified hydrogen fuel cell vehicles as a potential solution to vehicle triggered air pollution problem.

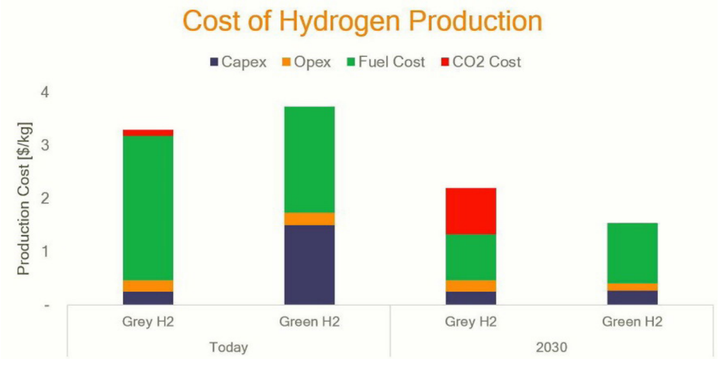
The Latvian government has developed a national hydrogen roadmap, which outlines the potential for hydrogen fuel cell vehicles and the necessary infrastructure to support them. In addition, the roadmap includes plans for the production of hydrogen from RES. Moreover, Latvia has significant potential of biomass. Biomass gasification is a mature technology that uses a controlled process involving heat, steam, and oxygen to convert biomass to hydrogen and other products, without combustion. Because growing biomass removes carbon dioxide (hereinafter – CO_2) from the atmosphere, the net carbon emissions of this method can be low, especially if coupled with carbon capture, utilization, and storage in the long term [14].

Latvia is already one of the leaders in the use of biomass for heat and electricity generation, and hydrogen produced from biomass could be yet another pathway in diversification of its use. In addition to transportation, Latvia is exploring the potential of hydrogen in other sectors such as industry and power generation. For example, the country's energy sector has already started to use hydrogen to balance the power grid during times of low renewable energy availability. The Latvian government is also promoting the use of hydrogen as a feedstock for the production of chemicals, such as ammonia, which are used in the production of fertilizers and other industrial products. To support the development of a hydrogen economy in Latvia, significant investments are needed in research and development, as well as in the production, storage, and distribution of hydrogen. The country will also need to develop supporting infrastructure such as refuelling stations and pipelines [3], [5]–[8].

While hydrogen offers significant potential for decarbonizing various sectors and achieving climate and energy goals, there are several challenges and issues that need to be addressed to realise its full potential. One of the main challenges with hydrogen applications is cost. The production, storage, and distribution of hydrogen can be expensive, particularly when produced from renewable sources. However, as shown in Fig. 1, and according to some researchers, the situation in green hydrogen production could also change for the best even by 2030.

Another challenge with hydrogen applications is infrastructure. The development of supporting infrastructure, such as refuelling stations and pipelines, is necessary for widespread adoption of hydrogen in transportation and other sectors. Building the infrastructure can be costly and time-consuming, particularly in areas where demand is low. Furthermore, there are concerns about the safety of hydrogen due to its flammability and potential for leaks. While hydrogen is safe when handled properly, there are risks associated with its production, storage, and transport that need to be managed carefully.

Another issue with hydrogen applications is the current lack of regulations and standards for its production, storage, and use. Establishing common standards and regulations will be necessary to ensure the safe handling and use of hydrogen and to support the development of a hydrogen economy. Finally, the current supply of hydrogen is largely dependent on natural gas, which produces greenhouse gas emissions during production. To realise the full potential of hydrogen as a low-carbon energy carrier, the production of hydrogen needs to shift towards RES [15]–[17].



Source: Rethink Energy

Fig. 1. Comparison of costs in green and grey hydrogen production (2022, 2030, in $/kg).

There are several strategies and solutions that can be implemented to address the challenges associated with hydrogen applications and support the development of a sustainable hydrogen economy. Some of them include:

- technological advancements: continued research and development can lead to new and more efficient technologies for producing, storing, and distributing hydrogen, which can help reduce costs and increase the competitiveness;
- scale-up of production: by scaling up the production of hydrogen, economies of scale can be achieved, which can help drive down the cost of hydrogen production;
- supporting infrastructure: developing the necessary infrastructure, such as refuelling stations and pipelines, can help promote the adoption of hydrogen in transportation and other sectors. Governments and private enterprises can invest in building this infrastructure to create a national, transnational or regional hydrogen network;
- safety regulations: establishing common safety regulations and standards for the production, storage, and transport of hydrogen at the EU level can help ensure the safe handling and use of hydrogen and promote public confidence in the technology;
- policy support: governments can provide policy support, such as tax incentives, grants, and subsidies, to promote the development and adoption of hydrogen technologies. This support can help reduce the cost of hydrogen and encourage investment in hydrogen-related infrastructure;
- collaboration: collaboration between stakeholders, including governments, industry, and academia, can help accelerate the development and adoption of hydrogen technologies. Collaboration can lead to knowledge sharing and transfer, increased investment, and the development of common standards and regulations;

- shift towards renewable energy: the production of hydrogen should enhance shift towards RES such as wind and solar power, which, hence, can help reduce GHG associated with hydrogen production and support the transition to a low-carbon economy.

Addressing the challenges associated with hydrogen applications will require a multifaceted approach that includes technological advancements, supporting infrastructure, safety regulations, policy support, collaboration, and a shift towards renewable energy. Implementing these strategies can help overcome these challenges and support the development of a sustainable hydrogen economy. Continued research and development can help overcome many of the technological challenges associated with hydrogen applications.

Some potential areas for technological advancements include:

- electrolysis: electrolysis is the process of splitting water molecules into hydrogen and oxygen using an electric current. Advances in electrolysis technology can lead to more efficient and cost-effective production of hydrogen from renewable energy sources;
- fuel cells: fuel cells convert hydrogen into electricity with high efficiency, producing only water as a by-product. Advances in fuel cell technology can improve their performance and reduce their cost, making them more competitive with conventional technologies;
- hydrogen storage: storing hydrogen can be challenging due to its low energy density, which means that large volumes of hydrogen are needed to store a significant amount of energy. Advances in hydrogen storage technology, such as improved materials for hydrogen storage, can help increase the energy density of hydrogen storage and reduce the cost;
- distribution infrastructure: the development of a hydrogen distribution infrastructure, including pipelines and refuelling stations, is crucial for the widespread adoption of hydrogen in transportation and other sectors. Advances in distribution infrastructure technology can help make hydrogen more widely available and accessible;
- safety: addressing safety concerns associated with hydrogen, such as its flammability and potential for leaks, is crucial for public acceptance of the technology. Advances in safety technology, such as better sensors and leak detection systems, can help improve the safety of hydrogen applications [17]–[20].

Continued R&D can help overcome many of the technological challenges associated with hydrogen applications. Advances in electrolysis, fuel cells, hydrogen storage, distribution infrastructure, and safety technology can help reduce costs and increase the competitiveness of hydrogen, making it a more viable solution for decarbonizing various sectors and achieving climate and energy goals. At the same time, hydrogen has a wide range of potential applications, particularly in the context of transitioning to a low-carbon economy.

The key applications of hydrogen include, but are not limited to:

- transportation: hydrogen fuel cell vehicles are a promising alternative to gasoline-powered vehicles, producing only water as a by-product. Hydrogen can also be used as a fuel for buses, trucks, and trains, particularly in long-haul applications;
- energy storage: hydrogen has the potential to be used as a form of energy storage, particularly in combination with

RES such as wind and solar power. Hydrogen can be produced during times of excess renewable energy production and stored for later use;
- power generation: hydrogen can be used in fuel cells to generate electricity. This can be particularly useful in remote areas or for backup power generation;
- industry: hydrogen is used in a variety of industrial applications, particularly in the production of ammonia for fertilizer and other chemical processes;
- buildings: hydrogen can be used in buildings for heating and cooking, particularly in areas where natural gas is not available;
- Maritime transport: hydrogen fuel cells can also be used in maritime transport applications, particularly in shipping.
- aviation: hydrogen has a potential to be used as a fuel for aviation, particularly for short-distance flights [20]–[22], [24], [25].

This paper will assess various applications of hydrogen as a sustainable and low-carbon energy source. We will focus on its use in transportation, energy storage, power generation, industry, buildings, maritime transport, and aviation [15], [18], [24]. The assessment will consider the technological, economic, and environmental aspects of hydrogen applications in each of these sectors.

2. ASSESSING THE POTENTIAL OF HYDROGEN IN DIFFERENT SECTORS

Hydrogen has emerged as a promising energy carrier for a low-carbon future, offering a range of potential applications in different sectors. The use of hydrogen has been identified as a key strategy for reducing GHG, particularly in sectors that are difficult to decarbonize.

2.1. Transportation

Transportation is one of the critical sectors where hydrogen has the potential to make a significant impact as a low-carbon energy source. Hydrogen fuel cell vehicles are a promising alternative to traditional gasoline-powered vehicles, as they produce only water as a by-product and do not emit harmful pollutants that contribute to air pollution and climate change. In addition to personal vehicles, hydrogen can also be used as fuel for larger modes of transportation such as buses, trucks, and trains. One of the advantages of using hydrogen in these applications is the long-range capability of fuel cell vehicles, making them suitable for long-haul transportation needs.

The use of hydrogen in transportation faces some challenges, including the limited availability of refuelling infrastructure and the high cost of fuel cell technology. However, there has been increasing interest in the development and deployment of hydrogen refuelling infrastructure, particularly in regions where there are ambitious climate goals and a strong commitment to decarbonizing transportation. Furthermore, there have been significant technological advancements in hydrogen fuel cell technology, making it more efficient and cost-effective.

As a result, hydrogen has the potential to play a major role in the future of clean transportation. In addition to reducing GHG emissions, the use of hydrogen in transportation can also improve air quality by reducing harmful pollutants that contribute to respiratory diseases. Furthermore, the use of hydrogen as a fuel in transportation can enhance energy security, as it reduces dependence on imported oil and provides an alternative to traditional fossil fuels. Hydrogen-powered buses, trucks, and trains are already in use in various parts of the world, and several major automakers have announced plans to release hydrogen-powered vehicles for the consumer market.

It is also significant to note that using hydrogen fuel cells also work well in trolleybuses as range extenders, which enables the system to increase reachable distance beyond the current network and provides resilience and flexibility against electricity grid blackouts. Replacing the diesel range extenders currently in use will greatly reduce GHG emissions, whilst providing the same level of operational flexibility. Ten hydrogen powered trolleybuses are currently in daily operation in Riga and they also are the first vehicles of this type worldwide [23].

However, the cost of hydrogen fuel cell technology and the limited availability of hydrogen refuelling infrastructure remain significant barriers to wider adoption of hydrogen in transportation. Despite these challenges, the potential benefits of hydrogen in transportation are significant, particularly for long-haul transportation needs where other low-carbon options such as battery-electric vehicles may not be practical. As such, continued investment in the development of hydrogen fuel cell technology and the deployment of hydrogen refuelling infrastructure is critical to unlocking the potential of hydrogen in transportation.

There are several examples of hydrogen-powered transportation initiatives and projects in Europe:

- The H2ME project: The Hydrogen Mobility Europe (H2ME) project is a European public-private partnership aimed at expanding the deployment of hydrogen fuel cell vehicles and infrastructure in Europe. The project has supported the deployment of over 1,000 fuel cell vehicles and over 40 refuelling stations across Europe [26];
- The JIVE project: The Joint Initiative for Hydrogen Vehicles across Europe (JIVE) is a European initiative aimed at deploying fuel cell buses in several cities across Europe. The project has supported the deployment of over 150 fuel cell buses across 14 cities in Europe [27];
- The H2Ports project: The H2Ports project is a European initiative aimed at demonstrating the feasibility of using hydrogen in ports and shipping. The project will deploy a range of hydrogen-powered equipment, including forklifts and cargo handling equipment, as well as a hydrogen refuelling station, at the Port of Valencia in Spain [28];
- The H2-Share project: The H2-Share project is a European initiative aimed at deploying a fleet of hydrogen-powered trucks for logistics operations. The project will deploy a range of fuel cell trucks for logistics operations in four European countries [29];
- The H2GO project: The H2GO project is a European initiative aimed at developing a network of hydrogen refuelling stations for heavy-duty vehicles in Europe. It will deploy 1000 hydrogen refuelling stations across Europe, with a focus on heavy-duty vehicle applications [30].

Here are some real examples of hydrogen initiatives and projects in the transportation sector in the Baltic States as well:

- The Latvian company "Riga Hydrogen City" is developing a fleet of hydrogen fuel cell buses for public transportation in Riga. The project is supported by the

European Union and aims at reducing emissions and improving air quality in the city [31];
- The Lithuanian company "Elinta Motors" is developing a hydrogen fuel cell truck for long-haul transportation. The company has already built a prototype and planned to start production in 2022 [32];
- The Estonian company "H2Pro" is developing a hydrogen production technology that can be used to power hydrogen fuel cell cars. The company is working with several partners to develop a complete hydrogen-based transportation system [33].

The advantages of using hydrogen in the transportation sector include:
- zero GHG emissions: hydrogen fuel cell vehicles produce zero emissions, which makes them a cleaner alternative to gasoline and diesel-powered vehicles. This can help reduce air pollution and improve air quality in urban areas;
- long driving range: hydrogen fuel cell vehicles have a similar driving range to gasoline vehicles and can be refuelled in a matter of minutes, making them suitable for long-distance travel;
- versatility: hydrogen can be used as a fuel for a variety of transportation modes, including cars, buses, trucks, trolleybuses and trains, which makes it a versatile solution for reducing emissions in the transportation sector;
- energy security: hydrogen can be produced from a variety of sources, including renewable sources such as wind and solar power, which can help increase energy security and reduce dependence on fossil fuels [10], [12], [19].

However, there are also several disadvantages associated with using hydrogen in the transport sector:
- infrastructure challenges: one of the main challenges of using hydrogen as a fuel for transportation is the lack of infrastructure, such as hydrogen refuelling stations, which makes it difficult for consumers to adopt hydrogen fuel cell vehicles;
- cost: hydrogen fuel cell vehicles are currently more expensive than gasoline and diesel-powered vehicles, and the cost of producing and distributing hydrogen is also relatively high compared to other fuels;
- safety concerns: hydrogen is a highly flammable gas and requires special handling and storage procedures to ensure safety. This can make it more challenging to establish a widespread hydrogen infrastructure for transportation;
- technology development: while hydrogen fuel cell technology has made significant advances in recent years, further research and development are needed to improve the efficiency and durability of fuel cells and reduce costs [15], [8].

Despite these challenges, the potential benefits of using hydrogen in the transport makes it an attractive solution for reducing emissions and increasing energy security. Hydrogen fuel cell vehicles produce zero emissions and offer the same driving range and refuelling time as conventional gasoline vehicles. This makes them particularly attractive for long-haul applications where battery electric vehicles may not be as practical due to their limited driving range and longer charging times. Several initiatives and projects are already underway in Europe aimed at developing hydrogen-based transportation systems.

However, there are still technological and infrastructural challenges that need to be addressed to make hydrogen-based transportation systems more practical and cost-effective. These include developing more efficient and affordable fuel cell systems, establishing a widespread network of hydrogen refuelling stations, and addressing safety concerns associated with handling and storing hydrogen.

2.2. Energy Storage

Hydrogen has the potential to be a key component of energy storage systems, particularly in combination with RES. One of the main challenges of RES is their intermittency, which means that they may not always produce energy when it is needed. Hydrogen can help address this challenge by storing excess renewable energy as hydrogen gas through electrolysis. During periods of excess renewable energy production, electricity can be used to split water molecules into hydrogen and oxygen. The hydrogen gas can then be stored in tanks or pipelines for later use. When renewable energy production is low, the stored hydrogen can be used to generate electricity through fuel cells or burned in combustion engines. The use of hydrogen as an energy storage medium has several advantages. Unlike batteries, hydrogen storage systems can be scaled up easily and can store large amounts of energy over long periods of time. Hydrogen also has a high energy density, which means that it can store more energy per unit of volume than other storage media such as batteries [9], [13]. This makes it particularly suitable for long-term energy storage applications. While there are still technical and economic challenges associated with hydrogen energy storage, its potential to store large amounts of energy over long periods of time makes it a promising solution for integrating RES into the grid and improving energy security. Examples of hydrogen-based energy storage projects in Europe include:

- Store&Go: The Store&Go project is the EU-funded project that aims at demonstrating the feasibility of large-scale hydrogen storage using underground salt caverns. The project is being carried out in Germany, Italy, and the United Kingdom [34];
- HyBalance: The HyBalance project is a pilot project that aims at demonstrating the feasibility of producing and storing hydrogen from wind energy. The project is being carried out in Denmark and involves the use of a wind turbine to produce hydrogen through electrolysis, which is then stored in tanks for later use [35];
- H2Future: The H2Future project is another EU-funded project that aims at demonstrating the feasibility of using hydrogen as a storage medium for excess RES. The project is being carried out in Austria and involves the use of excess wind and solar energy to produce hydrogen through electrolysis, which is then stored in tanks for later use [36].

There are currently no large-scale hydrogen energy storage projects underway in the Baltic States. However, there are some initiatives and research projects exploring the potential of hydrogen energy storage, such as:

- The Baltic Energy Innovation Centre (BEIC): The BEIC is a research and development centre in Latvia that focuses on developing innovative energy solutions, including hydrogen energy storage. The centre is working on developing a hydrogen-based energy storage system that can be integrated with wind and solar power systems [37];
- Hydrogen Valley: Hydrogen Valley is a joint initiative between Estonia, Latvia, and Lithuania aimed at promoting the use of hydrogen in the region. While

the initiative does not currently include any hydrogen energy storage projects, it is focused on developing a regional hydrogen infrastructure that could support future energy storage projects [38].

These initiatives demonstrate growing interest in hydrogen energy storage in the Baltic States, but there is still much work to be done to develop and scale up these technologies. Advantages of energy storage with hydrogen include:

- scalability: hydrogen storage can be easily scaled up or down to meet changing energy demands;
- long-term storage: hydrogen can be stored for long periods of time, making it a viable option for seasonal storage of renewable energy;
- versatility: hydrogen can be used for a range of energy applications, including transportation, power generation, and heating;
- zero emissions: hydrogen energy storage produces no harmful emissions, making it a clean and sustainable energy option.

Disadvantages of energy storage with hydrogen include:

- cost: hydrogen storage can be expensive, particularly compared to other forms of energy storage like batteries;
- efficiency: the process of converting electricity to hydrogen and then back to electricity can result in significant energy losses;
- safety concerns: hydrogen is highly flammable and requires specialized handling and storage facilities;
- limited infrastructure: there is currently limited infrastructure for hydrogen storage and distribution, making it difficult to implement on a large scale [13], [18], [20].

2.3. Power Generation

The use of hydrogen in fuel cells to generate electricity is a promising area for the development of a sustainable and low-carbon energy system. Fuel cells offer a highly efficient method of generating electricity with minimal emissions, making them an attractive option for a range of applications, including remote power generation and backup power supply. Here the potential applications of hydrogen fuel cells for power generation, as well as the advantages and challenges associated with this technology are explored. Additionally, we will examine current examples of hydrogen fuel cell power generation projects in Europe and the Baltic States, and discuss the implications for the future of power generation [8].

There are several examples of power generation projects in Europe that utilise hydrogen fuel cells:

- The HYDRA project in Germany is exploring the potential of hydrogen fuel cells for backup power generation in data centres. The project is being conducted by the Technical University of Munich in collaboration with several industry partners [39];
- The H2OCEAN project in France is developing a hybrid energy system that combines wind power and hydrogen fuel cells for remote power generation on offshore islands. The project is a collaboration between several industry partners and research institutions [40];
- The Haeolus project in the Netherlands is developing a hybrid power system that combines wind power, energy storage, and hydrogen fuel cells for remote power generation in the Wadden Sea. The project is being led by the Energy

Research Centre of the Netherlands in collaboration with several industry partners [41];

- The HyBalance project in Denmark is exploring the potential of hydrogen fuel cells for balancing the electricity grid. The project involves the construction of a power-to-gas plant that converts excess wind power into hydrogen, which can then be used to generate electricity through fuel cells [42];
- The BigHit project in the United Kingdom is developing a hybrid power system that combines wind power, energy storage, and hydrogen fuel cells for remote power generation on the Scottish island of Orkney. The project is being led by the European Marine Energy Centre in collaboration with several industry partners [43].

These projects demonstrate the potential of hydrogen fuel cells for power generation in Europe, particularly for remote and off-grid applications. However, continued research and development, along with increased investment in infrastructure, will be necessary to advance the adoption of this technology and realise its full potential.

There are currently no large-scale power generation projects using hydrogen in the Baltic States, but there are some research initiatives and smaller pilot projects that explore the potential of hydrogen as a fuel for power generation, for instance:

- Riga Technical University has been researching hydrogen fuel cells as a way to generate electricity for remote areas, particularly in Latvia's rural regions where grid access is limited [44];
- In 2021, Latvia's state-owned energy company "Latvenergo" launched a pilot project to test the feasibility of using hydrogen as a fuel for backup power generation at one of its power plants [45];
- Estonia's National Institute of Chemical Physics and Biophysics is also conducting research into using hydrogen fuel cells for power generation, particularly in the context of integrating renewable energy sources into the grid [46].

These projects are still in their early stages and more R&D activities are needed before hydrogen-based power generation becomes a viable option in the Baltic States. Advantages of power generation with hydrogen include:

- clean energy source: hydrogen fuel cells produce electricity without emitting pollutants or greenhouse gases;
- versatility: hydrogen can be produced from a variety of sources, including renewables, nuclear, and fossil fuels;
- high efficiency: hydrogen fuel cells are highly efficient, converting up to 60 % of the energy contained in the hydrogen to electricity;
- reliability: hydrogen fuel cells are reliable and can provide uninterrupted power for long periods of time;

Disadvantages of power generation with hydrogen include, but are not limited to:

- high cost: current hydrogen fuel cell technology is expensive and not yet competitive with other forms of power generation;
- infrastructure challenges: the development of a hydrogen infrastructure, including production, storage, and distribution facilities, requires significant investment;
- safety concerns: hydrogen is highly flammable and requires special handling and storage precautions to ensure safety;
- limited availability: while hydrogen is abundant in nature, it is not readily available in its pure form and must be extracted or produced through energy-intensive processes.

2.4. Industry

Hydrogen has been widely used in various industrial applications, especially in the production of ammonia for fertilizers and other chemical processes. Ammonia is a critical component in the production of fertilizers, which is essential for agriculture and food production. The Haber-Bosch process, which uses hydrogen and nitrogen to produce ammonia, has been used for over a century to meet the global demand for fertilizers. In addition to the production of fertilizers, hydrogen is used in several other industrial applications, such as the production of methanol, steel production, and petroleum refining. Hydrogen is also used as a reducing agent in the production of silicon and other metals. The use of hydrogen in the industry offers several benefits, including reduced carbon emissions, increased energy efficiency, and improved production processes. However, there are also challenges associated with the widespread adoption of hydrogen in industry, such as the high cost of hydrogen production and distribution, and the need for significant infrastructure investments [10], [13].

Nonetheless, the potential benefits of hydrogen in the industry make it a promising area for further research and development. Here are some examples of industrial applications for hydrogen in Europe:

- in the Netherlands, a project called H2FUTURE is being developed to use green hydrogen produced by wind power to power the steel industry. The project aims at reducing CO_2 emissions by up to 50 % [47];
- in Germany, a company called "Covestro" is using hydrogen to produce aniline, a chemical used in the production of plastics. Hydrogen is produced using RES and helps reduce the carbon footprint of the production process [48];
- in the UK, a project HyNet is being developed to use hydrogen to power industrial processes in the North West of England, including the production of chemicals, steel, and cement. The project aims at reducing CO_2 emissions by up to 10 million tonnes per year by 2030 [49];
- in Sweden, the steel manufacturer "SSAB" is using hydrogen to produce fossil-free steel in a pilot plant. The hydrogen is produced using fossil-free electricity and will help reduce the carbon footprint of the steel production process [50].

In the Baltic States, the use of hydrogen in the industry is still in its infancy, with no large-scale projects currently in operation. However, there are some initiatives exploring the potential for hydrogen in the industry. For example, in Estonia, the company "Hiiu Elektrijaam" is investigating the use of hydrogen to produce electricity and heat for industrial and residential use. Meanwhile, in Latvia, Riga Technical University is researching the use of hydrogen in the production of green fertilizers. These are promising steps towards the development of a hydrogen-based industry in the region.

Advantages of hydrogen applications in the industry include:

- hydrogen can be produced from RES, making it a potentially sustainable and low-carbon option for industrial applications;
- hydrogen has a high energy density, making it useful for high-energy industrial processes;
- hydrogen can be used as a feedstock in chemical processes, reducing the need for fossil fuels;
- use of hydrogen in the industry can help reduce GHG emissions.

At the same time, there are disadvantages that should be mentioned:

- hydrogen production can be energy-intensive and expensive, particularly if traditional fossil fuels are used as feedstock;
- hydrogen can be difficult and expensive to transport and store, particularly in large quantities;
- hydrogen has low ignition energy, making it potentially dangerous if proper safety measures are not taken;
- the development of a hydrogen infrastructure for industrial applications would require significant investment and coordination among various stakeholders.

Obviously, hydrogen has a significant potential for the industrial sector, particularly in the production of ammonia for fertilizers and other chemical processes. However, its widespread adoption faces challenges related to cost, infrastructure, and safety. Nevertheless, ongoing research and development are expected to lead to new and more efficient hydrogen technologies that can help overcome these challenges and increase the competitiveness of hydrogen in the industrial sector.

2.5. Building Sector

Hydrogen can also be used in buildings as a source of energy for heating and cooking, especially in areas where natural gas is not available or its availability is limited. The high cost of hydrogen production and the need for specialized infrastructure are currently barriers to the widespread adoption of hydrogen in building applications. However, there are several examples of hydrogen being used in buildings for heating and cooking in Europe [13], [19], such as:

- the H21 North of England project is exploring the use of hydrogen for heating in homes and businesses in the UK. The project aims at converting the gas networks in the north of England to run on hydrogen instead of natural gas [51];
- the Levenmouth Community Energy Project in Scotland is using hydrogen fuel cells to generate electricity for homes in the area. The project is also exploring the use of hydrogen for heating in the future [52];
- the European project GenComm is developing hydrogen-based energy solutions for buildings, including fuel cells and hydrogen boilers. The project is testing these solutions in a range of different buildings across Europe [53];
- The H2Nodes project aims at demonstrating the use of hydrogen in buildings [54].

These are just a few examples of the use of hydrogen in buildings for heating and cooking in Europe. There are currently limited examples of the use of hydrogen in buildings in the Baltic States. However, some initiatives and research projects are underway to explore the potential of hydrogen in this sector. In Estonia, the company “Enefit Green” is investigating the use of hydrogen as a fuel for combined heat and power plants that could supply district heating to homes and buildings. In Latvia, Riga Technical University is conducting research on the use of hydrogen as a fuel for heating and power generation in buildings, particularly in the context of energy storage and integration with renewable energy sources. In Lithuania, the Lithuanian Energy Institute is leading a project called HyLAW, which aims at developing a legal and regulatory framework for the deployment of hydrogen technologies, including their use in buildings for heating and power generation.

These initiatives demonstrate the growing interest and potential for the use of hydrogen in buildings in the Baltic States, although significant technological and regulatory challenges remain to be addressed.

The advantages of using hydrogen in buildings for heating and cooking are as follows:

- environmental benefits: hydrogen is a clean and renewable energy source, and its use can help reduce carbon emissions and improve air quality;
- energy security: hydrogen can be produced domestically, reducing dependence on foreign energy sources and increasing energy security;
- versatility: hydrogen can be used for both heating and cooking, making it a versatile energy source for buildings;
- potential for cost savings: while the initial investment for hydrogen infrastructure may be high, the cost of hydrogen production is expected to decrease over time, leading to potential cost savings in the long term.

However, there are also some shortcomings to using hydrogen in buildings, like:

- infrastructure requirements: hydrogen infrastructure is currently limited and expensive to build, requiring significant investment and planning;
- safety concerns: hydrogen is a highly flammable gas, and its use in buildings requires strict safety protocols and precautions to prevent accidents;
- efficiency: while hydrogen fuel cells have high efficiency in generating electricity, hydrogen combustion for heating and cooking may be less efficient than other energy sources;
- scale limitations: the use of hydrogen in buildings may be limited by the scale of production and storage facilities, which may be more suitable for larger industrial applications.

Overall, the advantages and disadvantages of using hydrogen in buildings depend on various factors, including the availability of infrastructure and the specific application. While there are some challenges to the widespread adoption of hydrogen in buildings, ongoing research and development efforts are addressing these issues. As demonstrated by the examples from Europe and the Baltic States, hydrogen-based solutions for building heating and electricity are being explored and implemented in various forms, from fuel cells to hydrogen boilers. As the technology continues to develop, hydrogen may become an increasingly important component of the transition to a more sustainable and decarbonized energy system.

2.6. Maritime Transport

Hydrogen fuel cells can provide a clean and efficient power source for shipping, where traditional fossil fuels are a major contributor to air pollution and GHG emissions. Hydrogen can be produced using RES and stored onboard ships, providing a zero-emission alternative to conventional fuels. The use of hydrogen in maritime transport is still in the early stages of development, but there is an interest to investment in this technology.

Examples of hydrogen in maritime applications in Europe include:

- HYDROVILLE, a hydrogen-powered passenger shuttle, which operates in Antwerp, Belgium. The vessel is powered by a fuel cell system and has a range of up to 35 nautical miles [55];

- HYSEAS III project aims at developing a hydrogen-powered ferry for use in Scotland. The ferry will be powered by a fuel cell system and is expected to be in operation by 2024 [56];
- ELEGANCE project, which is developing a hydrogen fuel cell system for use in maritime applications. The project is led by a consortium of companies and research institutions from across Europe [57];
- The Zemships project, which developed a hydrogen-powered passenger ferry for use in Hamburg, Germany. The vessel is powered by a fuel cell system and has been in operation since 2014 [58];
- The FLAGSHIPS project, which is developing two hydrogen-powered ferries for use in Norway. The vessels powered by fuel cell systems were expected to come into operation by 2022 [59].

These examples demonstrate the potential for hydrogen to be used in maritime transport, particularly for shipping and ferry services. Currently, there are no large-scale projects related to the use of hydrogen in the maritime transport in the Baltic States. However, the Estonian company "LMG Marin" has developed a concept for a hydrogen-powered ferry. The concept, called HySHIP [60], involves the use of a fuel cell system to power the vessel, with hydrogen produced from RES.

Advantages of hydrogen use in maritime transport include, but are not limited to:

- zero emissions: hydrogen fuel cells produce only water as a by-product, making them a clean and sustainable energy source for maritime transport;
- high efficiency: hydrogen fuel cells have a high energy density and can convert up to 60 % of the energy in the fuel into electricity;
- long range: hydrogen fuel cells can provide a long range for maritime transport, making them suitable for long-haul shipping;
- reduced noise pollution: hydrogen fuel cells produce much less noise compared to traditional diesel engines.

However, there are some disadvantages as well, such as:

- high cost: the cost of hydrogen fuel cell systems for marine applications is currently high, making them less competitive with traditional diesel engines;
- limited infrastructure: the infrastructure for producing, storing, and distributing hydrogen is currently limited, which can make it difficult for ships to refuel;
- safety concerns: hydrogen is highly flammable and requires careful handling to ensure safety;
- technical challenges: there are technical challenges associated with using hydrogen in maritime applications, such as the need for large storage tanks and the potential for corrosion.

In conclusion, hydrogen fuel cells have the potential to play a significant role in the maritime industry, particularly for shipping. While there are still technical and infrastructure challenges to overcome, ongoing projects and research show promise for the future deployment of hydrogen technologies in this sector.

2.7. Aviation

Hydrogen has been proposed as a potential fuel for aviation due to its high energy content and low emissions. Fuel cell-powered electric aircraft have been developed and tested, with a few small-scale commercial operations in the works.

In addition, hydrogen can be used in gas turbine engines as a direct replacement for jet fuel, with only minor modifications to the engine. However, the high cost of producing and distributing hydrogen, as well as the lack of infrastructure, are significant challenges to the widespread adoption of hydrogen in aviation. Currently, there are limited examples of hydrogen use in aviation in Europe. However, several research and development projects are underway, including:

- The European Union's Clean Sky 2 programme, which is developing and testing new aircraft technologies, including hydrogen fuel cells [61];
- Airbus' ZEROe concept aircraft, which would be powered by hydrogen fuel cells and could enter service by 2035 [62];
- The H2FLY project, which aims at demonstrating the feasibility of using hydrogen fuel cells for aviation through test flights [63];
- The HyFlyer project, which is developing hydrogen fuel cell-powered aircraft for commercial passenger flights [64];
- The Hy4 project, which has developed a four-seat aircraft powered by a hydrogen fuel cell [65].

These projects and initiatives indicate that hydrogen has the potential to play a role in the aviation industry in the future. Currently, there are no examples of the use of hydrogen in aviation in the Baltic States. However, the Baltic countries have expressed interest in the potential of hydrogen in aviation, with Latvia's Ministry of Transport plans to develop a national strategy for sustainable aviation, including the use of hydrogen.

Advantages of hydrogen use in aviation would include:

- hydrogen has a high energy content, which makes it a potentially attractive fuel for aviation as it could result in longer flight times and reduced fuel consumption;
- hydrogen combustion produces only water as a by-product, making it a zero-emissions fuel, which is particularly important for the aviation industry to meet sustainability goals;
- use of hydrogen fuel cells could potentially reduce the weight and noise of aircraft.

The disadvantages are as follows:

- production of hydrogen fuel is currently energy-intensive and expensive, which could limit its commercial viability for aviation;
- hydrogen fuel requires significant storage space and infrastructure, which could be challenging for the aviation industry;
- the use of hydrogen fuel cells in aviation is still in the early stages of development and would require significant investment to become a viable alternative to traditional jet fuel.

In conclusion, hydrogen has the potential to play a significant role in the aviation industry, particularly for short-haul flights. While there are still significant technological and infrastructure challenges that must be overcome, ongoing research and development in this field hold promise for the future of hydrogen in aviation.

3. CONCLUSIONS

Hydrogen has the potential to play a significant role in decarbonization of various sectors in the EU, and examples of hydrogen development projects demonstrate that there is a growing interest in the use of hydrogen as a clean energy source. However, the deployment of hydrogen technologies also faces various challenges such as high production costs, lack of infrastructure, and safety concerns. Nonetheless, continued research and development of hydrogen technologies can lead to new and more efficient ways of producing, storing, and distributing hydrogen, which can help reduce costs and increase the competitiveness of hydrogen.

Advantages and disadvantages of hydrogen applications vary depending on the sector and the specific application. For example, hydrogen fuel cell vehicles offer zero-emission transportation, but their high production costs and lack of refuelling infrastructure can be major obstacles. Hydrogen energy storage can help integrate RES, but the efficiency of hydrogen production and storage is lower than other energy storage options. Hydrogen power generation can provide backup power and off-grid power generation, but the high costs of fuel cells and the need for hydrogen supply chains are challenges.

Governments, research institutions, and private companies are investing in the development of hydrogen technologies, which can help overcome the challenges and drive the deployment of hydrogen technologies forward. In conclusion, the widespread adoption of hydrogen technologies is a long-term goal that requires the cooperation of various stakeholders and the development of innovative and cost-effective solutions. The current state of hydrogen applications and ongoing projects in Europe and the Baltic States demonstrate that hydrogen has the potential to play a significant role in the transition to a sustainable and low-carbon future.

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CALCULATIONS OF BASIC GEOMETRIC PARAMETERS FOR MOBILE SPACE ENVIRONMENT SIMULATION FACILITY "METAMORPHOSIS"

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The article presents the results of the analysis of approaches to designing a mobile vacuum system for simulation of space environment, which could help provide services of testing space objects at the request of the customers at a place and time acceptable to them, which allows saving time and assets in the development of space objects, their elements, including satellites. Such a system under a conditional name METAMORPHOSIS is developed at Riga Technical University (RTU). As a result of the conducted analysis, the methodological approaches to the determination of the structure of the vacuum system were determined and a description of the main systems which should be included in the designed mobile simulator of space environment, as well as the methods for assessment of characteristics of its structural elements were given. The results obtained allow deciding on using a cylindrical vacuum chamber with a horizontal structure type for the designed simulator, since the weight of test equipment in this case is minimal, and determining its main dimensions, which are also specified in the article.

Keywords: *Space environment simulation, strength, test and operating conditions, vacuum system.*

1. INTRODUCTION

Currently, due to the commercialization of space activities, the demand for launches of space objects (pico- and nanosatellites (PNS), etc.) on the part of commercial organisations, various societies, educational institutions, etc., constantly increases. At the same time, each object launched into space and its components must be tested to comply with the safety and declared functional characteristics of space objects and their components in accordance with the procedures and standards established in this field of activity. Such testing is carried out by special testing centres, which are stationary.

The services of these centres are expensive and not always available to small companies, societies, educational institutions, etc. This problem can be solved by creating a mobile ground simulator of space conditions. Such a project is being developed under a conditional name Metamorphosis at Riga Technical University ["Prototype development of transportable in intermodal traffic mobile space testing facility "Metamorphosis"" (Metamorphosis, project No. 1.1.1.1/18/A/133)]. The main properties of the space environment subjected to the Earth's orbit are: deep vacuum, low temperature of outer space and various types of radiation. The most important of them is deep vacuum. Therefore, the basis of the simulator is a vacuum chamber, and, therefore, simulators of outer space conditions are called vacuum chambers.

Vacuum space simulators are designed to create low-pressure, defined light and temperature conditions in a vacuum chamber to which the test object can be exposed in open space [1]–[5]. These are special chambers inside which the research sample is placed and certain climatic parameters are set, such as temperature regime, humidity level, rarefied atmosphere, dust and so on. Powerful vacuum pumps, heating and lighting devices and other components that make up the vacuum system ensure the setting of certain parameters. The main task of the research is to analyse the strength and resistance of the material to natural factors as well as space conditions.

First, the components and assemblies of spacecraft are designed in different variants. Second, important parameters are measured and collected for further analysis. This helps identify the weaknesses of the sample and improve them before being released to the market.

The components of vacuum space simulators include such elements:

- vacuum chamber [6], [7];
- vacuum pump system;
- vacuum measuring and/or control system;
- temperature control system;
- automated control system;
- piping system with shut-off valves and other fittings.

The aims of the study are to discuss the results of the analysis of approaches to designing a prototype of the mobile space test complex "Metamorphosis" and to conduct the necessary tests of original equipment for validation, verification, qualification and approval of the product in accordance with the requirements of ESA ECSS, in particular the ECSS-E-ST-10C standard.

2. STRUCTURE OF VACUUM EQUIPMENT TO SIMULATE OUTER SPACE

Comprehensive experimental testing of parts, apparatus and instruments is of paramount importance in aviation and space technology. That is why the "high-altitude" tests are important when artificial atmospheric conditions are created in ground-based equipment [7]–[10].

High-altitude testing systems or space simulation equipment is used to reproduce the conditions of the high atmosphere and outer space that are different from ground-based conditions in terms of temperature, pressure and composition of residual gases. This equipment, according to the degree of vacuum created, can be divided into systems that reproduce conditions in the high atmosphere with relatively low vacuum and into outer space simulators where an ultra-high vacuum must be supported.

Table 1. Altitude, Temperature, Pressure and Density Correlation

Altitude, km	Temperature, ºC	Barometric pressure, mm Hg	Density, kg/m3
1	8.5	674.12	1.1117
2	1.99	596.28	1.0066
3	- 4.51	525.98	0.9094
4	-11.02	462.46	$8.1942*10^{-1}$
5	-17.52	405.37	$7.3654*10^{-1}$
10	-50.00	198.70	$4.1357*10^{-1}$
11	-56.49	170.19	$3.6485*10^{-1}$
12	-56.49	145.44	$3.1180*10^{-1}$
15	-56.49	90.810	$1.9467*10^{-1}$
18	-56.49	56.719	$1.2159*10^{-1}$
20	-56.49	41.455	$8.8870*10^{-2}$
22	-56.49	30.305	$6.4966\text{-}10^{-2}$
25	-56.49	18.948	$4.0621\text{-}10^{-2}$
26	-53.75	16.219	$3.4336\text{-}10^{-2}$
30	-42.80	8.8777	$1.7901*10^{-2}$
40	-15.49	2.2191	$4.0003*10^{-3}$
50	0.85	$6.3441*10^{-1}$	$1.0754*10^{-3}$
100	-63.93	$2.4310\text{-}\ 10^{-4}$	$5.3993\ 10^{-7}$
150	706.90	$3.8428*10^{-6}$	$1.7682*10^{-9}$
I 200	953.61	$1.0226*10^{-6}$	$3.6109*10^{-10}$
250	1029.6	$3.2604*10^{-7}$	$1.0270*10^{-10}$
300	1084.8	$1.1956*10^{-7}$	$3.3521\ *10^{-11}$
350	—	$5.04*10^{-8}$	—
400	—	$2.37*10^{-8}$	—
450	—	$1.24*10^{-4}$	—
500	—	$7.07\ *10^{-9}$	—

As can be seen from the table above, at a distance of 500 km from the surface of the earth, the pressure is ~$7*10^{-9}$ mm Hg, as this distance increases, the pressure decreases even more. High-altitude systems of the first group are closed refrigerated chambers, the configuration of which depends on the nature of the tested objects. Such cameras range in size from a few litres to several thousand cubic meters.

As can be seen from the table, the temperature in the stratosphere at an altitude of 11 to 25 km is unchanged (- 56.5 °C). In higher layers of the atmosphere, there are zones of high and low temperatures. Vacuum pumps connected to the vacuum chamber, as a matter of priority, must support the required working pressure by pumping out air that penetrates through leaky connections or is released in the working process. In addition, the installed pumping system must provide a specified "speed up", i.e., in order to create "speed-up" corresponding to the take-off speed of a real aircraft, it is necessary to install vacuum equipment with high pump speeds to quickly create the necessary vacuum.

The components of vacuum space simulators include such elements:

- vacuum chamber [6], [7];
- vacuum pump system [11];
- vacuum measuring and/or control system [12]–[16];
- temperature control system [18];
- automated control system;
- piping system with, shut-off valves and other fittings.

Vacuum chamber. The chamber is the heart of the vacuum system [17], creating a safe barrier between the external environment and internal processes [9]. Vacuum chambers are built in a huge variety of shapes and sizes, limited only by application, imagination, and engineering consideration. The more 'standard' vacuum chamber shapes include: box, sphere, cylinder, D-shape, and bell jar. Additional components used in vacuum chamber construction include: endplates, feedthrough collars, and service wells.

Metal bell jar is used when frequent opening of the chamber is required and is equipped with an automatic lifting system. The cylindrical chamber is designed as a cylinder with 1–2 hinged or sliding doors. The box chamber has one swing door for easy access. A vertical chamber with removable cover is used to load volumetric objects, which are held vertically for the duration of the test. The D-shape chamber (when viewed from above) combines the thin wall of the cylindrical chamber with the volume and large, o-ring sealed access door of the box chamber making it appropriate for high vacuum applications.

All types of vacuum chambers (Fig. 1) have a similar design. The door has an inspection window and is hermetically sealed with a gasket. Heating elements, halogen lamps and a cooling system are located inside the chamber. The walls are coated with polymer compounds to protect against damage during testing.

The most commonly used material for high vacuum and UHV chambers is a 300-series stainless steel [11], [12] – most frequently 304L (carbon content >0.03 %), which is available in sheet, tube, bar, plate, and forged forms. This steel and others, such as 316L, have desirable vacuum chamber properties: mechanically strong, machinable, weldable; magnetic permeability close to 1; resistance to atmospheric corrosion; a high polish; and can be effectively outgassed by baking. For large space simulation chambers operating in the HV Torr range, mild steel is a cost-effective option. However, its magnetic, corrosion resistance, and out-gassing properties make it generally unacceptable.

When designing chambers, the strength calculations are always carried out, by using specialized programs.

Fig. 1. Vacuum chamber geometries [1].

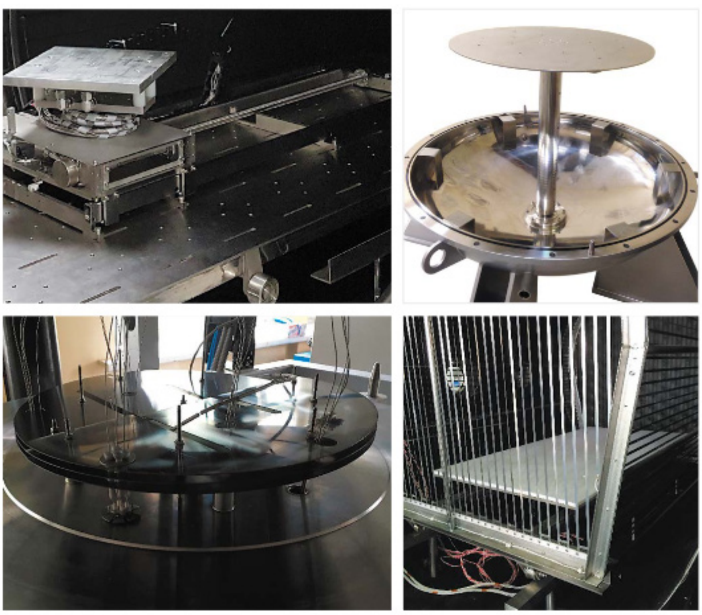

Fig. 2. In-chamber rigging [3].

In-chamber rigging (Fig. 2) is a device designed to fix test objects in place. It has a movable mechanism, so it allows you to move the product during processing and tilt it to the desired angle. It is also possible to rotate the table together with the product.

Vacuum pumps. Cryogenic, turbomolecular, mechanical pumps can be used (Fig. 3).

Vacuum sensors. Vacuum sensors are designed to control the vacuum inside the pressure chamber and support the required level of vacuum.

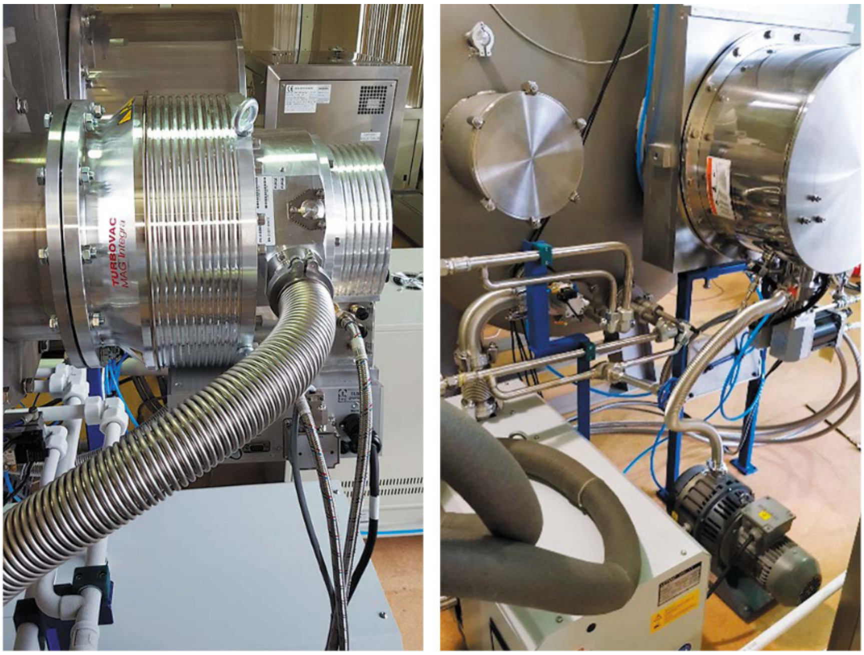

Fig. 3. Vacuum pumps [3].

Thermal control system. It is required to replicate extreme environmental conditions and temperature fluctuations, as well as the stability of equipment that is intended for further use in outer space. The system includes cooling screens and thermal plates, circulation thermostat, cryogenic piping, cryogenic separators, flow heaters, etc.

3. DETERMINATION OF THE STRUCTURAL APPEARANCE OF THE VACUUM CHAMBER

It can be concluded that the design of the vacuum chamber is of great importance in the operation of the entire test system. The correct definition of the design appearance not only determines the ease of use of the test bench, but also has a significant impact on its operational capabilities and characteristics. All of the vacuum chamber geometric shapes are the shapes with the greatest strength and stability in terms of resistance to the external compression force created by atmospheric pressure when pumping out air during the period of the vacuum chamber by purpose (when vacuuming). All forms, such as ball, cone, rectangular parallelepiped, are used in vacuum technology. However, it is necessary to decide what form of the vacuum chamber will be used to make the prototype.

The most resistant to external pressure is the shape of the ball. However, the manufacture of a spherical vacuum chamber is very laborious due to the need to manufacture a large number of segments and a large amount of welding and related work, and, therefore, it is expensive.

Conical vacuum chambers were also manufactured and used in practice. The base of the cone was arranged in the floor of the workshop, where the integration and testing of spacecraft took place, on the base, where there were rail tracks that had a gap in the vacuum seal. Removal and closure of the roof of the cone was carried out using a workshop overhead crane. Exactly for this reason, it was decided not to use a conical vacuum chamber for a mobile vacuum testing system.

Vacuum chamber in the form of a rectangular parallelepiped or similar shape with flat walls has the greatest coefficient of useful use of the volume of such a vacuum chamber – 0.85–0.9. Also, the advantage of chambers of this shape is great convenience in working with the test object. The main disadvantage of vacuum chambers in the form of a rectangular parallelepiped or their chambers with flat walls is a high metal content associated with the need to create a significant force set that keeps the wall of the vacuum chamber from external overpressure.

Since for intermodal transportation the mass of the test equipment plays an important role, it was decided to use a cylindrical vacuum chamber.

It is known that in world practice, there are two main structural types of orientation of cylindrical vacuum chambers: vertical and horizontal. The main advantage of the vertical type vacuum chamber is the lower material consumption and labour intensity associated with the absence of the need for complex supports, amplification systems, concentration and transfer of loads, since the chamber rests on the end part of the body around the entire perimeter. On the other hand, installation of pumping means on the upper (removable) cover significantly increases the lifting force and loan the cover discharge mechanism. Installing pumping devices on the lower bottom increases the risk of damage to the vacuum pumping system due to the penetration of foreign objects and particles. The analysis of the structures showed that the main negative feature of the vacuum chambers with horizontal design type is the presence of load concentrators in the form of a support system and the presence of oppositely polarized deformations of the cylindrical part of the vacuum chamber. Also, small horizontal chambers have an advantage over vertical ones in terms of maintenance, preparation for testing and dismantling of the test object after testing. On the basis of the analysis, it was decided to adopt a cylindrical vacuum chamber of a horizontal structural type for equipping the prototype.

4. DETERMINATION AND CALCULATION OF GEOMETRIC CHARACTERISTICS OF THE PROTOTYPE VACUUM CHAMBER

The main factor that determines the geometric characteristics of the space environmental simulator vacuum chamber is the maximum overall dimensions of the test object. On the other hand, as the mobile space testing vacuum system will be housed in a vehicle, the maximum overall dimensions are determined by the permitted dimensions of this vehicle (Fig. 4). In this case, the structurally maximum possible diameter of the vacuum chamber lies in the range of 1800–2400 mm, and the minimum dimensions are related to the sample size and its should be 360–400 mm.

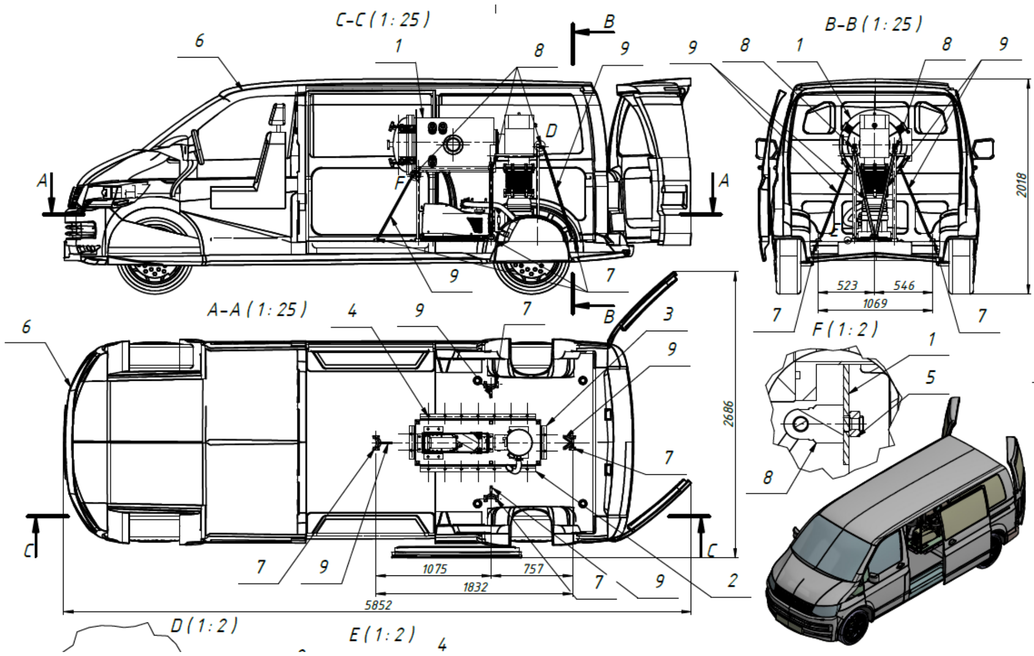

Fig. 4. Vacuum system “METAMORPHOSIS” is housed in a vehicle.

4.1 Determination of the Diameter and Length of the Cylindrical Part of the Vacuum Chamber

The diameter of the vacuum chamber [19] can be determined as the sum of the characteristic diameters (Fig. 5):

$$D = D_s + 2L_{cs} + 2h_{cs} + 2h_m, \quad (1)$$

where

D – the diameter of the vacuum chamber, mm;

D_s – the characteristic diameter of the test object, mm. $D_{s\ min}$=141,4mm; $D_{s\ nom}$= 148mm; $D_{s\ max}$=354mm;

L_{cs} – the distance from the test object to the cryogenic shrouds, mm;

h_{cs} – the thickness of cryogenic shrouds, mm;

h_m – the distance from the cryogenic shrouds to the body of the vacuum chamber, mm.

The length of the cylindrical part of the vacuum chamber can be determined as the sum of the characteristic length:

$$L = L_s + 2L_{cs} + 2h_{cs} + 2h_m, \quad (2)$$

where

L – the length of the vacuum chamber, mm;

L_s – the characteristic length of the test object, mm. $L_{s\ min}$=248mm; $L_{s\ nom}$=360mm; $L_{s\ max}$=472mm.

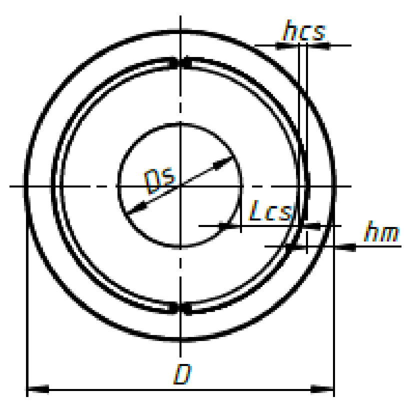

Fig. 5. Determination of vacuum chamber diameter size.

The main requirement of the standards [20], [21] for space environmental simulators is sufficient reliability of simulating real operating conditions, i.e., factors of outer space: 1) high vacuum; 2) zero reflection coefficient of electromagnetic radiation; 3) absence of convection and heat transfer through the thermal conductivity of the environment. High vacuum is understood as a state of gas, in which collisions of gas molecules with the walls of the vessel prevail over the collision of gas molecules with each other. High vacuum is understood as a state of gas, in which collisions of gas molecules with the walls of the vessel prevail over the collision of gas molecules with each other.

According to the standards [20], [21], the pressure in the vacuum chamber should not exceed 10^{-5} Torr and in any case ensure the achievement of the molecular regime of gas flow in the vacuum chamber, characteristic of the space environment.

The criterion for determining the nature of the movement and interaction of gas molecules is the Knudsen criterion:

$$K_n = L_m / D_s, \tag{3}$$

where

L_m – the mean free path of gas molecules;

D_s – the characteristic size of the vacuum vessel.

$$L_m = \frac{1}{\pi d^2 n \sqrt{2}}, \tag{4}$$

where

d – the effective diameter of gas molecule, m;

n – the number of molecules (concentration) per unit volume.

If we use the Botzmann equation

$$p \cdot V = n \cdot k \cdot T, \tag{5}$$

where

P – the gas pressure, Pa. According to the standards [20], [21], the minimum pressure in the vacuum chamber is 10^{-5}Torr and for air pressure it will be 1.33 10^{-3} Pa;

k is the Boltzmann constant, 1.38 10^{-23}J/K;

T is the gas temperature, K. The temperature of the atmosphere in the test bench chamber is 20^0 C or 293^0 K.

The expression for determination of the mean free path of an ideal gas molecule (4) can be rewritten:

$$L_m = \frac{kT}{\pi d^2 p \sqrt{2}}. \tag{6}$$

Since the initial atmosphere in the vacuum chamber of the test complex is air – the largest effective molecular diameter of a diatomic structure (N_2 and O_2) is about 3.5 10^{-10}m.

At the result the length of the average free path of an air molecule as an ideal gas (6) will be:

$$L_m = (1.38 \cdot 10^{-23} \cdot 293)/(3.14 \cdot (3.5 \cdot 10^{-10})^2 \cdot 1.33 \cdot 10^{-3} \cdot 1{,}414) = 5.6m. \tag{7}$$

The estimate of the free path for an ideal gas can be taken as the maximum. Turning to a real gas, it is necessary to introduce correction for the non-ideal nature of the gas. First, with increasing temperature, the vibrational motions of molecules increase, which is practically demonstrated as an increase in the free path and is expressed as Sutherland correction for mean free path:

$$L_m = \frac{kT}{\left(1+\frac{C}{T}\right)\pi d^2 p \sqrt{2}}, \tag{8}$$

where

C is the Sutherland constant. The Sutherland constant value for air is 120.

Then taking into account the correction, the free path for air at a temperature of 293 K and a pressure of 10^{-5} Torr will be 4.74 m.

In a real gas, gas molecules do not behave like rigid spheres, but rather attract each other at large distances and repel each other at smaller distances, which can be described using the Lennard-Jones potential where the radius of the molecule is rm=21/6σ~1.122 σ. Then the value of the free path of an air molecule at a pressure of 10^{-5} Torr and a temperature of 293 K will be 0.93 m.

This estimate of the mean free path can be taken as the most probable in assessing the molecular regime of gas flow.

There is also a way to estimate the bridged path length from the assumption that the real gas is pseido-viscous. In this case, the mean free path of a molecule for a real gas is determined as follows:

$$L_m = \frac{\mu}{P}\sqrt{\frac{\pi RT}{2M}}, \tag{9}$$

where

μ – the viscosity, Pa s (μ=18.5 μPa s);
P – the pressure, Pa (1.33 10^{-3} Pa);
R – the universal gas constant, 8.31446261815324m^3PaK^1 mol^{-1};
T – the temperature, K (T=293K);
M – the molecular mass g/mol.

Then, when substituted in (9) we obtain L_m=0.27 m. This estimate can be discarded provided that a known molecular gas flow regime is ensured. Thus, it was decided to accept for the vacuum calculation the main estimate of the free path of a gas molecule in the vacuum chamber of the space environmental simulator at 0.93m. From expression (8), taking into account the correction for the Lennard-Jones potential, we obtain a value of 0.186 m. Based on the obtained value of the mean free path and expression (3), let us determine the limitations of the overall dimensions of the vacuum chamber according to the Knudsen criterion to ensure the molecular regime of gas flow in the chamber for the main mode at maximum pressure (1 10^{-5} Torr):

$$D_s=L_m/K_n=0.93/10=0.093. \tag{10}$$

Thus, the characteristic size, i.e., the length of the shortest distance from the wall of the vacuum vessel to the test object should not exceed 0.093 m.

According to experimental data during thermal cycling with imitation of the shadow side of a spacecraft in a space environmental simulation facility with liquid nitrogen cryogenic shrouds with a temperature of 90–95 °K, the temperature in the region close to the surface of the space of the spacecraft is close to 150 °K.

A verification calculation needs to be made to account for the effect of viscosity at low temperatures. For example, when the temperature of the atmosphere in the local volume of the vacuum chamber decreases from 293 °K to 150 °K, taking into account the value of the Sutherland coefficient (for air 120) and initial viscosity μ_0=18.5 μPa s, the viscosity of air at a temperature of 150 °K will be 14.1 μPa s, and, the free path of a molecule in accordance with (9) will be 0.08715 m.

Since the effect of a decrease in temperature on the mean free path of a molecule in a viscous is very significant, we will take this limitation into account. Then the characteristic size of the vacuum chamber should not exceed 0.0872 m.

Substituting into (1) the obtained values of the characteristic diameter of the test object and the double distance from the test object to the cryogenic shroud (7–9), taking the thickness of the cryogenic shields as 10 mm and the distance from the cryogenic shroud to the body of the vacuum chamber as 40 mm, we obtain the calculated diameters of the vacuum chamber:

$$D_{min} = 141.4 + 2 \cdot 87.2 + 2 \cdot 10 + 2 \cdot 40 = 415.8$$
$$D_{nom} = 148 + 2 \cdot 87.2 + 2 \cdot 10 + 2 \cdot 40 = 422.4$$
$$D_{max} = 354 + 2 \cdot 87.2 + 2 \cdot 10 + 2 \cdot 40 = 628.4$$

Taking into account the technological tolerances, we initially take the calculated inner diameter of the prototype vacuum chamber:

$D_{min} = 400^{+10}$ mm;
$D_{nom} = 500^{+10}$ mm;
$D_{max} = 800^{+10}$ mm.

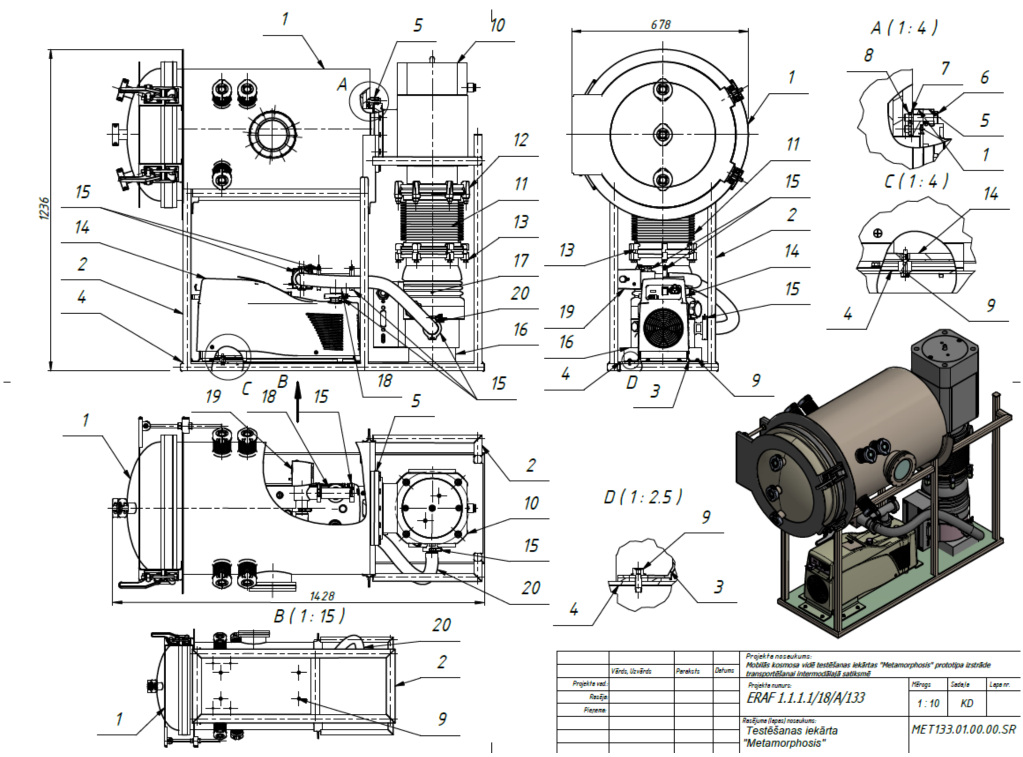

Fig. 6. Drawing of the vacuum system.

Substituting into (2) the obtained values of the characteristic length, we obtain the calculated total length of the cylindrical part of the vacuum chamber (Fig. 6):

- for a diameter of 400 mm, the length of the cylindrical part is taken as 650 mm;
- for a diameter of 500 mm, the length of the cylindrical part is taken as 780 mm.

4.2 Strength and Stability Calculations of Vacuum Chambers [19]

General provisions. The main shape of chamber is cylindrical (Fig. 7). The main structural material of the chamber is austenitic stainless steel grade AISI 304, which is suitable for use at a temperature of liquid nitrogen (70–95 °K / -203.15C – -178.15 °C).

The use of carbon steels is allowed only for external structures of chamber supports, connected with the vacuum chamber wall through the sheets of austenitic steel.

While the manufacturing of the chamber, joint processing of parts from carbon and austenitic steel is not allowed (only assembly is allowed) in order to prevent particles of carbon steel falling onto the austenitic steel part surface and further formation of corrosion sections of weakened material.

After the manufacture of the chamber, anticorrosion treatment of the outer surfaces of the chamber must be carried out by painting with paint based on impact-resistant and elastic epoxy resin (to ensure coating resistance to temperature deformations and resistance to moisture condensation during accelerated heating of cryogenic shrouds).

The vacuum chamber and its supports must be carefully grounded to reduce the corrosion effect during the formation of galvanic pairs.

Calculation has been made in accordance with ISO 16528-1:2007 and ISO 16528-2:2007 [20], [21] and includes: strength calculation for cylindrical shell, elliptical cover, saddle support, flat bottom and reinforcing rib of the flat bottom. Calculated parameters and calculation results are given in Tables 2–4.

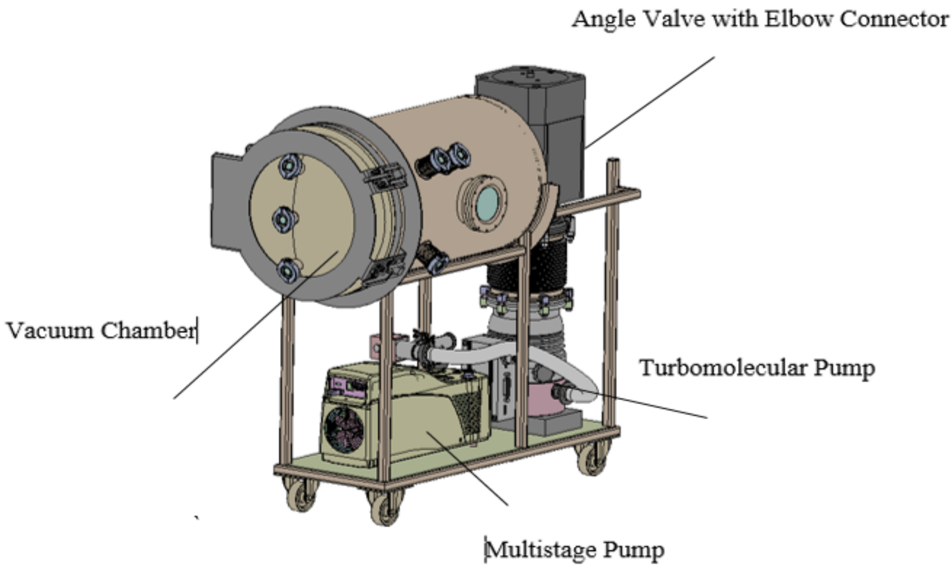

Fig. 7. Vacuum system "METAMORPHOSIS" for outer space simulating.

Table 2. The Initial Data for Calculations

Main part	Material	Diameter, mm	Thickness, mm	Length (height), mm	Total increment, (mm)	Weld Strength Factor
The flat bottom	AISI-304	800	5	5	0.5	0.9
The cylindrical shell	AISI-304	800	5	1300	0.5	0.9
The elliptical cover	AISI-304	800	5	268	0.5	0.9

Table 3. Operating Conditions

Part	Design temperature, °C	Design pressure, MPa	Permissible stresses, MPa	Estimated thickness with increments, mm	Permissible pressure, MPa	Strength condition
The flat bottom	30	(-0,1000)	149	9.457	0.1097	Satisfied
The cylindrical shell	30	(-0,1000)	149	3.849	0.2082	Satisfied
The elliptical cover	20	(-0,1000)	150	2.137	0.6911	Satisfied

Table 4. Test Conditions

Part	Design pressure, MPa	Permissible stresses, MPa	Estimated thickness with increments, mm	Permissible pressure, MPa	Strength condi-tion
The flat bottom	0	230	0.5	0.1693	Satisfied
The cylindrical shell	0	230	0.5	2.316	Satisfied
The elliptical cover	0	230	0.5	2.322	Satisfied

After strength and stability calculation under test and operating conditions, verification calculation must be carried out (Fig. 8).

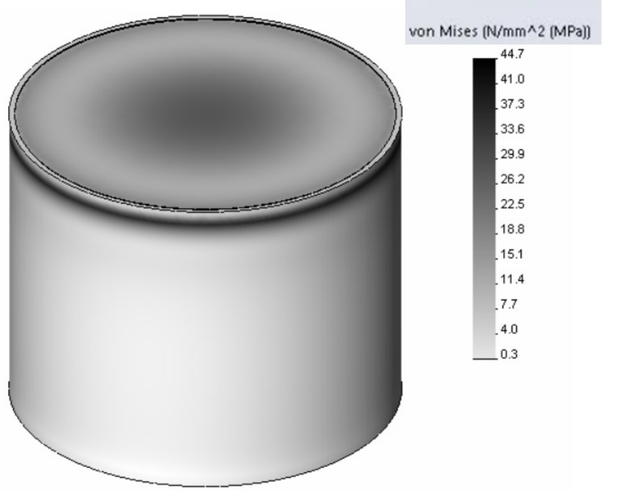

Fig. 8. Tense state in the chamber.

5. RESULTS AND DISCUSSION

There are different types of space simulation chambers, but all of them serve as a test environment for spacecraft, their subsystems, assembly components parts and materials.

For intermodal transportation, it was decided to use a cylindrical vacuum chamber with a horizontal structural type, because the mass of the test equipment, in this case, is minimal.

In the article, it has been discussed how to determine the diameter and length dimensions of the vacuum chamber and the dimensions for the prototype to be selected.

There are two types of space environment simulations systems: solar simulation chambers and thermal vacuum chambers – with solar simulator and without it. The basic systems that compose the space simulation chambers are: structure of the vacuum chamber, vacuum pump system, vacuum measuring and/or control system, temperature control system, automated control system, piping system with, shut-off valves and other fittings. The space simulation chambers have several vacuum pumps.

The function of the pumps is to produce a required vacuum level in a given time, conserving such a level during all test process. By controlling the temperature in vacuum chamber, it is possible to produce high and low temperatures, but in the space simulation system it is not necessary to duplicate exactly the environment of the outer space. However, it is necessary to duplicate the environment actions on the materials, components and spacecraft system and back reactions in all these parts.

The vacuum system "METAMORPHOSIS" is designed and manufactured to perform the necessary tests of the original equipment for product validation, verification, qualification and approval according to the ESA ECSS requirements – specifically the ECSS-E-ST-10C standard. Together, this gives a huge impetus in the European space industry.

ACKNOWLEDGEMENTS

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STUDY OF THE PERFORMANCE OF A PHOTOVOLTAIC SOLAR PANEL BY USING A NANOFLUID AS A COOLER

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In this paper, we study by numerical simulation, the cooling of a solar photovoltaic panel using a nanofluid as a cooler. The solar panel is subjected to a hot temperature that characterises the climate of the city of Bechar located in southwestern Algeria. The nanofluid (Al2O3-water) is introduced in the cavity with a constant horizontal speed and subjected to the ambient (cold) temperature. The equations governing the hydrodynamics of the flow and the heat transfer are described by the Navier-Stockes and energy equations. The finite element method is used to solve the system of partial differential equations (PDEs) based on the Galerkin method. We consider the effect of solid volume fraction and form factor for different values of Reynolds number on the results in the form of isotherms, streamlines, temperature, velocity, average Nusselt numbers and solar panel efficiency.

Keywords: *Finite element method, forced convection, nanofluid, photovoltaic solar panel.*

1. INTRODUCTION

Global warming, rising fuel oil prices and other environmental factors in today's world are prompting energy sector organisations to develop green energy technologies for use in commercial and residential markets. One of these technologies was invented in 1894 by regions with a hot climate such as the region of Bechar located in the southwest of Algeria.

The surface temperatures of photovoltaic panels increase due to the low yield of solar energy in electricity, because not all the energy absorbed by the photovoltaic cells can be converted into electrical energy. To satisfy the law of conservation of energy, the remaining solar energy must be converted into heat. The efficiency of photovoltaic cells is further reduced when installed in environments with hot climates, as the heat dissipation of the panels is reduced. Therefore, it is relevant to develop PV cell cooling methods to increase the output efficiency. The research [2] found that poorly ventilated PV panels in high ambient temperature environments could reach temperatures above 90 °C. These conditions are not only dangerous, but also reduce the efficiency and life of the panels. To date, active and passive methods of cooling photovoltaic panels have been studied and analysed. The authors in [3] studied an active cooling system for PV panels, in which the PV panels were cooled by forced convection, air being the coolant. This system allowed an increase in electrical efficiency of 4 to 5%.

Researchers [4] studied cooling combined photovoltaic-thermal solar panel by using water. This was accomplished by numerically solving the EDP system by the finite element method. The increase in the electrical efficiency of the panel at different operating temperatures was calculated from the thermal coefficient of the PV cells. The paper [5] presents the effect of nanofluids as a coolant in a solar photovoltaic panel. The authors have studied the effect of temperature on solar panels installed in the region of India where the temperature can reach 50 °C. The latter directly influences the conversion efficiency of solar energy into electricity. For this reason, they used fluids and nanofluids to cool solar cells. Rubbi et al. [6] reported results that indicated the overall efficacy of the MXene soybean oil-based nanoscale fluids compared to conventional fluids used for the purpose of cooling in the PV/T. Morphological studies carried out by Scanning electron microscopy showed spherical shape nanoparticles of CuO and leaf-shaped Al2O3 in particles with submicron range. In [7], the researchers studied the importance in the choice of coolant materials with base fluids for solar panel applications by plotting I-V and P-V spectrum. As a result, the cooling efficiency of both CuO and Al_2O_3 were found to be 18.2 %, which was higher than the conventional one. The obtained efficiency value was also compared with the reported data. This shows that CuO and Al_2O_3 will be a promising candidate with a base fluid of water for solar panel applications.

Abdallah et al. [8] presented a new experimental study on the use of hydrogel beads with different bed configurations as a cooling accessory under the solar panel. The best results were obtained using three rows of hydrogel beads with fins where the panel temperature dropped approximately 10 °C below the uncooled panel at 1000W/m leading to an increase in electricity production efficiency of 7.2 % compared to the uncooled system. The research [9] examined the increase in performance of the PV panel. The combination of PCM (OM35) and water as a cooling medium was experimentally evaluated. It was determined that the integrated PCM water cooling technology with continuous water supply contributed to the efficient thermal management of the PV panel which, in turn, improved the power output performance compared to cooling with the maximum permissible temperature mechanism.

Moreover, performance parameters such as electrical efficiency, electricity generation, power boost ratio, average temperature reduction, total power output and total energy efficiency are evaluated and reported as the water requirements of the building that can be allowed to pass through the PCM. The research [10] tests the effect of different designs for indoor and outdoor systems and the effect of using salt water in cooling solar panels. It is believed to be among the first experiments to study the use of salt water as a way to remove heat from solar panels in order to reduce the temperature of the PV module. It can be concluded that: Compared with the non-cooled panels, the new proposed internal configuration reduced the panel temperature by (12 °C and 14 °C) at the intensity of 800 W/m2 and 1000 W/m2 of solar radiation. The results showed that salt water can be used as an alternative to pure water because it gives the same performance. Although having the same performance, it is preferable to use salt water due to its availability and high potential for using this system for desalination purposes (future work).

Activated alumina tablets showed a higher spoilage rate at higher salinity. Kabeel and Abdelgaied [11] used quenching to reduce the surface temperature of the PV. On the other hand, inverters were used to reduce reflection loss and increase the rate of solar radiation absorbed by photovoltaic panels, several operating cases were studied. The cooling air coming out of the PV module was injected for two cases into the upgraded solar module to increase the rate of evaporation inside the solar collector, thus improving the freshwater productivity. The use of the air injection system also improved the fresh water production compared to the case without the air injection system. The average overall efficiency of the hybrid system was recorded. Peng et al. [12] studied the effect of solar PV surface temperature on the output performance, in particular, the efficiency was studied. Experimental work was carried out under various irradiation conditions to explore the variance of output voltage, current, output power and efficiency. Next, a cooling test was performed to see how much efficiency improvement could be achieved with the cooling condition. Since the test results showed that solar PV efficiency could have an increased rate of 47% with cooling condition, a cooling system was proposed to prepare a potential system for residential solar PV application. Sahay et al. [13] tested panel cooling system, using smoke flow visualization technology. There was a marked increase in the conversion efficiency due to the cooling of the PV panels. The data were analysed using ANOVA analysis to determine the causal effect of the cooling action. The cooling system was modified. If combined with the solar PV panel design, the cooling was expected to be more effective and thus better conversion efficiency was achieved. Singh et al. [14] developed new hybrid designs for converged collector ducts to a divergent chimney combined with an inlet bell orifice design that improved flow velocity by 71% and reduced the temperature of the PV panel by 8–12 ° C. The increased flow velocity boosted turbine power output by over 200 %. Certainly, the new hybrid solar chimney design added a contribution to the research community in developing a high-efficiency solar chimney design in order to meet future energy requirements. This study reinforces work previously done [4], by using identical PV/T plate and thermal glue properties. However, the study used a thin rectangular tank through which water flew and carried heat away from the panel. It is a cooling tank attached to the back of the panel by an approximate thermal paste of uniform thickness of 0.3 mm over the entire surface area of the tank PV panel user interface. The walls of the tank are approximately 1 mm thick and made of aluminium. Aluminium was chosen as the tank container material, due to its high thermal conductivity that promotes heat transfer across its boundaries, availability, and relatively low cost compared to other conductive metals such as copper.

The objective of this study is to increase the performance of a solar photovoltaic panel installed in an arid region such as the city of Bechar located in south-western Algeria. To achieve this objective, nanofluid is used to cool the solar panel. The configuration used in this study is shown in Fig. 1.

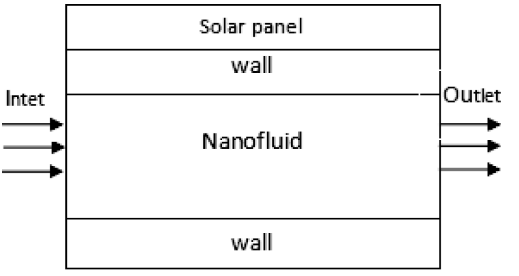


Fig. 1. Physical model

2. MATHEMATICAL FORMULATION

The flow of the nanofluid in the cooling line and the heat transfer between the panel and the nanofluid are governed by the conservation of mass, momentum and energy equations.

To solve the system of partial differential equations (PDEs), we adopt the following simplifying assumptions:

- The physical properties of the nanofluid are constant.
- The flow is laminar and bidimensional.

Using a Cartesian coordinate system and taking into account simplifying assumptions, the system of equations takes the following form:

In nanofluid zone

- Continuity equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

- Equation of momentum following x:

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho_{nf}}\frac{\partial p}{\partial x}+\frac{\mu_{nf}}{\rho_{nf}}\left(\frac{\partial^2 u}{\partial^2 x}+\frac{\partial^2 u}{\partial^2 y}\right) \tag{2}$$

- Equation of momentum following y:

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho_{nf}}\frac{\partial p}{\partial y}+\frac{\mu_{nf}}{\rho_{nf}}\left(\frac{\partial^2 v}{\partial^2 x}+\frac{\partial^2 v}{\partial^2 y}\right) \tag{3}$$

Energy equation:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha_{nf}\left(\frac{\partial^2 T}{\partial^2 x}+\frac{\partial^2 T}{\partial^2 y}\right) \tag{4}$$

In solid zones

$$\frac{\partial^2 T}{\partial^2 x}+\frac{\partial^2 T}{\partial^2 y}=0 \tag{5}$$

With: $\alpha_{nf}=\frac{k_{nf}}{(\rho c_p)_{nf}}$

$$\rho_{nf}=(1-\phi)\rho_f+\phi\rho_s \tag{6}$$

$$\mu_{nf}=\frac{\mu_f}{(1-\phi)^{2.5}} \tag{7}$$

$$k_{nf}=k_f\frac{(2-2\phi)k_f+(1+\phi)k_s}{(2+\phi)k_f+(1-\phi)k_s} \tag{8}$$

$$(\rho c_p)_{nf}=(1-\phi)(\rho c_p)+\phi(\rho c_p)_s \tag{9}$$

Dimensionless equations:

Equations (1) to (5) can be converted to the dimensionless forms by using the following parameters:

$$X = \frac{x}{D},\ Y = \frac{y}{D},\ U = \frac{u}{U_0},\ V = \frac{v}{U_0},$$

$$P = \frac{p}{\rho_{nf} U_0^2},\ \theta = \frac{T - T_c}{T_h - T_c}.$$

Therefore, using the above parameters leads to dimensionless forms of the governing equations as below:

In nanofluid zone

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \quad (10)$$

$$U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = \frac{\partial p}{\partial X} + \frac{1}{\left((1-\phi+\phi R_\rho)(1-\phi)^{2.5}\right)} \frac{1}{Re}\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) \quad (11)$$

$$U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = \frac{\partial p}{\partial y} + \frac{1}{\left((1-\phi+\phi R_\rho)(1-\phi)^{2.5}\right)} \frac{1}{Re}\left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}\right) \quad (12)$$

$$U\frac{\partial \theta}{\partial X} + V\frac{\partial \theta}{\partial Y} = \frac{1}{1-\phi+\phi R_{(\rho C_P)}} \frac{2-2\phi+(1+\phi)R_K}{2+\phi+(1-\phi)R_K} \frac{1}{Pr\,Re}\left(\frac{\partial^2 \theta}{\partial^2 X} + \frac{\partial^2 \theta}{\partial^2 Y}\right) \quad (13)$$

In solid zones

$$\left(\frac{\partial^2 \theta}{\partial^2 X} + \frac{\partial^2 \theta}{\partial^2 Y}\right) = 0 \quad (14)$$

Where:

$$Pr = \frac{\mu_f}{\rho_f \alpha_f},\ Re = \frac{UD\rho_f}{\mu_f},\ R_\rho = \frac{\rho_s}{\rho_f},$$

$$R_k = \frac{k_s}{k_f},\ R_{(\rho C_P)} = \frac{(\rho c_p)_s}{(\rho c_p)_f}.$$

The table below includes the boundary conditions used to solve the above system of equations

Inlet	U=1; V=0; θ=0
Outlet	P=0; Convective flux
Nanofluid-wall interface	U=V=0; Continuity
Wall-solar panel interface	U=V=0; Continuity
Top wall	U=V=0; T=1
Bottom wall	U=V=0, Adiabatic

3. RESULTS AND DISCUSSION

The finite element method is used in our model for discretizing the governing equations ((10) to (13)) along with the boundary conditions. We tested several meshes and opted for a mesh composed of 40000 elements. To describe the structure of the flow in the cavity, we fixed the following parameters of the nanofluid (Al2O3-water):

$Pr=7$, $R_\rho=3.885$, $R_k=60$, $R_{(\rho Cp)}=0.718$.

3.1 Streamlines and Isotherms

Figures 2 to 7 show the streamlines (left) and isotherms (right) for a form factor (A=15.25 and A=61), for different values of the Reynolds number ($5 \leq Re \leq 50$) and varying the nanoparticles volume concentration from 0 % to 10 %. Regardless of the value of Re and φ, the streamlines are in the form of horizontal lines parallel to each other. The intensity of the flow is most intense at the axis of symmetry of the pipe. According to the shape of the isotherms, and by fixing the volume fraction, we notice that the energy dissipation decreases with the increase of the Reynolds number Re, which means that in order to dissipate more heat from the solar collector, low velocities are used at the inlet of the pipe. The addition of the nanoparticles decreases the flow intensity, thus promoting an increase in the heat dissipation of the collector in the nanofluid.

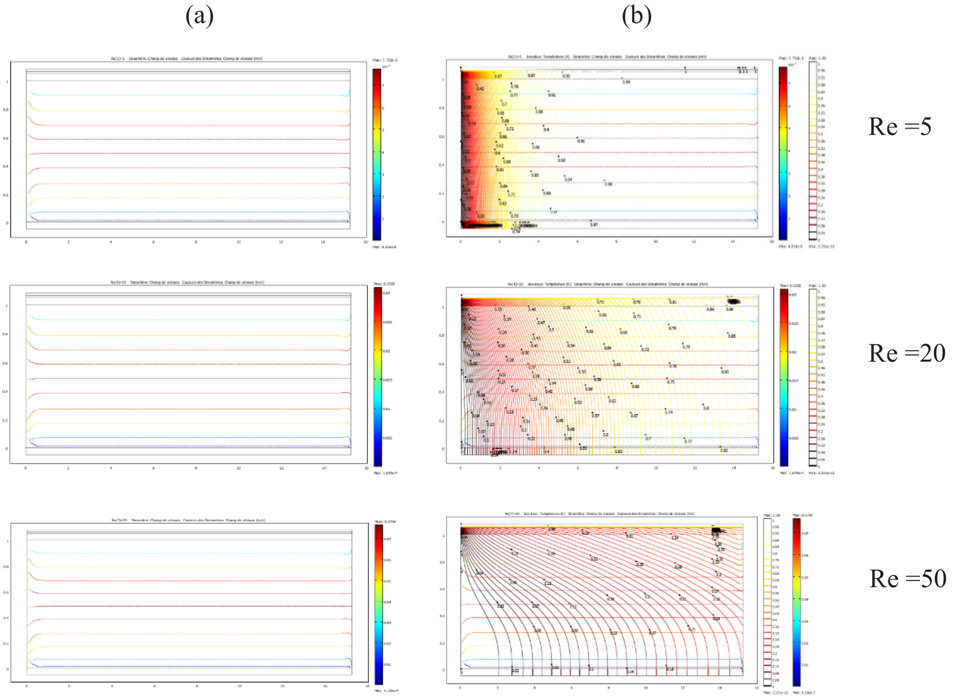


Fig. 2. Streamlines (a) and isotherms (b) for A=15.25 and φ=0.00.

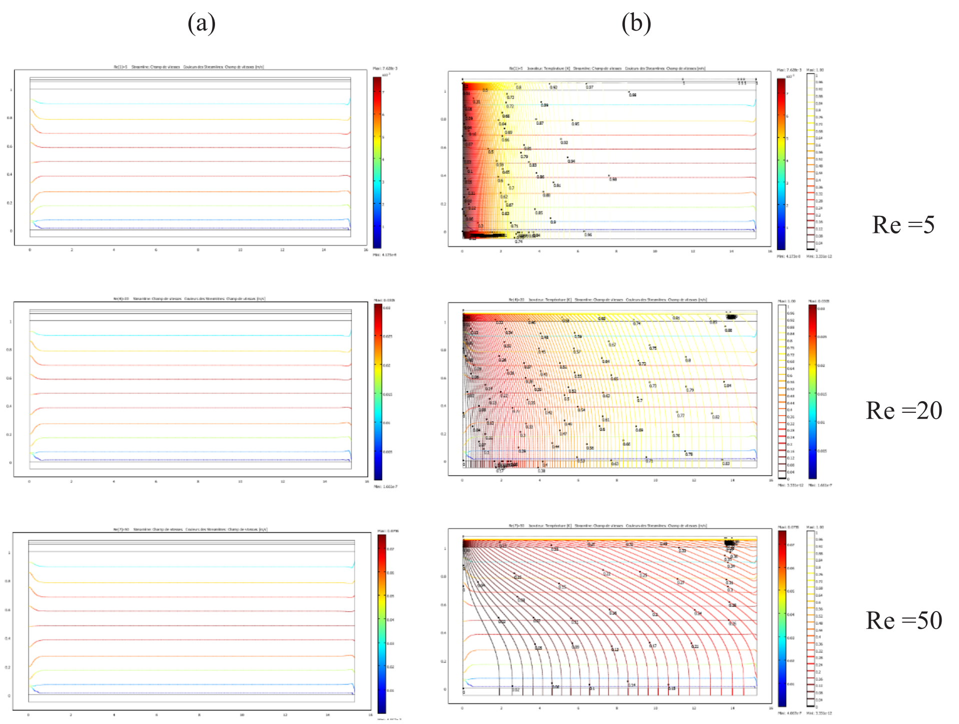
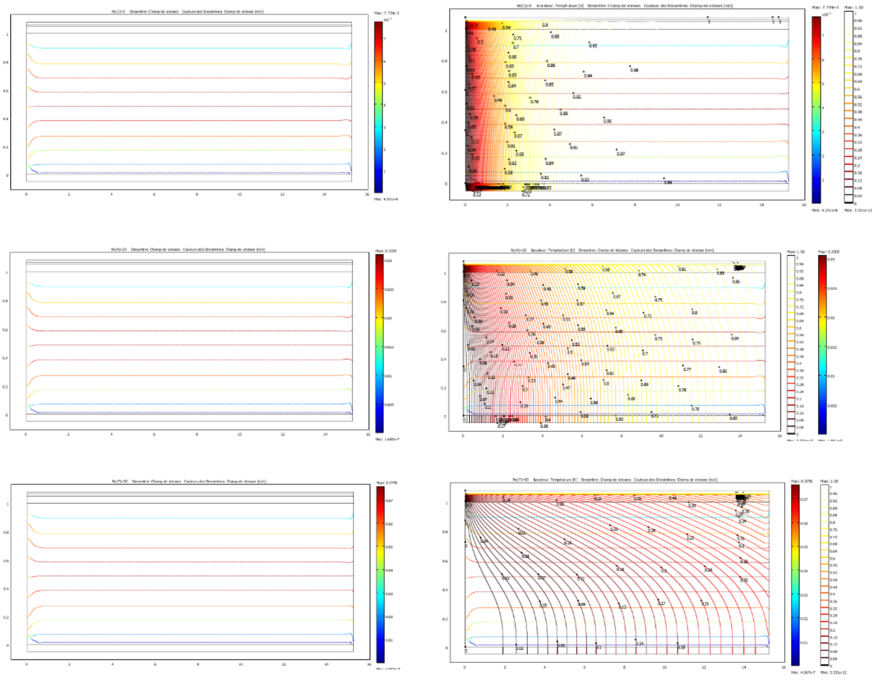


Fig. 3. Streamlines (a) and isotherms (b) for A=15.25 and φ=0.05.

(a) (b)



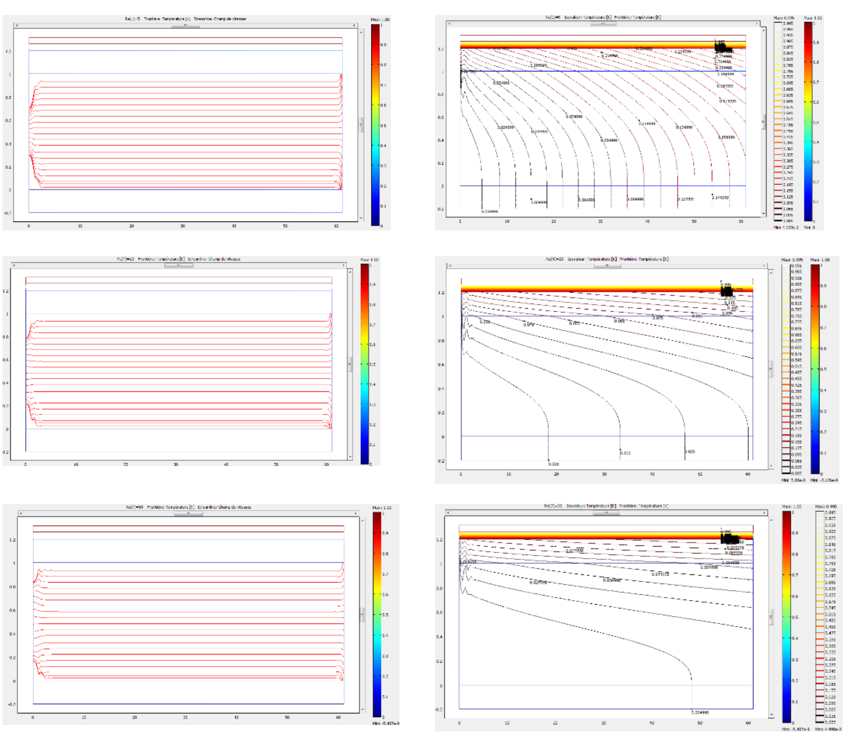
Re =5

Re =20

Re =50

Fig. 4. Streamlines (a) and isotherms (b) for A=15.25 and φ=0.10.

(a) (b)



Re =5

Re =20

Re =50

Fig. 5. Streamlines (a) and isotherms (b) for A=61 and φ=0.00.

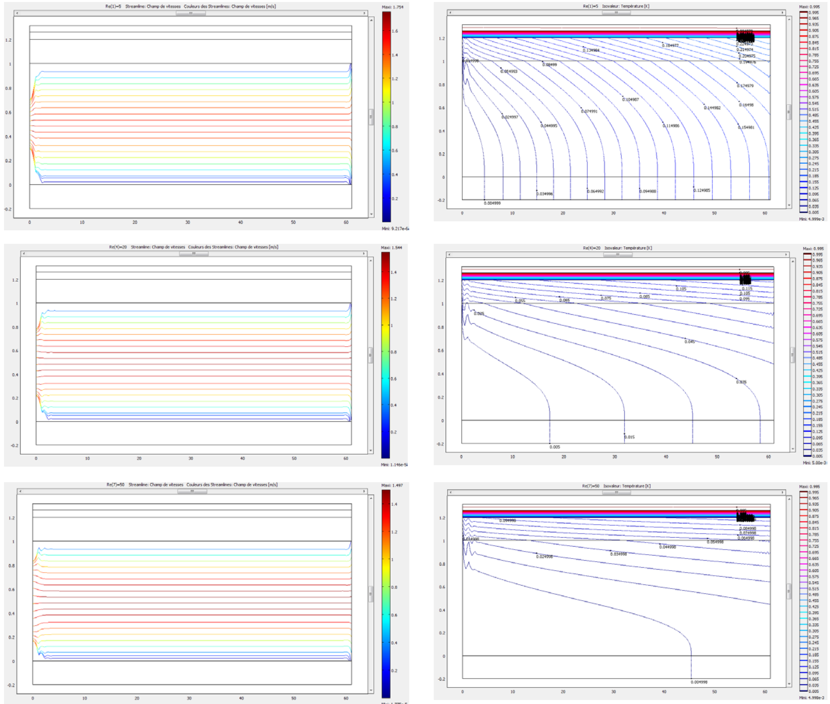


Fig. 6. Streamlines (a) and isotherms (b) for A=61 and j=0.05.

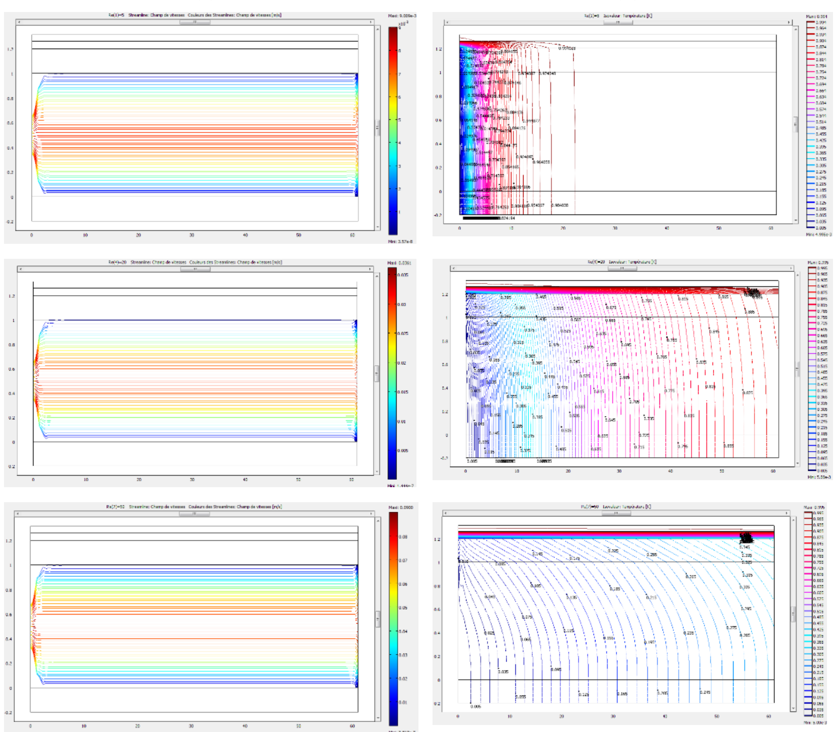


Fig. 7. Streamlines (a) and isotherms (b) for A=61 and φ=0.10.

3.2. Maximum Stream Function

Figure 8 shows the evolution of the maximum current function as a function of the form factor for different values of the volume fraction and Reynolds number.

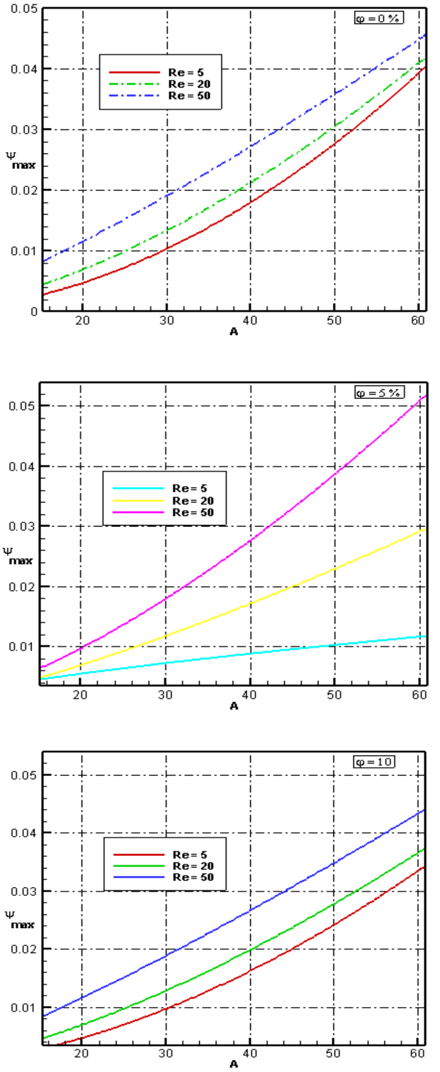


Fig. 8. Stream function vs aspect ratio.

By fixing the value of the form factor (A), the value of the maximum current function increases with increasing Reynolds number.

For a constant volume fraction and whatever the value of the Re number, the maximum current function increases with the increase of the form factor. By fixing the geometrical characteristics of the configuration and for a constant flow rate of the nanofluid, the maximum current function decreases with the increase of the nanoparticles volume fraction.

3.3. Average Velocity

Figure 9 represents the evolution of the average speed U_{avg} as a function of the Reynolds number Re for different values of the form factor A and ϕ varying between 0 % and 10 %.

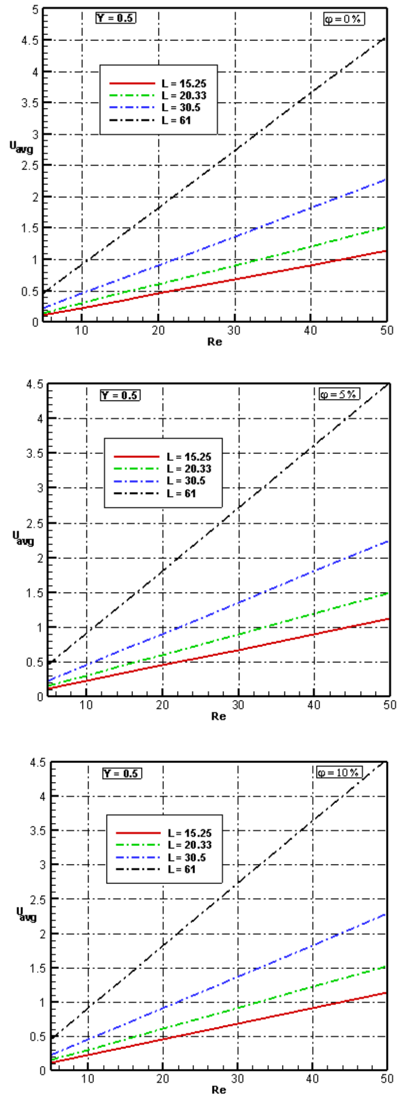


Fig. 9. Average velocity vs Re.

Whatever the value of the aspect ratio A, the flow is more intense at the lower wall of the sensor.

For A = 15.25 and A = 20.33, the intensity is large in the middle of this wall and this intensity shifts to the left for other values of A.

Whatever the value of A and φ the change in the average speed as a function of Re is linear:

$$U_{avr} = a\,\mathrm{Re} + b$$

A		15.25	20.33	30.50	61.00
φ=0.00	a	0.0227	0.0206	0.0455	0.0914
	b	0.0002	0.0927	0.0001	0.0004
φ=0.05	a	0.0225	0.0300	0.0451	0.0905
	b	0.0002	0.0002	0.0001	0.0004
φ=0.10	a	0.0228	0.0304	0.0457	0.0910
	b	0.0002	0.0002	0.0001	0.004

3.4. Temperature Evolution

The curve of Figure 10 represents the evolution of the temperature along the vertical passing through the middle of the pipe for Re = 5 and for different values of φ and A. The temperature increases as it approaches the lower wall of the sensor until a maximum value is reached. This maximum value decreases with the increase of A.

Figure 11 represents the evolution of the temperature along the horizontal passing through the middle of the pipe for Re = 5, A=15.25 and for different values of φ. The temperature increases as it approaches the lower wall of the sensor until a maximum value is reached.

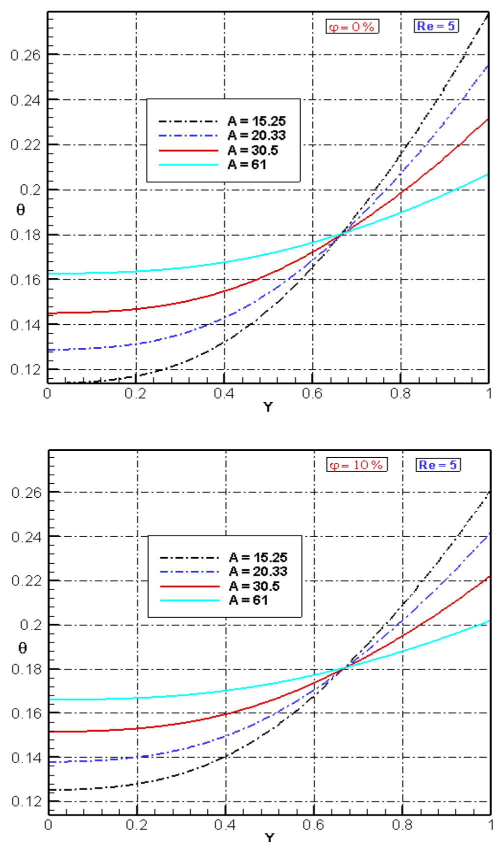


Fig. 10. Temperature evolution vs Y.

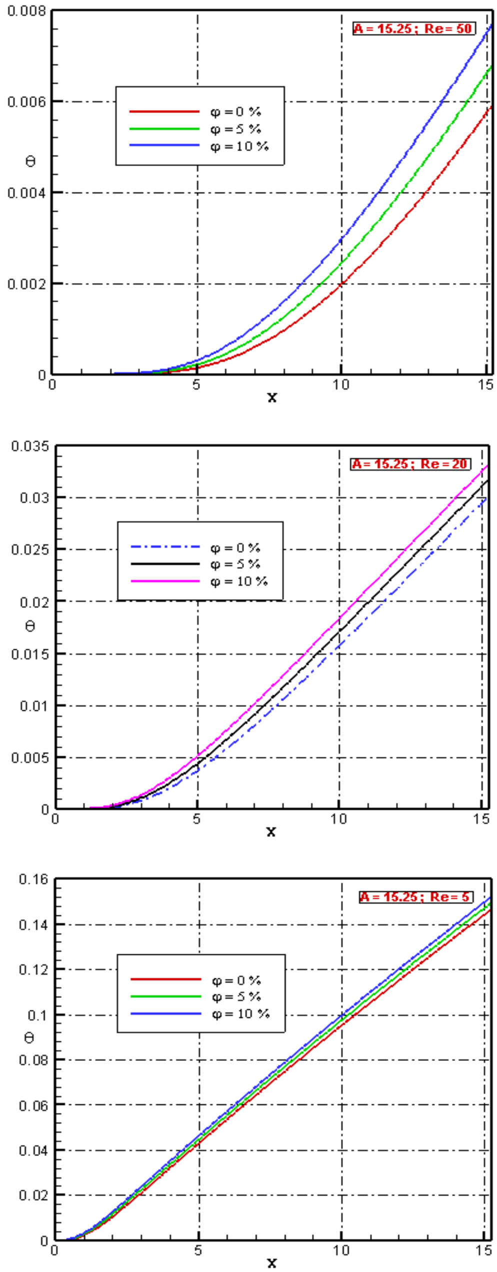


Fig. 11. Temperature evolution vs X.

3.5. Average Nusselt Number

Figure 12 demonstrates the evolution of average Nusselt number with Reynolds number for different values of aspect ratio (15.25 ≤ A ≤ 61) and for the base fluid (φ = 0) and two values of volume concentration.

For a given volume fraction, the Nusselt number increases with increasing form factor and decreases with increasing Nusselt. The cooling is done for a low inlet velocity.

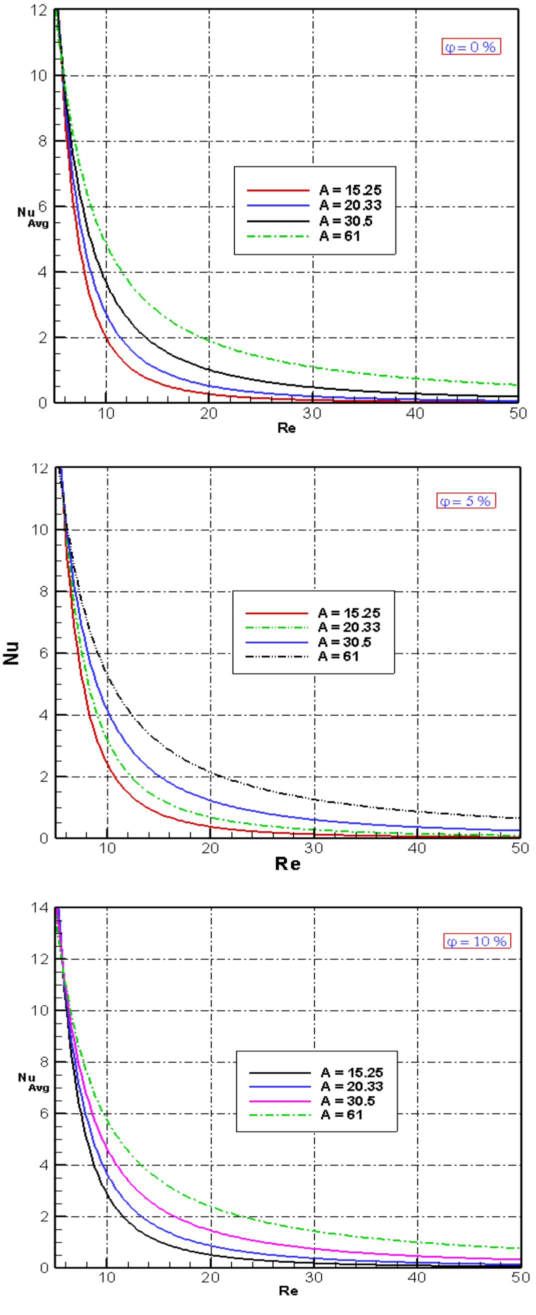


Fig. 12. Average Nusselt vs Re.

3.6. Cell Efficiency

Figure 13 shows the change in the efficiency of the solar cell as a function of Re for three values of volume fraction (ϕ=0; ϕ=0.05 and ϕ=0.10). Whatever the value of A, the efficiency (η) decreases with the increase of Re, the optimal configuration corresponds to A = 30.50.

Whatever the value of the form factor (A), the flow is more intense at the level of the lower wall of the collector. For A = 15.25

and A = 20 the intensity is large in the middle of this wall; this intensity shifts to the left for the other values of A.

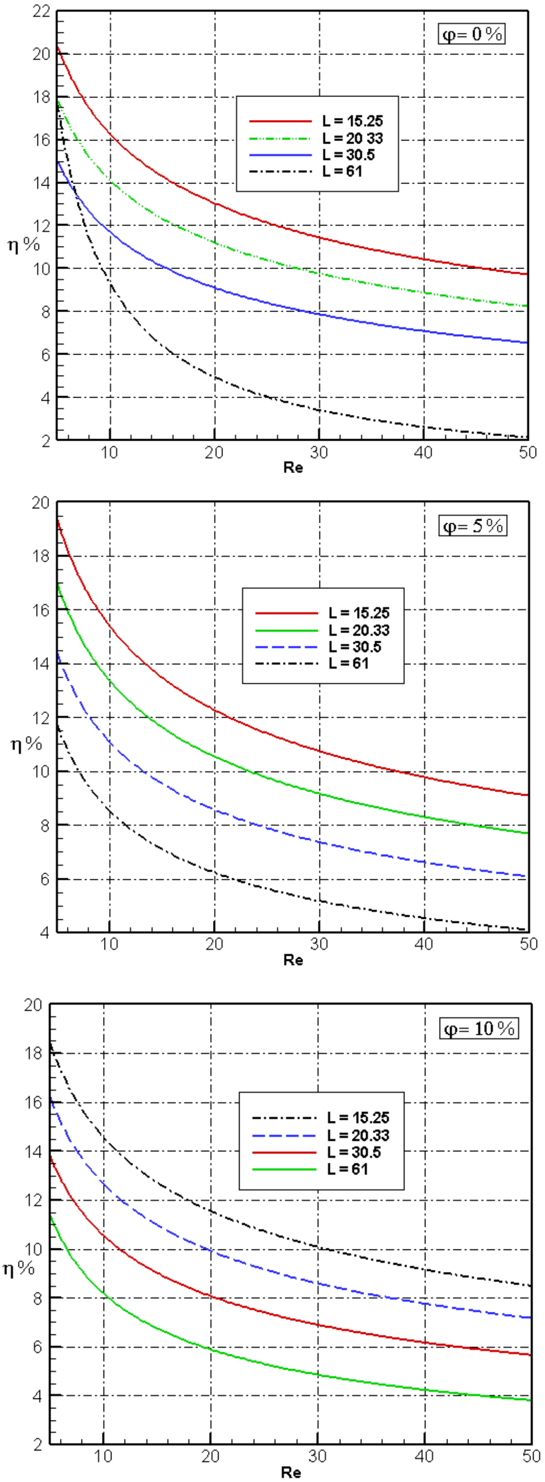


Fig. 13. Cell efficiency evolution.

4. CONCLUSIONS

Solar photovoltaic (PV) panels under extreme weather conditions considerably reduce their operation efficiency. It is envisaged to cool the solar panels by using a nanofluid as a cooler. The main results of this study are as follows:

- the addition of nanoparticles increases the heat exchange rate between the panel and the nanofluid when compared with the base fluid;
- low flow rate increases the exchange rate, which provides good cooling;
- longer pipes increase the efficiency of the solar panel.

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EVALUATION OF HEAT PUMP OPERATION IN A SINGLE-FAMILY HOUSE

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Since decarbonization of the energy sector is among the top priorities in the EU, with ambitious targets of carbon neutrality until 2050, the energy efficiency of the building stock and the use of renewables are those directions, which can bring the most considerable input towards the achievement of these goals. However, it is not always obvious how to efficiently combine different aspects of low energy demand, availability of renewables, part load operation conditions etc.

The results of dynamic IDA ICE simulations highlight that the introduction of renewable low-carbon energy sources should be thoroughly coupled with building energy systems and only their full compatibility can give a high efficiency of the entire energy supply system of the building. Analysing simulation data, it was concluded that for low-energy buildings, heat pumps would not always show higher COP values, compared to buildings with higher energy demand.

Ground source heat pump (GSHP) will not always be more efficient than air source heat pump (ASHP). If the ground/groundwater temperature is lower than 10 °C, for GSHP it will be almost impossible to over-compete ASHP within the same system. While COP with radiators and underfloor heating differs only by 10 %, both for ASHP and GSHP.

Keywords: Cold climate, energy efficiency, heat pump, IDA ICE, single-family house.

1. INTRODUCTION

Achievement of 60 % greenhouse gas (GHG) emissions reductions by 2030 and full decarbonisation by 2050 in the building sector is needed to meet the EU's climate objectives. Unfortunately, Europe is not on track: buildings still account for 40 % of the EU's total energy consumption and 36 % of CO_2 emissions. To reverse the trend, the European Commission has launched the "Renovation Wave", a strategy aiming to upgrade the existing building stock, and has put forward several legislative proposals to improve building energy efficiency and encourage heating fuel switching [1], [2]. Renovation of the existing building stock is inevitably associated with modernization and HVAC systems, with particular attention to the ventilation system [3], [4]. For different typologies of buildings, different retrofitting approaches are required, as an implementation of construction project planning is also important in renovation projects [5]. Study [6] analyses the typology of Latvian unclassified buildings and shows indoor comfort, indoor air quality and achieves a reduction in energy consumption within different retrofitting scenarios.

While [7] showed that the CO_2 concentration in schools often exceeded the maximum measuring capacity of the device – 4000 ppm as the classrooms were not properly ventilated. It is important to highlight that any renovation and energy conservation measures should not compromise the well-being and safety of the building occupants. Most old buildings and all new ones comply with zero-carbon-ready building energy codes. A zero-carbon-ready building is highly energy efficient and either uses renewable energy directly or uses energy supply that will be fully decarbonised by 2050, such as electricity or district heat [8]. The International Energy Agency in the same report confirmed that in buildings, bans on new fossil fuel boilers needed to start being introduced globally in 2025, driving up sales of electric heat pumps.

The Energy Performance of Buildings Directive (EPBD) [9] requires ensuring compliance of all new buildings within the EU countries with nearly zero-energy (NZEB) standards starting from 2021, while all new public buildings had the same requirement already from 2019. Study [10] evaluates possible ventilation solutions for nZEB multi-apartment buildings in three European geoclusters, where strong similarities are found in terms of climate, culture, construction typologies and other factors.

In 2021, the Commission proposed to revise the EPBD to make a step forward from the current NZEB to the zero-emission building (ZEB). A zero-emission building can be defined as a building with very high energy performance, while still required energy is fully covered by energy from renewable sources and without on-site carbon emissions from fossil fuels. The proposed ZEB requirements should apply from 2030 for all new buildings, while for public buildings already from 2027 [11].

NZEB and ZEB building concepts incorporate low energy consumption along with low-temperature requirements, thus empowering the integration of renewable energy sources. The use of heat pumps is efficient and economically beneficial both for NZEB and ZEB. NZEB implementation in Western Europe is hindered by several barriers described in [12], while implementation of the heat pumps requires thorough planning and calculation to achieve maximum techno-economical efficiency and it requires sophisticated assessment of uncertainties regarding system layout, temperature regimes and management strategies. The aim of this paper is to show the performance of the compression heat pump within one building layout but with different energy performance indicators.

Nowadays heat pumps are among the most promising and widely used solutions for heating in residential buildings also in cold climates. Different types of heat pumps are applied for heating, cooling and preparation of DHW purposes. The study [13] discovers the primary energy reduction of up to 30 % using an absorption heat pump connected to a district heating network in a warm and cold climate. The use of heat pumps is also acknowledged by Scandinavian researchers [14]; it was determined that a decentralized low-temperature district heat supply to low-energy buildings areas in Sweden could lead to higher utilization of large-scale heat pumps and excess heat while decreasing system costs and consumption of the electricity used for heating buildings.

The main advantages are low installation cost and efficient operation. Use of heat pumps is also widespread in the United States, where low-GWP refrigerants and non-vapor compression heat pumps are gaining attention to be replacements for current vapor compression heat pumps that rely on HFCs. U.S. regulators emphasise the use of advanced heat pumps solutions, such as heat pump water heaters, cold climate heat pumps, and low-GWP heat pumps making the heat pump market cleaner, more efficient, and more affordable.

In study [15], eight HVAC configurations covered advanced solutions such as heat pump water heaters, ground source heat pumps, cold climate heat pumps, and membrane heat pumps, and they were compared with traditional vapor compression heat pumps and gas furnaces. The operating cost assessment revealed that a gas furnace should only be used in cold places where the electricity price per kWh to gas price ratio is higher than 3. Heat pump water heaters should be recommended to places where the electricity price to gas price ratio is below 3. While the study from Norway [16] reports that even in cold climates air-water heat pumps are still dominating the market; however, the COP of ASHPs decreases significantly at lower temperatures. Market leaders qualify their HPs to perform with a COP value in the range of 4–5, while with output water at 35 °C, COP can decrease from 4.6 to 2.5 when the outdoor air temperature decreases from + 7 °C to -15 °C. For DHW purposes, when temperature requirements are at least 65 °C, the COP decreases almost to 1.3 for an outdoor air temperature of -15 °C [17]. ASHP is compared with GSHP in study [16], where ASHP has lower COP (2.0–2.5) versus GSHP (3.5–5) lower life span of 12–15 years versus 20 years, but only a little faster payback time of 6–10 years versus 8–10 for GSHP. The only significant drawback of the GSHP is the initial capital investments, which are 2–3 times higher for GSHP. At the same time, study [18] shows the benefits of combining ASHP and GSHP in a dual-source heat pump system with evaluation for three representative climates in Europe. The source control optimization method results in only slight efficiency gains (<0.35 %) but with a stronger effect on the ground/air use ratio (up to 25 % use of air in cold climates), reducing the thermal imbalance of the ground and leading to a consequent BHE size length and cost reduction.

Building energy efficiency regulations in Latvia are defined by several normative documents, which were elaborated according to the EPBD requirements. Starting from 2021, all new buildings are required to meet NZEB requirements, which are defined in Regulations No. 222 of the Cabinet of Ministers "Building Energy Efficiency Calculation Methods and Building Energy Certification Rules" [19]. According to the regulations, NZEB definition can be assigned in case if the building corresponds to the A or A+ class regarding the yearly energy requirements for heating kWh/m² and non-renewable primary energy consumption kWh/m².

Table 1. Permissible Heating Consumption, kWh/m²

Energy efficiency class of buildings	Residential and non-residential buildings		Residential buildings	Non-residential buildings	
	heating area, m²		Heated area above 250 m²		
	50– 120	120– 250	single-apartment, two-apartment and multi-apartment buildings, residential buildings for public use, communal houses of various social groups	office buildings, educational institution buildings, hotels, restaurants, sports facilities, wholesale and retail buildings	hospitals
A+	≤ 35	≤ 35	≤ 30	≤ 35	≤ 40
A	≤ 60	≤ 50	≤ 40	≤ 45	≤ 50
B	≤ 75	≤ 65	≤ 60	≤ 65	≤ 70

Table 2. The Minimum Permissible Level of Non-renewable Primary Energy Consumption, kWh/m²

Energy efficiency class of buildings	Residential buildings		Single-family houses, multi-apartment buildings, cohabitation houses of various social groups, residential buildings for public use
	Heated area, m²		
	50–120	120–250	above 250
A+	≤ 65	≤ 65	≤ 65
A	≤ 110	≤ 100	≤ 95
B	≤ 140	≤ 130	≤ 125

Additionally, the building should contain energy-consuming equipment of the installed engineering systems, which meet the requirements of eco-design and whose energy label is at least class A, if the corresponding energy label requirements are defined in regulatory acts. Within the energy performance assessment, it must be assumed that the indoor temperature conditions during the heating period are at least at the level of category II and during the non-heating period at least at the level of category III according to the *standard LVS EN 16798-1:2019 "Energy efficiency of buildings. Ventilation of buildings. Part 1: Input parameters of indoor microclimate for energy efficiency design of buildings and for assessment, taking into account indoor air quality, temperature regime, lighting and acoustics. M1-6 module" to the requirements of Annex B*. This means that the energy needed for cooling is also included in the EPC. Even if the systems are not considered in the design phase, EPC should account cooling energy of 30 kWh/m² for office buildings and 20 kWh/m² for other buildings.

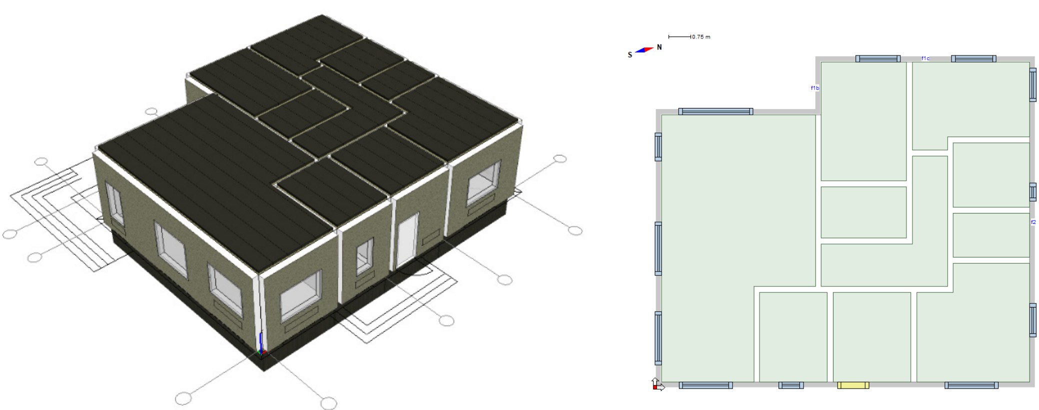
The economic benefit of the heat pump

operation can be achieved by operating it when energy price is low using dynamic energy price tariffs. This is possible if there is enough energy storage capacity according to the building demand profile. However, according to [20], the potential yearly profits of this approach could be around 3 %–4 % of annual heat pump operating costs. This low share is mainly due to the low share of energy-related costs in the total electricity retail price, mostly made up of time-invariant charges, levies, and taxes. The high share of these components thus represents a barrier in the current regulatory framework for the tapping of residential heat pump flexibility. Additionally, standardization in the device control technology should be supported. This paper aims at showing the difference in HP performance within the same building layout but with different energy performance rates. The purpose is to show that building energy performance can significantly influence HP performance. The results of this study will highlight that introduction of renewable low-carbon energy sources should be thoroughly coupled with building energy systems and only their full compatibility can give a high efficiency of the entire energy supply system of the building.

2. DESCRIPTION OF THE CASE STUDY

2.1. Building Geometry and Envelope

The one-storey single-family residential house was considered in this paper as a case study (Fig. 1). The building was divided into 10 zones of 4 types: living rooms, restrooms, corridors and a technical room. The total area of the building is 119.1 (m^2), total volume is 383.3 (m^3). The U-values were taken to ensure desired energy demands in space heating of 25, 40, 60 and 90 (kWh/m^2·year) (Table 3). Additional demand in DHW (domestic hot water) is set to 12 (kWh/m^2·year).



a) b)

Fig. 1. Case study model in IDA ICE.

Table 3. Envelope Configurations

Configuration	Aimed energy demand in space heating, (kWh/m²·year)	Average U-value, (W/m²·K)	Fan operation setback from 9–19 during weekdays, (%)
Configuration 1	25.9	0.1543	25
Configuration 2	41.4	0.2095	50
Configuration 3	60.7	0.2776	75
Configuration 4	92.0	0.3853	100

2.2 Heating Systems

For every configuration, two different heating systems were separately studied: air-to-water heat pump and brine-to-water ground source heat pump. Living rooms are heated with hydronic radiators and restrooms with underfloor hydronic heating. The underfloor heating was placed 20 mm under the floor surface into cement screed with heating design power up to 60 (W/m²). Both cases are equipped with a heat exchanger and a tank for domestic hot water of a volume of 220 (l). As heating energy source, three options were considered: gas boiler, air-to-water air heat pump, brine-to-water ground heat pump.

Table 4. Heating Systems

Type	Model name	Heating capacity, (kW)	Average estimated COP
Air-to-water air heat pump	Viessmann Vitocal-300 (WPZ)	9.2	3.5
Brine-to-water ground heat pump	SWC 120H (alpha innotec)	11.5	4.36

Radiator system supply temperature is +70 °C at -20 °C outdoors, +45 °C at 0 °C outdoors with 15 °C room design temperature drop, AHU supply temperature setpoint of +60 °C.

Heating floor system supply temperature is +40 °C at -20 °C outdoors and +30 °C at 0 °C outdoors with 5 °C room design temperature drop, AHU supply temperature setpoint of +40 °C.

2.3 Temperature Set Points

A proportional controller for every case accomplishes the air temperature control in the zones. For the rooms, control set points were taken as follows.

Table 5. Boundary Conditions for Zones

Zone	Air temperature, (°C)		Relative moisture, (%)		Light, (lx)	
	Optimal	Allowed	Min	Max	Min	Max
Living room	20–22	18–24	20	80	300	500
Toilet	20–22	18–24	20	80	300	500
Bath	20–22	18–24	20	80	300	500
Corridor	18–22	18–24	20	80	300	500

2.4 Ventilation and Infiltration

Exhaust ventilation air system was installed in restrooms; otherwise, air exchange rate was set to 0.45 (l/m^2·s) or 0.50 (h^{-1}) in living rooms. Corridor is left unventilated.

Air tightness of the building was assumed: the air leakage value n_{50} is 0.5 h^{-1} (corresponds to q_{50}=0.13 (l/m^2·s)), which means that air equivalent to half of a building volume of the flat leaks in from the outdoors during 1 h through the building envelope under a 50 Pa pressure difference between outdoors and indoors.

2.5 Weather Conditions and Heat Gains

The model was simulated in the location of Riga. Climate profile is taken from ASHRAE Fundamentals 2013 database, wind profile – for suburban area according to ASHRAE 1993. Solar heat gains were modelled with respect to the building site (Fig. 1b).

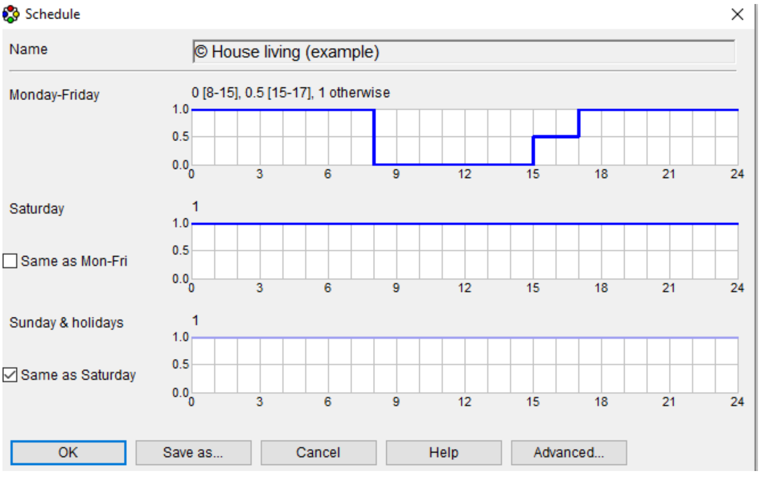


Fig. 2. Occupancy schedules.

Heat contribution from inhabitants were calculated according to occupancy schedules, predefined number of occupants and their activity level (Fig. 2).

3. METHODS

3.1 Simulation Method

Simulation was conducted using IDA ICE 4.7. The software allows a user to conduct comprehensive dynamic simulation of heat transfer and airflow in the building with respect to calculating energy loads. This tool also helps predicting thermal comfort parameters, as well as air quality and some other parameters defined by the user. Ultimately, using the software a mathematical model, that consists of tens of thousands of equations strongly depending on the number of zones, is solved considering detailed dynamic data: wind speed and directions, shades from nearby buildings, heat transfer between adjacent zones etc. The data could not be calculated manually in a sufficiently precise manner. Dynamic step simulation, finite difference method and transient calculations are used for balancing heating and cooling loads. Validation of the software was conducted in a number of studies. The mathematical model in IDA ICE is simulated using the equations from the mathematical library. For instance, the moisture, heat loads from people and thermal comfort parameters are modelled with the equations from ISO 7730 [21]–[25].

The PMV-index predicts the mean value of the subjective ratings of a group of people in a given environment. The PMV scale is a seven-point thermal-sensation scale ranging from -3 (cold) to +3 (hot), where 0 represents the thermally neutral sensation. Equation 1 shows how it can be manually found.

$$\mathrm{PMV} = \left(0.303 \cdot e^{-0.036M} + 0.028\right) \times \begin{pmatrix} (M-W) - 3.05 \cdot 10^{-3}\left(5733 - 6.99\{M-W\} - P_{vap}\right) - \\ -0.42(\{M-W\} - 58.15) - 1.7 \cdot 10^{-5} M \cdot \left(5867 - P_{vap}\right) - \\ -0.0014M \cdot (34 - t_{air}) - \\ -(3.96 \cdot 10^{-8} f_{cl}\{[t_{cl}+273]^4 - [\bar{t}_r + 273]^4\} - f_{cl} \cdot h_{cl}\{t_{cl} - t_{air}\}) \end{pmatrix}, \quad (1)$$

where

P_{vap} – partial water vapor pressure (Pa);
t_{air} – air temperatures (°C);
f_{cl} – clothing surface area factor;
t_{cl} – surface temperature of clothing (°C);
h_{cl} – convective heat transfer coefficient between air and clothes ($W/m^2 \cdot K$);
$\bar{t}_r$ – mean radiant temperature (°C);
M – metabolic rate (W/m^2);
W – effective mechanical power (W/m^2).

Corresponding to PMV PPD value, %, can be either found with Eq. (2). As it can be derived from the equation below, PPD value never gets below 5 %.

$$\mathrm{PPD} = 100 - 95 \cdot \exp\left(-(0.03353 \cdot \mathrm{PMV}^4 + 0.2179 \cdot \mathrm{PMV}^2)\right). \quad (2)$$

The values of PMV in the range of -0.7...0.7 and corresponding to them PPD < 15 % are considered to be acceptable. These values are calculated automatically during the simulation process in IDA ICE.

3.2 Model Description

The ground beneath the slab is modelled according to ISO 13370, 1.0 m of soil is assumed beneath with a constant ground temperature that equals 8 °C for all cases. Standard maximum time step is set to 1.5 h with a tolerance level equal to 0.02.

4. RESULTS AND DISCUSSION

Both heating systems show similar results and ground system is favourable in 3 out of 4 envelope configurations. Heating capacity in both cases delivers good thermal comfort in all envelope configurations. However, operative temperatures in the 3rd and 4th configuration drop below 20 degrees during colder days.

Table 6. Energy Demand in Heating (DHW included)

Configuration	Gas boiler, (kWh/m^2·year)	Air-Water, (kWh/m^2·year)	Brine-Water, (kWh/m^2·year)
Configuration 1	34.6	13.8	13.6
Configuration 2	50.2	19.1	18
Configuration 3	69.4	21.8	23.6
Configuration 4	100.7	36.4	33.8

Table 6 gives an overview of the energy required for heating purposes. For heat pump layouts, all configurations clearly show that energy input is considerably lower due to the contribution of ambient heat. Thus, use of heat pumps gives considerable primary energy savings, which influence a primary energy factor rating for a building energy performance certificate. Since electrical energy input is necessary for heat pumps, it is a very beneficial combination to couple it with PV panels. By proper sizing of PV arrays versus heat pump and heat storage, tank capacity can provide favourable conditions when all on-site produced renewable energy is used within the building boundaries, thus avoiding energy export to the grid.

Table 7. Average COP for Air Source Heat Pump during the Heating Season

	Conf. 1	Conf. 2	Conf. 3	Conf. 4
September	3.314	3.339	3.402	3.567
October	2.997	3.124	3.348	3.596
November	2.762	3.096	3.257	3.28
December	2.795	2.959	2.977	2.952
January	2.975	3.055	3.055	3.103
February	2.682	2.794	2.814	2.771
March	2.938	3.145	3.162	3.18
April	3.112	3.168	3.466	3.604
May	3.245	3.305	3.37	3.453
mean	2.95	3.088	3.188	3.261
mean*5832.0 h	17204.3	18009.2	18594.1	19015.9
min	2.682	2.794	2.814	2.771
max	3.314	3.339	3.466	3.604

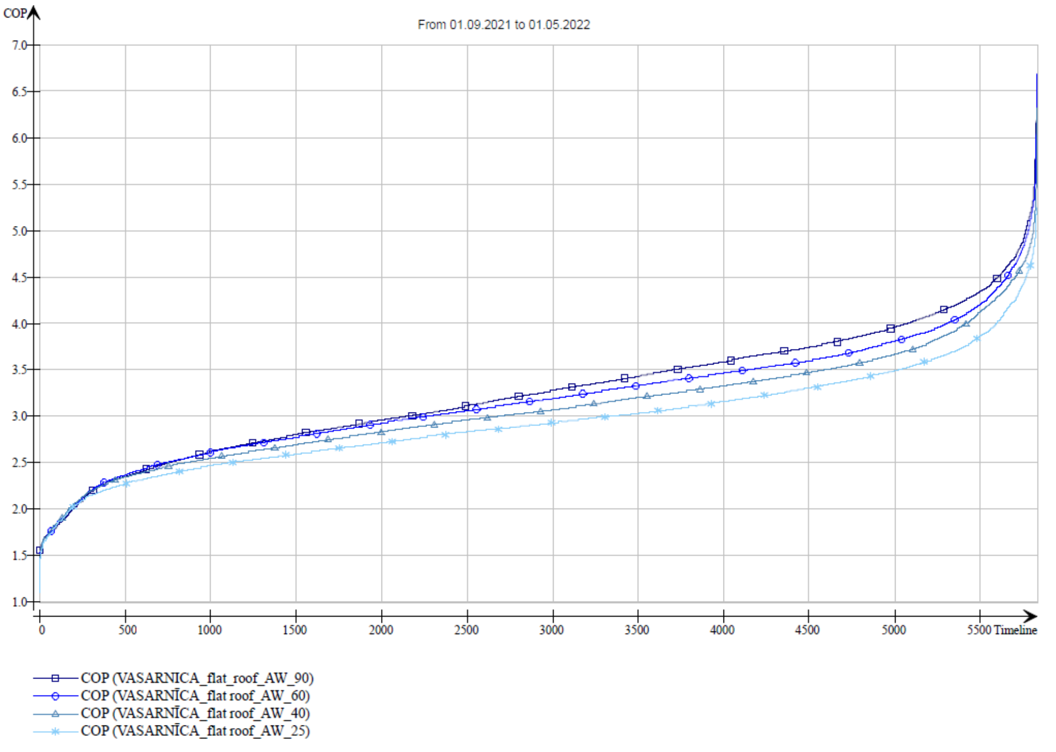


Fig. 4. Duration diagram for COP with an air source heat pump.

Figures 4 and 5 show the duration curves for COP of the air source and brine-water heat pumps. It is clearly seen that for the air source a heat pump COP duration curve has a similar path to the outside temperature duration curves, which can be explained by the direct correlation of the COP to the outside air temperature. However, it can be noted that for building with higher energy demand (COP (VASARNICA_flat_roof_AW_90, which corresponds to Configuration 4), mean COP values are higher than for buildings with lower energy consumption (Configurations 3-1). The difference for air source heat pump is between 2 % and 10 %, while a similar correlation is noted for the ground source heat pumps with deviations from 7 % to 22 %. Lower COP values for more energy efficient buildings in both cases with ASHP and GSHP can be explained by a higher share of DHW in the total energy demand. It can be clearly observed in Table 8. As long as DHW required temperature levels are 55–65 °C, it will drastically reduce COP of any HP, with exception of specific industrial HP, which can be connected in series [26].

For ground source HP, where brine temperature is constant, COP values during autumn and spring months are lower, then they are higher in winter months, when there is a dominating energy requirement for heating. Table 7 shows an opposite picture, where COP values of air source HP are higher during autumn and spring months, when outside air temperatures are higher. The fact that ASHPs are still dominating in Norway HP can be partially explained by these circumstances [16]. If you have energy efficient buildings and underground temperatures lower than 10 °C for a ground source heat pump, it will be very hard to achieve mean COP values higher than for ASHP.

COP in Brine-to-Water Ground Heat Pump

Table 8. Average COP for Ground Source Heat Pump during the Heating Season

	Conf. 1	Conf. 2	Conf. 3	Conf. 4
September	1.965	1.985	2.036	2.168
October	2.076	2.204	2.352	2.734
November	2.418	2.507	3.116	3.463
December	2.926	3.149	3.396	3.411
January	2.629	3.318	3.416	3.439
February	2.74	3.281	3.353	3.353
March	2.518	2.766	3.349	3.411
April	2.294	2.367	2.467	3.147
May	2.194	2.242	2.298	2.385
mean	2.444	2.693	2.933	3.138
mean*5832.0 h	14251.3	15706.3	17103.0	18297.9
min	1.965	1.985	2.036	2.168
max	2.926	3.318	3.416	3.463

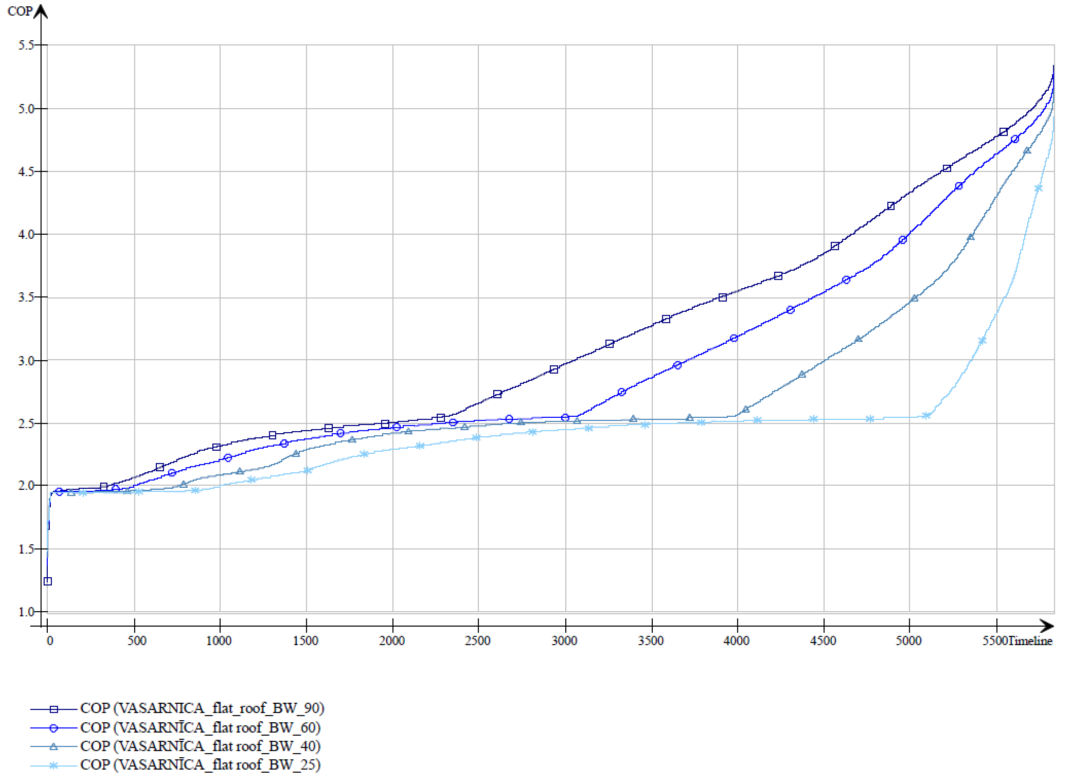


Fig. 5. Duration diagram for COP with a ground source heat pump.

5. CONCLUSIONS

Since decarbonization of the energy sector is among the top priorities in the EU, with ambitious targets of carbon neutrality until 2050, the energy efficiency of the building stock and the use of renewables are those directions, which can bring the most considerable input towards the achievement of these goals. However, it is not always obvious how to combine different aspects most efficiently.

There are numerous studies that show the benefits of the use of heat pumps in combination with low-energy buildings. Real measurements show that mean COP values are not as high as promised in the technical specifications. It can be explained by the fact that the part load operation of the heat pump is not addressed accurately during the design phase. Study [27] fully describes two approaches for addressing the part load operation and auxiliary consumption, where auxiliary consumption is a function of the part load ratio. This example underlines the sensibility of a heat pump in operating conditions. It shows that with a seasonal or bin method it is not possible to take this sensibility on operating conditions into account in a precise manner.

The current study shows evidence for two main conclusions.

1. For low-energy buildings, heat pumps will not always show higher COP values, compared to buildings with higher energy demand. COP is highly dependent on the temperature requirements, while in low-energy buildings, DHW demand with high-temperature requirement becomes dominating, decreasing the overall COP of the whole system.
2. GSHP will not always be more efficient than ASHP. If the ground/groundwater temperature is lower than 10 °C, for GSHP it will be almost impossible to over-compete ASHP within the same system. Considering ground heat exchangers, it is necessary to consider the seasonal energy extraction effect on the ground temperature.

In addition to the above-mentioned conclusions, this study shows a very small difference between mean COP values for both (ASHP and GSHP) systems within Configuration 1 for radiators and underfloor heating. For both systems, the COP differs only by 10 %.

The study shows that alternative energy sources can give a very significant reduction in primary energy use. At the same time, without thorough planning and proper coupling of building energy systems with alternative energy sources there is a high risk that expected benefits may not be achieved. It is unacceptable to use the generally accepted practice – of "better oversize, than undersize", which was acceptable for fossil sources. For alternative energy sources, the only possible way is a precise estimation of building load, demand profiles, storage capacity and design capacity of alternative energy source.

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DEVELOPMENT OF UNIFIED HYBRID WDM-PON WITH SPECTRALLY HIDDEN DATA CHANNEL SYSTEM AND FBG OPTICAL SENSOR NETWORK

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As the demand for fiber optical data transmission systems and other type of applications, which require optical media, like optical sensing increases, the unauthorized parties are becoming increasingly interested in such systems. Also, with such demand, more complex optical systems are required; thus, the network infrastructure is becoming more crowded. It is vital to economize on the available resources and infrastructure to ensure the needs of all interested business, governmental or end-user sides. Therefore, the present research focuses on the development of a unified hybrid optical system. The developed hybrid optical transmission system adds additional protection to the channels, allows for the unification of standard optical data transmission channels, optical sensors and spectrally hidden data transmission channel systems, and increases the efficiency of the optical components used.

Keywords: *Fiber Bragg grating (FBG) optical sensors, hidden data channels, hybrid optical data transmission system, wavelength division multiplexed passive optical network (WDM-PON).*

1. INTRODUCTION

Wavelength-division-multiplexed passive optical networks (WDM-PONs) and fiber Bragg grating (FBG) optical sensor technology are increasingly topical in modern optical communications [1], [2]. With the expansion of the applications and systems using the optical frequency spectrum as well as the increasing activity of different cyber threat actors [3]–[5], it is important to add different layers of protection to the optical transmission media. To lower the potential negative effect made by the harmful parties (e.g., eavesdroppers), it is important to conceal the occupied optical frequencies. In this research, we demonstrate successful simulation realization of 8-channel 10 Gbit/s (and 7 % FEC overhead) WDM-PON system where an additional 7-channel 2.5 Gbit/s (and 7 % Forward Error Correction (FEC) overhead (OH)) spectrum-sliced system has been embedded and spectrally hidden between each WDM-PONs transmission channel.

In addition to our previous reseach [6] in this field, such a hybrid model has now been improved and unified with 5 FBG optical sensor system by efficiently using an amplified spontaneous emission (ASE) broadband light source to provide out-of-band spectral concealment for hidden channels and also power the FBG optical sensor system. FBG optical sensors due to their various advantages [7], [8], for instance, immunity to electromagnetic interference, light weigth and small size are more frequently used in the industry and optical network infrastructure.

The proposed hybrid optical transmission system increases the efficiency, adds additional protection to the channel frequencies, and allows for the realization of such complex hybrid optical transmission solutions. The results gathered show that it is possible to configure and develop such a hybrid unified system without overlapping the realized data transmission channels and optical sensor channels while ensuring at least 20 km long transmission line with negligible (less than 0.5 dB) power penalty at commonly used [9] pre-FEC BER level of 10^{3} and an average bit error rate (BER) of 7.16×10^{-17} (for WDM-PON system) and 1.11×10^{-5} (for hidden channel system).

2. EXPERIMENTAL MEASUREMENT SETUP AND RESULTS

The developed hybrid optical system is realized in mathematical simulation software and it consists of the three main blocks – central office (CO), optical distribution network (ODN), and optical network terminals (ONTs). The simulation scheme (shown in Fig. 1) includes an 8channel 10 Gbit/s (10.7 Gbit/s including FEC OH) non-return-to-zero on-off keying modulated WDM-PON system that has been unified with a spectrally hidden data transmission system and a 5 FBG optical sensor system. Seven 2.5 Gbit/s (and 7 % FEC OH) modulated ASE slices containing hidden data are inserted between two WDM-PON data transmission channels. While the optical line terminal (OLT1) provides WDM-PON channel operation, OLT2 ensures the working principle of the spectrally hidden channel system.

Additional ASE1 source and notch (transient) optical filter is integrated within CO to provide concealment outside the optical hidden channel system working range, meaning that the ASE1 generated optical light is approximately at the same optical power level as the hidden channels. ODN includes FBG dispersion compensating module (FBG DCM) used for compensating the chromatic dispersion. Most importantly, the FBG optical sensor network of 5 sensors that are separated with 4 km long single mode fiber spans (SMF) – typical distance used in Latvia [10] between two fiber optical manholes or cabinets – is integrated inside this hybrid optical system. ONTs are structured into 2 parts where one is configured for the receiving and processing of standard optical data transmission channels while the other – for hidden data channels.

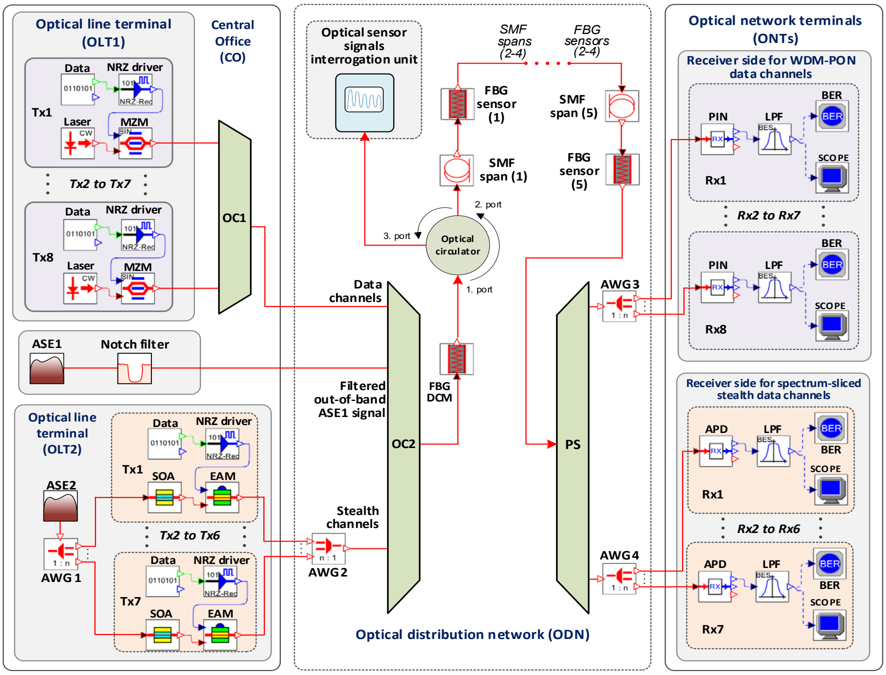

Fig. 1. Developed unified WDM-PON, FBG optical sensor, and spectrally hidden channel system setup.

Figure 2 depicts the proposed solution for a hybrid WDM-PON and spectrally hidden channel system where the spectrally visible and also hidden parts can be observed.

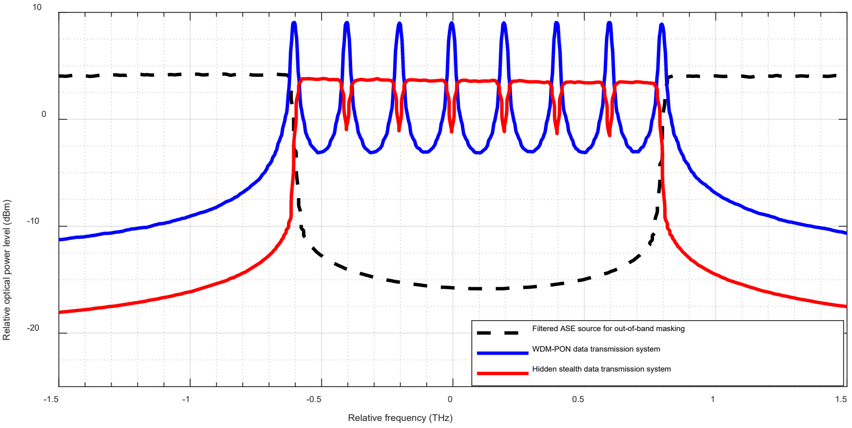

Fig. 2. The proposed solution for hybrid WDM-PON and spectrally hidden channel system.

Whereas Fig. 3 shows the received optical spectrum at the end of ODN, where a developed unified system of all three previously mentioned sub-systems can be visually observed. It is important to highlight that spectrally only WDM- PON and reflected signals of the FBG optical sensors can be seen, as the spectrally hidden channel system is concealed in that way, so no visual indications would suggest the existence of such a data transmission system.

Table 1 consists of the received average BER values for WDM-PON and spectrally hidden data channel systems with and without optical sensor system integration. As it is stated, a unified WDM-PON and hidden channel system can provide an average BER of 10^{-19} for the WDM-PON system and 10^{-6} for the hidden one. Although relatively small, yet still acceptable – the optical sensor system induces the increase of average BER values, resulting in 10^{-17} for the WDM-PON system and 10^{-5} – for the hidden channel system. Nevertheless, results for all configurations approve acceptable average BER levels in such hybrid optical system solutions.

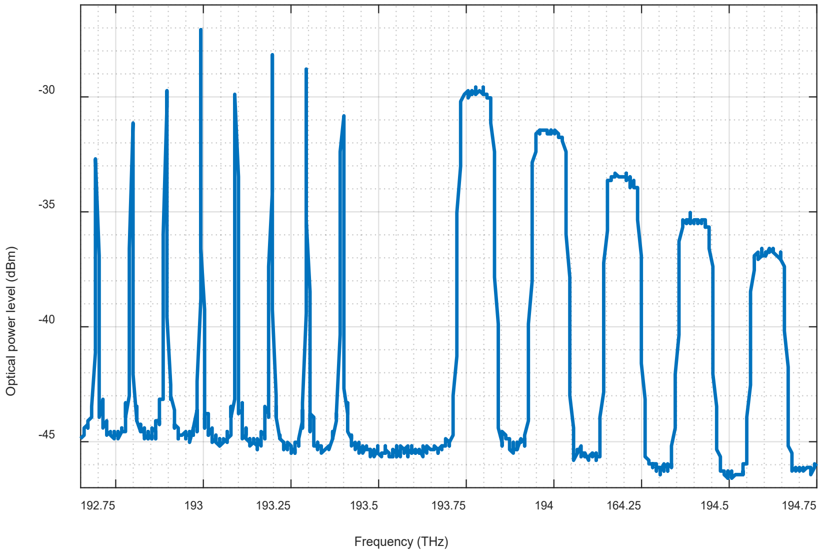

Fig. 3. The received optical spectrum of developed unified WDM-PON, FBG optical sensor, and spectrally hidden channel system.

Table 1. BER Averages for WDM-PON Data Channel and Spectrally Hidden Data Channel Systems with and without Optical Sensor System Integration after a 20 km Long Transmission Line

Average BER value	**Without the optical sensor system integration**	**With the optical sensor system integration**
WDM-PON data channel system	7.23×10^{-19}	7.16×10^{-17}
Spectrally hidden data channel system	1.13×10^{-6}	1.11×10^{-5}

3. CONCLUSIONS

Based on the performance results gathered, it can be concluded that the power penalty resulting from such implementation of a spectrally hidden data channel system and FBG optical sensor system in back-to-back configuration and 20 km transmission line was less than 0.5 dB (at pre-FEC BER level of 2×10^{-3}). From all the numerical and visual results of the data gathered, it can be stated that even with an integrated hidden data transmission system and FBG optical sensor system, the acceptable performance of such a hybrid optical system can be achieved if all the electro-optical components and their parameters are configured appropriately.

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