

A TECHNICAL AND ECONOMIC STUDY OF SUSTAINABLE POWER GENERATION BACKUP

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This study focuses on overview and general economic viability evaluation of four types of portable electric generators: diesel and petrol internal combustion engines, batteries/accumulators and inverter systems (especially lithium polymer and lithium-ion battery systems), hydrogen fuel cell systems and combination (hybrid) of the latter. It does not include the rarely used, inefficient forms of energy conversion, such as steam turbines, as well as energy generators that are difficult to adjust with consumption and supply variations (variable forms of RES like wind and solar energy). The main targets of the study are battery/inverter systems, hydrogen fuel cell systems, and hybrid battery/inverter and hydrogen fuel cell systems, with hydrogen fuel cell systems being the thematic core.

Keywords: *Battery/inverter systems, economic evaluation, electric generators, hydrogen fuel cell systems, NPV.*

1. INTRODUCTION

Electric generators have become a remarkable technological achievement that provides energy at times when it is not available through conventional sources – electricity distribution grids. If there is no electricity, but it is necessary to operate tools, machinery or lighting equipment, a viable solution and permanent energy source – a generator, is available. Its popularity is due to sustainable performance, operational stability and frequently – compact size. Therefore, during the last century, electric generators have gained wide recognition not only in construction, but also other sectors of the national economy, such as the military and healthcare [1].

Two general types of generators are mostly used worldwide – stationery and portable ones [2]. These generators are popular due to the availability of fuel and infrastructure. Stationary electric generators are larger, significantly heavy, usually very powerful and are used when large amounts of electricity are needed for extended periods of time. They are chosen for various projects, especially in energy intensive phases of construction [3]. Portable electric generators, on the other hand, are lighter and quieter: the characteristics that allow them to be used even in residential areas, for example, in case of a short-term power outages [4].

In Latvia, the following information was obtained from rentals, construction and electrical engineering companies regarding possession and availability of high-power electric generators (100 kilowatts (kW) or above). About 3000 100 kW generators are owned by construction and electrical engineering companies alone for provision of backup power, and about 2000 generators are readily available through rentals. Most

of these generators are used in construction and industrial facilities. The information regarding low and medium power electric generators is problematic to obtain, because they are widely used throughout the country and mostly utilized by small businesses and private owners.

However, portable electric generators tend to be dominating entity in the Latvian generator market due to their availability, modest price and large numbers. They are very useful but have both advantages and disadvantages. Among advantages, the following points should be brought forward:

- mobility: portable generators can be easily moved and used in different locations;
- compactness: these generators are relatively small, so their installation takes up little space;
- uninterrupted power supply: capable of providing continuous power supply – does not react to external conditions;
- autonomous energy supply: the ability to work autonomously, in case of accidents and network outages, even completely off-grid.

Their disadvantages, on the other hand, include:

- limited power: portable generators are usually of low power, so they can only run the most essential electrical appliances;
- high cost: some portable generators, such as inverter generators, can be expensive. The cost of the obtained electricity is higher than for stationary high-power generators;
- safety issues: mobile generators can cause injuries, burns, and even carbon monoxide poisoning if used improperly, especially in enclosed spaces [5] – [6].

They can provide a stable and steady supply of electricity, which makes them ideal and especially useful in extreme conditions such as storms or other unforeseen circumstances when the standard power supply is interrupted. However, at the same time, most of these generators still produce carbon dioxide (CO₂) emissions and, to a certain degree, are harmful to the envi-

ronment. Moreover, electric generators, including portable ones, produce a considerable share of CO₂ emissions in areas like ports, airports, customs, etc. [7]–[10]. In this regard, therefore, it is very important to analyse available avenues of decarbonisation of the stationary and portable generator sectors and provide a long-term solution for the pollution problem they cause.

2. THE STUDY DESCRIPTION

A study was carried out regarding the implementation of maximally CO₂ emission free portable electric generators, which can be divided by power, the type of energy conversion, and by the type of primary energy use. Division by power includes low power generators (up to 5 kW; they are suitable for households, small businesses or emergency situations), medium power generators (from 5 to 50 kW; they can provide more power, and often used in places of business and country houses or small hotels) and high power generators (over 50 kW; they are suitable for large businesses, factories or other large facilities like schools and hospitals).

At the same time, division by type of energy conversion includes mechanical drive-based generators (wind generators etc., conversion of renewable energy resources (RES)), afterburners like steam turbines, Stirling engines, etc., internal combustion engine drives (various fuels –

liquid, gaseous, both fossil and RES), solar photovoltaic converters – solar panel/inverter systems, electrochemical batteries/accumulators and inverter systems, and electrochemical process – fuel cells (fuel–hydrogen, methane, etc.).

The study focuses on comparison of internal combustion engine drives, batteries/accumulators and inverter systems (especially lithium polymer and lithium-ion battery systems), hydrogen fuel cell systems and combination of latter two. It does not include the rarely used, inefficient forms of energy conversion, such as steam turbines, as well as energy generators that are difficult to adjust with consumption and supply (variable forms of RES like wind and solar energy). The main targets of the study are battery/inverter systems, hydrogen fuel cell systems, and hybrid battery/inverter and hydrogen fuel cell systems, with hydrogen fuel cell systems being the thematic core [11] – [12].

2.1. Battery/Inverter Systems

Battery/inverter systems have become a popular choice for electric generators. They are quiet, environmentally friendly at the point of use and can generate electricity from stored RES, such as solar or wind energy.

Advantages of these systems include

but are not limited to:

- quiet operation, does not cause acoustic pollution;
- environmentally friendly applications with no emissions;
- can be used safely in closed areas;
- can operate solely on RES;

- short start-up and shutdown times – consumption can be precisely controlled, reducing energy losses.
- However, at the same time, systems have some disadvantages:
- at a comparable power, much larger dimensions and mass (up to 3 times greater mass) than internal combustion

engine powered electric generators;

- regular charging is required in a suitably prepared place – it is impossible to bring energy to any location;
- battery costs currently are over 400 EUR/kWh – significant costs in cases of higher energy consumption [13].

2.2. Hydrogen Fuel Cell Systems

Hydrogen fuel cell systems are the latest technology in the electric generator industry. They are quiet, environmentally friendly and can generate electricity using hydrogen of any origin.

The advantages of such systems are the following:

- they use hydrogen, which is RES and can be obtained at any place where there is access to water and energy [14] – [16];
- emissions in a form of water vapour do not cause pollution;
- quiet, i.e., do not cause acoustic pollution;
- safety operation in closed areas;
- short start-up and shut-down time –

consumption can be accurately controlled, reducing energy losses;

- fast re-filling.

Disadvantages of hydrogen fuel cell systems include:

- it is not always possible to be charged AEG with green hydrogen, as well as to obtain green electricity through electrolysis;
- hydrogen produced from natural gas can be regarded only partially environmentally friendly;
- at a comparable power, much larger dimensions and mass (up to 2 times the mass) than internal combustion engine powered electric generators.

2.3. Hybrid Battery/Inverter and Hydrogen Fuel Cell Systems

Fuel cell systems and batteries can work together to provide more options for transportation and energy. Fuel cell systems are designed to improve the interaction between batteries and electric propulsions. While each system has its own advantages, combining battery and fuel cell technologies can help reduce overall CO₂ emissions and increase the use of RES without compromising the system's performance.

Obvious advantages of connecting the fuel cell to the batteries systems are as follows:

- high energy efficiency: fuel cells offer high energy conversion efficiency com-

pared to conventional internal combustion engines, thereby reducing energy waste and increasing overall system efficiency;

- environmental benefits: fuel cells produce electricity through electrochemical reactions, resulting in reduced greenhouse gas emissions and air pollution compared to fossil fuel-based energy sources;
- range extension: integrating fuel cells with storage batteries can extend the range of mobile electrical systems, as fuel cells provide continuous power by generating electricity from a fuel source

(such as hydrogen) without the need for frequent recharging;

- fast refuelling: refuelling a fuel cell system can be faster than charging a battery because it involves refuelling rather than waiting for the battery to charge. This can be beneficial for time-sensitive applications such as electric vehicles.

Several disadvantages of such hybrid systems are as follows:

- cost: fuel cell systems are currently more expensive compared to traditional battery-based systems, mainly due to the high cost of fuel cell stacks and hydrogen infrastructure;
- hydrogen infrastructure: building a

widespread hydrogen infrastructure for refuelling can be a major challenge, as it requires significant investment in hydrogen production, storage, transportation and distribution;

- fuel availability and storage: availability and storage of hydrogen can be problematic, as hydrogen requires special infrastructure and processing procedures due to its low energy density and high flammability;
- durability and lifespan: fuel cell systems may have limitations in terms of durability and lifespan, especially in mobile applications with varying operating conditions and frequent start-ups and shutdowns. Long-term reliability can be a concern.

3. A FUEL CELL BASED HYDROGEN GENERATOR SYSTEM

The hydrogen fuel cell electric generators have a great market potential locally, as there are currently approximately 5000 generators with a capacity of 100 kW in Latvia. It can be concluded that the advantages of hydrogen fuel cell powered generators compared to diesel generators are that they do not produce both CO₂ emissions and noise pollution. Using hydrogen fuel cells, the 100-kW generator can run for 24 hours on a single charge and saves up to 46 tons of CO₂ /year. CO₂ savings depend on how often it is used.

During the study, special attention was paid to technical characteristics of the mobile hydrogen generator mounted on a trailer. Uniform parameters of electricity supply (output) were defined as follows: 100 kW output power (electricity), amount of stored energy 800 kWh for electricity generation. Also, the following components were selected for creation of such mobile generator: trailer, 100 kW fuel cell, 48 kg hydrogen storage system, 5 kWh battery module, power control module.

A conceptual design of the hydrogen fuel cell electric generator is shown in Fig. 1.

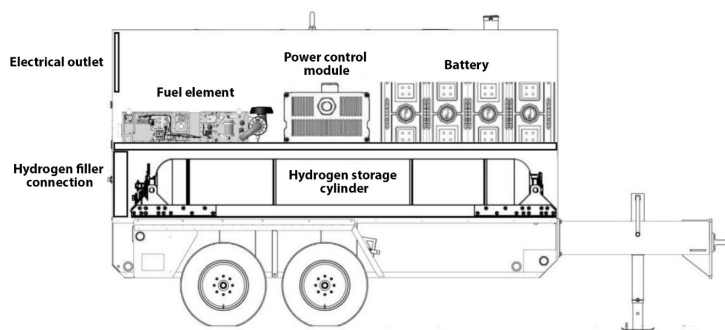


Fig. 1. A conceptual design of the hydrogen fuel cell electric generator.

A technical design of hydrogen fuel cell electric generator with the end panels can

be seen in Fig. 2 and conceptual scheme of the hydrogen generator in Fig. 3.

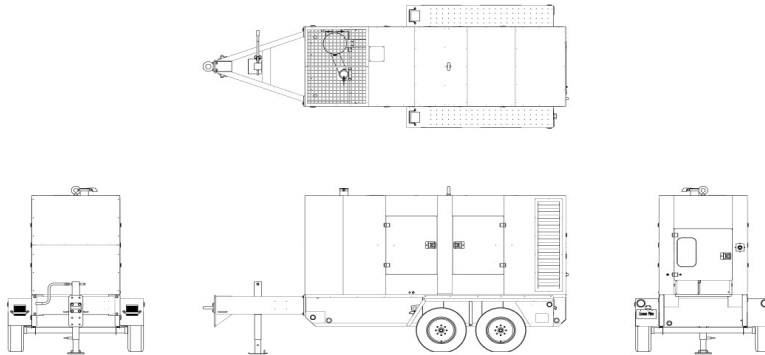


Fig. 2. An overview of the hydrogen generator with the end panels.

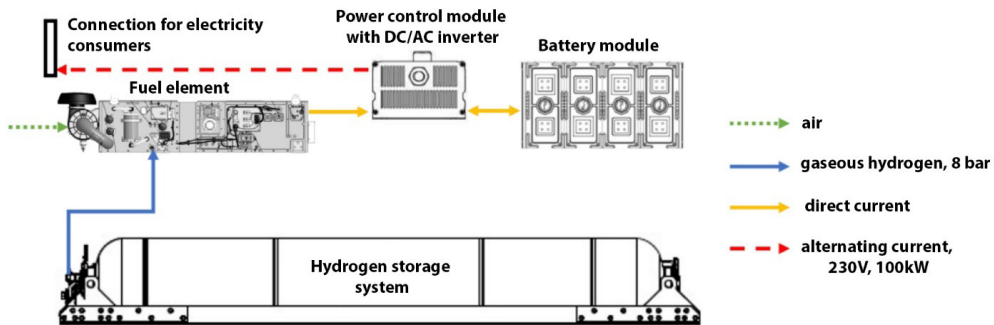


Fig. 3. A conceptual scheme of the hydrogen generator.

3.1. The Operational Principle of the System

The hydrogen storage system, with a capacity of 48 kg, provides the necessary amount of hydrogen for the generation of 800 kWh of electricity. The working pressure of the cylinder system is 350 bar. A direct current is generated by oxidizing hydrogen in a thermochemical process in a fuel cell. The direct current from the fuel cell is fed through the device control module after conversion in a DC/AC inverter as an alternating current to the consumer's connection contact. The control system module initiates the switching on of the fuel

cell when the consumer is connected.

The following technical components are needed for the generator: trailer suitable for transportation on public roads, fuel cell, power 100 kW, hydrogen storage system, capacity of 48 kg and working pressure of 350 bar, elements of the gaseous hydrogen supply system, battery module, capacity of 5 kWh, power control module with integrated battery charge control module and DC/AC or direct current/alternating current inverter, consumer connections, metal constructions, their fastenings and connections,

electrical installation elements, including high-voltage and low-voltage wiring. All these components, except for the fuel cell

and hydrogen storage system, can be considered standard components available in the market and can be separately acquired.

3.2. Selection of Hydrogen Storage System

For the selection of the hydrogen storage system, several potential suppliers of composite cylinder systems were inquired. Although the technical specification and drawings were sent only by the company “Worthington Cylinders GmbH”, after conducting in-depth research on shared websites, it was concluded that equivalent

composite cylinder hydrogen systems were offered by several manufacturers and such systems were considered a standard product in the automotive industry. Using information collected from suppliers, a standard hydrogen filling, storage and delivery system was designed as depicted in Fig. 4.

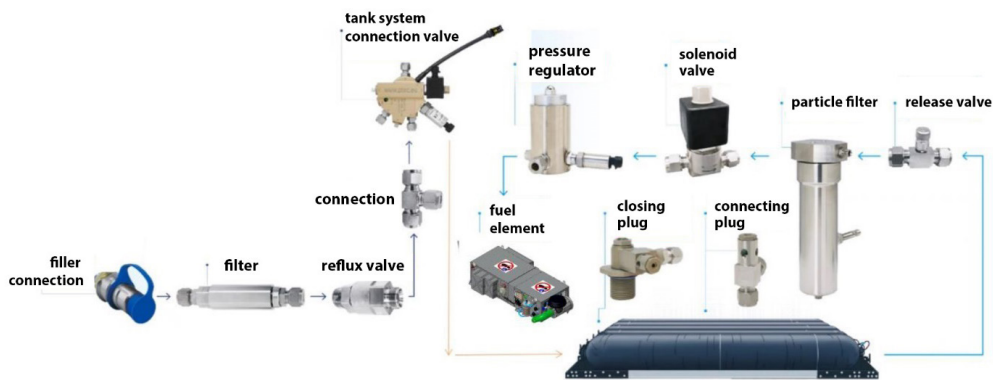


Fig. 4. A standard hydrogen filling, storage and delivery system.

Several potential suppliers who could offer a 100-kW power fuel element were approached for the selection of fuel cells. The technical specification was received

from “Ballard Power Systems Europe” and “PowerCell Sweden AB”. A comparison of the most important technical parameters of both systems is listed in Table 1.

Table 1. Comparison of the Most Important Technical Parameters of Ballard Power Systems Europe and PowerCell Sweden AB

Parameters	Ballard Power Systems	PowerCell
System power	100 kW	100 kW
Operating voltage	280–560 V	250–500 V
Work capacity	21–360 A	50–450 A
Weight	256 kg	212 kg
Hydrogen supply pressure	8 bar	8–12 bar
Working temperature	-30 - +50 °C	-30 - +45 °C
Efficiency ratio, max	57 %	55 %
Power control system	CANbus	CANbus
Operational duration	25 000 h	20 000 h
Defence class	IP54	IP54

Looking through the parameters, it was concluded that although no significant differences were present, it would be more

appropriate to use “Ballard Power Systems Europe” fuel cell due to higher efficiency and duration of operation.

4. THE ECONOMIC EVALUATION

The use of electric generators of all kinds, including portable ones, is determined not only by technological but also economic parameters, which are closely related to technical ones. It is especially important to evaluate their cost, because users are professionals who need long-term economic benefits from the potential investment. Therefore, an economic evaluation was performed comparing internal combustion generators using petrol and diesel (systems of two different combustion processes) with battery/inverter system and hydrogen fuel cell/inverter systems.

The following unified electricity supply (output) parameters were defined for all

system:

- 100 kW output power (electricity);
- 8-hour working day with an average workload of 80 %;
- regular use – 245 d/year;
- filling/transportation to and from the filling/refuelling location takes place outside working hours (it is included in expenses);
- for battery system – battery replacement after 1000 charging cycles (battery price 150 EUR/kWh).

The total amount of energy to be delivered, considering the above conditions, was calculated as follows:

$$E = 100 \text{ kW} * 8 \text{ h} * 245 \text{ d} * 0.8 = 156\,800 \text{ kWh} = 156.8 \text{ MWh}$$

The determined work modes show that each of the considered generator types must have 800 kWh of energy reserves available (8-hour working day with a load of 100 kW – max energy amount of 800 kWh). The

average load is used to model the energy consumption of longer periods (monthly, yearly), but the daily consumption can also be used as the maximum in some cases, too.

4.1. Maintenance Cost Estimate

Maintenance cost estimates were done for all technologies under review. For internal combustion engine generators, they included refuelling, oil changes, filter changes and other regular activities, with average maintenance costs of about 100–200 EUR/MWh/year.

For battery/inverter system maintenance costs included battery replacement

and inverter maintenance, with average maintenance costs of about 50–100 EUR/MWh/year.

In the case of hydrogen PEM fuel cell inverter system maintenance costs included electrolyte replacement and other activities. They brought expected average maintenance costs to about 50–75 EUR/MWh/year [17].

4.2. CAPEX and OPEX

OPEX represents operating expenses, and CAPEX represents capital expenditures. OPEX covers day-to-day operations, while CAPEX involves acquiring assets for long-term use. The main difference between OPEX and CAPEX is the duration of the benefits they generate. Operating expenses provide short-term benefits, whereas capital expenditures provide long-term benefits. Another significant difference is how expenses are recorded in financial state-

ments. Operating expenses are recorded as expenses in the period they are incurred. Capital expenditures are recorded as assets on the balance sheet and are depreciated over their useful life [18]. In this comparison, OPEX and CAPEX differences stand out rather significantly.

CAPEX was calculated for acquisition of electric generators with electric power of 100 kW, and the outcome of this calculation is shown in Table 2.

Table 2. Acquisition of Electric Generators and Generator Systems (100 kW)

Technology	Acquisition costs (EUR)
Internal combustion engine (petrol)	20 000
Internal combustion engine (diesel)	25 000
Batteries/inverter	340 000 (400 EUR/kWh for battery and 20 000 EUR for inverter)
Hydrogen PEM fuel cells	200 000 (100 000 EUR for fuel cell, 20 000 EUR for investors, 10 000 EUR for power control unit and 70 000 EUR hydrogen balloons)

On the other hand, OPEX for different technologies mainly includes such options as fuel and its calorific value. For a comparison, it was necessary to recalculate the calorific value of petrol and diesel fuel from kWh/kg to kWh/l. For diesel, this conversion factor is 0.84, and for petrol it is 0.72.

Fuel costs for 1 MWh electricity generation, considering the efficiency of various technologies and fuel prices, are summarised in Table 3. At the end of 2023, the retail prices of petrol and diesel fuel in Latvia were very similar – it was assumed to be 1.7 EUR/l.

Table 3. Fuel Costs for 1 MWh of Electricity Generation

	Heat capacity, kWh/kg	Fuel price, EUR/kg	Amount of fuel 1MWh/kg	Fuel cost, EUR/MWh, at 100 % efficiency
Gasoline	12.5	2.43	80	194.29
Diesel fuel	12.8	2.02	78.13	158.11
Electricity from the grid				150.00
Hydrogen	36	10.00	27.78	277.78

As shown in Table 4, evaluating the efficiency of each specific conversion technology (primary energy into electricity)

significantly increases the cost of each technology for production of 1 MWh_e.

Table 4. Evaluation of Technology Efficiency (%) for Generation of 1 MWh

	Conversion efficiency, %	Fuel costs, EUR/MWh, 100 % efficiency	Fuel costs, EUR/MWh, at the lowest efficiency of the given technology	Fuel costs, EUR/MWh, at the highest efficiency of the given technology
Internal combustion engine (petrol)	20–30	194.29	971.45	647.63
Internal combustion engine (diesel)	30–40	158.11	527.0333	395.285
Batteries/inverter	85–90	150.00	187.5	166.67
Hydrogen PEM fuel cells	40–70	277.78	694.45	396.83

Maintenance costs for 156.8 MWh energy production depend on the complexity of the technology, and the comparison of

maintenance costs (EUR/MWh, EUR/year) is given in Table 5.

Table 5. The Comparison of Maintenance Costs (EUR/MWh, EUR/year)

Technology	Maintenance costs (EUR/MWh)	Maintenance costs (EUR/year)
Internal combustion engine (petrol)	100	15 680
Internal combustion engine (diesel)	200	31 360
Batteries/inverter	75	11 760
Hydrogen PEM fuel cells	75	11 760

Total operating costs, including maintenance costs, to produce 156.8 MWh of

energy are summarised in Table 6.

Table 6. Total Operating Costs, Including Maintenance (EUR, EUR/year)

Technology	Fuel costs (EUR)	Maintenance costs (EUR/year)	Costs (EUR/year)
Internal combustion engine (petrol)	101 549	15 680	117 229
Internal combustion engine (diesel)	61 979	31 360	93 339
Batteries/inverter	26 133	11 760	37 893
Hydrogen PEM fuel cells	62 223	11 760	73 983

4.3. NPV Evaluation

To be able to compare economic viability of all generator technologies in a long run, the net present value (NPV) method was utilised with valuation period of 10 years – working life of professional equipment, as the chronological base. The following discount rates were used in the model – 5 %, 10 %, and 15 %.

Additional assumptions in the NPV model were chosen:

- after every 4 years (1000 charge and discharge cycles) the battery is changed;
- the battery system is transported daily 50 km to the charging point (transportation costs per day – fuel 10 EUR/day, wages and other costs – 40 EUR /day);

- the price of fossil fuels increases by 10 %/year;
- the price of hydrogen decreases by 10 % /year;
- the price of electricity decreases by 5 %/year;
- maintenance costs increase by 10 %/year.

Applying the NPV model, it was found that at low discount rates (5 % and less) the hydrogen fuel cell system was the most profitable. As the discount rate increases, the best solution is the battery/inverter system (see Figs. 5–7).

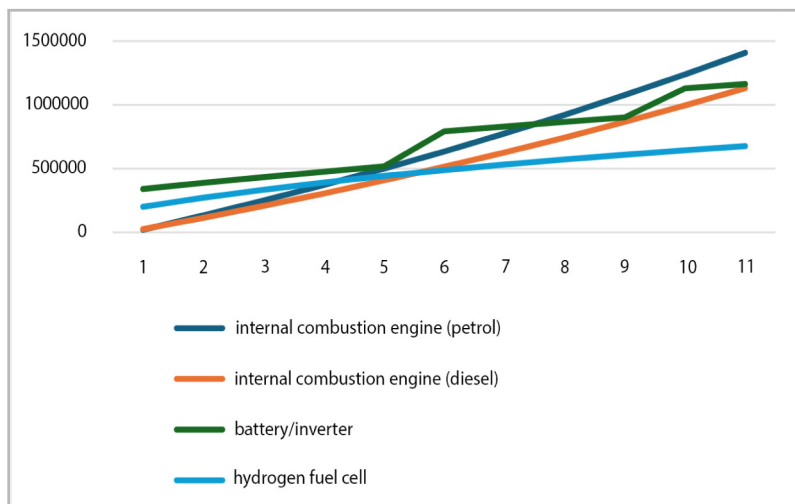


Fig. 5. NPV model with a 5 % discount rate.

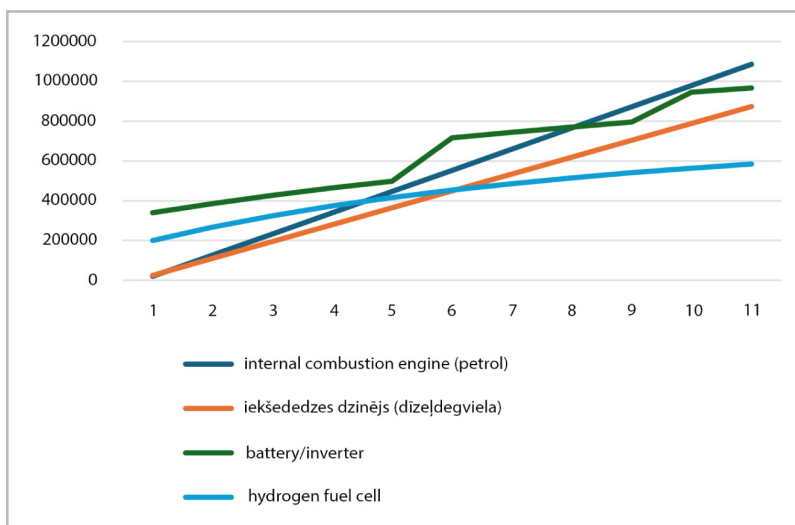


Fig. 6. NPV model with a 10 % discount rate.

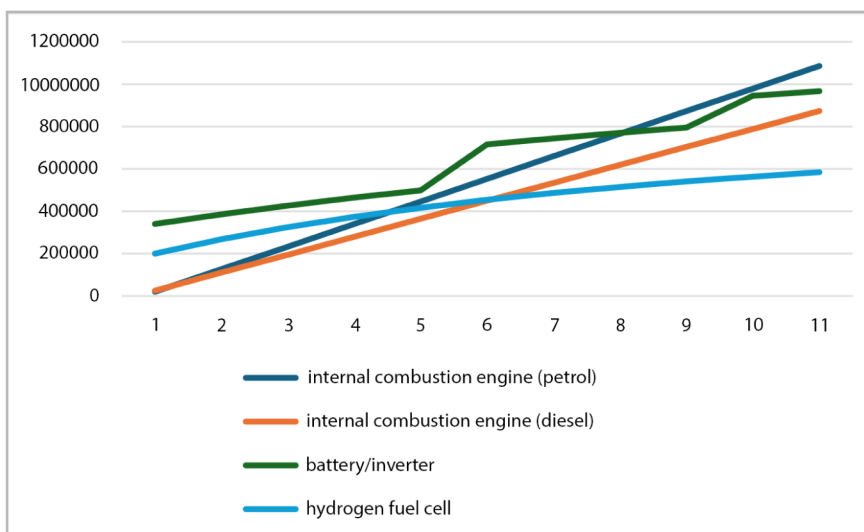


Fig. 7. NPV model with a 15 % discount rate.

5. CONCLUSIONS

- If only CAPEX is considered, internal combustion engine-powered autonomous generators are the cheapest. However, if also OPEX costs are taken into consideration, battery/inverter systems and hydrogen fuel cell systems may be cheaper in the long run.
- Battery/inverter systems are more expensive up front but can be cheaper in the long run than internal combustion engine-powered autonomous generators due to lower fuel costs.
- Hydrogen fuel cell systems are expensive at the initial stage but can be cheaper than internal combustion engine-powered generators in the long run because fuel costs are even lower than batteries/

inverters. However, it is important to note that the cost of electricity is only one factor to consider when choosing a generator. Other important factors include system reliability, efficiency and overall cost effectiveness.

- The study confirms that the production of portable hydrogen generators is promising. They have the potential to find wide application both in the national economy and in the military sector, since the operation of the generator of such technology, compared to generators powered by internal combustion engines, ensures a significant reduction in noise levels and a reduction in CO₂ emissions.

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