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ZAGOTAVLJANJE AVTONOMIJE VOJAŠNIC Z OBNOVLJIVIMI VIRI ENERGIJE

SECURING AUTONOMY OF MILITARY BARRACKS THROUGH RENEWABLE ENERGY SOLUTIONS

Povzetek V prispevku je predstavljen koncept, s katerim želi Ministrstvo za obrambo v okviru projekta Defence RESilience Hub Network in Europe vzpostaviti mrežo energetsko samozadostnih vozlišč v Sloveniji in EU za zmanjšanje energetske odvisnosti vojašnic od zunanjih virov. Matematični model mikroenergetskega sistema vojašnice vključuje več energijskih vektorjev in naprave za njihovo pretvorbo in shranjevanje s poudarkom na vodikovih tehnologijah. Primer vojašnice v Belgiji kaže, da je energetski sistem s sončno in vetrno elektrarno sposoben zagotoviti zadostno količino vodika za transport, sistem pa lahko popolnoma avtonomno obratuje do 30 dni. Hkrati je bil izračunan tudi ogljični odtis vojašnice kot energetskega sistema, ki nakazuje potencialno zmanjšanje vplivov na okolje.

Ključne besede ***Vojašnica, samozadostno obratovanje, obnovljivi viri energije, vodikove tehnologije, ogljični odtis.***

Abstract This article presents a concept of establishing a network of energy self-sufficient nodes in Slovenia and the EU, within the Defence RESilience Hub Network in Europe project initiated by the Ministry of Defence of Slovenia (MORS). The goal is to reduce the energy dependence of military facilities on external suppliers. A mathematical model of a military site's micro-grid incorporates multiple energy vectors and their conversion and storage, with a focus on hydrogen technologies. A case study of a military site in Belgium shows that an energy system with solar and wind power can provide sufficient hydrogen for transportation needs and operate the site autonomously for up to 30 days. Additionally, the carbon footprint of the military base as an energy system was calculated, indicating potential reductions in environmental impacts.

Key words ***Military site, self-sufficient operation, renewable energy sources, hydrogen technologies, carbon footprint.***

Introduction

It has long been argued that at times when human lives are at stake, other concerns and priorities are more important, thus neglecting the contribution to global carbon emissions from fossil fuels, which currently still underpin most military mobility, infrastructure, and weapons (Schaik and Akash Ramnath, 2022). The 2015 Paris Agreement does not specifically address the defence sector, leaving it up to the military to decide for itself how to meet its carbon footprint goals. According to the European Defence Agency (EDA), the European defence sector is one of the largest energy consumers in Europe, and is equivalent to the consumption of a small EU Member State (Confédération Européenne des Syndicats Indépendants (CESI), 2022). With EU ambitions for climate neutrality by 2050 (European Commission, 2019), it is important that the EU defence sector takes all the necessary steps and measures to reduce its carbon footprint. Within this approach the EU has set up the Defence RESilience Hub Network in Europe (RESHUB), which includes the sector-coupling of green mobility and green power generation in the defence and civilian sectors in already-existing military bases, with the Ministry of Defence of the Republic of Slovenia (MORS) as one of the initiators of the hub establishment project in the European Union (Mori et al., 2022a). RESHUB is a pan-European project which aims to create self-sufficient and autonomous defence capabilities within the territory of the EU by reducing energy dependence on external sources, and using renewable energy sources in sites and infrastructure managed by the ministries of defence of each participating country. This approach also ensures greater robustness of energy supply and storage, and the development of an industrial base for electric and hybrid mobility.

Under the RESHUB concept, the specifications of the advanced, comprehensive, modular, and adaptable renewable energy system have been defined to meet the identified needs of the defence sector while accommodating specific site requirements and construction. RESHUB is comprehensively designed to meet the needs of a wide range of defence applications in peacetime or emergency situations, while also providing services to the civilian sector, hence redefining the dual use (civil and defence) of novel energy systems in defence. With the objective of surpassing the current state of the art, the RESHUB concept provides a high degree of modularity which allows for optimal adaptation to the purpose and scope of RESHUB, its location, and other specific requirements. The identification process includes all the relevant components for renewable energy sources: energy conversion and efficiencies of technologies; potential energy storage systems for heating and cooling (deployable, modular, compact, and mobile units), as well as power battery racks and H2 storage systems (electrolyzer-H2 tank-fuel cell); energy generation/use from storage (efficiency of storage systems); energy distribution and optimization of energy use; energy recovery (i.e. waste heat from various sources) and interconnectivity (heating, cooling, electricity) at the site; connection to the public power grid; electric vehicle charging stations; hydrogen vehicle refuelling stations; an energy management micro smart grid; and integration with transportation (Mori et al., 2022b).

All these components inherent to specific energy vectors or their conversion to another energy vector were modelled using a mathematical model featuring a high level of modularity in terms of the topology of the system, component sizing, and operating strategies. Metadata includes component efficiencies alongside specific power/energy data, the expected lifetime, technology maturity and availability, and mature and near-mature technologies in Europe. The software code was thus developed to obtain all possible microgrid combinations, taking into account all constraints for each microsite. This means that the availability of renewable energy sources, the requirements of the specific site, the energy demand, the integration of clean transport (excess electricity and hydrogen consumption), the already-existing energy infrastructure, the proposed technical solutions and so on served as inputs to the model.

In addition to all the technologies and requirements identified, listed, and evaluated, this paper focuses on specific generic and site-specific requirements which include the following: (i) energy storage for 3, 10, and 30 days to meet the site's average and maximum electricity consumption; (ii) the ability of the storage to provide hydrogen generation and refuelling for transportation vehicles; and (iii) the energy source conditions specific to each site and (iv) early risk assessment as a basis for safety analyses. Since all the activities related to energy infrastructure, especially in the introduction of hydrogen into the energy system and in mobility, are also closely related to the reduction of environmental impacts, the carbon footprint of the different topologies and operational scenarios is evaluated to show the potentials to reduce the carbon footprint compared to the reference case (the original topology of the military site).

This paper presents the topology of the RESHUB power system, which can be deployed at any military site that has renewable energy sources (RES – e.g. sunlight, wind) for power generation. The mathematical model, developed to incorporate technologies from RES and hydrogen infrastructure, uses the metadata available for a given military site. The power system is linked to the transportation sector to provide the desired available hydrogen for mobility. Analyses were carried out for scenarios for the entire year and for the required autonomy for 3, 10, and 30 days. Data is provided for sizing the power system to meet the site's local energy consumption. The excess electrical energy flow for hydrogen conversion or possible curtailment was calculated. The environmental objective was to compare the carbon footprint for the case where electricity is drawn exclusively from the grid, with the carbon footprint for the case where part of the electricity is generated by the installed RES system and part is drawn from the grid. In addition, the carbon footprint of the heat generation at each military site was calculated to provide an overview of the sources of the carbon footprint. As a case study, a military site in Belgium is presented, where both photovoltaic panels and wind turbines could be installed to cover the electricity demand of the site.

1 CONCEPTUALIZATION OF ENERGY HUBS AND METHODOLOGY

A conceptual network of hubs has been defined within the RESHUB project, with the aim of providing self-sufficient and autonomous capabilities in support of defence capabilities within the territory of the EU to reduce energy dependence on external sources. They include local power plants for renewable energy production, conversion of surplus energy into hydrogen, storage of energy in hydrogen reservoirs, and hydrogen consumption for electricity and heat production. Each military site is a hub which is designed to address various energy and community related challenges within both the military and civil sectors, such as (i) increasing the proportion of energy from renewable sources in the energy sector; (ii) improving the robustness of the military site's energy supply; (iii) extending the duration of the military site's autonomous operation; and (iv) building a refuelling infrastructure for military and civilian electric and hydrogen vehicles.

1.1 The topology of the system

The developed concept of interconnected hubs, each of which represents an independent energy system with the topology shown in Figure 1 (see page 104), is an essential component of an EU-wide energy system which enables the transition of the military energy sector and the mobility sector to renewable energy sources, since its energy characteristics lead to a surplus of green hydrogen and/or green electricity which can be used in external power grids, industry, or transportation. The combination of green hydrogen and green electricity is crucial for achieving the future environmental targets mandated by the EU (European Commission, 2021) and is also set out in national documents.

The main building blocks of the energy system are renewable energy and appropriate energy converters to make the system reliable and efficient: photovoltaics, wind turbines and other power plants, electrolysers, hydrogen storage, fuel cells, Li-ion battery stacks, hydrogen and possibly electric fuelling stations, and an intelligent energy management system. The basic characteristics of the operation of the components are shown in Table 1.

Table 1: Basic characteristics of the elements included in the RESHUB energy system with specific operational rules

Element	Characteristics	Operational rules
PV panels	Power production depending on local solar radiation characteristics	Operates with maximum available power, eventual excess energy is consumed by the utility grid
Wind turbines	Power production depending on local wind conditions	Operates with maximum available power, eventual excess energy is consumed by the utility grid
Barracks	Power and heat consumption. Power consumption profiles are based on data provided by distributors	In the autonomy regime, electricity consumption is decreased to 60%

Hydrogen filling station	Providing hydrogen for vehicles. Hydrogen compressors present additional power consumption	Constant consumption of hydrogen and power during daytime is assumed. During the autonomy operating mode, hydrogen consumption can be reduced to 30% of the nominal value
Electrolyser	Hydrogen production from green electricity	Load follows available solar power
Fuel cell	Electricity generation	Primarily for backup during the autonomy operating mode, otherwise operates only when solar electricity is not available, and the hydrogen tank is over 80% full
Battery	Storage of surplus electricity	Operating range during the normal operating regime is between 50% and 90%, during the autonomy regime it can be discharged down to 10%
Hydrogen tank	Storage of hydrogen	When it is discharged below 25%, hydrogen is added from an external source (outside contractor)

The designed energy system interacts with external hydrogen and electricity networks as a producer or consumer, depending on the needs of the system and the environmental conditions. However, its operation is designed to generate enough green hydrogen or green electricity to meet the daily consumption of military and civilian vehicles during specified periods of time. In addition to supporting mobility based on renewable hydrogen, the hub provides local energy generation and storage of renewable electricity and green hydrogen for an extended period of time, and significantly reduces dependence on external energy sources, providing a local, independent, reliable energy source for the autonomous operation of military sites in the event of natural disasters and crises (autonomy operation case).

In addition, the system is designed to provide efficient military-civil dual use, i.e. to help the civilian population during energy supply interruptions (e.g. power outages, natural disasters, etc.). Additional power generation, storage, hydrogen, and an electric charging system can support and strengthen the national energy and transportation systems. In addition, highly energy-efficient systems can help balance the grid, increase grid flexibility, facilitate the integration of RES, improve energy security, and lead to reduced energy imports. The designed system can be operated to either increase hydrogen production to support hydrogen mobility, or to use renewable solar power for grid stabilization or electric mobility, adapting to the current conditions. Additional advanced modes of operation can be developed through a network of interconnected hubs that can take advantage of local conditions and operate as an independent grid within the national electricity and hydrogen grids. A network of hubs can also participate in power-to-gas activities by injecting hydrogen into the national natural gas distribution network, thus influencing the energy system in a larger part of the country, not only in the local communities around the developed energy hubs.

The developed energy system provides technologies to support local communities in developing environmentally friendly public and private transport, while addressing four EU policies: Environmental Policy ("Environment Policy: General Principles and Basic Framework | Fact Sheets on the European Union | European Parliament," n.d.), Energy Policy ("New Energy Efficiency Directive published," n.d.), the Common Security and Defence Policy ("The Common Security and Defence Policy | EEAS," n.d.) and Safe, Sustainable and Connected Transport ("Safe and sustainable transport | European Union," n.d.).

1.2 Methodological approach and boundary conditions

The specific requirements for the operation of a military site's microgrid power system required a custom-developed mathematical model of the system (Figure 2, see page 104), as available commercial tools do not provide sufficient flexibility in terms of freely defining operating strategies; in this specific case hydrogen does not necessarily represent only an energy storage functionality, its sufficient production represents one of the key requirements of the system. The simulations are based on predefined series of possible energy production with solar power plants and wind turbines, and profiles of electrical energy and hydrogen consumption. Electricity generation at a solar power plant and a wind turbine power plant was estimated using data for a reference meteorological year provided by publicly accessible databases ("Renewables.ninja," n.d.). The orientation and inclination of the solar modules were determined according to the location of the military site, while the installed power was adjusted to the site's electricity consumption. A commercially available model of the wind turbine was selected, whose annual energy output approximately matches the consumption of electricity of the military site. The electricity consumption profiles for the military site were determined using available consumption data and are described in (MORI et al., 2022b). The hydrogen consumption profile for transportation was estimated, because detailed information is not available. The consumption of hydrogen at the refuelling station is evenly distributed between the hours of 7am and 9pm. In addition, the electricity consumption profile of the hydrogen refuelling station is linked to the hydrogen consumption profile, and is estimated based on the specifications of the refuelling station.

The mathematical model calculates the electrical energy and hydrogen balance of the system for each hour of a year (8760 time steps). Taking into account the available electrical energy and consumption, the following rules for the energy management and control of the microgrid were implemented in the mathematical model:

1. The available renewable energy sources (solar, wind) are used in a different order of priority in normal mode (Figure 3, see page 105) and in autonomous mode (Figure 4, see page 105). In normal operation mode the priority is (i) electrolyser, (ii) barracks and refuelling station, (iii) battery, and (iv) utility grid.

During the autonomous operating regime (Figure 4, see page 105) the priority is (i) barracks and refuelling station, (ii) electrolyser, (iii) battery, and (iv) utility grid.

2. Electricity for the local grid (barracks and refuelling station) is provided from a variety of sources (Figure 5, see page 106), ranked as follows: (i) RES (solar and wind) power plant, (ii) fuel cell, (iii) battery, and (iv) utility grid.
3. In normal mode, the fuel cell operates only when renewable energy is not available and when the level in the hydrogen tank exceeds a specified limit, which depends on operation strategy and should provide sufficient hydrogen for the expected consumption. The hydrogen limit in autonomy mode is typically lower than in normal mode, as hydrogen is not being saved for an eventual critical situation.
4. The electrolyser is powered exclusively by energy from the RES solar or wind power plant, and the power consumption follows the available solar energy up to its rated power.
5. An external hydrogen source is used to maintain the hydrogen tank at a certain minimum level which enables the self-sufficiency of the system during the autonomy mode.

2 THE CARBON FOOTPRINT OF THE MILITARY SITE

The life cycle assessment method (LCA) was used to calculate the carbon footprint of energy production at the Belgian military site for all the modelled operating regimes (International Organization for Standardization, 2006a; International Organization for Standardization, 2006b). The goal of the study was to compare the carbon footprint of power generation (electricity and heat) at the observed military site for different operating regimes: the base case and simulated scenarios (‘solar, ‘wind’, and ‘combined’ cases). The scope of the study was the operation of the military site in one year. The functional unit was the energy required (based on the consumption profile) for the operation of the military site (electricity, heat), with additional hydrogen demand (24,638 kg) for the mobility sector. The inventory data were determined based on the results of the energy balance for the different operating regimes of the military site. Environmental footprint methodology (“Developer Environmental Footprint (EF) -,” n.d.) was used as a life cycle impact assessment (LCA) methodology, with the goal of evaluating the carbon footprint as a targeted indicator of environmental impact. Gabi Sphera software with an integrated generic database was used for modelling to determine the emission factors (“Sphera LCA Data - Most Reliable LCA Data | Sphera (GaBi),” n.d.). The emission factors used in this study do not follow the GHG protocol but include upstream emissions for all processes in the energy system. The emission factors used in the calculation are presented in Table 2, where the carbon footprint of each technology included in the observed energy system is listed for specific conditions in Belgium. The reference year of data is 2018, with validity till 2023.

Table 2: Climate change (carbon footprint) of different technologies per unit for Belgium according to Environmental Footprint 3.0 life cycle impact assessment methodologys

Climate change, kg CO2 eq.			
Description	Label	CF	Units
PV electricity	PV BE	0.0695	kg CO2 eq./kWh
Wind electricity	Wind BE	0.00717	kg CO2 eq./kWh
Electricity grid mix	BEmix	0.207	kg CO2 eq./kWh
H2 with PV electrolysis	H2-PV BE	3.84	kg CO2 eq./kg
H2 with Wind electrolysis	H2-Wind BE	0.44	kg CO2 eq./kg
H2 with electricity mix electrolysis	H2-Bemix	11.3	kg CO2 eq./kg
Thermal energy from light fuel oil	Heat LFO BE	0.32328	kg CO2 eq./kWh
Thermal energy from natural gas	Heat NG BE	0.22572	kg CO2 eq./kWh
Average diesel passenger car	Car – diesel	0.16844	kg CO2 eq./km
Average diesel truck	Truck – diesel	0.8654	kg CO2 eq./km

For mobility (cars, trucks andfuel cell electric vehicles – FCEV), technology production (car production) is not considered, as emission factors are only associated with the fuel consumption of cars and trucks with diesel engines and the hydrogen consumption ofFCEVs. Additional assumptions:

- Data for LCAs are taken from the results of mathematical modelling of mass and energy balances in RESHUB;
- In the case of hydrogen distribution by the contractor, the grey hydrogen is assumed to show the potential of green hydrogen generated on site with the RES power system;
- In the case of power supply to the Belgian military site from the grid, the Belgian electricity mix is used;
- In the case of surplus from RES, the electricity is fed into the grid. In this case, we can assume avoided impacts according to the carbon footprint of the Belgian electricity mix;
- The carbon footprint of heat generated with light fuel oil and natural gas is assessed for the Belgian military site. However, the heat energy system was not the focus of this study, although it is an important contributor to the overall carbon footprint of the military site.
- The avoided carbon footprint due to hydrogen sold to third parties was assessed using electrolysis with the Belgian electricity mix;
- The mobility sector was included to define the baseline condition. The baseline in the mobility sector assumes the use of diesel fuel, which emits large amounts of greenhouse gases.

Although the boundaries of the energy system under consideration (mass and energy flows) are fixed to the military site, it could also be assumed that environmental impacts are avoided by the use of hydrogen in the mobility sector, and the RES power distribution (instead of the Belgian energy mix) in the power grid. In the baseline scenario, which is optimal from an operational and environmental perspective, 24,638 kg of hydrogen is provided for the mobility of military and/or public sector vehicles. Under a classical stoichiometric approach, which does not include vehicle production (which would further expand the observed system), the use of hydrogen in various FCEVs would not generate a carbon footprint. The assumptions made to align diesel and FCEVs are:

- In the case of passenger cars, current passenger cars with an average fuel consumption of 5-7 L of diesel fuel per 100 km will be replaced by fuel cell passenger cars with a fuel consumption of 0.9-1 kg of hydrogen per 100 km. In the case of FCEVs, this means a 40-55% reduction in energy consumption per kilometre;
- For trucks, current trucks with an average fuel consumption of 30-40 L of diesel fuel per 100 km will be replaced by fuel-cell-powered trucks with a fuel consumption of 7-10 kg of hydrogen per 100 km. This means 10-25% less energy consumption for FCEV trucks;
- The 24,638 kg of hydrogen is equivalent to about 81,300 L of diesel fuel when compared to the lower heating value. However, to evaluate the avoided carbon footprint, the aforementioned lower energy consumption in the vehicles' tank per distance travelled must also be taken into account, meaning that 24,638 kg of hydrogen allows for:
  - driving 2,737,555 km in a fuel-cell-powered passenger car consuming 0.9 kg of hydrogen per 100 km, and avoiding the consumption of the 136,877 L of diesel fuel which would be required to drive the same distance in a diesel-engine passenger car consuming 5 litres of diesel fuel per 100 km;
  - driving 2,463,800 km in a fuel-cell-powered passenger car consuming 1 kg of hydrogen per 100 km, and avoiding the consumption of the 172,466 L of diesel fuel which would be required to drive the same distance in a diesel-engine passenger car consuming 7 litres of diesel fuel per 100 km;
  - driving 351,971 km in a fuel-cell-powered truck consuming 7 kg of hydrogen per 100 km, and avoiding the consumption of the 105,591 L of diesel fuel which would be required to drive the same distance in a diesel-engine truck consuming 30 L of diesel fuel per 100 km;
  - driving 246,380 km in a fuel cell-powered truck consuming 10 kg of hydrogen per 100 km, and avoiding the consumption of the 98,552 L of diesel fuel which would be required to cover the same distance in a diesel-engine truck consuming 40 L of diesel fuel per 100 km.

If we convert these numbers to a carbon footprint, we get the not produced carbon footprint due to avoiding the use of diesel cars or diesel trucks. This is called avoided carbon footprint:

– 461.11 t CO_2 eq. using only passenger cars (average passenger car diesel, average load, 5 L diesel per 100 km, 0.16844 kg CO_2 eq./km).
– 304.59 t CO_2 eq. in the case of truck use (average truck diesel, average load, 30 L of diesel per 100 km, 0.8654 kg CO_2 eq./km).

3 RESULTS AND DISCUSSION

The same topology and strategy, with fixed sizes of basic elements and variable parameters, were used at all the military sites observed in RESHUB. The fixed parameters were an electrolyser of 500 kW, a battery of 1000 kWh, a hydrogen tank of 4000 kg, and a fuel cell of 400 kW. The fuel cell, which is not used in normal operation, was scaled to peak consumption. Three cases with different topologies were simulated: (i) the 'solar' case: power generation exclusively by the PV system; (ii) the 'wind' case: power generation exclusively by the wind turbine; and (iii) the 'combination' case: power generation with a combination of the PV system and the wind turbine. The main objective was to provide sufficient hydrogen for the refuelling station, i.e. 67.5 kg/day (the same at all the military sites), and electricity for normal operations according to the consumption profile of the military site. Other definitions, assumptions, or constraints included:

a) Electricity consumption: consumption profiles were generated using the available daily consumption data for 2017-2019;

b) The available solar power was based on data from renewables.ninja ("Renewables. ninja," n.d.) for a 1000 kW system with an azimuth of 0° and a tilt of 40°;

c) The available wind power was based on data from renewables.ninja ("Renewables. ninja," n.d.) for a 1000 kW turbine of type Vestas V90 2000, with a hub height of 80 m.

d) The variable parameters were the nominal power of the solar power plant, and the nominal power of the wind turbine.

3.1 Modelling the energy balance of the Belgian military site

Figure 6 (top, see page 106) shows the graph of available solar and wind energy at a given location, with electricity consumption based on consumption profiles created from available daily consumption data for 2017-2019.

Table 3 shows all the settings and basic results for all three cases considered. The sizes of the power generation system of the RES are (i) a PV system of 3000 kWp in the 'solar' case; (ii) a wind turbine of 800 kW in the 'wind' case; and a PV system of 1600 kWp and a wind turbine of 800 kW in the 'combined' case. The 'module area' listed in Table 3 is estimated from the installed power, with overall module efficiency estimated to be 19%. For the 'solar' case, the power of the electrolyser was increased to 1000 kW to reduce the required power of the PV power plant, since with a 500 kW electrolyser, the rated power of the solar power plant would have to be 9000 kW to meet the energy balances throughout the year. The sizing of the hydrogen system (electrolyser, hydrogen tank, refuelling station, and fuel cell) was based on the systems analysed for military sites in the RESHUB project, since detailed information on the expected hydrogen consumption at the Belgian military site was not available.

Table 3: Settings and basic results of the 'solar', 'wind' and 'combined' cases at a military site in Belgium

	Solar case	Wind case	Combined case	Units
Settings				
Solar power plant				
Total module area	15800	/	8420	m²
Installed power	3000	/	1600	kW
Azimuth/tilt of panels	0° / 40°	/	0° / 40°	
Wind power plant				
Installed power	/	800	800	kW
Hub height	/	80	80	m
Electrolyser				
Maximum power consumption	1000	500	500	kW
Minimum power consumption	50	50	50	kW
Average efficiency	0.55	0.55	0.55	
Maximum H2 charge	0.95	0.95	0.95	
Fuel cell				
Maximum power output	650	650	650	kW
Average efficiency	0.55	0.55	0.55	
Battery				
Capacity	1000	1000	1000	kWh
Maximum charge	0.9	0.9	0.9	
Minimum charge	0.1	0.1	0.1	
Charging efficiency	0.94	0.94	0.94	
Discharging efficiency	0.94	0.94	0.94	
Hydrogen tank				
Capacity	4000	4000	4000	kg
Maximum charge for adding hydrogen	0.25	0.25	0.25	
External H2 input	100	100	100	kg
Refuelling station				
Average compressor consumption	13.75	13.75	13.75	kW
Results				
Site				
Energy consumption	1686	1686	1686	MWh
Energy from grid	1091	1501	506	MWh
Energy to grid	1431	96	1147	MWh
Solar power plant				
Produced energy	3895	/	2077	MWh
Load factor	0.1482	/	0.1482	
Wind power plant				
Produced energy	/	2130	2130	MWh
Load factor	/	0.3039	0.3039	

	Solar case	Wind case	Combined case	Units
Electrolyser				
Energy consumption	1767	1767	1767	MWh
Hydrogen output	24640	24637	24637	kg
Surplus hydrogen	0	0	0	kg
Load factor	0.2017	0.4034	0.4034	
Battery				
Energy input	226.6	51.83	327.8	MWh
Energy output	200.2	45.8	2889.6	MWh
Roundtrip efficiency	0.8836	0.8836	0.8836	
Hydrogen tank				
Min. mass of hydrogen	1186	1170	3700	kg
Max. mass of hydrogen	3809	3807	3807	kg
Added hydrogen	0	0	0	kg
Refuelling station				
Energy consumption	75.28	75.28	75.28	MWh
Hydrogen output	24640	24640	24640	kg

The electrolyser is set to operate only until a certain state of charge of the hydrogen tank is reached, so no excess hydrogen is produced if this state of charge is reached. The fuel cell does not operate in the normal operating mode, as it only serves as an additional energy source in the autonomous mode, while in the other operating regimes shorter-term balancing of electricity is managed by batteries, which feature higher electrical energy roundtrip efficiencies. If hydrogen production is insufficient, hydrogen can be supplied from an unspecified and unlimited external source in charges of 100 kg per hour, as long as the hydrogen charge remains below the specified 25%. This limit ensures that at least 1000 kg of hydrogen is always available in emergency situations where autonomous operation is required. However, the proposed system topologies provide sufficient quantities of hydrogen throughout the year and the mass of stored hydrogen never falls below 1000 kg, so no additional hydrogen is required. With a sufficient supply of hydrogen, the refuelling station is also able to operate as planned and deliver the required amount of hydrogen to consumers, both military and civilian vehicles.

The monthly and annual integrals of electrical energy generated and consumed in the 'solar' case are shown in Figure 7 (see page 107). The installed capacity of the PV power plant must be much higher than the rated capacity of the electrolyser, because of the low PV load factor in winter. This results in a large amount of PV electricity being fed into the grid. However, despite the large surplus of electrical energy from the PV plant, the system also needs electricity from the grid to meet energy demand during the night and during periods with low solar irradiation.

In the 'wind' case (Figure 8, see page 107), the installed power of the wind turbine (Table 3) is comparable to the rated power of the electrolyser because there is a constant wind supply at the microsite. Since the wind turbine mostly meets the energy demand of the electrolyser, only a negligible amount of electricity is fed into the grid. However, the energy needs of the barracks must be met with energy from the grid. The system is primarily designed to supply hydrogen consumers, but it can also be operated in autonomous mode. The power consumption of the barracks and the refuelling station from the utility grid during normal operation is therefore not a concern.

In the 'combined' case, the wind turbine still provides enough energy for hydrogen production, while at the same time PV energy can be used by other consumers (the barracks and refuelling station). This results in only a small amount of energy being required from the grid (Figure 9, see page 108). The energy consumption from the grid can be further reduced by increasing the capacity of the PV or wind turbines, but this leads to an even more oversized energy system and a significant increase in the energy surplus.

3.2 Autonomy of the Belgian military site

In the autonomy calculations, the combined case was evaluated using the topology and boundary conditions presented in the previous section (Table 3; Figure 9, see page 108). The potential of autonomous operation (without the grid and without an external hydrogen source) was tested for 3-, 10-, and 30-day autonomous operation, starting at different times of the year. The simulations showed that the system can operate fully autonomously for 30 days with combined electricity. Wind energy is distributed relatively evenly throughout the year, and together with solar energy is sufficient for daily hydrogen consumption. The hydrogen level in the hydrogen tank remains constant and can be kept at the upper limit (Figure 10, see page 108).

The stored hydrogen serves as reserve energy for emergency situations. Figure 11 (see page 109) shows the system operating in the autonomous mode starting at 0 AM of the fourth day of the year (autonomy is critical at the beginning and end of the year; in summer, photovoltaics provide sufficient energy for normal operation). In the autonomous mode energy is supplied by renewable sources, the fuel cell and the battery (Figure 11, middle) while the grid (Figure 11, top) is off. The fuel cell is only in operation during the autonomy mode (green line, Figure 11, middle). As a result, the hydrogen content decreases (dark green line, Figure 11, bottom). It can be seen that even after 30 days of autonomous operation, the hydrogen level is still well above 50% (dark green line, Figure 11, bottom), since the electrolyser is still able to provide some hydrogen (light green line, Figure 11, bottom) with the surplus of renewable energy. Operation of the electrolyser intensifies after the end of the autonomous mode and the hydrogen level increases (light and dark green lines, Figure 11, bottom). This means that the system may be able to survive even longer periods of autonomous operation.

3.3 Carbon footprint of the Belgian military site

The results of the different operating regimes are presented in comparison to the base case, which represents the carbon footprint of the military site prior to each proposed and simulated scenario ('solar, 'wind', and 'combined case'). In the base case the carbon footprint of electricity, heat and diesel (for the mobility sector) consumption is included. The amount of diesel included is calculated based on the hydrogen use (24,638 kg) alternative using passenger cars or trucks (presented in Section 3). The emission factors used are presented in Table 2 for Belgian energy generation technologies. The results are presented in Table 4 and in the diagram in Figure 12 (see page 109).

Table 4: Carbon footprint (CF) for three operational regimes at the Belgian military site, in t CO_2 eq./year

Carbon footprint in tons	base case	solar	wind	combined
PV	0.00	230.96	0.00	123.18
Wind	0.00	0.00	15.30	15.30
GRID	349.03	229.97	311.19	110.94
H2 supplied	0.00	0.00	0.00	0.00
Avoided (SURPLUS RES to grid)	0.00	-300.80	-20.50	-242.95
Avoided (H2 surplus)	0.00	0.00	0.00	0.00
Heat	2246.13	2246.13	2246.13	2246.13
CF-car (high)	461.11	0.00	0.00	0.00
CF-TRUCK (low)	304.59	0.00	0.00	0.00
CFTOT	High: 3056.27 Low: 2899.75	2406.25	2552.09	2252.56

From the results of the carbon footprint of the Belgian military site for one year of operation in the three scenarios, we can see that heat generation has by far the largest share of the total carbon footprint in the Belgian case, as natural gas and light fuel oil are used for heating. In the 'solar' case and the 'combined case' there are some avoided impacts due to the surplus of PV or wind power fed into the grid.

The combined case represents the optimum, with a relatively low carbon footprint from PV and wind power. There are fewer avoided impacts due to excess electricity than in the solar case, however the total carbon footprint for the combined case is lower than in the solar case. The carbon footprints for the analysed cases show that they all have a lower carbon footprint than the base case.

Conclusion

Several operating scenarios were simulated for the military site using a mathematical model, which was developed with the aim of enabling the analysis of the specifics of advanced multi- energy vector systems in defence, to determine the impact of various operating strategies, component sizing, renewable energy sources, and other relevant operating parameters. In the analysed case, green hydrogen is generated on-site using photovoltaic or wind energy, while in the case of hydrogen shortcomings, hydrogen could be delivered to the site from a distributor or other military site in RESHUB. In the latter approach, the military sites included in RESHUB could use energy in the form of green electricity or green hydrogen from other military sites that have excess energy at any given time. This increases the autonomy of each military site integrated into RESHUB.

The conceptualization of RESHUB is presented based on the analysis of hourly consumption, the predefined topology of the energy system, the availability of RES, the required daily hydrogen consumption, and technologies included in the RESHUB energy system. One of the main tasks in the study was to answer the question of whether the 3-, 10- and 30-day autonomy of a military site in a critical situation is possible with unchanged consumption of energy. It was shown that a system with combined solar and wind power supply is capable of providing both sufficient hydrogen and electricity for autonomous operation for up to 30 days.

Most of the hydrogen produced at military sites is used in the mobility sector: military vehicles or civilian cars and trucks. The use of green hydrogen in the civilian sector also establishes the coupling of the military and civilian mobility sectors, and in addition, the green electricity fed into the country's power grid represents a coupling of the military and electricity sectors.

The annual carbon footprint of the military sites was calculated for all the modelled scenarios. Although the focus of the mathematical modelling was on electricity and hydrogen generation, the heat generated was included in the carbon footprint assessment, as it is the largest contributor to the carbon footprint due to the large amounts of fossil fuels used (natural gas, LFO, etc.). The mobility sector was also included in the carbon footprint assessment to show the reduction in the carbon footprint by using hydrogen instead of diesel fuel for transport. Apart from heating, it was shown that in some scenarios a large amount of avoided carbon footprint can be expected due to the injection of green electricity into the power grid and the surplus of green hydrogen that can be sold to third parties. If the system considered is extended to include hydrogen mobility, there is a further significant indirect avoided carbon footprint.

From an environmental and a financial point of view, it is very important to take other measures, such as building insulation, use of RES (biomass, solar panels), heat pumps, geothermal energy, etc., to optimize heat production, reduce its environmental impact and de-fossilize heat production. In addition to insulation, one of the fundamental steps in heat distribution is the renovation of the heat distribution system, where there are already large energy losses.

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Figure 1
Basic topology of the RESHUB energy system (Mori et al., 2023)

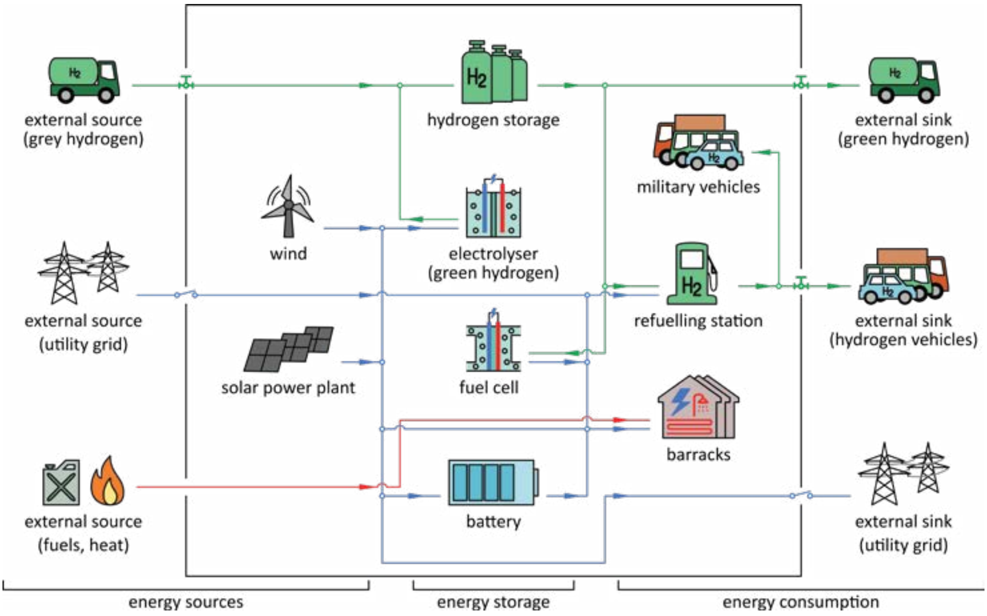


Figure 2
The structure of the custom-developed mathematical model

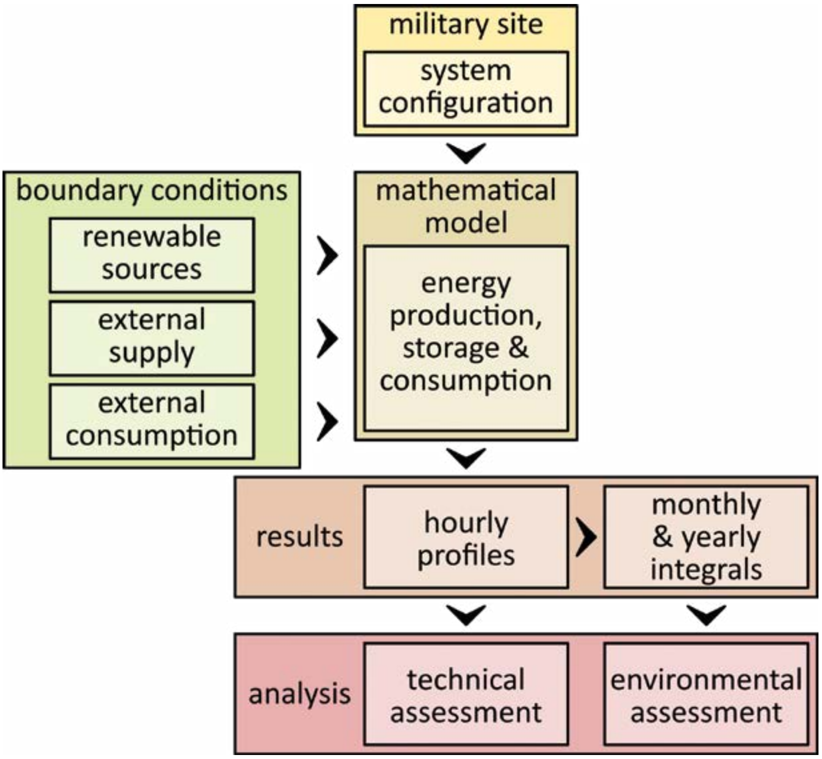


Figure 3 Priority of RES use during normal operation

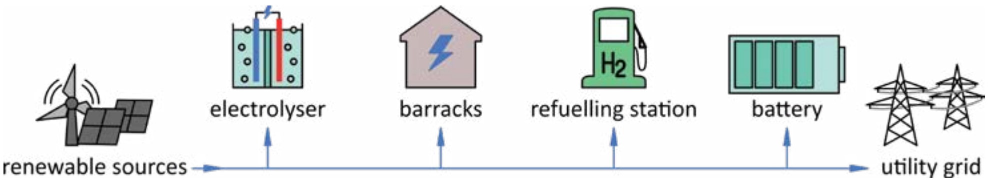


Figure 4 Priority of RES use during autonomous operating regime

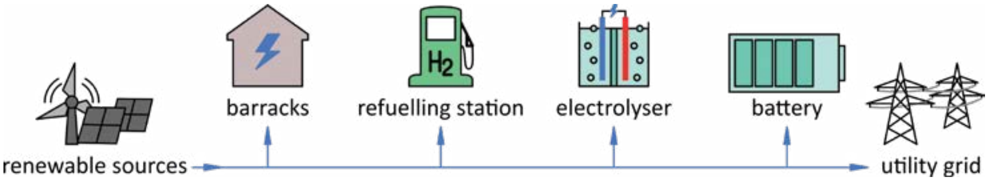


Figure 5 Priority of provided electricity from available sources

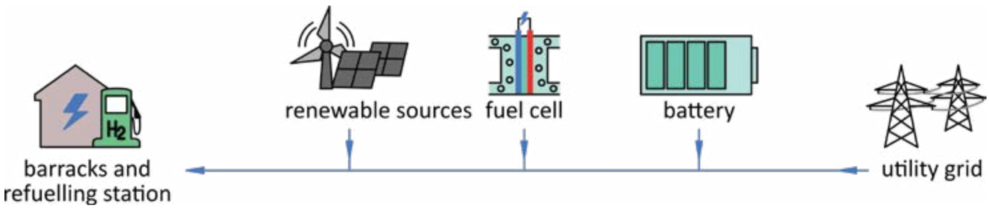


Figure 6 RES availability and consumption profile, military site, Belgium

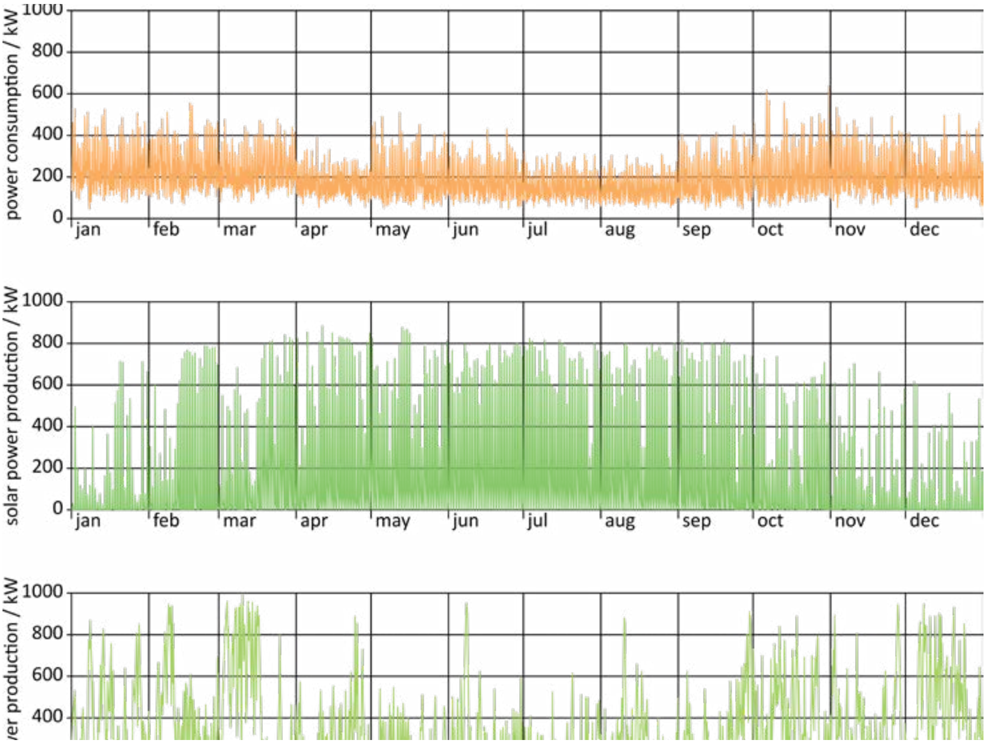


Figure 7
Monthly and yearly integrals of generated and consumed electric energy in the 'solar' case at a military site in Belgium

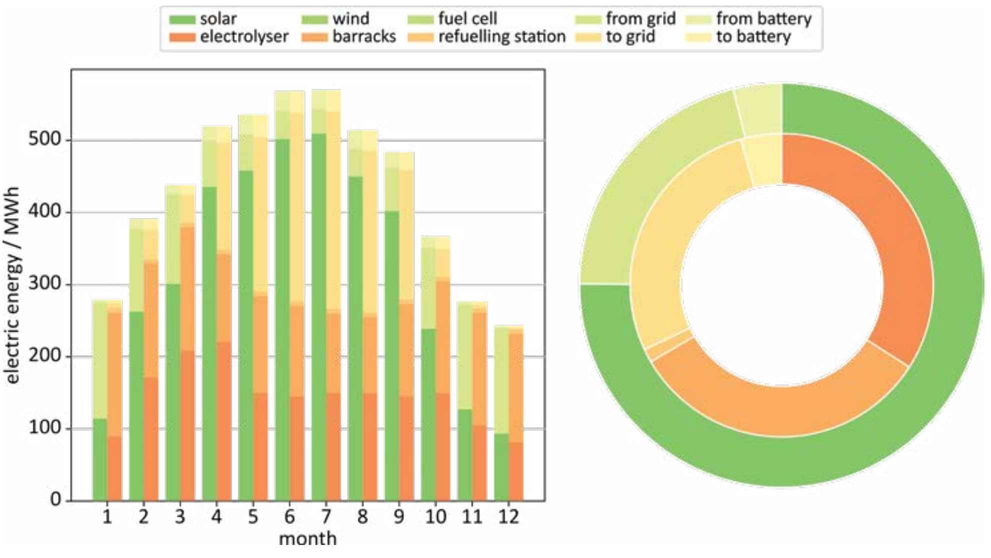
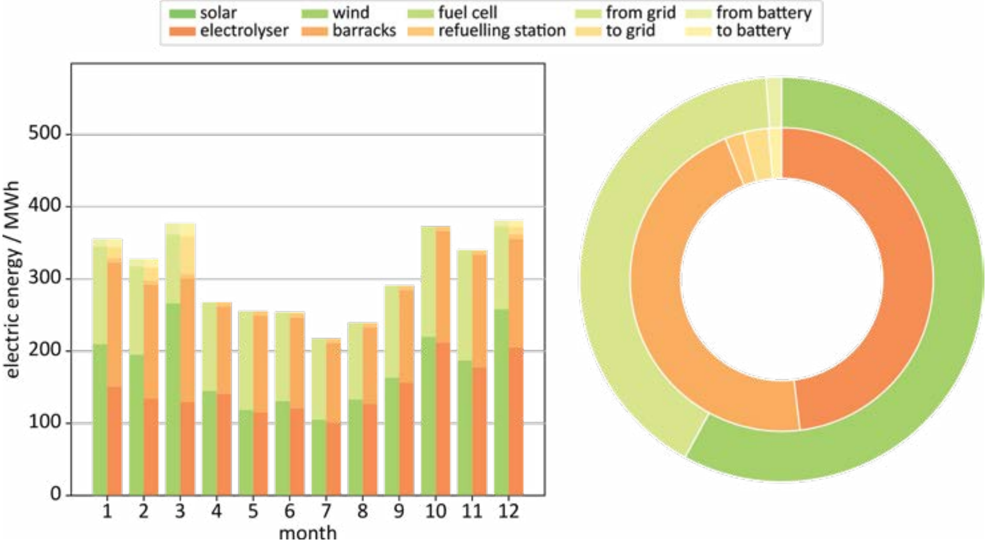


Figure 8
Monthly and yearly integrals of generated and consumed electric energy in the 'wind' case at a military site in Belgium



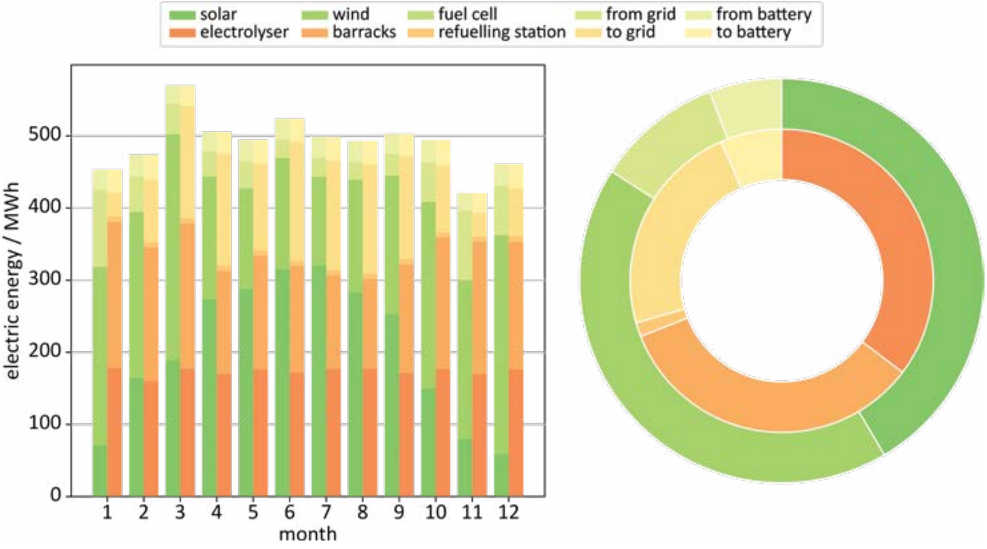


Figure 9 Monthly and yearly integrals of generated and consumed electric energy in the 'combined' case at a military site in Belgium

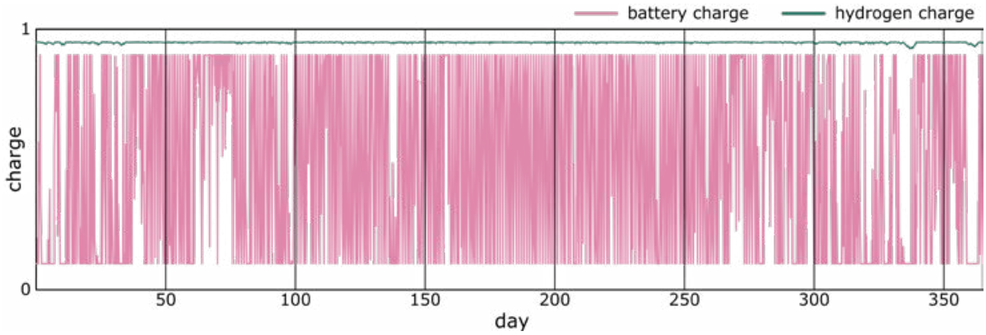


Figure 10 State of battery charge and hydrogen charge during normal operation at a military site in Belgium

Figure 11 Detailed view of system performance during autonomous operation at a military site in Belgium

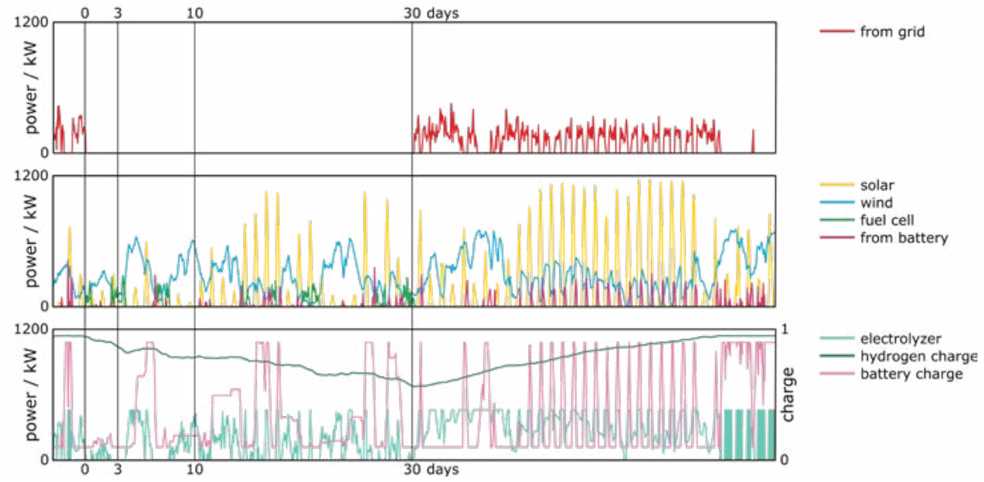
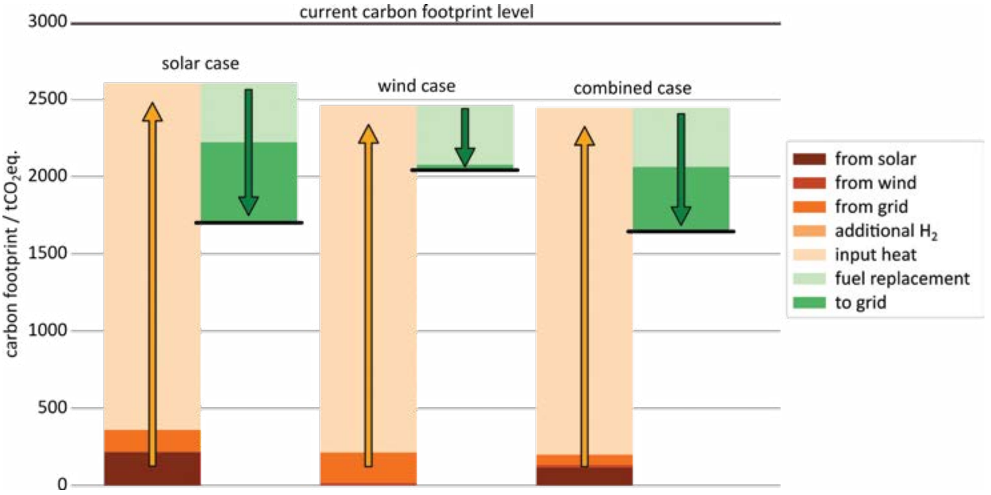


Figure 12 Total one-year carbon footprint in tons CO2 eq. for the Belgian military site



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Boštjan Drobnič, PhD, holds a PhD in Mechanical Engineering. He works at the Faculty of Mechanical Engineering, University of Ljubljana as an assistant and researcher in advanced energy systems, hydrogen technologies, and life cycle assessment. He has actively contributed to numerous national and international projects within the Laboratory for Heat and Power. Since 2015, he has been a member of the editorial board for ŠTeKam, a student technical conference. His expertise is evident in over 60 published papers and over 40 expert reports, showcasing his significant impact in the field.

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