NATO Energy Security Centre of Excellence

PHASE 1 REPORT

Performance Analysis

of

Hybrid Power Generation and Management System

(HPGS)

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Author: CDR Andrea Manfredini (ITA-Navy)

Co-Authors: Adam Capell, Domantas Paluckas, Gintaras Labutis

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Executive Summary

Information sharing is an essential element of the mission mandated to NATO Energy Security Centre of Excellence (ENSEC COE). In this way allies and partner nations can receive maximum benefit from the activities carried out by the organizations of the Alliance.

This Report summarizes the experience gained by NATO ENSEC COE over 2016-2018 when the possibility of using a deployable Hybrid Power Generation and Management System (further HPGS) capable of exploiting renewable energy sources (solar, wind) as well as conventional power generation (diesel fuel generators) had been tested. Where possible, direct comparative tests were conducted with conventional power generators. Additionally, the feedback from the personnel responsible for operating and servicing the HPGS was received and analyzed.

The Report gives the analysis of HPGS prototype delivered by PFISTERER Kontaktsysteme GmbH (further PFISTERER) in 2016 as part of a NATO ENSEC COE five-year project with the objective to investigate HPGS as a valuable solution in increasing the energy security at military deployed camps. It details the progress of HPGS testing history and provides the analysis of three-year test results, including the deployment during three national/international military exercises.

The HPGS analysis was concentrated on the following key aspects such as fuel savings from hybrid power generation, HPGS deployment functionality with the focus on its ease of operation, installation, logistics and transportability. The analysis also includes theoretical calculations with the comparison of actual fuel savings together with internal HPGS energy demand and the increase the time between the regular HPGS generators' maintenances.

It has to be mentioned that **currently the HPGS is still in the prototype and testing phase** so further improvements based on the recommendations of this Report are expected.

During the HPGS tests it was found that the deployment of HPGS resulted in fuel savings that varied from the demand levels and demand patterns. In addition, the contribution of renewables during the tests was dependent on specific ambient conditions (sun, wind). This suggests that although the renewable power positively impacts on overall energy security of the military deployed camp, it would be an optional add-on, especially for Tier-1 and Tier-2 camps[1], rather than the necessity.

During the tests it was found that HPGS was quite vulnerable to mechanical impacts the System experienced during its transportation to the exercise area, especially its Mobile Energy Management System (further MEMS). Thus further design and reliability improvements has to be made with regards to HPGS robustness and resilience.

[1] Tier-1 DFI camp is described as infrastructure where the personnel will operate under field conditions. It will span a period of several weeks or months. Tier-2 camp provides basic support for the initial phase of operation. It provides only austere working and living space. It will span the period of between one and two months to two years.

To conclude, the results obtained from the HPGS performance analysis indicate that there is an encouraging evidence to use the hybrid electric generation systems (diesel generators, storage batteries and renewable power generation sources) in military deployed environments. However, in this particular HPGS analysis, the usage of renewables (i.e. photovoltaics and wind power) has raised additional questions regarding further applications.

Keywords: HPGS, Hybrid Power Generation, Renewables, Alternative Energy Sources, Generators, Deployed Force Infrastructure – DFI, Energy Security, Energy Efficiency, NATO, NATO ENSEC COE.

Contents

I. Abbreviations and Acronyms

AC – Alternating Current

ADR – European Agreement concerning the International Carriage of Dangerous Goods by Road

CIS – Communications and Information System

CRO – Crisis Response Operations

DC – Direct Current

DFI – Deployed Force Infrastructure

NATO ENSEC COE – NATO Energy Security Centre of Excellence

FAT – Factory Acceptance Test

HPGS – Hybrid Power Generation and Management System

MEMS - Mobile Energy Management System

IATA – International Air Transport Association

IESMA – Innovative Energy Solutions for Military Applications, the Bi-Annual Conference organized in Vilnius, Lithuania, by NATO ENSEC COE

IMDG – International Maritime Dangerous Goods

ISO – International Organization for Standardization

LAN – Local Area Network

MCR – Maximum Continuous Rating

NATO – North Atlantic Treaty Organization

NMC – Lithium Nickel Manganese Cobalt Oxide

NSIP – NATO Security Investment Program

PV – Photovoltaic

SHAPE – Supreme Headquarters Allied Powers Europe

SOC – State of Charge

II. List of Tables

III. List of Figures

1. Introduction

Reliable and flexible sources of power generation are essential to increase the operational capabilities, while also optimizing the use and management of energy resources.

Deployable modular Hybrid Power Generation System (HPGS) is designed to reduce fuel consumption by increasing power generation efficiency and therefore improving the energy supply security of the military camps. This is achieved with energy storage technologies, namely with high capacity batteries by storing surplus energy and returning it to the load when needed. The batteries also provide additional security of power in case of short term diesel generators failure. A HPGS system also can incorporate renewable sources of energy, such as PV and wind generation to further reduce diesel generators' fuel consumption. It has been demonstrated that hybrid power systems can reduce fuel consumption by 20% – 30%[2] along with further increase of time between the regular diesel generators maintenance. The aim of such systems is to achieve a continuous secure supply of energy while minimizing the use of conventional fuels thus ensuring the effectiveness of energy usage during military operations. These systems can also provide indirect but essential benefits like reducing the logistics burden in risky environments as reduced fuel consumption means fewer resources are needed to be supplied to the camp and less frequent thus minimizing human life risks. A Deployed Force Infrastructure's reduced demand for fuel improves its energy security and resilience when fuel supplies become difficult to obtain as HPGS has the capacity to store the energy and is able to produce energy from the renewables.

In 2015 NATO ENSEC COE started the project, Deployable modular HPGS[3]. The key 5-years project objectives were to test the feasibility of such System for military applications. PFISTERER, a German company, expert in power generation and distribution technologies, was announced as the winner of the international tender with its hybrid power generation solution - Hybrid Power

[2] Total savings achieved are dependent on average load of the system and ambient/weather conditions.
[3] The purchase of HPGS was funded by the Canadian Government (total value of the project: 1.000.000 CAN dollars).

Generation and Management System (HPGS) that included two diesel generators, battery storage, solar panels and wind generator together with Mobile Energy Management System (MEMS). Additionally, two smaller generation capacity – Mini HPGS were supplied.

Based on a five-year Cooperation Agreement signed on the 4th of February 2016 between NATO ENSEC COE and the LTU Ministry of Defense, the HPGS was delivered to the Logistics Battalion of Lithuanian Armed Forces in Marijampolė city, Lithuania, in order to test HPGS efficiency and overall benefits in the operational environments.

The HPGS prototype was designed to provide a maximum 150 kW peak generation and to be deployable especially in Tier 1 and Tier 2 DFIs[4], supporting approx. 100 - 150 pax energy needs. It was required that the System should be robust, reliable and modular with good deployable capabilities regarding the transportation and the set-up.

The main components of HPGS consisted of two 75 kW diesel generators, 25 kWp PV array, 6.5 kWp wind turbine and 100 kWh battery pack. The HPGS was controlled via MEMS.

Over the three year period the Project goals were to:

1. Analyze HPGS performance in providing electricity for DFIs and to investigate whether HPGS would be beneficial for military use in saving fuel and increasing energy security.
2. Test transportability, operability and resilience of HPGS system for military applications.
3. Prove that the total fuel savings of the HPGS are equal 30%[5] or more compared to similar conventional generators as specified by PFISTERER.

Project goals resulted in the following project activities:

- To deploy HPGS in military exercises.
- To run HPGS tests comparing the System to conventional generators (no batteries, no renews etc.) for a range of loads at military camps.

[4] See note 1.

[5] Depending on loading and ambient/weather conditions.

- To analyze HPGS tests data and to calculate the fuel savings.
- To analyze the contribution of renewable energy sources on power generation.
- To test HPGS in extreme environments (low and high temperatures, high elevations, humidity).
- To identify the limitations of the HPGS system and recommend solutions for further improvements.

This Report covers HPGS tests that were executed during the last two and half years (March 2016 – Sep 2018) including analysis of test results.

1.1. Backgrounds

During the period of March 2016 – Sep 2018 there have been a number of HPGS tests conducted along with military exercises and HPGS demonstration events. Although every effort had been made to conduct the tests on the HPGS and conventional generators in comparable conditions, this was not always been possible. For example, the conventional generator that was used in comparable tests was rated at 200 kW while the HPGS generators were rated at 150 kW. The other test issues have been related to tests methodology, specifically measurements of fuel consumption at HPGS and conventional generators. This may account for some discrepancies in the final test results and possibly, on the final conclusions.

Figure 1 shows a timeline of HPGS testing events while T*able 1* details the test history and the HPGS project's mile-stones.

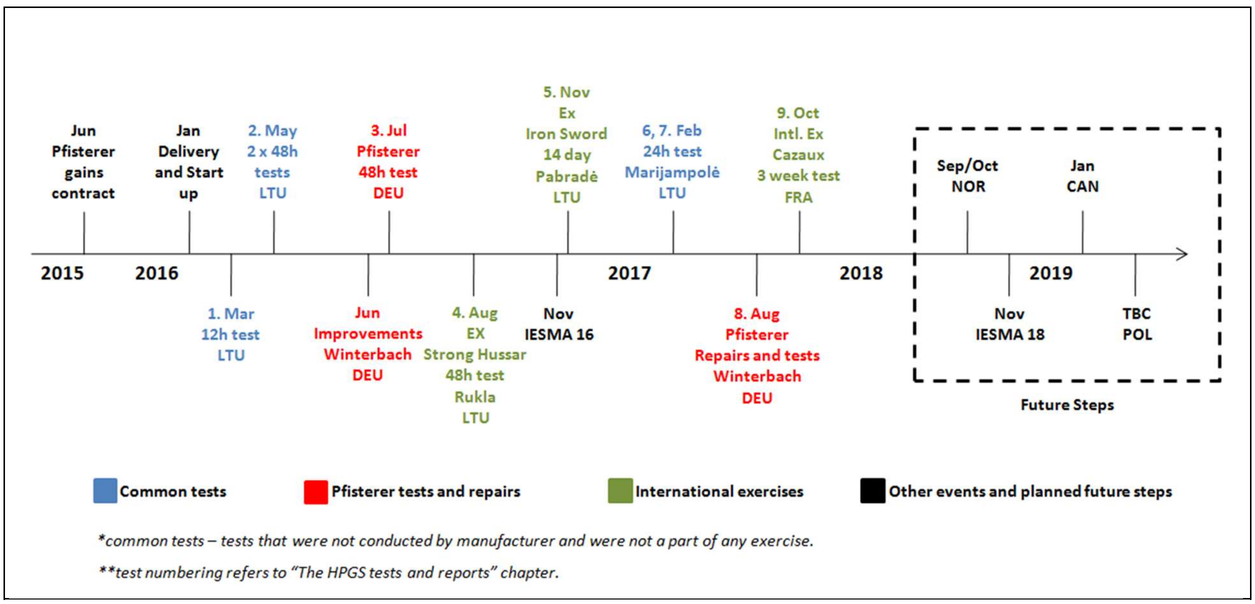


Fig. 1. NATO ENSEC COE HPGS Project timeline

Table 1: The history of HPGS tests

DATE	PROJECT ACTIVITIES AND RETALED TESTS
23 JAN 2015	Tender launch
22 MAY 2015	PFISTERER was announced as a tender winner
16 JUN 2015	HPGS delivery and service contract signature
30 JUL 2015	ENSEC COE and PFISTERER reps meeting in Vilnius devoted to the detailed project planning
05 AUG 2015	Project plan accepted and approved
21-23 DEC 2015	FAT and inspection at PFISTERER premises in Winterbach, Germany
15 JAN 2016	HPGS delivery (Marijampolė, Lithuania), HPGS commissioning and start-up operations
04 FEB 2016	Official commissioning event, Marijampolė, VIP-day (press release)
15 MAR 2016	12 hrs acceptance test in Marijampolė, Lithuania
23-31 MAR 2016	On-site training, Marijampolė, Lithuania
14 MAY 2016	HPGS demonstration during the public event - Armed Forces and Public Unity Day in Vilnius, Lithuania
20 MAY 2016	2 x 48 hrs HPGS tests in Marijampolė, Lithuania
07 JUN 2016	HPGS is announced as winner of the Energy Transition Trophy Competition in Paris, France
13-17 JUN 2016	HPGS demonstration at EUROSATORY Exhibition, Paris, France
25 JUN – 08 AUG 2016	HPGS after-test improvements and 48 hrs test at PFISTERER premises, Winterbach, Germany
17-26 AUG 2016	HPGS employment during the military exercise STRONG HUSAR: 48 hrs test in Rukla, Lithuania
15-18 NOV 2016	HPGS display/demonstration at IESMA conference, Vilnius, Lithuania
19 NOV – 03 DEC 2016	HPGS employment during the military exercise, IRON SWORD: 14 days test in Pabradė, Lithuania
14 FEB 2017	HPGS 24 hrs test in Marijampolė, Lithuania
23 FEB 2017	HPGS 2.5 hrs test in Marijampolė, Lithuania
10 AUG 2017	Repairs and additional testing at PFISTERER premises, Winterbach, Germany
02-12 OCT 2017	HPGS deployment at National military exercise, Cazaux, France (10 days tests)

1.2. Producer’s warranty terms and conditions

The System has two years Producer’s warranty provided by PFISTERER, covering service maintenance and System repairs.

During the warranty period PFISTERER completed repairs and regular servicing via subcontracting the Lithuanian Company “Energotecha” Ltd.

Because of the specificity of this prototype, better assistance and deeper involvement by the manufacturer would have been desirable in order to have a more rapid resolution of the technical problems that occurred.

In a general way, during the test phase of a new product the wider support from the manufacturer is fundamental. To be noticed that in this particular case, PFISTERER had never had the opportunity to work on a product designed for military applications.

PFISTERER recognized some undue delays and for that reason the warranty’s extension for additional 6-month period was granted.

2. System's description

2.1. General description

Figure 2. HPGS deployed in Marijampolė, Lithuania (PFISTERER, 2017)

The HPGS is a deployable modular hybrid power generation system that is capable of producing up to 2500 kWh per day with 150 kW peak loads[6] for approximately a 100-150 pax camp needs. The HPGS has been designed to reduce power generators fuel consumption and to increase energy security in a military infrastructure via battery storage and MEMS. It also utilizes renewable energy sources - sun and wind - to further reduce the fuel consumption. HPGS can operate as stand-alone generator system but it also can be integrated into the existing power grid architecture.

A detailed list of system's components is presented below:

a. Two diesel generators set

Constant output: 101.4 kVA @ cos phi 0.8: 80 kW

Output voltage: 230 V / 400 V / 50 Hz three phase

Fuel tank capacity: 2 x 240 l (inter-connected)

b. PV system

Peak power: 25.2 kWp

[6] The System is limited to 150 kW peak due to the main characteristics of the inverter.

Output Voltage: 400 V / 50 Hz three phase

PV Modules[7]: DAS 300 Wp (84 pcs)

Inverter: SMA Tripower 25000TL-30

Dimensions (set up): Approx. 37 m x 7.5 m

c. Wind Turbine

Output Voltage: 400 V / 50 Hz three phase

Rated Output Power: 6.5 kW

Peak Output Power: 7.5 kW

Propeller Diameter: 5.3 m

Inverter: Smartwind SW-7.5

Mast: 12.5 m high

d. Electrical Storage and MEMS

Battery technology: Lithium MNC

Battery Capacity: 100 kWh

Battery Module Capacity: 75 Ah (x 12)

Battery Inverter: 280 kW

MEMS software: ADS-TEC

e. External Cooling/Heating Unit

Cooling unit:

Required Input Power: 6.2 kW - 400/230 V / 50 Hz three phase

Maximum cooling capacity: 13 kW

Heating unit:

Max input power: 15 kW - 400 V / 50 Hz three phase

Max heating capacity: 15 kW

[7] Initially, *PV modules are actually DAS 250 Wp giving 21 kWp. Later, Pfisterer has supplied 18 more DAS 250 Wp panels to add externally to the HPGS and achieve the specified 25 kWp.*

Transportation case/hull solution

The HPGS is housed within two 20' ISO standard containers. The main container (CrossPower Container) houses two diesel generator sets as well as the electrical storage (batteries) and HPGS MEMS including cabling and provides interfaces for external renewable energy generation modules, as well as the electricity feeders. The battery system section and the generators sections are separated by a thermally insulated wall. Monitoring and control display is integrated into the external container wall to aid general operational activities and it is located behind a lockable flap. The diesel generator control panels are also behind this flap. The generators side wall contains two big hatches which can be opened to access the generators for the maintenance. The battery side fold out door opens up to the whole container length for maintenance and repair. In normal operation the side wall stays closed and the System is operated via the external monitor display. The system can also be accessed remotely and share the HPGS data and can be controlled remotely from the external computer/laptop/phone or via Wi-Fi connection to a dedicated PFISTERER's data control system. In addition, MEMS data can be downloaded from MEMS directly through the LAN port.

Even though each component complies with European electrical distribution standards, the system as a whole can provide two different power supply characteristics, either 400 V or 230 V, @ 50/60 Hz outlets, allowing full operability for both the American military and European military forces power requirements.

Power supply details are listed below:

Socket connections (behind three lockable external flaps):

- 3 x 400 V, 63 A outlets or 3 x 230 V, 16 A outlets (one for each load)
- 1 x Power inlet PV
- 2 x Power inlet Wind (one for spare turbine in case separate mounting is possible)
- LAN data connection to download operational data (located underneath 15'' touch screen)

Also housed within the container are:

- 3 x electricity distribution boxes (feeders)[8]:
    - Inlet: 50 Hz, 63 A
    - Outlets: 3 x 32 A, 400 V or 3 x 16 A, 400 V or 3 x 20 A, 230 V

  (Also includes 25 m of extension cables)

- 1 x AC inverter/transformer box:
    - Inlet: 230 V, 50 Hz converting to 110 V, 50-60 Hz
    - Outlets: 1 x 23 A, 2 x 16 A

  (Also includes 5 m extension cable)

- 1 x DC inverter/transformer box:
    - Inlet: 230 V
    - Outlet: 24 V DC, 2 kW

The second 20' ISO standard container houses all PV components, wind generator and mast, the battery cooling/heating unit and power distribution boxes (feeders)[9].

The total weight of HPGS is 26 tones.

[8] These are movable and will be used within the camp as required.

[9] It is possible to deploy only the CrossPower container if there is no plan/conditions to use the renewables, however the cooling/heating unit and distribution boxes will need to be transported separately.

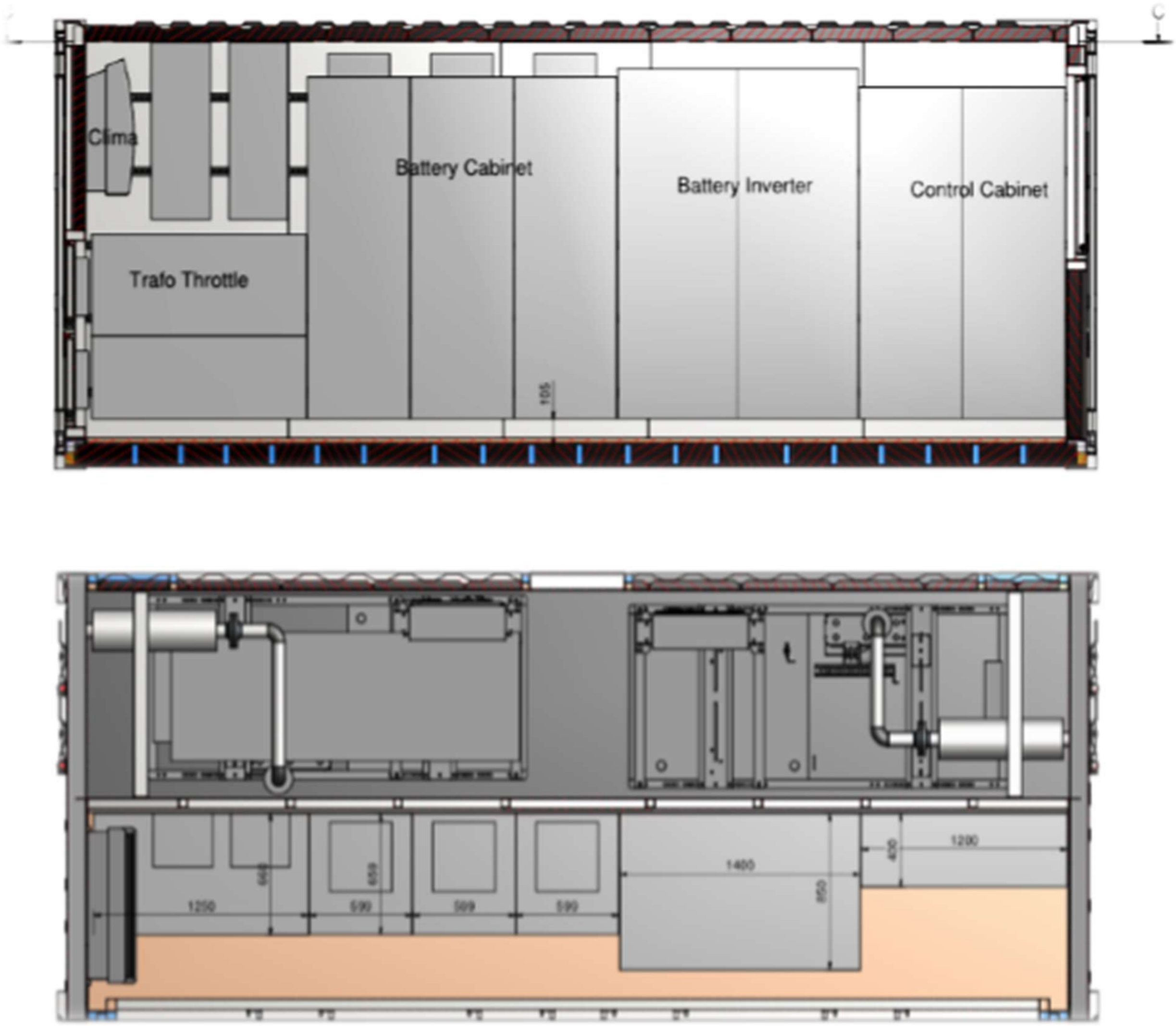


Figure 3. Above, the interior design of HPGS Container components. Below, the internal set-up of HPGS container which stores the two gensets, batteries and system controls (PFISTERER, 2017)

<u>Fuel compatibility</u>

For the specifications, the diesel generators are able to operate with different types of fuel.

The rated fuels to use are listed below:

- Diesel fuel F-54
- Aviation fuel F-44 (also known as JP-5)

For further information about NATO fuel listing, see NATO Logistics Handbook - October 1997.

2.2. Functional description: demand and supply profiles

As for any other hybrid generation system, the basic principle is that excess generated energy can be stored/accumulated in the batteries and returned to the load. In most cases deployed military camps power demands can be predicted, generally having a steady base load with peak loads in the morning, noon and in the evening. *Figure 4* shows a typical demand profile and power generation/supply profile for a deployed military camp using the HPGS for a 24 hrs period. As the peak loads can be predicted, energy can be stored beforehand to supply the peak loads mainly using the batteries, which can reduce the total time the diesel generators are on.

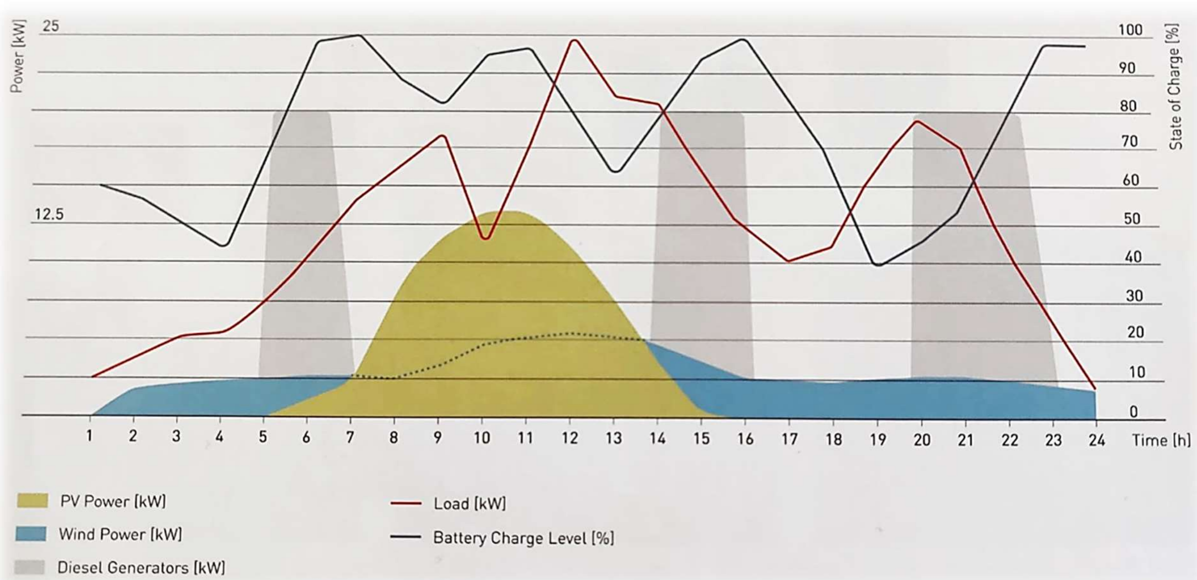


Figure 4. An example of HPGS evaluated load and power generation profile in 24 hrs period (PFISTERER, 2015)

In normal conditions the power supply is performed through HPGS batteries pack, charged by generators and/or renewables. The System can also operate in "Black Start" mode where it will supply the loads directly from one 75 kW generator in case of System failure[10]. This has to be done manually via the generator and would only be implemented as a redundancy in case of

[10] "Black Start" mode bypasses the HPGS inverters and directly supplies the loads. As the generators output 230 V / 400 V @ 50 Hz, "black Start" may not be suitable for US military equipment.

complete system failure. In "Black Start" mode the PV and wind turbine energy production charge the batteries as additional energy generation sources.

The HPGS is designed to operate in "on" and "off" grid modes and therefore theoretically is capable of charging the batteries from external networks, however, this has not been explored yet.

Figure 5 shows a detailed system schematic of the HPGS.

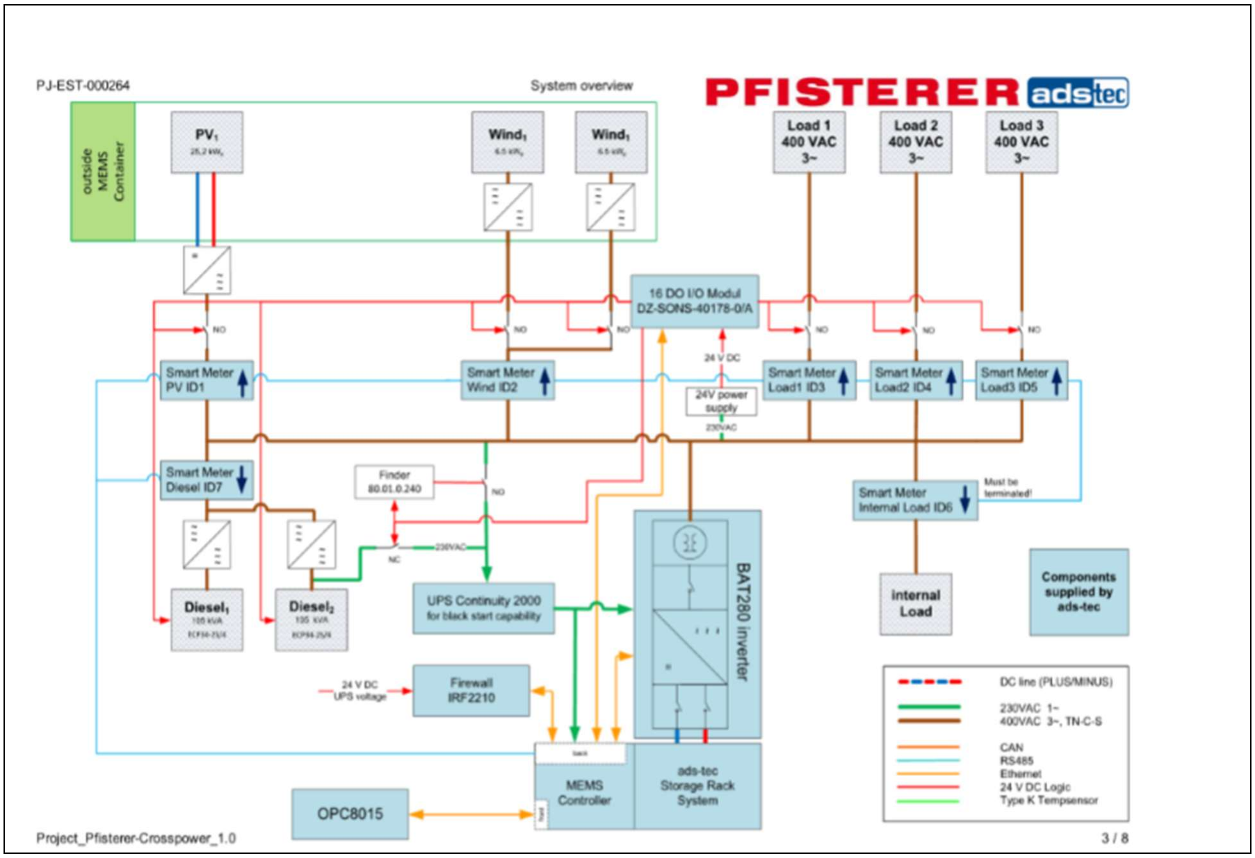


Figure 5. HPGS schematic drawing (PFISTERER, 2017)

The DFI distribution grid can be set up with the supplied distribution boxes and the inverter box as required (see next figure).

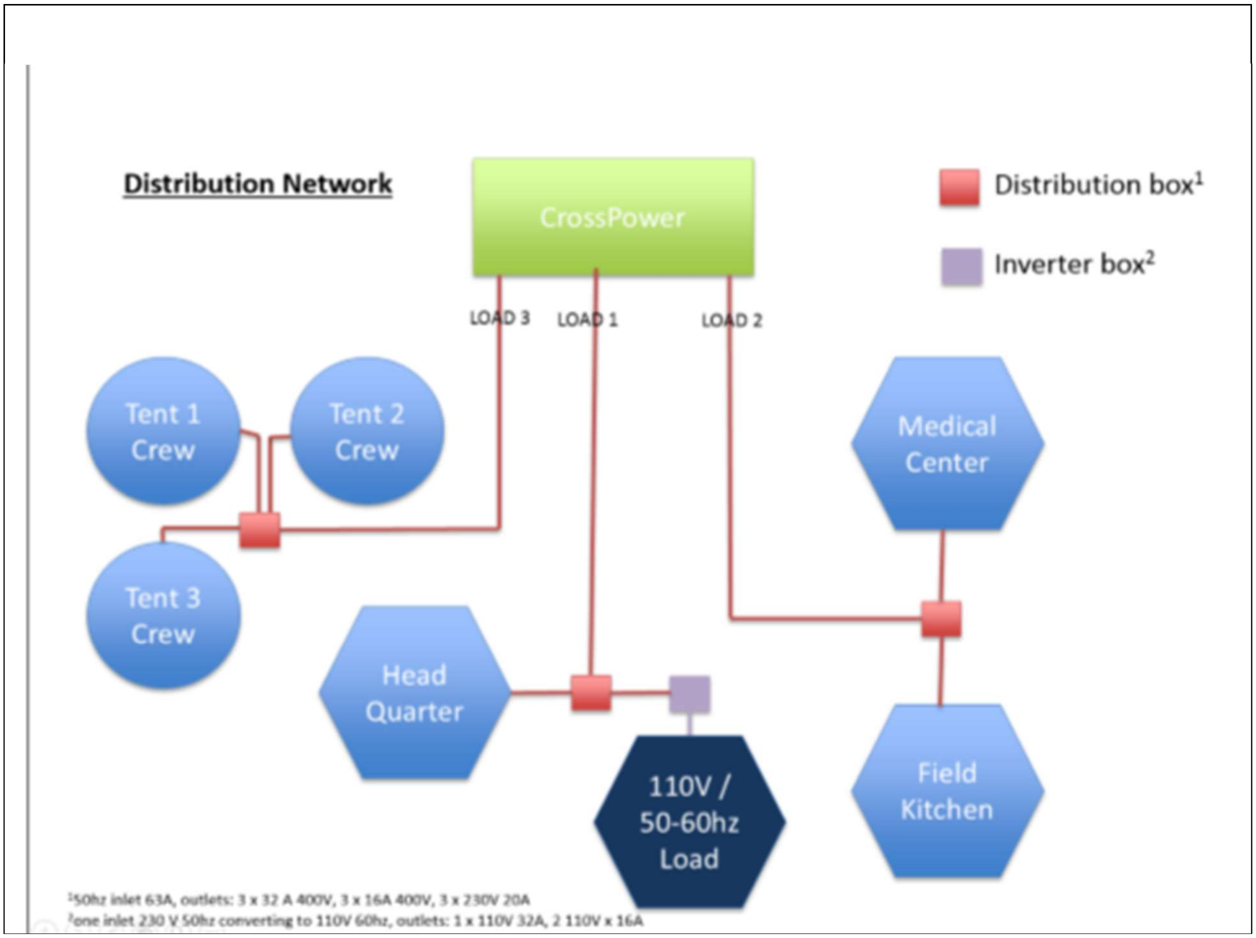


Figure 6. An example of power distribution network (PFISTERER, 2017)
110V / 50-60 Hz load is adjusted for US military power requirements

2.3 MEMS (Mobile Energy Management System)

The MEMS is the core component of the HPGS giving flexibility to manage power sources and loads by automatically controlling them. HPGS is split into three loads and internal load. Three loads are categorized below and are controlled automatically.

- Load 1: Critical load - must always have power (i.e. operations management center, medical unit, etc.).
- Load 2: Important load - should be supplied with power but can be shed automatically if necessary (for example field kitchen).
- Load 3: Secondary load - can be shed automatically.

The prioritization of loads is set via the state of charge (SOC) axis, F*igure 7*. The user can enter switching thresholds (SOC thresholds) for each generator/load. If the SOC-value set for a generator falls below its threshold, the generator is automatically turned on. If the SOC-value of a load falls below its threshold, the load will be shed[11].

Figure 7. HPGS generator and SOC menu (PFISTERER, 2017)

[11] ATTENTION: the generator SOC switch limits should be set such that they ensure the required battery charge level, but a charge level of 100% should be avoided to protect battery from damage.

During the HPGS operation MEMS will control generators operation in such a way that it will use the generators as little as possible. If practicable, the load will be completely generated by the alternative energy sources that charge the batteries. Once the battery charge level falls below a set SOC [40%], one of the generators will automatically switch on until the upper SOC limit [80%] is reached. During the battery charging mode from the generators, the HPGS diesel generator is running at a higher efficiency than a conventional generator of the same size as HPGS diesel generator operates close to its maximum continuous rating (MCR) while charging the batteries. *Figure 8* shows the power generation management for increasing load demand. If the load is decreasing the process is reversed.

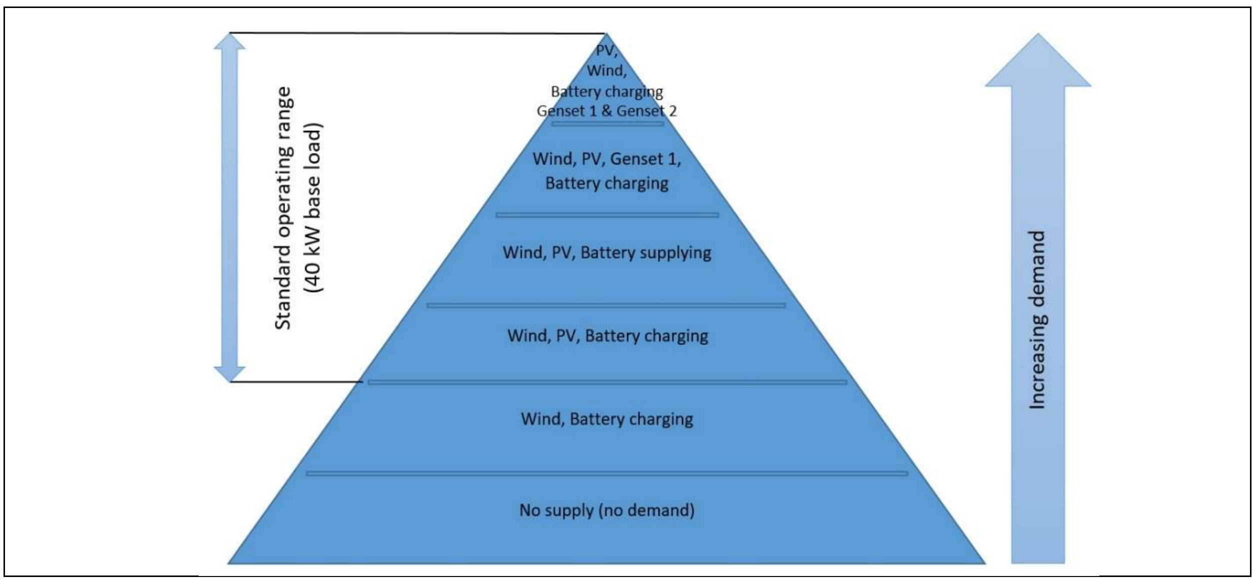


Figure 8. Power generation management scheme for increasing load (PFISTERER, 2017)

In general operation the system is managed via the 15'' touch screen interface. The following main information is available.

Overview (start page) showing the condition of the CrossPower-System

Position	Description
1	Pop-up-menu (main menu)
2	Sub-menu buttons
3	Signal lights: - turned on (green) - switched off (red)
4	Arrows indicating the flow of energy
5	Fault indicator (low/high voltage, overcurrent, temperature too high/low, hardware failure, etc.see chapter 4.5.1 Annex 40 User manual SRS100)

The pop-up-menu (main menu) can be accessed via the symbol (upper left corner). Here you can access other menu pages.

Figure 9a. Operation Menu, Pfisterer's HPGS User Manual (PFISTERER, 2017)

Figure 9b. Operation Menu, Pfisterer's HPGS User Manual. (Pfisterer, 2017)

2.4. Training on operating HPGS

Training is essential for assembling and operating the HPGS. The training course is developed by PFISTERER for soldiers with basic technical and electrical knowledge. The HPGS training usually takes 2 - 3 days. HPGS system assembly training is provided to all soldiers responsible for HPGS assembly and installation. However the HPGS system operation and management training is limited to soldiers - electricians responsible for HPGS operations.

The first training module is devoted to electricians and it covers HPGS operation aspects and together with key electrical theory and electrical engineering issues and health and safety requirements[12].

The second training module is devoted to the assembly of HPGS system (setting up the PV panels, assembling wind turbine, connecting external cooling/heating unit to CrossPower container). For a 3 - 4 people team, assembly can take between 3 - 6 hours depending on weather conditions and personnel experience as well as what type of lifting equipment is used. Once the system is assembled and cables are connected the HPGS starting activities and procedures will follow[13].

It is important to notice that the training material is based only on the Operation Manual and no extra didactical material is provided.

[12] System max voltage 750 V DC, 400 V AC

[13] In general, the HPGS power generation can be turned on to supply power immediately after the required temperature of batteries section reaches the operational requirements. The renewable energy sources can be connected at the later stage.

Figure 10. Training in Marijampolė (Lithuania): preparing HPGS cooling/heating module

2.5. Mini HPGS

In addition to HPGS, two Mini-HPGS are designed as small demonstration units. Mini-HPGSs represent the system of diesel generator, battery, solar power generation and system management module (no windmill). The systems are transported on a standard trailer, allowing them to be easily deployed. The main benefit of the mini HPGS is the capability of silent operation during missions as the load can be supplied by the batteries for short periods of time.

Mini HPGSs require conventional diesel fuel and can provide electricity to the following characteristics: 230 V, 50 Hz, 16 A.

They can be used for single loads up to 3 kW and consist of the following components:

- Battery storage capacity: 3.9 kWh
- Diesel Generator Set: 6 kVA
- PV System: 1 kWp, (4 modules 250 Wp each, 6.5 m^2 of total PV area)
- Total weight is about 500 kg

During initial tests at the beginning of 2017 both Mini-HPGS got broken and even now the manufacturer is unable to return the repaired systems. Therefore no data was collected or analyzed.

The fault occurred with the battery pack, specifically with the charging unit. Those events suggested that the control systems were not robust enough. It was recommended to the Producer to upgrade and to improve Mini-HPGSs.

Figure 11. Mini-HPGS

3. Tests report

Nine HPGS tests were conducted from the beginning of 2016 in order to analyze the performance characteristics and effectiveness of HPGS as well as to provide the recommendations for further improvements. It should be noted that for all of the tests, except for PFISTERER repair tests in July 2016 and August 2017, the maximum solar capacity was 21 kWp, as the additional panels were not set up in the final configuration (25 kWp).

Those tests presented below are in chronological order:

Test 1: 12 hours HPGS acceptance test (Mar 2016), Marijampolė, Lithuania

The test was ran for 12 hours in parallel with a conventional generator[14]. The base load was 25 kW with a peak of 120 kW. The wind turbine generated no energy. The PV's power generation was approximately 19 kWh. The energy produced by the HPGS and by conventional generator was 529 kWh. HPGS consumed 151 liters of fuel compared to the conventional generator which consumed 212 liters. This gave an average fuel saving for the HPGS of 29%. Further it was calculated that the time between maintenance for the HPGS diesel generators was increased by 1.8 times.

Test 2: 48 hours test (May 23 – 27, 2016), Marijampolė, Lithuania

This was a second comparative test between the HPGS and a conventional 200 kW genset. Each system had average 25 kW demand and peak 100 kW load and was operating for a duration of 48 hours.

The total energy produced throughout the experiment was 2348 kWh for both HPGS and the conventional generator system. The HPGS used 714 liters of fuel with an efficiency of 3.29 kWh/l while conventional generator consumed 911 liters with a fuel efficiency of 2.58 kWh/l. It was calculated that HPGS saved 22% fuel compared to the conventional generator.

[14] 200 kW generator was used in this test.

No available data on weather, contribution PV or wind.

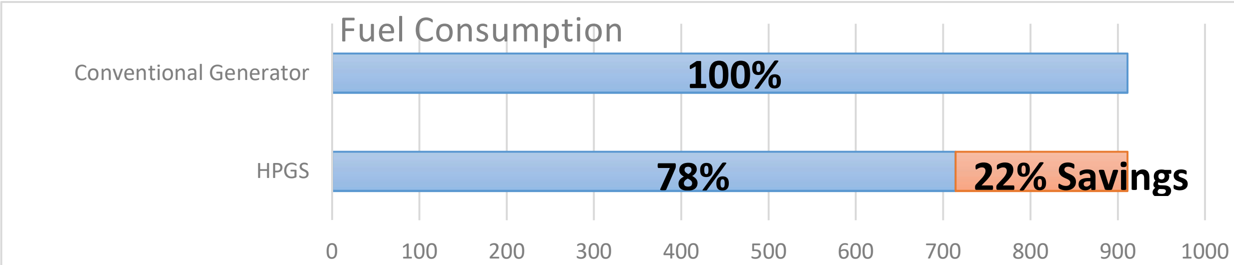


Figure 12. Fuel consumption comparison between HPGS and a conventional 200kW generator (May 2016, Lithuania)

Test 3: 48 hours test and improvements (Jul 2016), Pfisterer Lab. Testing in Winterbach, Germany

After the initial tests the HPGS system was sent to Winterbach, Germany (Pfisterer production and testing facilities) for necessary repairs and improvements.

The following key improvements were made for HPGS:

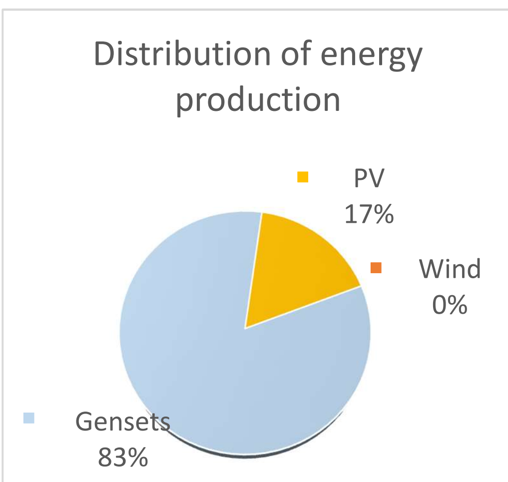
1. Wind speed measuring device was installed along with new type of fuel meters for generators.
2. Regarding the hardware the following was improved:
   - The alternator of the 1st generator was replaced.
   - The new air-conditioning system to improve heating/cooling of the battery compartment was supplied.
   - 18 extra 250 Wp PV modules were supplied to increase the solar capacity up to 25 kW as stated in the Tender documents.
3. MEMS software was updated to improve the HPGS status monitoring.

PFISTERER then conducted a 48 hours test supplying an average 35 kW load. However, no fuel consumption data was provided. It has to be said that the goal of this test was to ensure that the HPGS operating correctly rather than analysis of the system performance.

Test 4: 48 hour test during EX “Strong Hussar” (Aug 17 – 26, 2016), Rukla, Lithuania

During this exercise HPGS was compared to a 200 kW conventional diesel generator to supply for approx. 200 pax a TIER 1 camp. Approximately half of the camp was supplied by HPGS generated energy while the other half was provided with the conventional generator. The camp load varied between 10 and 15 kW. The HPGS cooling (air-conditioning) unit was not used. During the day, there was considerable sun, permitting the solar array to produce power, which achieved a 16 kW peak. There was no wind during the trial, so no energy was produced by wind turbine.

Over this test the HPGS saved 37% of fuel compared to the conventional generator and had a fuel efficiency of 2.59 kWh/l compared to 1.63 kWh/l for the conventional generator. 17% of the total energy produced in this test was generated by solar. The HPGS generators were running for approximately five hours a day while the conventional generator was running 24 hours a day. Running for only a few hours a day significantly increases the time between the maintenance. At the very end of the trial, the HPGS's second generator developed a grounding fault and stopped working. This ground fault showed the utility and reliability of having two generators as opposed to one in terms of redundancy.



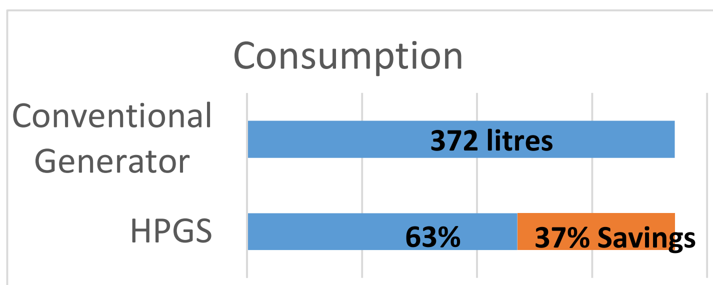


Figure 13. HPGS energy production and fuel consumption comparison at EX "Strong Hussar" (August 2016, Lithuania)

<u>**Test 5:** Tests in the 14-days multinational EX "Iron Sword" (Nov 19 – Dec 3, 2016), Rukla, Lithuania</u>

In this exercise the HPGS was used to supply energy to accommodation for both Lithuanian Logistics Battalion soldiers and US soldiers. Occasionally the power was also supplied to Estonian soldiers.

Some technical problems appeared during this test. The wind turbine's hoist arm was broken during the installation, so wind power generation was not set up. Solar panels had lower generating capacity as 9 out of 21 solar panels were not generating the energy because of improper connection to the inverter.

Despite the above listed technical problems, the HPGS was generating the energy and continuously supplying to the camp. This situation evidenced that HPGS can operate at the sufficient levels even when the renewable energy sources were not available due to technical/engineering problems or weather conditions. The test lasted for 286 hours and supplied energy to approximately 250 soldier camp with average load of 14.3 kW.

The HPGS generator had run for 68.6 hours over this test period (24% of the whole test time): this means that the period between generators service can be extended by 4 times.

The HPGS consumed 1647 liters of fuel, producing 4107 kWh in total (2.48 kWh/l).

During this exercise there were no comparable tests between HPGS and conventional generator sets.

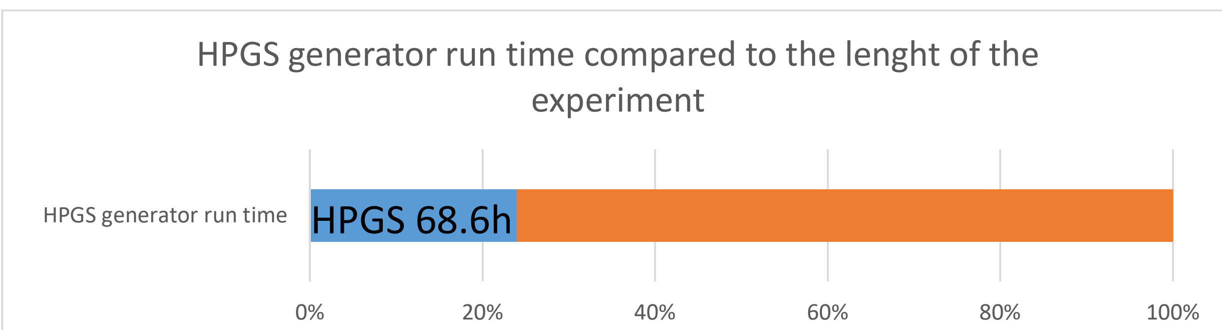


Figure 14. HPGS generators operating time vs length of experiment in Ex "Iron Sword" (November 2016, Lithuania)

Tests 6 and 7: Two x 24-hours tests (Feb 14 - 23, 2017), Marijampolė, Lithuania

These tests were conducted at the Lithuanian Army Logistics Battalion territory, Marijampolė city, and were arranged in order to assess the performance of the HPGS.

During the first test a conventional 200 kW diesel generator, normally employed during military activities, was used as the comparison to HPGS which operated at the same time with the same load. The load was constructed from space heaters which were turned-on and turned-off according to a predetermined schedule in order to simulate a military camp's variable load. At all times the HPGS and the conventional generator were supplying the power to same number of heaters. In this experiment the average load was 24 kW and the maximum load was 66 kW.

Over the 24-hour HPGS test 96% of energy was produced from fossil fuel, 3% from sun and 1% from wind. The peak solar power was 4.4 kW (from 21 kWp rated solar array) as the weather was cloudy and the peak wind power production was 1.6 kW (from 6.5 kW wind turbine). It was also calculated that approximately 10% of the energy produced in this test by the HPGS was used by internal consumption (internal losses). While the conventional generator ran for the whole 24 hours, the HPGS generators were running for just over 8 hours. This represents a 66% reduction in the HPGS generator run time.

In order to moderate error in fuel consumption estimation, the diesel fuel consumed by the HPGS in this test was measured by using three different methods and then calculating the average. The fuel consumed by HPGS in this experiment was 189 liters. It is important to note that at the beginning of the test, the HPGS battery state of charge was 77% and after the test it was 49%. If exact comparison was to be made, the battery had to end the test with the same state of charge, which would have required a little bit more fuel. Over the test, 551 kWh of energy distributed to the loads. This gave the HPGS a fuel efficiency of 2.91 kWh/l. Since the conventional generator used 204 liters of fuel, its fuel efficiency was 2.70 kWh/l. Overall the HPGS saved 7% of fuel compared to a conventional generator.

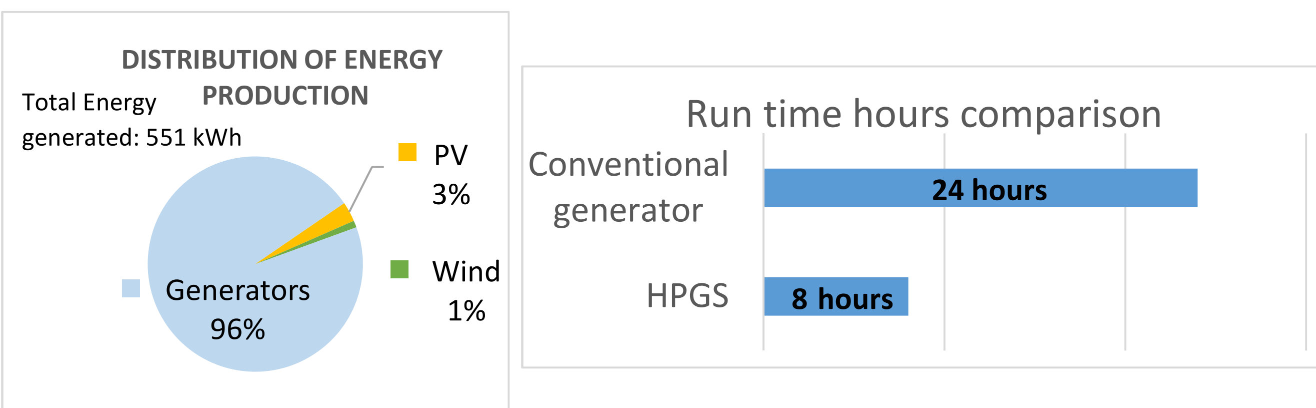


Figure 15. HPGS energy production and run time hours comparison (February 2017, Lithuania)

As 7 % of fuel saved was a surprisingly low result, therefore a second test was ran on the 23rd of February. For the second test the same test scenario for a period of 2.5 hours at a high load was used in order to verify the first test results and to eliminate any possible error. The average load was 64 kW and the maximum load was 105 kW. The HPGS was operating for one complete battery charge cycle and the conventional generator was run for the exactly the same time. Although both generators powered the same heaters the power demand (load) was changing: this was because some of the heaters had thermostats that turned the power demand on and off depending on the temperature. The difference between the load measured for HPGS and the load measured for the conventional generator was less than 2%. The peak solar power was 5.3 kW and the peak wind power was 2.2 kW.

Over the duration of the test the generators produced 92%, solar panels produced 6% and wind turbines produced 2% of the total energy. This was the best performance of wind energy production during HPGS testing. However the wind generator reached its maximum rated power only for few seconds!

While the conventional generator continuously ran for 150 minutes, HPGS generator 1 ran for about 115 minutes and HPGS generator 2 only ran for 20 minutes. Of the power produced by the HPGS, 7% was used internally. Again, the fuel consumption was measured by using three different methods. An average of these readings gave the result of 54 liters of fuel. As the total production was 158 kWh of energy over the experiment, the power generation efficiency at HPGS was 2.92 kWh/l. Powering exactly the same load over the same amount of time, the conventional generator consumed 47 liters of fuel, meaning that its efficiency was 3.36 kWh/l. Overall the HPGS retained a similar performance level, while conventional generator increased its performance under these specific loading conditions.

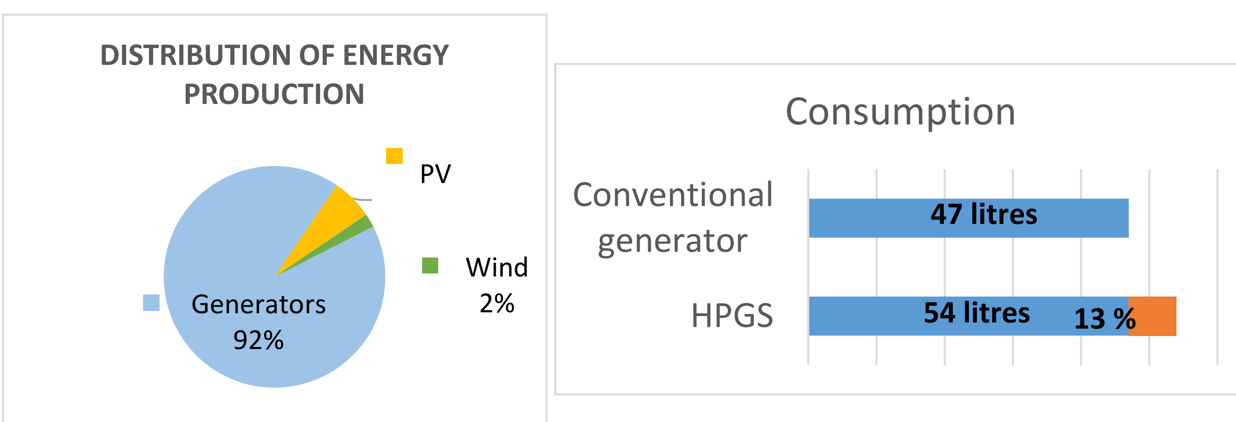
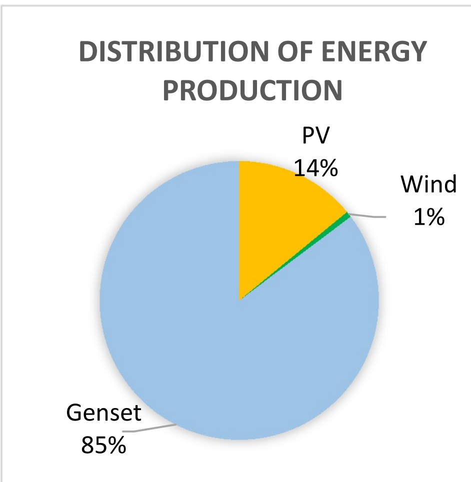


Figure 16. HPGS energy production and fuel consumption comparison (February 2017, Lithuania)

Test 8: Repair works at Pfisterer and 24-hours test (Aug 2017), Winterbach, Germany

The test was conducted over a 24 hours period against a conventional generator. The load was produced by different combinations of resistors with an expected maximum of 120 kW and was measured using power meters. Over the experiment, total of 1280 kWh were produced by each generator. Roughly 85% of the HPGS energy production was done by diesel generators, 14% by the solar panels and 1% from the wind turbine (simulated). During the experiment, conventional 200 kW generator consumed 420 l (3.05 kWh/l), while HPGS consumed 351 l (3.65 kWh/l), saving 20% of fuel. HPGS diesel generators ran for 15 hours and conventional diesel generator ran for 24 hours. This means that the time between maintenances could be increased by 1.6 times.



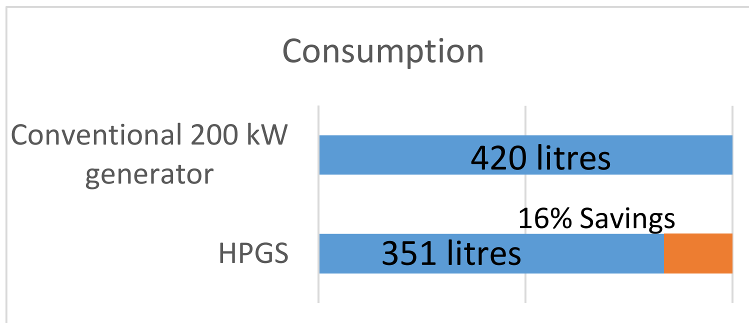


Figure 17: HPGS energy production and fuel consumption comparison in Pfisterer 24 hour test (August 2017, Germany)

Test 9: 10-days test CN3 EX (Oct 2 -17, 2017) Cazaux, France

The test period was 10 days. Initially HPGS was operating at very little load (1 kW) for the first 3 days. Later the demand was increased to 14 kW, with a peak demand of 30 kW. Those conditions were set up for 2 days and after this period the load was returned to a value below 10 kW. The HPGS produced in total 2942 kWh of energy while consuming 774 liters of fuel over 10 days (3.80 kWh/l); this was the highest efficiency that had been achieved during HPGS tests. In this test the wind turbine produced very little energy, on the other hand, solar generation produced 701 kWh which is 24% of total energy produced. Optimal weather conditions, combined with the low average load explains why the HPGS was able to achieve much better production efficiency than in previous tests. It has to be mentioned that the test was not set up as a comparative test against a conventional generator and therefore the comparative analysis was not done.

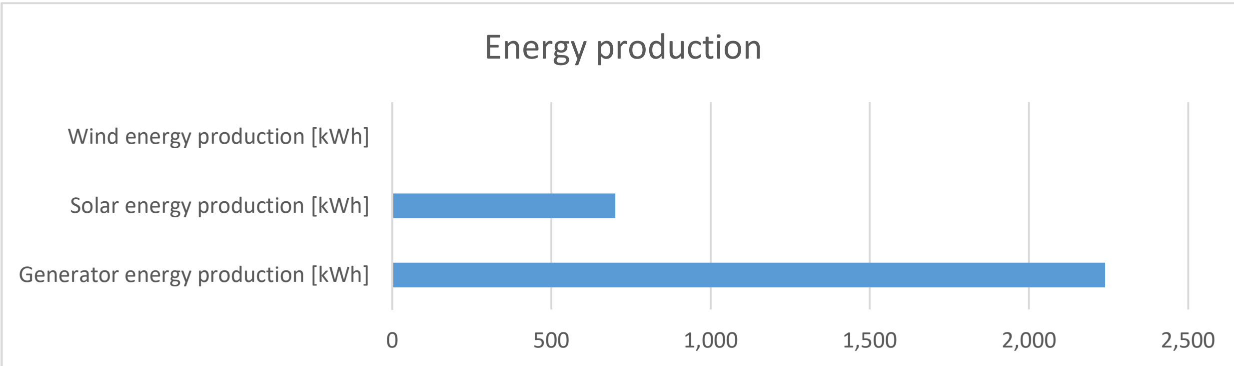


Figure 18. Energy generation from different sources in Ex CN3 (October 2017, France)

3.1. The overview of test results

Table 2. Summary of the results of HPGS tests

TEST/EXERCISE PLACE PERIOD	TEMP[15] (AVG)	DURATION	LOAD (AVG)	HPGS[16] LOAD	HPGS FUEL EFFICIENCY	200 KW GEN. FUEL EFFICIENCY	HPGS FUEL SAVING[17]
ACCEPTANCE TEST LITHUANIA MAR 2016	2ºC	12 hrs	44 Kw	29%	3.5 KWh/l	2.45 KWh/l	29%
COMPARATIVE TEST LITHUANIA MAY 2016	18ºC	48 hrs	49 kW	33%	3.29 KWh/l	2.58 KWh/l	22%
PFISTERER REP. TEST GERMANY JUL 2016	-	-	-	-	-	-	-
EX STRONG HUSSAR LITHUANIA AUG 2016	21ºC	48 hrs	13 kW	9%	2.6 KWh/l	1.63 KWh/l	37%
EX IRON SWORD LITHUANIA NOV 2016	2ºC	14 days	14 kW	9%	2.48 KWh/l	-	No direct comparison available
COMPARATIVE TEST #1 LITHUANIA FEB 2017	-1ºC	24 hrs	24 kW	15%	2.91 KWh/l	2.7 KWh/l	7%
COMPARATIVE TEST #2 LITHUANIA FEB 2017	3ºC	2.5 hrs	64 kW	43%	2.92 KWh/l	3.36 KWh/l	-15%
PFISTERER COMP. TEST GERMANY AUG 2017	n.a.	24 hrs	53 kW	36%	3.65 KWh/l	3.05 KWh/l	20%
EX CN3 FRANCE OCT 2017	15ºC	10 days	7 kW	5%	3.8 KWh/l	n.a.	No direct comparison available

An overview of the results from the tests are shown above in *Table 2*. It can be seen that the tests were conducted over a range of temperatures from -1°C to 21°C, with the average loads from 7 kW to 64 kW, and durations from 2.5 hrs to 10 days. The highest fuel efficiency recorded for the HPGS was 3.8 kWh/l during Cazaux exercise, while the lowest one was 2.48 kWh/l during the Iron Sword one. The maximum loading was 43% for a duration of 2.5 hours and the minimum tested was 5% only; under this condition the HPGS achieved its maximum fuel efficiency (3.8 kWh/l).

[15] Average temperatures should be considered as indicative as they have been collected from the archived weather data (www.wunderground.com, accessed online, Aug 2018).
[16] The percentage is calculated as the portion of HPGS max load (150 kW).
[17] Compared to a 200 kW conventional generator.

Figure 19 graphically illustrates the fuel saving attained; the greatest saving was 37%, though it should be noted that during this related test the conventional generator was operating at its lowest efficiency (1.63 kWh/l). The lowest saving was during the “test 2” comparison test, where the HPGS was -15% less efficient; the test was short but conducted at the highest load 64 kW (43 % loading). The HPGS achieved an efficiency of 2.29 kWh/l, almost exactly the same as the previous test, “test 1”, which was at only 15% loading under very similar environmental conditions. In this test the conventional generator had its largest fuel efficiency of 3.36 kWh/l.

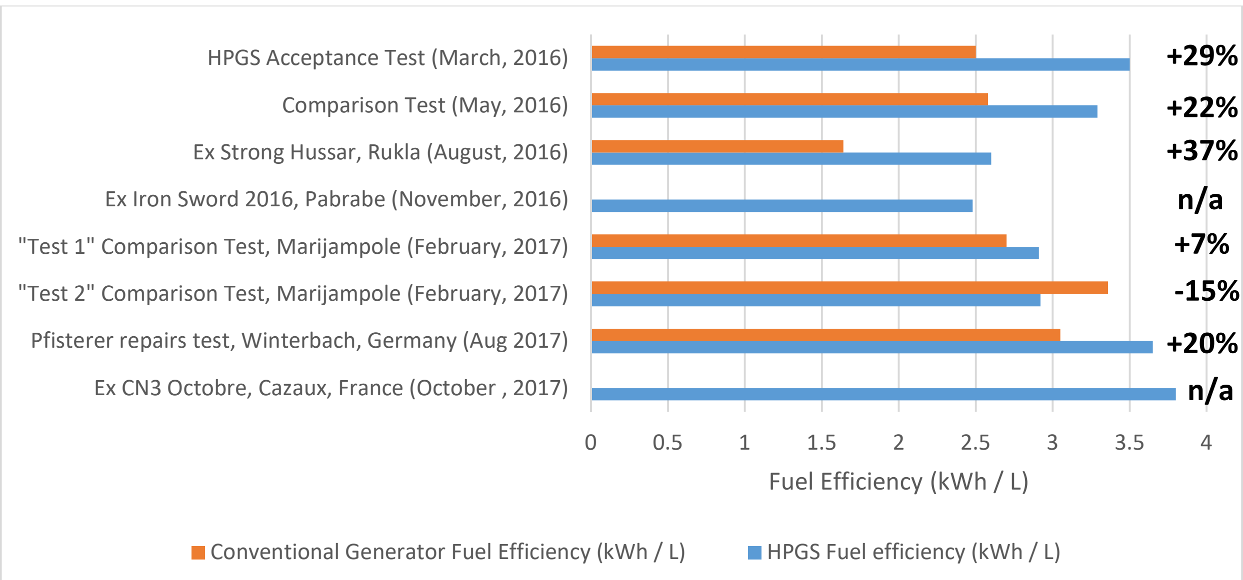


Figure 19. HPGS vs a conventional 200 kW generator: fuel efficiency comparison at various tests

NB: Due to logistic constraints, the tests used a 200 kW generator rather than a desirable 150 kW one, comparable to the HPGS generator maximum generating power. It is likely that if 150 kW generator was used, the percentage saving in favor of HPGS would have been smaller. This has been accounted in the loading analysis (see paragraph 4.5 of this Report).

4. Installation and deployment

4.1. Functional analysis

The installation of the HPGS mainly focuses on deploying the renewables: the solar array and the wind turbine. This is because the main CrossPower container comes ready to use once it is earthed and has reached the minimum internal temperature (above 10°C) in battery section. On those temperature conditions HPGS can provide power immediately from energy stored in the battery pack or the generator will be automatically turned on to supply the power for the battery charge.

The footmark for PV modules deployment is approximately 37m x 7.5m[18] which needs to be considered before deploying. It should be noted that the placement is flexible as the PV system can be set up away from the CrossPower container (at maximum of 25 m[19]) and connected by cables due to its modular design. For optimal solar energy capturing PV should face perfectly south. The wind turbine has to be set up at least away from large buildings and trees as these can cause turbulence and will reduce wind power performance. Security should also be considered before deploying the renewable modules, for instance as wind turbine is 12 m high. Below, the deployment of each sub-system is given in detail.

Wind Turbine installation

In order to set up the wind turbine, two aluminum tube sections are bolted together and a triangular frame is attached for lifting later. A third section of tubing is attached to the outside of the CrossPower container. The joined tubing then needs to be lifted 2.6 m and connected to the third section of tubing with a pin rod. This wind power installation can be executed by a 3–4 soldiers team: the lifting of the mast is arranged with a specially constructed towing/lifting tool. Once the mast has been connected, the wind turbine is then attached, see *Figure 20*. The wire from the turbine is fed though the center of the mast and guided by a rope inserted earlier. Once

[18] Plus approx. 30 m^2 for additional 18 non-framed solar panels.
[19] In order to avoid resistance losses in the electrical cables.

this is completed, the structure is then winched up on cable attached to a fixed point, potentially a vehicle, situated directly behind the wind turbine. Once fully upright, the mast is fixed in place with bolts. The total time to erect the wind turbine will vary depending on weather, personnel number and if machinery is used. An approximate time with three people with a forklift would be 2-3 hours. During installation the wind turbine should not be erected in strong crosswinds as this could lead to excess stress to the pivot joint, leading to failure.

Figure 20. Wind turbine and its installation, Marijampolė, Lithuania (2018)

Solar Panels installation

The framed solar array is pulled out from each side of the container and is integrated on a rail system (each side has three rail units with 12 modules in each for a total of 36 solar modules on each side). A further 12 modules are built into the front side of the container and protected by metal panels whilst in transit. This gives a total of 84 modules (giving 21 kWp) plus 18 unframed flexible panels, *Figure 21,* that would need setting up externally to reach the 25 kWp capacity.

Assembly of PV modules is done manually, however, the solar panel frames are very heavy and can deform the rail system. The further installation of deformed/bent panel frames require additional manpower. Portable roller beds are supplied to aid deployment, however these are not robust enough. The extendable frames are very long, extending 15 m in each direction and therefore need flat ground for deployment. Furthermore setting up the PV system on soft surface would be difficult due to the weight of the frames and supporting systems will be required to prevent the frames from sinking into the soft ground (i.e. sand). Once the frames are pulled out, each panel is then unfolded: this requires a minimum of three people to extend and to fix the frame with bolts and to adjust the height of panels in a required position.

Finally the whole structure needs to be anchored down with guide ropes so that the panels are not damaged during winds or gusts. The panels will then be connected up in series with the connectors provided. The connectors should be labeled in a much clearer way as wrong connections have been a repeated problem in past experimentation due to poor labeling. Optimally the panels should be facing towards the south and at the appropriate angle[20] fronting the sun, so the solar energy production is maximized. A deviation towards east or west is possible but at reduced performance of the photovoltaic system. As previously mentioned, it is important to avoid any surrounding buildings, trees or obstacles which could cast a shadow over the PV panels.

Figure 21. Part of additional 4Kwp solar panel array (Pfisterer, 2017)

[20] As much as possible in a perpendicular way respect the sun rays incidence at noon.

Figure 22. Solar panels assembly, Marijampolė, Lithuania

Cooling/heating unit

The external battery cooling/heating unit has to be moved from PV container and connected though air canals to the CrossPower container. It requires around 3 – 4 personnel to move it and takes around ten minutes to connect to the side of the container using flexible insulated tubes. The weight of the unit is about 400 kg, so the forklift is required.

Figure 23. External heating/cooling unit (Pfisterer, 2017)

The operation of HPGS

The operation of HPGS is fairly easy. The operator has to follow the start-up procedures. Regular checks and maintenance operations, including fuel refueling, are conducted by one or two operators. Having two generators, this allows the maintenance to be carried out on one generator while the other one is used for power generation[21]. Depending on weather conditions, additional duty would be on ensuring that the PV panels are clean from sand or snow in order to maximize their efficiency.

It has to be mentioned again that the HPGS system can only be started after the battery section reaches the required minimum operation temperature (above 10°C).

The HPGS computer/monitor starts only after the whole HPGS system is started.

If the system fails to start or malfunctions, a warning alarms will provide the info on which HPGS subsystem is out of order. However, the basic operators training program covers only simple fault cases as for other and sometimes serious technical problems the Producer's assistance is needed. Furthermore, full access or control of HPGS software is only accessible by PFISTERER personnel. That means that even some basic procedures like the System Reboot after a failure is not possible without PFISTERER'S support. As this HPGS is a prototype, the dependency on the Manufacturer can be tolerated, but for a final solution deployable in battlefield it should not be appropriate. Finally, accessing the HPGS remotely could potentially be attacked by hackers.

[21] Depending on length of maintenance, battery charge level and load.

4.2. Logistics and Transportability

The HPGS system is housed in two 20'containers. The first container with batteries, inverters and generators weights approximately 15 tons, the second container with PV system, wind turbine (including mast), cooling/heating system and spare parts is around 11 tons. The total weight of HPGS is approximately 26 tons.

In Lithuanian Armed Forces the SISU E13 TP 8x8 trucks is used for containers transportation[22]. The HPGS containers are loaded and unloaded with the hook lift Multibit model MHS 135, which is installed on the SISU truck. For lifting operations, detachable platforms are used (see *Figure 24b*). This gives the capability for independent moving operations without additional equipment such as cranes. However, during delivery the containers are tilted at 45°: this could damage the system components if not properly secured, and therefore it is preferable a crane has to be used if available.

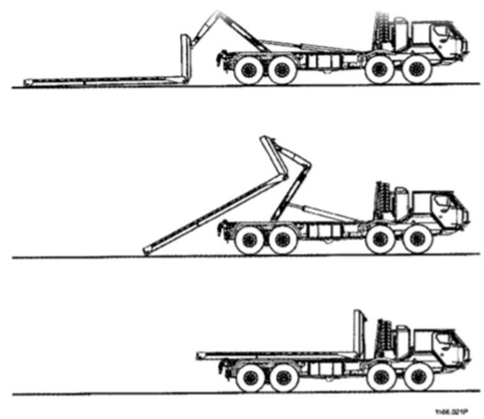


Figure 24a. SISU E13 TP8x8 truck with integrated Multilift model MHS135 during loading
Figure 24b. SISU loading diagram (SISU documentation)

Due to the road regulations weight limit[23], both containers can't be transported on one truck, therefore two trucks are necessary, which increases the overall cost of transportation.

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[22] Any truck of similar size, load capacity and equipped with suitable loading device could be used.
[23] According to European Road Regulations, maximum weight of the 3 axle truck allowed is 24 tons. The weight limit varies in different countries. However, this limit is the most common.

Currently there are six external thin metal panels, each with six bolts securing them on the PV container, to protect the PV stored in the front side. During transportation one panel sustained minor damage while in transit most probably because of vibrations caused a few screws to become loose, *Figure 25*.

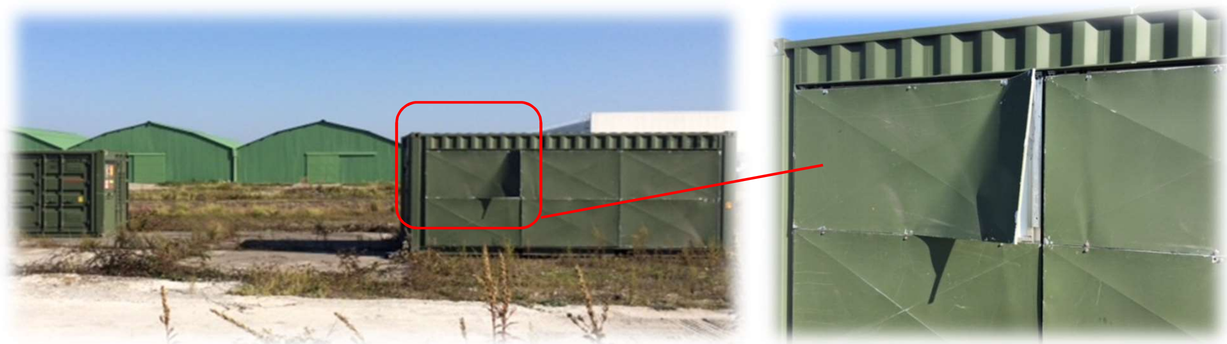

Figure 25. Damaged HPGS panel

<u>Lithium battery limitations</u>

One of the main issues and subjects of consideration concerning the logistics of the HPGS are the lithium batteries. The packaging for transport and shipping must be in compliance with the respective current regulations such as IATA (air), IMDG code (maritime traffic), ADR (road traffic in Europe).

Persons involved with the transport of dangerous goods, such as these batteries must be trained in the applicable requirements regarding dangerous goods. The packaging of the batteries must be designed in accordance with UN directives: a Class 9 hazard label is to be attached to the package as are markings indicating the correct shipping designation (lithium-ion batteries) and UN number (3480). The regulations apply to both new and used batteries. Currently a complete ban applies to all lithium batteries, new or used, for civil air carriers so transporting the HPGS system with lithium batteries by air is not possible.

As the use of lithium batteries[24] is one of the major limitations in transportation of the system, especially for air travel, another common energy storage technology was analyzed. Specifically, the use of flooded lead acid batteries was considered as they can be transported by air and do

[24] The system uses lithium-NMC batteries but for ease of analyse were compared to lithium-ion.

not have the potential to ignite if damaged. Acid is accessible in any part of the world so the batteries could be transported dry and the acid supplied in the final destination. Lead acid batteries are generally much safer and also cheaper however, this is traded for a lower energy density and therefore higher weigh for the same electrical capacity. If the 100 kWh capacity would be designed using lead acid batteries it would be 2.6 times the current battery weight, adding an extra 1500 kg. As system weight is a key specification that should be minimized, with the aim to transport both containers on a single truck this is not desirable. However, this is not the main drawback of lead acid batteries; they are extremely sensitive to temperature and above 25°C and they degrade more rapidly compared to lithium-NMC, which can operate up to 45°C. In hot climates this would require a much larger lead acid capacity or strict temperature regulation of the system. Further, the batteries would require regular maintenance and have smaller depths of discharge: 50% at 800 cycles whereas lithium has 80% at 2000 cycles, representing a 2.5 times longer life span. Effectively, lithium batteries can charge and discharge more quickly, at a higher rates and for longer which is critical for this system. *Table 3* details the differences between lead-acid and lithium-ion battery technology.

Table 3: Performance characteristics of a lead-acid vs lithium-ion battery

Specification	Lead-acid	Li-ion
Energy Density (Wh/L)	60-110	300 - 700
Specific Energy (Wh/kg)	40	100 - 260
Energy Density (W/kg)	180	250 - 350
Cycle life	800 @ 50% DoD	2000 @ 80% DoD
Temperature Sensitivity	Degrades significantly above 25°C	Degrades significantly above 45°C
Efficiency	100% @ 0.05 C-rate 80% @ 0.25 C-rate 60% @1 C-rate	100% @ 0.05 C-rate 99% @ 0.25 C-rate 92% @1 C-rate
Cost ($/kWh)	100	400

In the current state of technology, the lithium-NMC batteries are the best solution and a work-around for the transportation of the batteries should be investigated further. Potentially the System could be sent via the air without the batteries installed, but pre-purchased in the final destination. This could be a suitable solution as battery costs have decreased drastically from

2015 and are expected to drop further to $200 per kWh by 2020 (Hensley, Newman, and Rogers. McKinsey Quarterly, 2012). This would give a total cost of $20,000 to purchase a new battery pack. In the meantime, the main transportation of HPGS will be limited to land and to sea shipping.

HPGS maintenance

Routine inspections for generators should be done every 8 hours. General maintenance check–ups are the following: generators oil / cooling liquids refilling, and checking the filter's status is done daily. Further inspections and maintenances shall be done each week, month and year or after a specified amount of operational hours. The HPGS, batteries and inverters, other electrical devices, fuses, connectors and plugs are checked and tested monthly. Solar panels should be visually checked every week and, if necessary, they should receive timely cleanings[25]. Controlling of the electrical function and measuring of the string voltage should be done yearly. Containers, mounting structures, should receive monthly visual inspections.

It is noted that both generators are installed in the CrossPower container in a way that makes maintenance operations complicated because the difficulty of reaching some mechanical parts.

[25]The cleaning checks would depend on the deployed environment, may require water in dusty conditions.

4.3. The contribution of renewables solutions

Even though the core elements of the HPGS are the battery storage and generators, the use of renewable sources of energy to increase system's effectiveness should not be overlooked.
Based on past experiments, calculations concerning the use of renewable energy sources have been done to understand their benefit.

SUN

According to the data provided by manufacturer, the solar panel maximum efficiency is 15%. This means that 15% of total sunlight that falls onto the panel surface can be converted into useable energy in the form of electricity. Considering the standards of contemporary solar panels and their efficiencies, this is by far not the best result possible. Modern solar panel efficiency is around 20% with a maximum theoretical of 29% for silicon panels. Additionally, it should be considered that the novel PV panels are lighter, more robust and could continue to function even if partially damaged.
Considering the contribution results in past experiments, PV influence to the total energy production fluctuates between 3% – 24%, depending on weather conditions and average load.

It has to be mentioned that the latitude influences PV power generation capacity. HPGS tests were executed in relatively narrow latitude range (45 to 54 degree North). It is expected that the HPGS overall efficiency will increase when deploying the System south.

WIND

So far, the input of wind energy was unreliable and contributed little to the overall power generation. In most experiments the wind was either not strong enough or it was not able to perform due to technical faults. There were also situations where the deployment area did not allow good wind energy production. As of now, wind energy brings no real benefit since its transportation and set up time may not be balanced by its energy production capacity. The contribution of the wind power generation could marginally increase when deploying the System in more favorable wind generation environments.

Author's Note

When the HPGS final report will be written, new data deriving from future experiments will be taken into consideration. In that context we will see if the contribution of renewables will be in line with the data available today or they will lead to a substantial revision.

4.4. Use of the System in extreme environments

So far, the HPGS was only tested in a relatively narrow range of temperatures [-1°C to 21°C]. Further tests are already planned for early 2019 in Canada in order to evaluate the performances in low temperature conditions and for a longer operational period (up to 3 months).

In general, ambient temperature conditions are extremely crucial for proper ignition and functioning of the generator. In diesel engines, air is compressed and becomes hot, when peak temperature and pressure is achieved the fuel is injected, which then ignites in the given conditions.

Increased altitudes can lead to start-up failure, so adequate levels of air are required for proper start up and operation. In areas of high altitude, air pressure drops reducing the air density. This can create problems with generator start up if not accounted for.

Another factor that has an effect is the availability of ambient air to facilitate heat dissipation from the generator. A lot of heat is created during the combustion process and needs to be dissipated into the environment to reduce engine temperature. At higher altitudes, due to the low air density, heat dissipation occurs at a much slower rate than it would at sea levels, resulting in high engine temperatures for a sustained period of time. The engine remains hot and overheating is a common problem in such cases.

In conditions of extreme humidity, water vapor in the air displaces oxygen, which can effect ignition.

Freezing temperatures also impede the operation of diesel generators. In cold environments, igniter as well as oil and fuel may impact starting and the ability of the generator set to continue in operation. Diesel fuels are susceptible to gelling in below freezing conditions. This can lead to shut down and failure of the generator. If it is very cold, ice may form in the ventilation and air cleaning systems which can also cause operation failure.

As it is stated in the user's manual, it is not recommended to use the system on board ships or at high altitude (>3000m) as the system has not been designed for this.

Additionally, the operational efficiency and operational stability of HPGS is impacted by the performance of lithium batteries. The temperature regimes and battery usage profiles are crucial for a proper operation of HPGS.

During the operation, the main (CrossPower) container should be closed and an internal temperature between 10°C to 30°C has to be maintained at less than 90% humidity. Furthermore, the container should be warmed to at least 10°C by using heating unit that has to be powered by generator. An optimal ambient temperature of 23°C for batteries is desirable. This is the System design issue as the batteries and the MEMS are installed next to the diesel generators. This makes the cooling of the batteries more difficult when the generators are running and requires more energy to maintain the required temperature. The batteries should not be subjected to unnecessarily high charging and discharging cycles[26] to protect them from damage.

Insufficient ventilation, direct exposure to sunlight or the effect of other heat sources in the operating space could cause the battery cells to age prematurely or sustain irreversible damage. With the use of cooling/heating system the ambient temperature range can be widened, however, what is the reliability of HPGS in extreme temperatures is uncertain as no in-depth study has been conducted and should be investigated further.

The wind turbine could be damaged if the wind is too strong therefore an over speed control is set at no more than 12–13 m/s. If the wind limit is reached, the system automatically deaccelerates the turbine to protect it. In cold climates the forming of ice on the rotor or rotor blades may cause vibrations which could reduce performance or even damage the turbine, which will result in its total loss. The wind turbine must be set up only when there's no strong cross-winds. The inverter in wind system can operate in temperature interval between -25°C to +40°C, in accordance to PFISTERER's specifications.

Solar panel efficiency is affected negatively by temperature increases. Depending on their installed location, heat can reduce output efficiency by 10% – 25%. The ideal temperature specified by manufacturer is around 25°C. As the temperature of the solar panel increases, its

[26] The maximum battery discharge cycles should not exceed 48 per day.

output current increases exponentially, while the voltage output is reduced linearly. As a result, heat can severely reduce the solar panel's rated production of power, *Figure 26* (CivicSolar Inc. 2018).

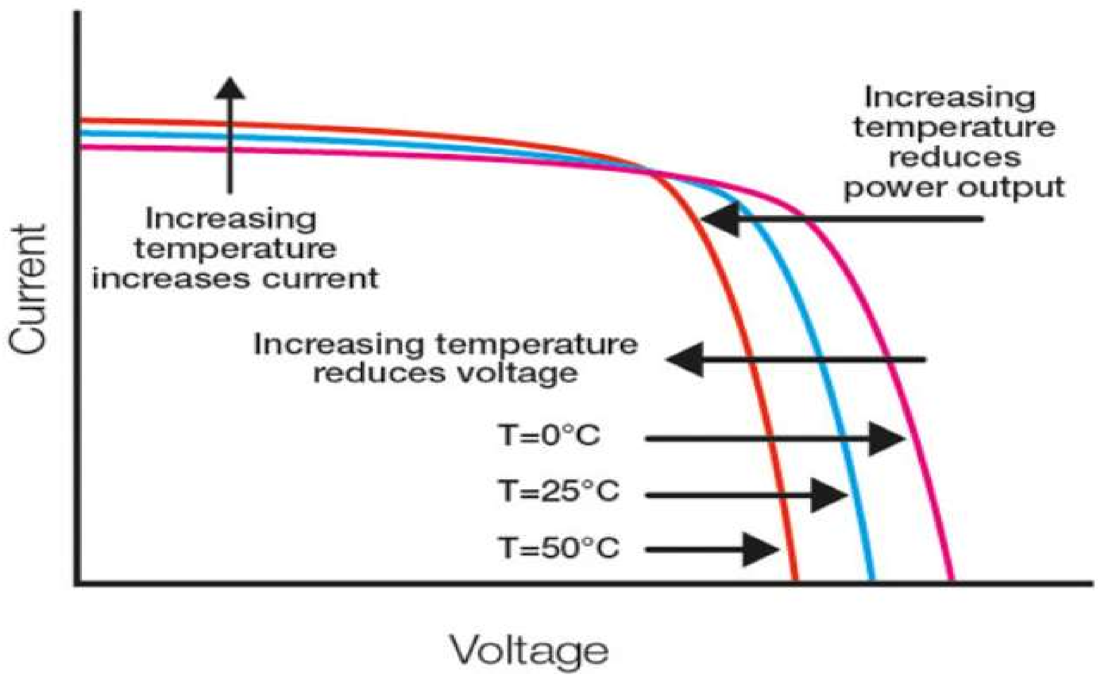

Figure 26. The impact of temperature on solar panel power output (Seawardsolar.com, accessed online, Sep 2018)

On the other hand, in colder climates given clear skies, the PV system should perform at its highest efficiency, due to the lower temperature. The inverter in the PV system can operate in temperature interval from -25°C to +60°C and in humidity conditions of 0 – 100%.

The advantages and drawbacks in different environments discussed above regarding the renewable power emphasize the benefits in modularity of the System when selecting specific deployment conditions.

4.5. HPGS Load Analysis

The results from each test were plotted in *Figure 27*.

Figure 27 show the plot for the fuel efficiencies of the HPGS and the 200 kW conventional generator[27] across a range of loads. The evidence based estimates of the efficiency profile for a 200 kW and a 150 kW diesel generator have also been plotted[28].

A log trend line for the 200 kW generator was chosen as this represented the efficiency curve expected of a conventional generator; it can be seen that the linear theoretical 200 kW trend line approximates the experimental result at higher loads well. Further, the theoretical 150 kW plot is very similar to the 200 kW result at mid-range loadings, suggesting an indicative comparison can be made.

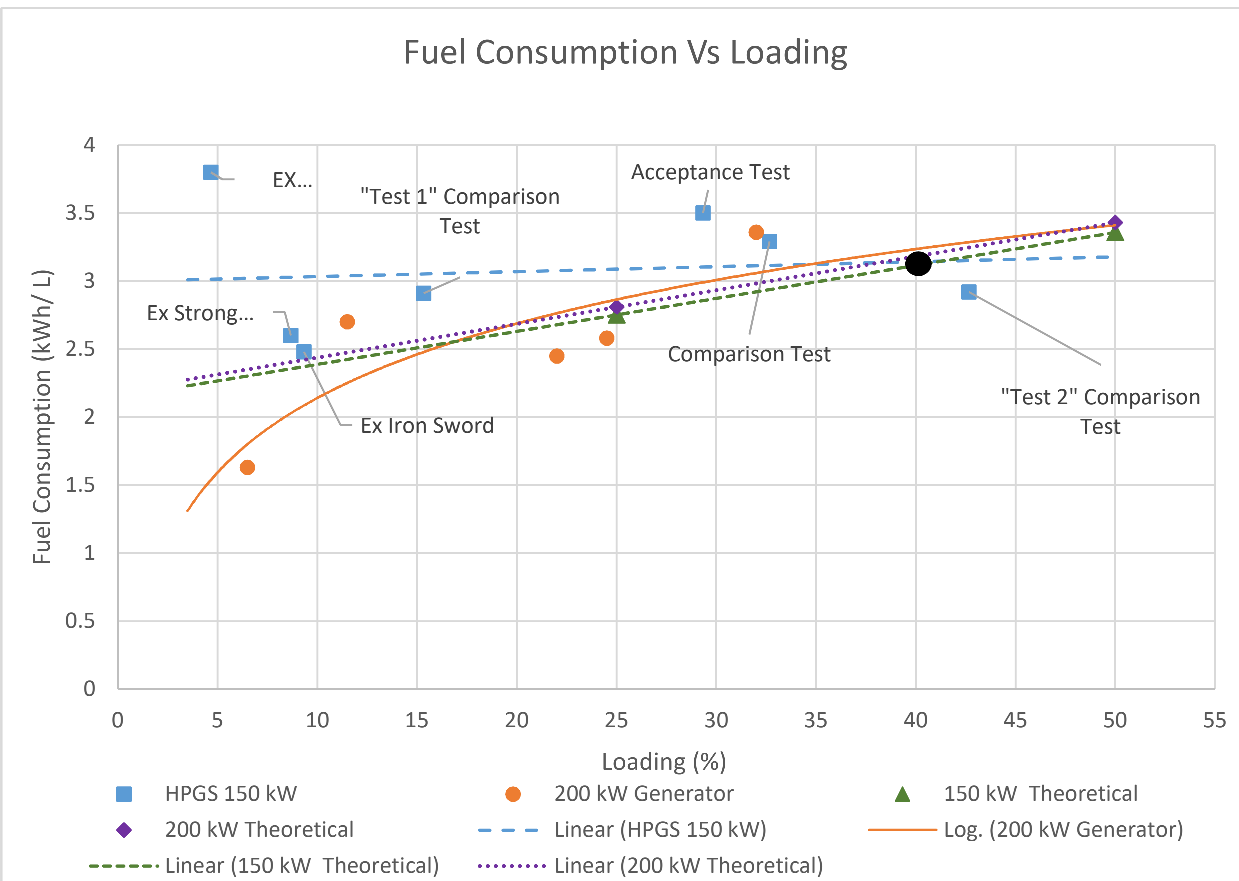

Figure 27. Graph of fuel consumption vs loading

[27] The 200 kW conventional generator was not the same across all HPGS tests.
[28] Data sourced from dieselserviceandsupply.com. [Accessed online, Aug 2018].

The graph indicates that the HPGS efficiency is the highest at lower loading conditions, where the conventional generators lack the efficiency. The positive HPGS energy generation outcome is due to energy storage (battery storage system) and renewable sources of energy (when available). During the HPGS battery recharging phase, gensets charge the batteries at the maximum power which is the optimal functional condition for diesel engines. Further, energy production from renewable sources does not require fuel and therefore increases efficiency of the HPGS. At very low loading conditions the renewables can cover a larger percentage of total load, maximizing the overall efficacy of the System.

According to the data in *Figure 27*, the efficiency intersection with the HPGS performance (blue dashed line) for a 150 kW conventional generator (green dashed line) can be seen (●black circle). **The HPGS becomes less efficient than a conventional 150 kW generator as the loading increases and after roughly 40% average loading[29] there is no fuel savings**.

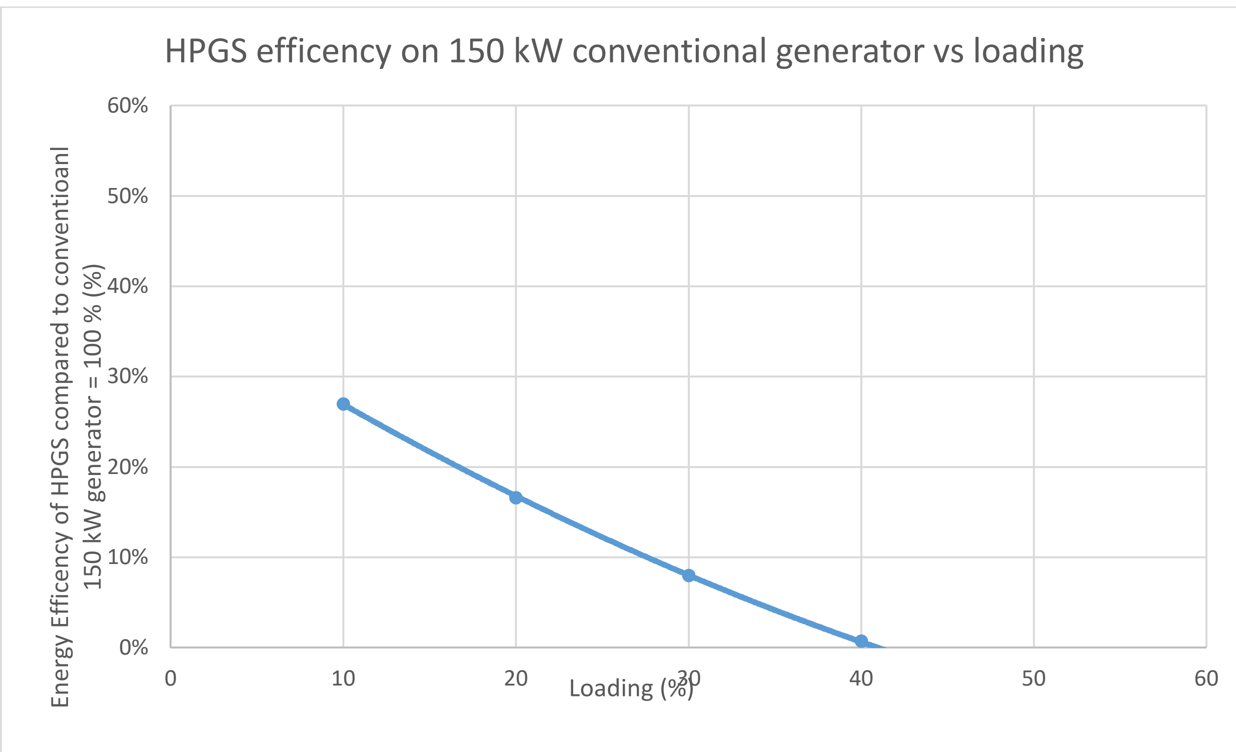

Figure 28. Difference between HPGS and a 150 kW conventional generator fuel efficiencies vs loading

[29] It should be noted that this value was found using estimated numbers so errors should be taken into consideration.

Elaborating the same data from *Figure 27*, a saving efficiency curve was plotted, *Figure 28*. It shows the HPGS fuel savings in percentages compared to a conventional 150 kW generator versus the loading conditions [%]. The dependency between the average load and the convenience of using the HPGS respect a conventional 150 kW generator is quite linear in the 10% - 40% range:

- around 30% in case of an average electric load about 10% (15 kW)
- around 20% in case of an average electric load about 20% (30 kW)
- around 10% in case of an average electric load about 30% (45 kW)
- no particular convenience in case of an average electric load about 40% (60 kW)
- losses in case of an average electric load above 40% (> 60 kW)

Theoretically the convenience of using the HPGS respect a conventional 150 kW generator should be infinite for a very low load, or in any case for load values (including internal system load) lower than the production capacity given by renewable sources.

It has to be noted that conventional generators have better efficiencies at high loads in comparison to HPGS. This can be explained by looking at the diesel generators inside the HPGS. As there are two 75 kW generators, on high loads both of these generators need to be running to supply the load and charge the batteries. This consume more fuel than one conventional diesel generator with a combined power output of 150 kW, *Table 4*.

In addition, the HPGS needs additional energy for internal load to keep the energy management system running and supply the cooling unit.

On higher loads the battery would experience more charging cycles and therefore require further cooling and bigger internal losses (see next paragraph).

Table 4: Comparison of fuel consumption of two 75 kW diesel generators vs a 150 kW type

GENERATOR	FUEL CONSUMPTION @ 25% LOAD (37.5 KW)	FUEL CONSUMPTION @ 50% LOAD (75.0 KW)	FUEL CONSUMPTION @ 75% LOAD (112.5 KW)	FUEL CONSUMPTION @ 100% LOAD (150 KW)
HPGS 2 X 75 KW GENERATORS[30]	13 l/h (one)	23 l/h (both)	34 l/h (both)	46 l/h (both)
CONVENTIONAL 1 X 150 KW GENERATOR	15 l/h	22 l/h	32 l/h	41 l/h

<u>Internal consumption</u>

The HPGS is far more complex than a conventional generator. Losses occur not only in generators due to friction, drag, exhaust and engine cooling, but also in other parts of the system (as described later). The batteries, transformers, wires and inverters are not 100% efficient and therefore losses occur in storing and transmitting the energy produced. Some of the energy is used to maintain the required battery temperature in warm or cold climates. Energy is also needed to control the power management system. While the cooling unit and management system is a part of general operation, it still adds to the reduction of the total energy output and therefore can be considered to contribute to internal losses depending on external temperature conditions and the size of the required load.

<u>Test limitations</u>

There are many factors that would have influenced the outcome of tests. Factors would include different environment, a range of loading conditions and potential methodology errors.

One of the main limitations of the tests is that the HPGS was compared to a 200 kW conventional generator rather than a 150 kW generator, as a 200 kW generator would be less efficient at lower loads, however this has been accounted for the analysis and was found to have little influence.

[30] If both generators work at maximum capacity, they can supply the load up to 150 kW in total. The total load is distributed evenly between two generators.

Further, during the experiments it was not possible to confirm if the load on HPGS was exactly the same as the load on conventional generator as there was no monitoring equipment on the conventional generator, therefore the loads may not have been accurately the same, leading to some discrepancies.

A second limitation was in measuring the fuel used. For the conventional generator the fuel amount was calculated either by using the fuel gauge on the truck and by the soldiers counting the added quantity. However, the accuracy the gauge on the fuel truck is unknown, leading to approximations. The fuel was measured for the HPGS in different ways: via the HPGS system data and by the amount of fuel added each time by soldiers. An average was then found.

Also, most of the experiments were time based and therefore the battery SOC was not the same at the beginning of the experiment and at the end. This means that the total energy production could not be evaluated precisely. For example if the SOC was lower at the end of the test, an additional amount of energy would have be required to charge the batteries up to their initial SOC, requiring more fuel.

Finally, the maintenance status of the conventional generators was unknown.

4.6. The impacts of increased time between regular generators maintenance

Based on past experiments and tests the conclusions about maintenance of HPGS and a conventional generator can be made considering the operational hours. During the experiments the conventional generator was running constantly without interruptions whereas the HPGS had two generators that were only operating when the battery required charging at high loads. This arrangement meant that the second HPGS generator was in operation for very short periods of time, therefore the analysis was based on the average use of the two generators as they can be switched to ensure equal runtimes.

With battery storage system and renewable energy sources the HPGS generators ran for a reduced duration of time producing the same amount of energy as the conventional generator. As seen in the *Table 5*, while the HPGS was running on lower loads, the time between scheduled maintenances substantially increased.

In addition, the wind turbine and solar panels were supplying additional percentage of total energy needed thus reducing the run time hours of the gensets.

The *Table 5* (next page) represents the comparison of mean time between maintenance.

To be noticed that even if a specific tests using traditional 75 kW genset have not been run instead of 150 kW gens, it can be concluded that potentially the below numbers in the column "INCREASED TIME BTWN MAINTENANCES" could be a little diminished.

Table 5: Results for mean time between maintenance for HPGS generators vs a 200 kW conventional one

TEST/EXERCISE PLACE PERIOD	DURATION	LOAD (AVG)	HPGS RUN TIME	CONV. GENERATOR RUN TIME	INCREASED TIME BTWN MAINTENANCES
ACCEPTANCE TEST LITHUANIA MAR 2016	12 h	43 kW	7.0 h	12 h	1.8
COMPARATIVE TEST LITHUANIA MAY 2016	48 h	49 kW	-	48 h	-
PFISTERER REP. TEST GERMANY JUL 2016	-	-	-	-	-
EX STRONG HUSSAR LITHUANIA AUG 2016	48 h	13 kW	10 h	48 h	4.8
EX IRON SWORD LITHUANIA NOV 2016	14 days	14 kW	68.6 h	286 h	4.2
COMPARATIVE TEST #1 LITHUANIA FEB 2017	24 h	24 kW	8 h	24 h	3.0
COMPARATIVE TEST #2 LITHUANIA FEB 2017	2.5 h	64 kW	1.8 h	2.5 h	1.4
PFISTERER COMP. TEST GERMANY AUG 2017	24 h	53 kW	15 h	24 h	1.6
EX CN3 FRANCE OCT 2017	-	-	-	-	-

5. General recommendations and possible improvements

5.1 Further HPGS testing

The analyzed HPGS pilot testing project shows the benefits of a hybrid power generation system: fuel savings and increased DFI energy resilience. Additionally, the amplified mean time between the maintenance benefit for the gensets has been proved.

However, further testing will be required to obtain more reliable values about potential fuel savings and the increase of mean time between the maintenance at different loads. The additional tests have to be executed at wider range of temperatures and ambient conditions.

As further testing is necessary for more sophisticated evaluation of the performance of the HPGS, where the recommendations can be provided on design changes for operability, transportation, assembly of HPGS ease of use/operation.

Numerous tests were conducted on the HPGS, however, further testing is still needed to provide conclusive understanding of HPGS. It is recommended that the tests should focus on the following areas:

<u>Loading Tests</u>

Current HPGS data focuses on a narrow loading range. Further experiments should concentrate on average loadings between 40% to 60% of HPGS nominal load. At least 3 to 5 (48 hour) tests at different loads should be conducted in this range to produce a reliable performance curve. Additionally, it would be preferred to test the system in comparison with 150 kW conventional diesel generator under the same loading and experiment conditions for a direct comparison. In the ideal test case 2 X 75 kW conventional generators should be used for comparison with HPGS performance.

<u>Tests on extreme conditions</u>

So far, the HPGS was only deployed in moderate environments, with a temperature range from -1^{o}C to +21^{o}C. Further testing should expand in both higher and lower temperatures is needed to accurately evaluate HPGS system's performance under these conditions. Additionally, other climate and environmental factors should also be considered, such as humidity, high level of dust, and the altitude and latitude.

Grid Connection Tests

In order to expand the benefits of HPGS as deployable generator, it would be beneficial to test the system's capacity to be integrated into the civil power grid.

5.2. Suggested HPGS re-engineering

To improve the installation process and deployment opportunities of the HPGS, several changes to the design should be made, particularly to the renewable components, as these are the most time consuming to set up.

Wind Turbine System

At the moment a stronger fixed point is needed for hand operated towing lift[31]. If the wind turbine is to be set, the mast could be made telescopic (hydraulic or mechanical type): it would be much easier to operate and faster to set up with fewer personnel.

Secondly, the electrical cable should be placed externally along the outside of the mast rather than through its center: this would decrease deployment time and improve maintenance access as well as reduce the probability of damaging the wire during assembly process.

Instead of using horizontal axis wind turbine, a vertical axis wind energy generator may be used: it needs less wind power to rotate and can produce more power in unfavorable wind conditions while horizontal axis wind turbine is more efficient during higher winds.

PV System

The PV container and slide out mechanism of the current system is difficult to handle and set up in the field, especially for numerous repeated deployments (with the risk of getting deformed). Again, there is a risk of physical injury when pulling out the solar panels from the container. The steel frame adds unnecessary weight and is limited to very flat and hard surfaces. An alternative design would have smaller individual/independent PV units with separate frames. These should then be connected together with cables, which would reduce the weight of the system (less danger of bending and damage). As the modules would be smaller they would have more flexibility and could be turned in any direction[32]. At the moment no directional or minor directional flexibility is allowed.

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[31] It was noticed that the motor for wind generation is big and heavy and that the generator assembly with wind vane is quite difficult.

[32] Potentially this could be done using an automated sun tracking system to utilize the maximum amount of sun light.

Another PV product available is the thin-film solar panel technology. Its main advantage of is that the amorphous silicon can be deposited on a variety of substrates, which can be made flexible and come in different shapes so it can be rolled out of a trailer and unfolded quickly. It would also greatly reduce the weight since there would be no need for heavy steel frames. These flexible solar panels can be used in freezing temperatures and are waterproof, making them suitable for permanent operation in various weather conditions. However, thin-film PV have efficiency of only around 6% - 9% as opposed to the current 15%, making its versatile application come at expense of efficiency.

However, a there is a current development of flexible panels rolled up into a container. These systems are able to be deployed in minutes. These could be very effective for deployment of larger capacity systems.

Cooling/Heating System

The cooling system could be redesigned to increase its efficiency. The tubes in which air is reaching the batteries are attached to the container door facing the batteries. Due to various circumstances these doors are being opened and closed which causes cool air to escape. A different way for cool air to reach the batteries is needed, or the location of the batteries should be changed. The cooling/heating unit is not functional as it is external module; it would be beneficial to have the conditioning system integrated inside the container with the batteries. This would make deployment and transportation of the cooling system easier: the current weight of external heating/cooling unit is approximately 500 kg, therefore a motorized lifting is needed.

Also, in order to reduce the heating/cooling load, the shading should be placed on the external cooling unit and on CrossPower container: shading (a simple net or a double roof) further increase the HPGS efficiency in hot climates.

Exhaust Heat Recovery System

The heat of the exhaust gases (thermal losses) could be used to heat the water of showers or to generate hot air to be used for the air conditioning system of infrastructures adjacent to the HPGS installation. Part of it could be used for warming the batteries compartment, if necessary.

5.3 Some other “Instant” Comments

In this paragraph, some instant comments and feedbacks received from the personnel responsible for operating and servicing the HPGS during these three years were inserted and analyzed. Sometimes they are just a list of technical bugs with suggested improvements, sometimes there are questions only, without answer to be found during the next testing period. As the author of this report, I think it is extremely valid to have collected these suggestions, sometimes complaints, because they come from those who really need to use this system in the field, when it is too late to get lost in engineering ruminations!

Assembling and disassembling

For HPGS installation/assembly the motorized lift is used. It takes approximately 8 hrs for 8 soldiers team to assemble HPGS with motor lift assistance… it’s too much!

During the HPGS on-loading and off-loading operation from the transportation platform the System’s containers experience mechanical hits. Those hits negatively affect HPGS hardware/software management modules and internal wiring. The current anti-vibration predispositions are not enough.

Storage/containers solutions

The system spreads across two 20’ containers with a total weight of about 26 tons. It is recommended that the weight should be reduced (max 24 tons). This weigh reduction will allow to transport HPGS on one single truck[33].

For improving modularity, it is suggested that the system could be divided into three containers[34]:

- 10’’ container to house the two generators back-to-back; it will give better access for maintenance.
- 10’’ container to house batteries, energy management electrical systems, cables, connectors, transformers/inverters and the integrated cooling/heating unit. The physical separation between

[33] If 40’’ container transportation truck is available.

[34] 2 x 10’’cointainers, plus 1 x 20’ container.

diesel generators and battery compartment will reduce the battery temperature cooling load as there will be no generator producing heat next them.

- 20' container for the PV system with a higher capacity array. However, it would only be possible if wind generation system would be redesigned or removed completely, as the mast sections are quite long.

Designing the modules in this way will give more flexibility in operations and improve transportability of the system as each component will be smaller and more manageable.

MEMS

HPGS start and operation instructions should be simple and clear[35]. Also it is strongly recommended that it should be step-by-step checklist for HPGS the personnel.

All improvements and error control is organized at PFISTETER in Germany[36]. This means that all diagnostic errors have to be fixed at PFISTETER's premises and soldier has very limited control over the HPGS operation and problem solving. This risky issue has to be clarified before the System is finally transferred to Armed Forces.

Is the computer screen thermally sensitive? Is possible a blackout in case of low and high temperature? In any case it is suggested to have installed some analog monitoring devices for checking (e.g. generator voltage, power output, oil pressure etc.,) and some hardware switches for simple emergency operation in case electronic devices fail.

It is not clear for the operating personnel what type of reports the HPGS system can generate. This training part is not included in the HPGS training modules.

The access to HPGS computer data is only available when the whole HPGS is in operating mode. Again, no access to data in preheating mode or in sleeping mode.

[35] As evidence of non – optimal functionality of MEMS has to be noticed that there is an "error" diagnostics sign in HPGS computer screen which has to be deleted every time when there is a need to start HPGS. It takes few minutes to dim this sign.

[36] The HPGS system control is in Pfisterer IT Cloud.

Other HPGS functionality aspects

The time necessary to reach operational temperature of the batteries section is very long. During that time HPGS cannot be started. For example it takes 2 hrs to increase the temperature from 6^oC to 10^oC. Again, batteries section is not properly separated from inverters parts: that means that every time when doors are opened to check the inverter block the heat that is needed for conditioning the batteries is lost.

Service personnel competencies

In general, the personnel responsible for HPGS operation possesses basic electrical engineering qualifications and serve other generating equipment at the Battalion. There is an ongoing demand to increase the competencies of the service/operational personnel in order to make them more independent from expensive manufacturer's request for technical intervention. The average team of qualified personnel has to be of 7-8 soldiers with 2-3 in reserve. It is not clear whether formal certification for HPGS service/maintenance team is needed and what is the scope of mandatory training: the certification and mandatory training increase HPGS over all maintenance costs.

Warranty

Producer's warranty terms and conditions should be improved and extended as HPGS is still in a development/testing phase.

General and final

Avoid over-engineering and build it simple and sturdy!

6. Conclusions

Over the past two and a half year multiple tests have been conducted in number of military exercises and demonstrations in Europe (France, Germany, Lithuania) where the ambient temperatures ranged from -1°C to 21°C and across different average loads between 7 kW and 64 kW (nearly 5% to 45% of HPGS nominal maximum load). As the System is still in the prototype stage it requires some further improvements before it can be potentially deployed in operations. However, the concept is promising: the tests show HPGS is able to save fuel, in comparison with a 150 kW conventional generator, while the average load is below 40% of its nominal maximum load, thus increasing the resilience of energy in a deployed military camp through the battery storage and renewables sources. The results indicate that the HPGS is able to save up to 30% of fuel running at 10% of its maximum load (15 kW), however, as the load increases, the HPGS fuel efficiency decreases: at 20% of maximum load (30 kW) it saves about 20% of fuel, while at 30% loading (45 kW) it only achieves a saving of 10%. Using approximations, the HPGS no longer saves energy after 40% (60 kW) of its maximum load, even if there is evidence of possible considerable increasing in efficiency when favorable ambient conditions.

It has to be said that solar energy was beneficial, but PV should be redesigned to increase deployment effectiveness and versatility. Additionally, an increased generation capacity of the PV system should be investigated. The data shows that PV influence to the total energy production fluctuates from 3% to 24%, depending on the load and geographical/weather conditions.

The input of wind energy was very low. It was non beneficial and contributed little to the overall power generation. In most experiments the wind was either not strong enough or the wind energy generation module was not able to perform due to technical issues. As of now, wind energy brings no real benefit to the HPGS solution since its transportation and set up time may not be balanced by its energy production. The removal of wind energy generation system would be most cost effective except for specific deployment areas characterized by constant winds.

As overall consideration, it has to be said that the renewable power generation is an additional option able to increase the whole capacity of hybrid generation system.

From the logistic perspective, it was demonstrated that the mean time between the required maintenance for the diesel generators could be increased by more than 2 times. Despite of the fact that solar and wind generation solution has minor problems/defects, the part of the equipment related to traditional fuel system generally operates without particular problems.

Currently, the HPGS MEMS and electrical components are vulnerable during transportation and need greater protection against shock and vibrations. In addition, due to its size, weight and restrictions on transportation of lithium batteries, the deployment of HPGS is more complicated and expensive compared to a similar power conventional generator. Therefore, additional improvements should be also related to the improvement of HPGS transportability. As mentioned before, the lithium batteries have certain limitations for transportation, particularly for air convoy due to civilian safety regulations, however they are reliable and resilient to environmental conditions as well as have superior efficiency and energy density parameters. With the continued development of energy storage technology and decreasing price of lithium batteries, this limitation could be overcome.

As there is a need to test the HPGS in extreme environments the further experimentation is required in order to have more accurate and test data and potential savings in those conditions. It has to be said that those additional HPGS tests are planned for fall of 2018 and 2019 as it is shown the Project time-line (*Figure 1*).