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CONCEPT OF A MOBILE CONTAINER-BASED COGENERATION PLANT (CCHP) FOR THE TECHNICAL ORGANISATION OF ENERGY ISLANDS AS A POTENTIAL TOOL FOR ENHANCING DEFENCE LOGISTICS RESILIENCE

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Abstract.
The increasing vulnerability of energy infrastructure to grid disturbances, natural hazards and crisis situations creates a need for energy systems capable of autonomous operation when conventional supply is unavailable. While islanded multi-energy systems, combined cooling, heating and power (CCHP) technology, energy storage and mobile energy resources have been studied, their integration

into a rapidly deployable, containerised CCHP-based energy island for critical infrastructure remains insufficiently investigated. This study presents the technical concept of a mobile containerised CCHP plant with an electrical capacity of approximately 2 MW, intended to supply four critical facilities (500 kW each) during prolonged outages, supported by a 500 kW/1 MWh battery energy storage system deployed in a standard 20-foot container. Using an energy-balance analysis based on manufacturer catalogue data and a technical feasibility assessment, the study obtains a catalogue overall efficiency of 86.2% and confirms the feasibility of supplying the assumed load while utilising recovered thermal energy; the battery system supports short-term load balancing, island-grid stability and black-start operation. Key constraints include dependence on continuous fuel availability, reduced efficiency under part-load operation, and the need for a suitable heat off-taker and deployment site. The principal contribution is the integration of dispatchable CCHP generation, battery-supported island operation and containerised mobility into a single energy architecture for critical infrastructure; prototype testing, dynamic islanding studies, BESS control validation and quantitative fuel-resilience assessment remain necessary before practical deployment. Locally available fuels, including woody biomass, represent a potential direction for further improving the resilience of mobile energy islands.

Keywords:
energy island; trigeneration; defence logistics resilience; mobile CCHP system; critical infrastructure resilience

Introduction

The transformation of contemporary energy systems is accompanied by increasing uncertainty in energy supply, growing dependence on complex infrastructure networks, and rising exposure to natural, technological, geopolitical, and military disruptions. These challenges are particularly significant for critical infrastructure and defence-related facilities, for which interruptions in electricity, heating, or cooling supply may directly affect operational continuity and the provision of essential services. Consequently, energy resilience, understood as the ability of an energy system to withstand, adapt to, and recover from disruptive events, has become an increasingly important element of modern energy security. In this context, decentralised generation, microgrids, and islanded energy systems are gaining importance because they can reduce dependence on centralised energy infrastructure and maintain local energy supply when grid connectivity is unavailable or unreliable (Albarakati et al. 2022; Mallah et al. 2024; Pepermans et al. 2005; Pudjianto et al. 2007).

The concept of an energy island or islanded microgrid has traditionally been associated with the capability of a locally integrated energy system to operate independently of the main grid. Such systems can combine distributed generation, energy storage, controllable loads, and multiple energy carriers to improve supply reliability and operational flexibility. Recent research increasingly considers islanded systems as integrated multi-energy environments rather than electricity-only networks. For example, Huylo et al. (2025) investigated an islanded campus microgrid integrating combined heat and power (CHP), district heating and cooling, renewable generation, and battery and thermal energy storage. Their results demonstrated the potential of coordinated generation and storage to reduce emissions while maintaining reliable

energy supply. Similarly, Sandvall et al. (2025) demonstrated, using a model-based analysis, how sector coupling between electricity, industry, and heat can support the transition of island energy systems while improving the utilisation of renewable and excess-energy resources. These studies confirm that the resilience and efficiency of islanded systems increasingly depend on the integration of several energy vectors and flexible storage technologies rather than on isolated electricity generation.

The development of multi-energy and combined-generation systems has therefore become an important direction in contemporary energy research. Combined heat and power (CHP) and combined cooling, heating, and power (CCHP) systems enable the simultaneous utilisation of electrical and thermal energy and, in the case of trigeneration, cooling energy as well. Their principal advantage is the possibility of increasing the useful utilisation of primary fuel through the recovery of heat that would otherwise be rejected to the environment. The integration of multiple energy carriers also provides additional flexibility in matching generation with the heterogeneous demand of end users (Chicco and Mancarella 2009; Mancarella 2014). Recent studies extend this approach toward increasingly complex multi-energy configurations. Yang et al. (2026), for example, developed a week-ahead energy management model for a pelagic island energy system incorporating diesel generators, gas-fired CHP units, renewable sources, batteries, hydrogen storage, fuel cells, absorption chillers, refrigeration units, and desalination technologies. Their work illustrates the growing tendency to treat islanded energy systems as coordinated multi-energy systems capable of supplying electricity, heat, cooling, and other essential services under uncertain operating conditions.

Energy storage constitutes an important complementary component of such systems. Battery energy storage systems can compensate for short-term fluctuations between generation and demand, improve the stability of islanded networks, and enable generating units to operate within more favourable operating ranges. The importance of storage is particularly evident when renewable generation is introduced into islanded systems because of the temporal mismatch between renewable production and demand. Huylo et al. (2025) demonstrated the benefits of combining renewable generation with battery and thermal storage in an islanded CHP-based campus system, while Palys and Daoutidis (2024) examined renewable ammonia as a potential long-duration storage medium for islanded energy systems. More broadly, Dugan et al. (2021) demonstrated that mobile energy storage can improve power-system resilience, indicating that storage should be treated not merely as an auxiliary component but as an important element of resilient islanded energy architectures.

At the same time, recent research on islanded systems has increasingly focused on achieving energy independence while reducing environmental impacts and dependence on conventional fossil fuels. Zhao et al. (2025) proposed an integrated zero-carbon energy system for offshore islands combining renewable generation,

energy conversion, hydrogen storage, fuel cells, desalination, and refrigeration. Romero et al. (2026) investigated hybrid renewable energy systems for off-grid islands and demonstrated the potential of combining photovoltaic and wind generation with battery storage and conventional generation. Chu et al. (2026) similarly proposed a multi-energy complementary system for an island natural-gas processing station, integrating natural-gas-based generation, photovoltaic generation, and waste-heat utilisation. Nasab et al. (2026) investigated a high-fidelity hybrid configuration combining gas turbines, solid oxide fuel cells, and photovoltaic generation in an islanded industrial microgrid. These studies demonstrate substantial progress in the optimisation and integration of low-carbon and multi-energy island systems.

However, the technical requirements of critical infrastructure differ in important respects from those of conventional remote or renewable-energy island applications. Critical facilities may require continuous and predictable energy supply, rapid restoration after a disruption, and the ability to operate independently of damaged infrastructure. Moreover, in emergency or military conditions, the availability of local renewable resources cannot always be assumed, while fuel logistics and the physical deployability of generating equipment may become decisive factors. In such circumstances, dispatchable generation based on high-efficiency CHP or CCHP technology may provide an important complement to renewable generation and storage. The role of flexible generation is particularly relevant because islanded systems must maintain supply even during periods of insufficient renewable production or adverse weather conditions. Yang et al. (2026) explicitly addressed such conditions by considering stressful weather and uncertainty in renewable generation, while Sandvall et al. (2025) demonstrated the role of dispatchable generation and thermal storage in maintaining system flexibility during the energy transition.

Another important research direction concerns the mobility of energy resources. Conventional microgrids and energy islands are generally designed as stationary systems and therefore require permanent infrastructure, dedicated generation assets, and relatively long implementation periods. Mobile energy systems offer a different approach by allowing generation and storage resources to be transported to locations where the existing energy infrastructure has been damaged, is unavailable, or cannot provide sufficient capacity. Cabrera et al. (2023) investigated a containerised microgrid concept for electricity supply in non-interconnected areas, demonstrating the applicability of container-based architectures to decentralised power supply. Dugan et al. (2021) similarly emphasised the role of mobile energy storage in enhancing grid resilience. Research on mobile microgrids and their application to critical infrastructure further indicates that containerised and rapidly deployable energy resources can provide an important bridge between centralised grid infrastructure and temporary autonomous supply systems.

The relevance of mobile energy systems is particularly pronounced in the context of defence, civil protection, and critical infrastructure resilience. Military

installations, emergency response facilities, medical infrastructure, communication systems, and logistics centres may have to maintain operations despite disruptions to centralised electricity networks. In such circumstances, a mobile generation unit capable of supplying more than one form of useful energy can provide advantages over electricity-only emergency generators. CHP and CCHP configurations can simultaneously address electricity and thermal loads and, where required, provide cooling for medical, administrative, communication, or logistics facilities. The concept is therefore consistent with the broader development of flexible energy systems capable of adapting to changing operating conditions (Miao et al. 2020; Lund et al. 2014; Mancarella 2014).

The resilience perspective also requires consideration of the security of the energy infrastructure itself. Decentralised energy resources may reduce dependence on vulnerable transmission and distribution networks, but their strategic importance may simultaneously make them potential targets during hostile actions. Consequently, the resilience of critical energy systems must be considered together with physical protection, cybersecurity, organisational preparedness, and continuity of fuel supply. These requirements are reflected in European and national frameworks concerning critical infrastructure resilience and cybersecurity, including Directive (EU) 2022/2557, Directive (EU) 2022/2555, the Polish National Critical Infrastructure Protection Programme, and national crisis-management and cybersecurity legislation (European Parliament and Council 2022a; European Parliament and Council 2022b; Narodowy Program 2023; Ustawa 2007; Ustawa 2026). From this perspective, mobile CCHP systems should be regarded not simply as energy-generation devices but as components of a broader resilient infrastructure architecture (Pudjianto et al. 2007; Pepermans et al. 2005).

Despite the considerable development of research on microgrids, CCHP systems, energy storage, renewable integration, and mobile energy resources, these research streams have only partially converged. Existing studies predominantly address the optimisation and operation of stationary multi-energy systems, the integration of renewable generation and storage in islanded environments, or the use of mobile energy resources for temporary electricity supply. Other studies focus on the decarbonisation and techno-economic optimisation of island energy systems (Huylo et al. 2025; Zhao et al. 2025; Sandvall et al. 2025; Chu et al. 2026; Romero et al. 2026; Nasab et al. 2026). Although these contributions provide an important foundation, a comparatively less investigated aspect is the integrated concept of a rapidly deployable, containerised CCHP unit forming the core of an energy island for several critical facilities, with simultaneous consideration of electrical and thermal energy balances, battery-supported island operation, mobility requirements, and resilience of fuel supply.

This gap is particularly relevant for applications in which the objective is not primarily the decarbonisation or economic optimisation of an islanded energy system,

but the rapid establishment of an autonomous energy supply capability following the disruption or unavailability of centralised infrastructure. In such applications, the generating unit must combine sufficiently high energy efficiency with dispatchability, transportability, modularity, the ability to supply multiple critical consumers, and compatibility with energy storage and temporary energy infrastructure. The integration of these requirements creates a different design problem from that considered in conventional stationary microgrid studies. In addition, the resilience of a mobile CCHP-based energy island depends not only on its conversion efficiency but also on the continuity of fuel supply, the possibility of operation under variable loads, and the ability to rapidly establish and maintain island-mode operation.

The concept of such a solution was discussed during the "Science for Defence" series of scientific conferences organised by Poznań University of Technology and the Armed Forces Support Inspectorate. The discussions concerned, among other issues, the potential of decentralised and mobile energy systems to strengthen the resilience of supply chains supporting critical infrastructure and military installations. These considerations provided the basis for further development of the technical concept investigated in the present study.

Accordingly, the aim of this article is to evaluate the technical feasibility of a mobile, containerised combined cooling, heating, and power (CCHP) plant intended to constitute the core of an energy island serving critical facilities under normal, emergency, and crisis conditions. The study focuses on a nominal approximately 2 MW generating unit and evaluates its ability to supply multiple facilities, the associated electrical and thermal energy balance, the role of battery energy storage in stabilising island operation, and the technical requirements associated with mobile deployment. Particular attention is given to the relationship between generation capacity and the assumed demand of critical facilities, the utilisation of recovered thermal energy, the operational consequences of variable load, and the continuity of fuel supply.

The scientific contribution of the study lies in integrating these aspects into a single technical concept of a mobile CCHP-based energy island rather than analysing generation efficiency, storage, mobility, and infrastructure resilience as separate problems. The proposed approach links the energy balance of a containerised CHP/CCHP unit with the spatial and operational organisation of an islanded supply system for several critical facilities. It also identifies the principal technical constraints that determine the feasibility of such deployment, including fuel availability, heat utilisation, part-load operation, storage requirements, transportability, and site conditions. In this respect, the study is intended as a feasibility-oriented contribution providing a technical basis for the further development and experimental verification of mobile CCHP systems for critical infrastructure and selected defence applications.

The analysis therefore addresses the following research problem: can a standardised, mobile containerised CCHP unit with approximately 2 MW of electrical

capacity provide a technically feasible basis for establishing a resilient energy island supplying several critical facilities, while maintaining adequate energy efficiency and operational flexibility under crisis conditions? To answer this question, the study combines an energy-balance analysis based on manufacturer data with an assessment of consumer demand, battery energy storage integration, containerised deployment requirements, and fuel-supply resilience. The resulting framework provides a basis for assessing the applicability of mobile CCHP technology as a rapidly deployable component of resilient energy infrastructure.

Research problem, research gap, aim, and methodology

Modern energy systems are increasingly exposed to disruptions caused by extreme weather events, failures of critical infrastructure, cyber threats, and armed conflicts. Critical facilities, including hospitals, command and administrative centres, and logistics infrastructure, may require an autonomous energy supply when the main grid is unavailable or severely degraded. Stationary microgrids and other distributed energy systems can improve energy resilience, but their permanent installation limits their applicability where energy infrastructure must be rapidly restored at a different location. Conventional emergency generator sets provide dispatchable electricity but generally do not utilise the available fuel simultaneously for electricity and useful heat and therefore offer more limited opportunities for multi-energy supply. These considerations create a need for rapidly deployable energy systems capable of combining dispatchable generation, multi-energy production, energy storage, and autonomous island operation.

Recent research has demonstrated the potential of islanded multi-energy systems, CHP/CCHP technologies, battery energy storage, and mobile energy resources to improve energy efficiency and resilience. However, these research areas have predominantly been investigated separately or in stationary applications. Studies of islanded CHP and multi-energy systems have focused mainly on energy management, renewable integration, storage optimisation, and decarbonisation, whereas research on mobile energy resources has primarily addressed temporary electricity supply and grid resilience. Consequently, the integrated technical concept of a rapidly deployable, containerised CCHP unit serving as the core of an energy island for several critical facilities remains comparatively less investigated. In particular, further analysis is required concerning the relationship between the electrical and thermal capacity of the mobile generation unit, the assumed load of critical facilities, the supporting role of battery energy storage, and the operational constraints associated with fuel supply, part-load operation, and heat utilisation.

The research problem addressed in this study is therefore the technical feasibility of establishing a temporary autonomous energy island using a mobile containerised

CCHP unit as the primary dispatchable energy source. The aim of the article is to develop and evaluate the energy balance of a mobile CCHP power plant with an electrical output of approximately 2 MW and to assess its applicability to an energy island supplying four critical infrastructure facilities, each with an assumed electrical demand of 500 kW. The study additionally evaluates the technical role of a 500 kW/1 MWh battery energy storage system in supporting islanded operation, including short-term load balancing, operational stability, and black-start capability.

The research hypothesis is formulated as follows: A mobile CCHP unit with an electrical output of approximately 2 MW, integrated with a battery energy storage system and deployed in a standard containerised configuration, is technically capable of constituting the primary generation source for an energy island supplying four critical facilities, while achieving an overall cogeneration efficiency above 85% under the assumed operating conditions.

The hypothesis is evaluated through an energy-balance analysis based on manufacturer catalogue data, a technical feasibility assessment, and a case study representing four 500 kW electrical loads. The analysis focuses on the relationship between electrical and useful thermal output, the utilisation of recovered heat, the role of battery storage in island operation, and the principal constraints associated with fuel availability, part-load operation, deployment conditions, and mobility. The study is therefore intended as a feasibility-oriented assessment rather than an experimental validation of a physical prototype.

The energy balance calculations are based on catalogue data for a Caterpillar gas engine (technical specifications per ISO 3046/1, reference conditions: inlet air temperature 25°C, altitude 150 m a.s.l., rotational speed 1500 rpm). The adopted values of electrical output (2000 kW), thermal output (2000 kW), and efficiency represent rounded nominal values consistent with the equipment class; detailed catalogue data are provided in the energy balance subsection. The lower heating value of natural gas used in the calculations was 35.64 MJ/Nm^3, determined for a gas composition with a methane number of 84.7, consistent with the unit's catalogue data. The consumer demand (500 kW per facility) was adopted as an average value based on literature data for public utility buildings (district hospitals, administrative facilities) in Poland (Albarakati et al. 2022; Mallah et al. 2024). The energy storage parameters (rated power 500 kW, capacity 1 MWh, lithium-ion technology) were adopted as a design assumption consistent with commercially available industrial-class units (e.g. Tesla Megapack, Huawei LUNA2000-C&I). Efficiency calculations were performed using an analytical method in accordance with ISO 3046/1. All values in the energy balance represent rated outputs at the nominal operating point of the unit (100% load).

The electrical efficiency (per ISO 3046/1) was calculated as:

$$\eta_{el} = \frac{P_{el}}{P_{chem}} = \frac{2023\,ekW}{4764\,kW} = 42.5\%. \tag{1}$$

where:
η_{el} – electrical efficiency [%],
P_{el} – electrical output of the unit [kW],
P_{chem} – chemical power supplied in the gaseous fuel [kW].

The catalogue value of electrical efficiency is 43.9%, as stated in the manufacturer's technical specification per ISO 3046/1. The value computed directly from the balance equation above ($\eta_{el} = \frac{2023}{4764} = 42.5\ \%$) is slightly lower because the denominator P_{chem} = 4764 kW is the gross fuel chemical power (LHV × 481 Nm^3/h), which is marginally larger than the net fuel power basis used in the ISO 3046/1 efficiency denominator (auxiliary loads are excluded). Accordingly, the catalogue value η_{el} = 43.9% is adopted as the reference electrical efficiency throughout this analysis. For the energy balance summary (Table 1), rounded design values are used (P_{el} = 2000 kW, P_{chem} = 4700 kW), consistent with the equipment class, whereas the non-recoverable loss equation uses exact catalogue values (P_{chem} = 4764 kW, P_{el} = 2023 ekW, Q_{th} = 1984 kW) to maintain arithmetic accuracy. This dual-value approach is clearly distinguished throughout the paper.

$$\eta_{th} = \frac{Q_{th}}{P_{chem}} \cdot 100\%, \tag{2}$$

where:
η_{th} – thermal efficiency of the system [%],
Q_{th} – total useful thermal output [kW].

The useful thermal output in the study represents the sum of heat recovered from: jacket water circuit (472 kW), lube oil cooler (181 kW), first-stage aftercooler (405 kW), and exhaust gases cooled to 120°C (926 kW), giving Q_{th} = 1984 kW ≈ 2000 kW and η_{th} ≈ 42.3% (catalogue value).

The overall efficiency was calculated as:

$$\eta_c = \eta_{el} + \eta_{th} = 43.9\% + 42.3\% = 86.2\%. \tag{3}$$

where:
η_c – overall efficiency of the cogeneration system [%].

In this analysis, rounded values of P_{el} = 2000 kW, Q_{th} = 2000 kW, P_{chem} = 4700 kW, and η_c > 85% are adopted, consistent with the power plant class.

Non-recoverable losses:

$$P_{str} = P_{chem} - P_{el} - Q_{th} = 4764\,kW - 2023\,kW - 1984\,kW = 757\,kW, \quad (4)$$

where:
P_{str} – non-recoverable losses[kW].

In the trigeneration configuration, cooling is produced by an absorption chiller driven by the engine's waste heat. At a COP of 0.6–0.8 and full utilisation of Q_{th}, the chiller delivers a cooling output $Q_{ch} \approx$ 1200–1600 kW. Incorporating cooling does not alter the fuel balance or η_{el} it raises the effective fuel energy utilisation index above 86%.

This paper addresses both the cogeneration mode (electricity and heat) and the trigeneration mode (electricity, heat, and cooling), the latter being the target configuration described qualitatively. All calculations were performed at the unit's nominal operating point (100% load). Diurnal and seasonal variation in the facility load profile was not modelled and constitutes a subject for future research. The adopted demand of 500 kW per facility is an averaged value and may deviate from actual peak demands. Energy storage parameters were adopted as a design assumption rather than an optimisation result. The analysis does not cover capital costs, CO_2 emissions, or life-cycle assessment (LCA). Transport conditions (assembly mass, trailer requirements, oversize-load permits) are described qualitatively on the basis of general ISO 668 Class 1C (20-foot) container standards.

Energy demand balance for a mobile container cogeneration plant

A fundamental aspect of mobile cogeneration systems operating within energy island structures is the correct determination of the energy balance, encompassing both the generation side and the demand side. This analysis forms the basis for evaluating the ability to ensure supply continuity and the energy resilience of critical facilities in emergency or crisis situations. The energy balance must account for the characteristics of end consumers (load profile, diurnal and seasonal variation, supply priorities) as well as the technical parameters of the generating unit, including its efficiency, operational flexibility, and compatibility with energy storage systems.

The study adopts public utility facilities as the reference case, since these buildings must maintain a high level of energy autonomy and island-mode operation capability during crisis conditions (e.g., power grid failures, natural disasters, states of emergency). Due to limited access to military infrastructure data, the practical objective of this analysis is to use the conclusions drawn to support the implementation of the proposed solutions in selected military facilities.

Demand characteristics of the supplied facilities

The electrical power demand of public utility facilities is strongly dependent on their operational profile, their role within the critical infrastructure system, and the geometric and technical parameters of the building (usable area, volume, energy performance standard, and technical equipment).

The average connected power for this type of facility spans a wide range, typically from approximately 100 kW to 800 kW. Representative electrical power demand values for selected facility categories are as follows:

- small educational facilities, municipal offices: approx. 100–250 kW,
- district hospitals and healthcare facilities: approx. 400–600 kW,
- sports facilities and event halls: approx. 600–800 kW.

For the purposes of further analysis, an averaged electrical power demand of 500 kW per facility was adopted. The distribution of connected power for each building category is shown in Figure 1; the 500 kW reference line indicates the averaged value used in subsequent calculations. This assumption enables energy balance calculations and an assessment of the potential for forming an energy island based on a standardised mobile cogeneration unit.

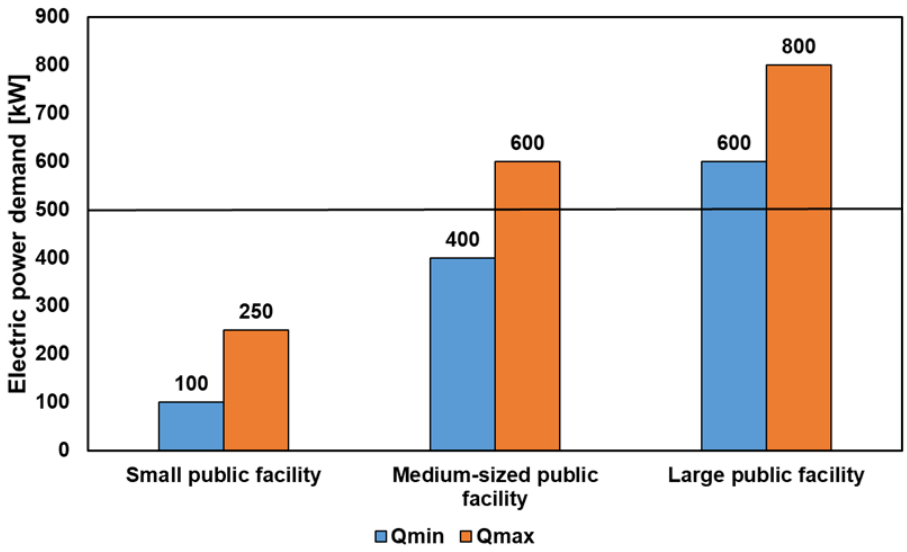


Figure 1. Balance of demand for electrical power for selected public utility facilities.
Source: own study

Generating unit characteristics and energy balance

The core component of the analysed mobile cogeneration power plant is an industrial gas engine coupled to a synchronous generator, characterised by high efficiency in converting the chemical energy of the fuel into electrical and thermal energy.

Based on catalogue data for the Caterpillar gas engine (technical specifications per ISO 3046/1, reference conditions: inlet air temperature 25°C, altitude 150 m a.s.l., rotational speed 1500 rpm, natural gas LHV = 35.64 MJ/Nm^3, methane number 84.7), the following energy balance was established. Rounded values used in balance calculations are given without brackets; exact catalogue values are given in brackets:

- fuel chemical power (LHV): the total power input in the fuel, expressed against the lower heating value of natural gas (LHV = 35.64 MJ/Nm^3), is approximately 4700 kW (catalogue value: 4764 kW at a gas flow rate of 481 Nm^3/h),
- electrical output (P_{el}): the unit delivers an electrical output of 2000 kW (catalogue value: 2023 ekW at a generator efficiency of 97.4%), enabling stable, sustained supply to loads in island mode; output voltage 400 V at 1500 rpm.
- useful thermal output (Q_{th}): total heat recovery is approximately 2000 kW, comprising:
- heat from the engine jacket water circuit: 472 kW, lube oil cooler: 181 kW, and first-stage aftercooler: 405 kW – totalling 1058 kW from the liquid cooling circuits,
- heat recovered from exhaust gases (to 120°C, LHV basis): 926 kW. Total heat recovery: Q_{th} = 1058 kW + 926 kW = 1984 kW ≈ 2000 kW.
- energy losses: the difference between the chemical energy of the fuel and the sum of useful outputs (electrical and thermal), amounting to approximately 700 kW (catalogue value: 757 kW, of which 127 kW is heat rejected to atmosphere including the generator), attributable to engine casing radiation, generator losses, and unrecovered heat in exhaust gases below 120°C.

The unit's efficiency indices are very high. According to the engine catalogue data (per ISO 3046/1), the electrical efficiency η_{el} is 43.9%, the thermal efficiency η_{th} is 42.3%, and the overall efficiency $\eta_c = \eta_{el} + \eta_{th}$ = 86.2%. (Eq. 3). Table 1 uses rounded values ($\eta_{el} \approx 43.9\%$, $\eta_{th} \approx 42.3\%$, $\eta_c > 85\%$), consistent with the equipment class and used in balance calculations. The electrical-to-thermal power ratio is approximately 1:1 (precisely P_{el}/Q_{th} = 2023/1984 ≈ 1.02), which is of critical importance for energy islands where electrical and thermal demand occurs simultaneously. Fig. 2 shows the distribution of energy flows consumed and produced by the system together with generated losses. The appendix presents a balance diagram of the analysed CCHP power plant, including energy streams, the control volume boundary, and the breakdown of individual energy streams into generation and conversion forms.

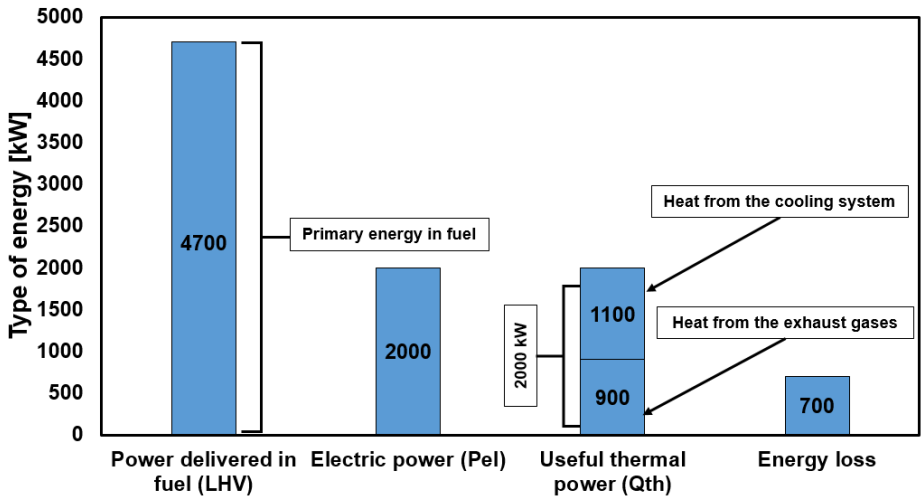


Figure 2. Energy balance of the analysed trigeneration power plant.
Source: own study

Energy island concept and energy storage system

Assuming an average demand of 500 kW per facility, a single cogeneration unit with an electrical output of approximately 2 MW is capable of supplying up to four medium-sized public utility facilities. For small facilities, it could cover the electrical demand of approximately twenty buildings; for large facilities, the supply potential would cover two buildings.

Under real operating conditions, however, the system load varies over time. Even when simultaneously supplying four facilities, the system experiences:

- power reserves,
- short-term electrical energy surpluses.

To stabilise the parameters of the island grid and improve supply reliability, the integration of the cogeneration unit with a battery energy storage system is essential. Such solutions, as mentioned earlier, were discussed during the fifth edition of the Science for Defence conference.

The main benefits of integrating industrial energy storage systems (e.g. Tesla Powerpack, Huawei LUNA2000) include:

- engine operation at the optimal efficiency point,
- peak demand coverage exceeding the rated generator output,
- black-start function for autonomous restart and supply restoration to the entire energy island following a power outage

Table 1. Energy balance summary of the mobile CCHP generating unit

Parameter	Value	Unit
Fuel chemical power (LHV)	4 700	kW
Electrical output	2 000	
Useful thermal output (total)	2 000	
Losses	700	
Overall efficiency	86.2 (cat.) / > 85 (adopted)	%
Supply potential	4	facilities

Source: own study

A system designed in this manner enables efficient technical organisation of energy islands while ensuring a high level of energy sovereignty. An additional advantage is the high fuel utilisation efficiency achieved through the cogeneration process.

For this concept, a battery energy storage system (BESS) was adopted as a design assumption with the following parameters: continuous rated power 500 kW, nominal capacity 1 MWh, lithium iron phosphate (LFP) cell technology, DC bus voltage 600–800 V, charge/discharge cycle efficiency ≥94%. These parameters correspond to commercially available industrial-class modules (e.g. Tesla Megapack 2XL: 1.9 MW / 3.9 MWh; or smaller configurations such as 2×Huawei LUNA2000-200KTL-H1: 2×200 kW). The storage system operates in three scenarios: (1) island grid stabilisation – frequency and voltage deviation compensation during rapid load changes (−1 to +1 Hz, response time ≤20 ms), (2) daily load levelling – charging during off-peak (night-time) hours and discharging during peak periods, enabling the gas engine to operate within a narrower, more efficient load range (80–95% of rated power), (3) black-start – energising the generator excitation circuit and power plant auxiliary systems following a grid voltage loss; estimated cold-start time is 10–15 minutes. The BESS does not alter the unit's fuel balance but significantly improves power quality in the island grid and extends engine service life by limiting part-load operation. Based on the energy balance presented above, a feasibility analysis is conducted in the following section.

Feasibility analysis of a container-based cogeneration plant

To implement the concept of a mobile energy island based on a cogeneration unit, a feasibility analysis must be carried out. A key aspect is ensuring the functional capability of the system while maintaining its mobility and adaptability at the deployment site.

The mobile generating unit is based on a natural-gas-fuelled reciprocating engine integrated with a synchronous generator and heat recovery circuits. The complete installation is housed in a standard container enclosure. The system is designed for cogeneration operation, with the option of further expansion to a trigeneration configuration (combined production of electricity, heat, and cooling).

The high overall efficiency of 86.2% (per ISO 3046/1: $\eta_{el} = 43.9\%$, $\eta_{th} = 42.3\%$) results from effective waste heat recovery across four circuits (jacket water, lube oil, aftercooler, and exhaust gases), enabling a significant reduction in specific fuel consumption.

A critical operational requirement is the continuous supply of gaseous fuel. According to the power plant catalogue data, at 100% load the natural gas consumption is 481 Nm^3/h (at 0°C, 101.3 kPa), corresponding to a specific consumption of 8.19 MJ/ekWh (ISO 3046/1). This value is consistent with the previously assumed range of 450–500 m^3/h. Under mobile deployment conditions, fuel supply can be achieved via a temporary connection to the gas distribution network (required fuel valve inlet pressure: 10–35 kPa) or by means of mobile LNG regasification stations.

The use of a 20-foot container is considered the optimal solution for a unit of approximately 2 MW. It allows a functional internal layout divided into engine, electrical, and hydraulic sections. Furthermore, it enables transportation using available and potentially acquired air transport assets. Road and rail transport using standard low-bed trailers and railway flatcars may, due to the total weight of the system, require the acquisition of the appropriate permits for oversized or abnormal-load transport. The installation site must be equipped with a hardened, vibration-resistant base and provide access for a crane of adequate lifting capacity.

The system forms an independent energy island via mobile switchboards that split the 2000 kW output into four 500 kW supply lines. The use of quick-connect electrical and hydraulic couplings enables rapid system commissioning without permanent installation works. In the absence of a heat off-taker, integrated fan coolers allow the unit to operate safely at full electrical output.

The high overall efficiency reduces specific fuel consumption relative to conventional separate generation. Furthermore, island-mode operation removes dependence on the external transmission and distribution network infrastructure. By nature, the system is independent and resilient to grid outages; the sole operational constraint is fuel supply, which can be mitigated by securing an on-site fuel production or storage capability. An important factor is the shortening of the energy supply chain and the maximisation of proximity between the raw material source, energy generation systems, and the final energy consumer. This is particularly significant for supplying critical civilian infrastructure and permanent military installations.

Among the risks to be noted is load variability. Prolonged part-load operation adversely affects engine durability, which underlines the importance of energy storage systems to absorb surplus energy and extend equipment service life, which is

its unquestionable advantage. Noise emission is one of the environmental factors to consider. Typical 2 MW class containerised cogeneration units generate a sound pressure level of 75–85 dB(A) at 1 m from the enclosure (manufacturers' catalogue data). Standard technical containers provide acoustic insulation in the order of 20–25 dB; the use of containers with enhanced acoustic insulation (Class A absorptive materials per PN-EN ISO 11654) reduces emissions to ≤55 dB(A) at the site boundary, in compliance with the Polish Regulation on permissible noise levels in the environment (Minister of the Environment 2014). In operational environments (crisis zones, military applications) environmental requirements may be relaxed, but safety exclusion zones of 50–80 m radius should be maintained for occupational health and safety reasons. In a cogeneration context, an efficiency risk arises when there is no heat off-taker: system efficiency then falls to the level of electrical efficiency ($\eta_{el} \approx 43.9\%$), and surplus heat is rejected via integrated fan coolers – a standard arrangement for industrial containerised cogeneration units (MWM, Caterpillar catalogue data). In this case, the solution may be to install additional heat storage tanks (exchangers) on the recipient side.

The use of a standard 20-foot container for a mobile cogeneration power plant with an output exceeding 2 MW represents a technically justified solution. The unit is capable of supplying four large public utility facilities, providing the foundation for the construction of efficient, reliable energy islands in crisis situations as well as in areas with underdeveloped grid infrastructure.

Fuel resilience of energy islands under crisis conditions

In crisis conditions, particularly those of a military character, damage to transmission infrastructure may cause significant restrictions in access to hydrocarbon fuels – natural gas in particular. For the containerised cogeneration systems analysed in this paper, this represents a significant operational risk, since continuity of fuel supply is a prerequisite for maintaining stable system operation.

For this reason, the identification of alternative, locally available energy sources capable of enhancing the fuel resilience of energy islands becomes justified. One such direction is the use of woody biomass.

Woody biomass is characterised by high spatial availability and local harvestability. In the context of Poland, this is particularly significant given that the country's forest cover of nearly 30% creates a potentially broad raw material base for local biomass-based energy systems.

An example of the potential of locally available woody biomass energy is the area managed by the Regional Directorate of State Forests in Szczecinek (RDLP Szczecinek). An analysis of timber resources demonstrated that RDLP Szczecinek possesses a stable and substantial raw material base. According to RDLP Szczecinek

data, the total standing timber volume in the directorate area amounts to approximately 148.8 million m^3, with an annual harvest of approximately 2.985 million m^3. Of particular relevance is the fact that approximately 605,000 m^3 of the harvested material constitutes energy wood or timber of reduced technical quality, available for energy applications without reducing the raw material supply to the wood-processing industry (Grzegorczyk et al. 2026).

It should be noted, however, that the use of woody biomass in containerised cogeneration systems requires further concept development. Additional technical, economic, and operational analyses are needed to evaluate the actual potential of this approach.

Conclusions

The results of the study confirm that a mobile, containerised cogeneration system can provide a technically feasible basis for establishing an autonomous energy island for selected critical facilities. The analysed configuration, based on a natural-gas-fuelled reciprocating engine with an electrical output of approximately 2 MW and a total useful thermal output of approximately 2 MW, achieved a catalogue overall efficiency of 86.2%, with an adopted value of more than 85% used in the energy-balance analysis. This confirms the technical potential of cogeneration for increasing the useful utilisation of fuel compared with separate electricity and heat generation. The results are consistent with the broader literature on distributed multi-generation and multi-energy systems, which identifies the simultaneous utilisation of electrical and thermal energy as an important means of improving primary-energy utilisation (Chicco and Mancarella 2009; Mancarella 2014). The present study extends this perspective to a mobile and rapidly deployable configuration intended specifically for critical infrastructure applications.

The analysis also confirms the feasibility of using a single approximately 2 MW electrical unit to supply several critical facilities through four 500 kW distribution lines. Within the assumptions adopted in the study, the configuration can provide electricity and useful heat to facilities such as hospitals, administrative buildings, and logistics centres and can be expanded to a trigeneration arrangement when cooling demand is present. This result is compatible with previous research demonstrating the suitability of CHP-based and multi-energy island systems for supplying diverse energy demands (Huylo et al. 2025; Yang et al. 2026). However, unlike studies primarily focused on stationary campus, industrial, or renewable-based island systems, the present concept combines multi-energy supply with containerisation and rapid deployment. This distinction is important for applications in which the energy system itself must be transported to the affected location following disruption of existing infrastructure.

The study further confirms the importance of energy storage for the operation of the proposed island system. The assumed 500 kW/1 MWh BESS is intended to compensate for short-term load variations, support voltage and frequency stability, reduce prolonged operation of the gas engine under unfavourable part-load conditions, and provide a black-start capability. These functions are consistent with previous studies identifying battery storage as an important component of resilient microgrids and islanded energy systems (Dugan et al. 2021; Huylo et al. 2025). At the same time, the present analysis indicates that the BESS should be considered primarily as an operational-support component rather than a substitute for the dispatchable generation source. Its relatively limited energy capacity compared with the generating capacity means that it is suitable for short-term balancing and operational support, whereas sustained island operation remains dependent on the availability of the primary fuel.

A comparison with recent research on island energy systems indicates that the main distinction of the proposed concept lies not in the individual technologies employed, but in their integration and intended operational context. Recent studies have investigated islanded systems incorporating CHP, renewable generation, batteries, thermal storage, hydrogen, fuel cells, desalination, and other energy-conversion technologies (Huylo et al. 2025; Palys and Daoutidis 2024; Zhao et al. 2025; Romero et al. 2026; Nasab et al. 2026; Yang et al. 2026). Other research has addressed sector coupling and the coordinated operation of electricity, heat, and industrial energy systems in island environments (Sandvall et al. 2025; Chu et al. 2026). These studies demonstrate the growing maturity of multi-energy island concepts. The contribution of the present work is therefore more specific: it addresses the technical organisation of a mobile, containerised CCHP-based energy island designed to be rapidly deployed for critical facilities when permanent grid infrastructure is unavailable, damaged, or insufficient. The proposed configuration links generation capacity, thermal-energy utilisation, battery-supported island operation, container-based mobility, and fuel-supply requirements within one technical concept.

The results therefore provide support for the research gap identified in the study. Existing literature largely addresses stationary islanded systems, optimisation of multi-energy configurations, integration of renewable sources and storage, or mobile energy resources considered primarily as temporary electricity-supply assets. The present work demonstrates the feasibility of combining these functional requirements in a mobile CCHP configuration in which the generating unit constitutes the core of a temporary autonomous energy island. The study consequently contributes a feasibility-oriented technical framework for assessing such systems in applications where rapid deployment, energy independence, and continuity of supply are more important than long-term optimisation of a permanent energy system.

At the same time, the results identify several constraints that limit the applicability of the proposed concept. The most important is the continuity of gaseous-fuel supply. Although the analysed unit can be supplied from a gas distribution network

or through mobile LNG regasification infrastructure, the resilience of the energy island remains dependent on the availability and security of the fuel supply chain. This limitation is particularly relevant under military or severe crisis conditions, when damage to infrastructure may restrict access to conventional fuels. The analysis of locally available woody biomass presented in the study indicates a possible future direction for increasing fuel resilience; however, this option cannot yet be considered validated for the analysed containerised system and requires additional technical, economic, and operational investigation.

The analysis also confirms that high nominal cogeneration efficiency does not automatically translate into equally high system-level efficiency under all operating conditions. In particular, when there is no heat off-taker, recovered thermal energy must be rejected through cooling systems and the effective utilisation of the fuel approaches the electrical efficiency of the generating unit. Similarly, prolonged part-load operation may adversely affect engine efficiency and service life. These findings reinforce the importance of matching the generation profile with the demand of connected facilities and support the proposed role of BESS and, where appropriate, thermal storage in improving operational flexibility. Further research should therefore address dynamic load profiles rather than relying solely on nominal or design-point operating conditions.

The mobility of the proposed system constitutes an additional advantage, but it also introduces requirements that were not fully validated experimentally in the present study. Containerisation facilitates road, rail, and potentially air transportation, while quick-connect electrical and hydraulic interfaces can reduce deployment time. However, the actual deployment capability depends on transport regulations, total system mass, lifting requirements, site preparation, acoustic protection, connection procedures, and local safety conditions. These aspects should therefore be treated as engineering constraints rather than assumed benefits of containerisation alone.

The present study is subject to several limitations that define the scope of the conclusions. The analysis is based primarily on manufacturer catalogue data, assumed load characteristics, and a technical feasibility assessment; no physical prototype or field demonstration was undertaken. The proposed BESS configuration was adopted as a design assumption and was not experimentally validated under dynamic islanding conditions. Likewise, the effects of variable heat demand, detailed transient behaviour, protection coordination, power-quality performance, and long-duration operation under crisis conditions require further investigation. The fuel-resilience assessment is also conceptual and should be complemented by quantitative analysis of fuel storage requirements, alternative fuel pathways, logistics, and supply-chain disruption scenarios.

Future research should therefore focus on the development and experimental verification of a prototype mobile CCHP system, including laboratory and field tests under variable electrical and thermal loads. Particular attention should be given to

dynamic islanding and black-start performance, BESS sizing and control, part-load efficiency, thermal-energy storage, fuel-supply autonomy, and the integration of alternative locally available fuels. Further studies should also incorporate techno-economic and life-cycle assessments and investigate the resilience of the complete energy island against simultaneous energy, infrastructure, and cybersecurity disruptions.

In conclusion, the study demonstrates that a mobile containerised CCHP unit can constitute a technically viable core of a resilient energy island for selected critical infrastructure and defence-related applications, provided that fuel availability, heat utilisation, load variability, and deployment constraints are adequately addressed. The principal contribution is not the introduction of a new generation technology, but the integration of established CHP/CCHP, battery storage, island operation, and containerised mobility concepts into a single rapidly deployable energy architecture. This provides a technical basis for further development and experimental validation of mobile multi-energy systems intended to increase the resilience and operational autonomy of critical infrastructure under emergency and crisis conditions.

Appendix 1

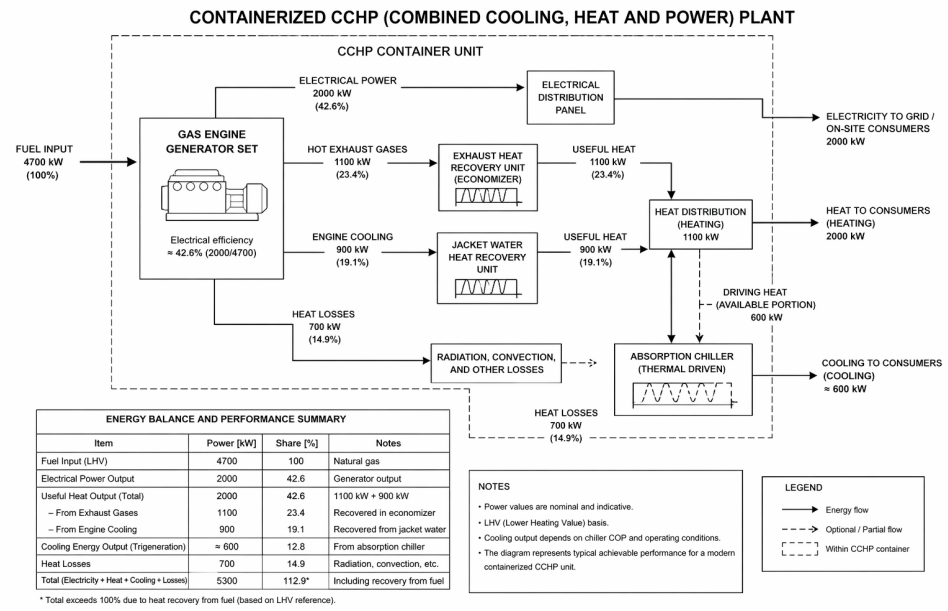


Figure 3. Schematic diagram of a containerised Combined Cooling, Heating, and Power (CCHP) system with integrated trigeneration.

Source: own study

Appendix 2

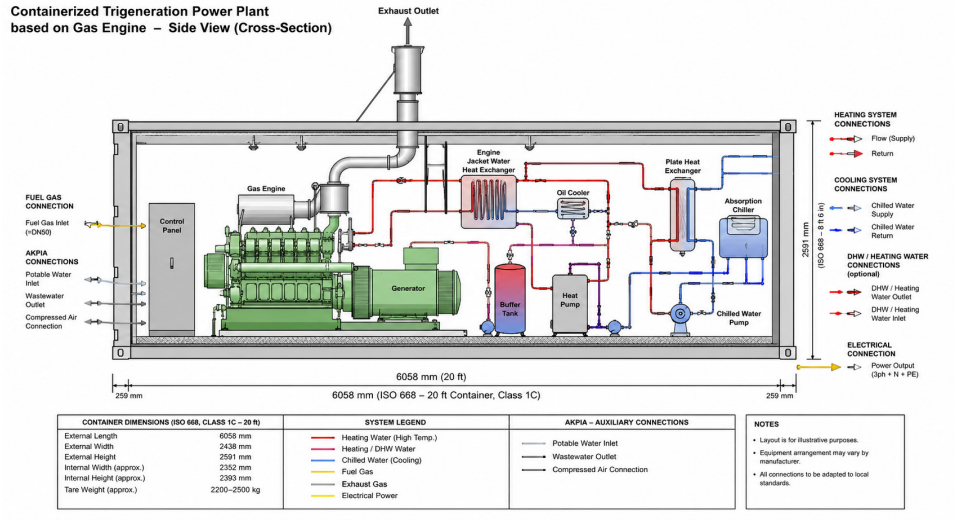


Figure 4. Schematic Cross-Section of a Containerised Gas Engine Trigeneration Unit in a 20-ft ISO 668 Class 1C Container.

Source: own study

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