HORIZON EUROPE PROGRAMM
Topic HORIZON-JTI-CLEANH2-2024-04-01

GA No. 101192169

RESCUE

Reliable and Efficient Dual Fuel System for Civil Protection during Natural Disasters using HT-PEM Technology

RESCUE

Deliverable report

D2.3 – Evaluation Protocol

Clean Hydrogen Partnership
Co-funded by the European Union

WP	2	System Requirements
Deliverable No.	D2.3	Evaluation Protocol

Dissemination level	PU	**Due delivery date**	December, 2025
Deliverable Type	Report	**Actual delivery date**	December 30th, 2025

Lead beneficiary	THW
Contributing beneficiaries	all

Document history

DATE	VERSION	CHANGES MADE / REASON FOR THIS ISSUE	AUTHOR / PARTNER
01/12/2025	0.1	Initial Draft	THW – JL
04/12/2025	0.2	Internal Review	THW – SBH
10/12/2025	0.3	Internal Review	DLR – DSC PROACT - EGE

Dissemination level: PU = Public, SEN= Sensitive, limited under the conditions of the Grant Agreement.

Project details

PROJECT TITLE	
PROJECT NUMBER	101192169
PROJECT ACRONYM	RESCUE
PROJECT NAME	Reliable and Efficient Dual Fuel System for Civil Protection during Natural Disasters using HT-PEM Technology
CALL	HORIZON-JTI-CLEANH2-2024
TOPIC	HORIZON-JTI-CLEANH2-2024-04-01
STARTING DATE OF THE PROJECT	01-01-2025
PROJECT DURATION	48 months

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Executive Summary

This deliverable defines the Evaluation Protocol for the RESCUE project, establishing the methodological and technical foundation for assessing the performance, usability, safety, and regulatory compliance of the RESCUE mobile power generation system. Building on the consolidated user requirements collected in WP2, the document translates operational needs, environmental constraints, and functional expectations into a structured and traceable evaluation framework.

The report first outlines the end-user context, summarising the workshop-based requirements elicitation with the German Federal Agency for Technical Relief (THW) and the German Federal Office of Civil Protection and Disaster Assistance (BBK). These discussions identified key operational scenarios—primarily large-scale flooding—where RESCUE's hydrogen–methanol mobile power generator will be deployed to support pumping operations, water purification units, lighting, base-of-operation infrastructures, and other mission-critical equipment. The workshop also clarified expectations for size, weight, transportability, power output, runtime, electrical integration, system-level safety and environmental robustness regarding Temperature, Rain and Vibrations.

The central component of this deliverable is the KPI catalogue, which converts the consolidated requirements into measurable evaluation criteria. The KPI set covers all essential domains: transportability and deployment, electrical power delivery, inverter and grid-interface performance, operating modes, human–machine interaction, environmental performance, fuel and tank systems, and implementation of Integrated Situational Awareness and Analysis (ISAA). Each KPI includes a clear pass/fail threshold and, where relevant, an optional performance target to guide optimisation. This ensures traceability between requirements and verification procedures while enabling objective validation during Factory Acceptance Tests, Site Acceptance Tests, and field deployments.

To operationalise the KPIs, an exemplary Validation & Test Plan is provided. It specifies verification methods — inspection, measurements, functional demonstration, endurance testing and environmental simulation — and assigns each KPI to the appropriate testing stage. The plan ensures systematic evaluation in both laboratory and real-world conditions, supporting iterative development and feedback-driven refinement in WP6 and WP7.

In summary, requirements, KPI set, and test plan, form the End-User Evaluation Protocol. This protocol ensures that (a) system design is driven by real operational needs, (b) prototype testing is reproducible and auditable, and (c) project partners can demonstrate clear compliance with performance goals. As such, this deliverable provides a comprehensive and coherent basis for testing the RESCUE system throughout its development lifecycle and prepares the consortium for structured field validation activities.

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List of Abbreviations

ADR – European Agreement concerning the International Carriage of Dangerous Goods by Road
BBK – German Federal Office of Civil Protection and Disaster Assistance
BoO – Base of Operations
DoA – Description of Action
DLR – German Aerospace Center
EDXL – Emergency Data Exchange Language
FAT – Factory Acceptance Test
FR – First Responder
GA – Grant Agreement
HMI – Human Machine Interface
IBC – Intermediate Bulk Container
IEC – International Electrotechnical Commission
IP – Ingress Protection
ISAA – Integrated Situational Awareness and Analysis
KPI – Key Performance Indicator
5G – 5th Generation Mobile Network
MUST / SHOULD – Requirement priority categories
THD – Total Harmonic Distortion
THW – Technisches Hilfswerk (German Federal Agency for Technical Relief)
WP – Work Package

1. Umbrella Scenario and Use Cases

1.1. Umbrella Scenario

The umbrella scenario for the RESCUE system is a large-scale, multi-hazard emergency event, in which critical infrastructure is disrupted and electrical power is either unavailable or insufficient to support emergency response operations. Such incidences may be provoked by severe flooding, prolonged blackouts, major storms, earthquakes, industrial accidents, or any situation, in which first responders must sustain autonomous operations for extended periods of time. The scenario provides a unifying framework for evaluating the RESCUE hybrid energy system under realistic operational conditions, ensuring that all use cases align with a common mission context while allowing each sub-scenario to target specific technical and logistical requirements.

During major emergencies, first responders deploy a wide range of electrically powered equipment — pumps, communication systems, lighting, IT infrastructure, water purification units, heating and cooling devices, and more. These deployments vary from highly mobile, frequently relocated assets to fixed installations that must operate continuously for days or even weeks. This diversity makes the umbrella scenario particularly suited for assessing the performance, reliability, and flexibility of the RESCUE system, which is intended to replace or supplement conventional diesel generators with a cleaner, quieter, and more efficient energy solution. The umbrella scenario ensures that the system is tested in a comprehensive operational picture that reflects real-world stress factors: environmental extremes, continuous load demands, logistical constraints, and the need for rapid redeployment.

1.2. Use Cases

1.2.1. Continuous Power Supply for Pumping Operations

During flood events, such as those experienced in the Ahr valley and other regions of Europe, THW and other emergency services deploy high-capacity pumping units with a flow-rate of up to 15.000 litres/minute that to remove water from critical infrastructure, residential buildings, and industrial sites. These pumps often require continuous electrical power over several days to multiple weeks, with only short interruptions during relocation. Traditionally, these missions rely on diesel generators, which must be refuelled frequently and maintained under challenging environmental conditions.

The RESCUE system provides an opportunity to demonstrate a low-emission, low-noise, long-duration energy supply with reduced maintenance needs and extended operational autonomy. The use case is particularly relevant for validating the system’s abilities in sustained power delivery, grid-independent operation, rapid start/stop cycles, and ruggedized deployment in polluted, water-saturated, or debris-rich environments.

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1.2.2. Power Supply for Bases of Operation (BoO)

Large-scale disasters often require the deployment of temporary Bases of Operation (BoO), supporting between several dozen and several hundred responders. These field camps provide accommodation, sanitation, communication, medical support, command infrastructure, and logistic hubs. In current practice, power for these bases is provided by medium- to large-scale diesel generator units, which must run continuously for weeks or months.

Figure 1:Exemplary Implementation of the RESCUE System into a Base of Operations (BoO)

This use case evaluates how the RESCUE system can serve as a primary or supplementary power source for a BoO, supplying highly variable loads such as heating and cooling systems, kitchens, ICT equipment, and lighting. The scenario is particularly suited to assess the system's acoustic footprint, fuel logistics, integration into existing distribution networks, energy management modes (eco/adaptive/turbo), and its capability to improve environmental conditions for deployed personnel by reducing noise, fumes, and vibration. Extended runtimes and fluctuating consumption patterns make this a critical test case for validating robustness, energy storage integration, and fuel-cell-based power stability.

1.2.3. Energy Supply for Water Treatment Units (THW SEEWA)

SEEWA units are deployed to restore access to drinking water during international and domestic emergencies. Their standardized equipment — pumps, filtration systems, disinfection units, and sensor platforms — requires a stable and reliable 24/7 power source over extended periods. Historically, this has been provided by diesel generators transported alongside the rest of the equipment.

This use case evaluates the suitability of the RESCUE system for continuous, mission-critical operation with stable power quality requirements. In addition, SEEWA deployments highlight the logistical aspects of transporting the system across borders or by air freight, including regulations for the safe transport of hazardous materials (ADR), rapid setup, connection flexibility, and operability in remote or infrastructure-poor regions. It provides a valuable scenario to test the system's reliability in long-duration, clean-power applications, where interruptions may directly impact public health.

1.2.4. Mobile Lighting and Rapid Redeployment Operations

THW frequently deploys mobile light towers (LiMa units) to illuminate streets, critical areas, and operational sites during blackouts, large accidents, or extreme weather conditions. These light towers often operate for several months, as observed during the Ahr valley flood response, and must be regularly repositioned as power availability changes or operational priorities shift. This results in repeated cycles of shutdown, relocation, and immediate restart.

This use case is ideal for validating the RESCUE system's capabilities in frequent start/stop operations, rapid redeployment, and power delivery to small but critical loads. It highlights the need for fast warm-start behaviour, reliable operation under unbalanced loads, and robust handling of repeated thermal and electrical cycling. Additionally, it enables assessment of the system's ability to reduce noise pollution in residential areas affected by prolonged outages.

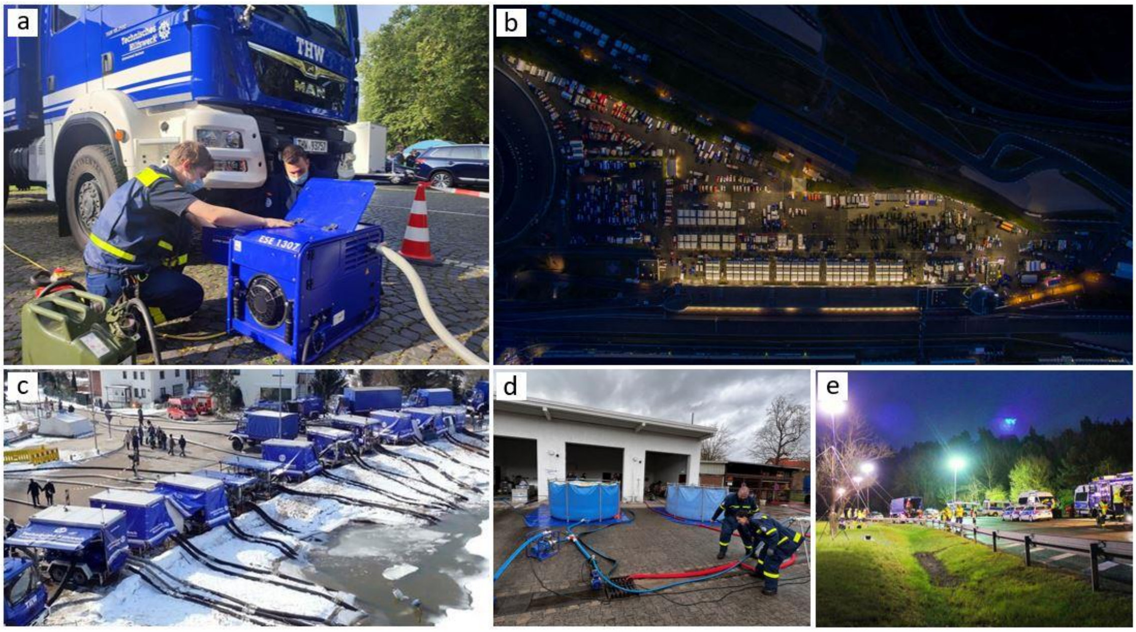

Figure 2: Overview of disaster relief actions carried out by THW relating to four use-cases and differing energy demands. Small scale general energy provisioning for e.g. (a) tools, (b) energy supply for Bases of Operations (BoO), (c) large-scale high-capacity pumping, (d) mobile drinking water treatment plants, (e) illumination using light posts.

2. User Workshop 1

The first User Workshop was held on 28.03.2025 as an internal online meeting, with eight THW members and one participant from the German Aerospace Center (DLR). All participants are experts in the field of mobile power generation. In the beginning, an overview of the project scope, timeline, and the expected development of the RESCUE Power Generator was provided. All requirements derived from the project call were presented, and the preliminary solution developed by the consortium was introduced. The planned system architecture was explained, consisting of a fuel cell container and a fuel container.

The project plan and the specific tasks of THW within the project were then discussed. This included an exploration of possible application scenarios for the power generator within THW operations, with a particular focus on the framework scenario of large-scale flooding. A preliminary modular test plan was also presented.

Subsequently, system performance requirements based on THW experiences were addressed. The rationale behind a 100 kW output capacity was discussed, including implications for the inverter design. The load profile of a typical BoO was analysed as a basis for defining system requirements, along with runtime and fuel tank capacity. It was noted that most THW operations last less than 24 hours; therefore, the tank capacity should be sufficient to ensure continuous operation for at least this duration.

Finally, the participants discussed safety and regulatory aspects. This included the classification of relevant hazardous materials and the question of whether the system could be transported within the 1000-point ADR regulation (regulatory exemption that allows for simplified transport conditions when the total quantity of dangerous goods on a vehicle, calculated by specific hazard-based multipliers, does not exceed 1000 points). Electrical integration topics were also covered, such as the required socket types, feed-in capacities for island operation, compatibility with renewable energy sources, and possibilities for parallel operation with existing power grids or other energy sources.

2.1. Application Scenarios

During the workshop, several potential application scenarios were discussed to assess the suitability of the system for real THW operations. The identified *framework scenario* was large-scale flooding, representing a typical deployment environment for THW units. In such a situation, the mobile power generator could be used to supply electricity to operational bases, critical infrastructure, and water treatment units, as well as for powering pumps, lighting systems, and small-scale public energy services in crisis areas.

Participants emphasised that a modular test plan would be essential to validate the system under realistic field conditions. Proposed test scenarios included power supply for staging areas, continuous operation of electric pumps, energy provision for water treatment processes, and supply of critical building infrastructures. Test durations ranging from one day to four weeks were suggested, primarily using methanol as the base fuel with the option to switch to hydrogen for hybrid testing. The modular approach allows the test plan to evolve alongside technological progress and enables testing under varying environmental conditions, including seasonal variations.

Workshop participants also noted that, in case of a real disaster operations coincide with planned test periods, the mobile power system could be deployed operationally, thereby generating valuable real-world data. Additional potential applications include the use at training facilities, during multi-day field exercises, or for powering high-load equipment such as plasma cutting machines.

2.2. Requirements Analysis

At the beginning of the requirements analysis, it was discussed that the RESCUE system should meet about the same application criteria that THW demands for a 100 kW diesel generator, although the differences between the two technologies mean that not all criteria are transferable. Based on this, the following topics were identified that require separate elaboration.

2.2.1. Size, Weight, and Transport

A major topic of discussion concerned the transportability of the system, as it will be approximately three times larger than a diesel generator with similar electrical power. It remains to be determined whether the components will be housed in 10-foot or 20-foot containers. Participants highlighted that 20-foot containers pose logistical challenges, as they require larger deployment areas and are more difficult to transport due to weight restrictions. Compact solutions were therefore preferred and participants pointed out that deployment sites are often difficult to access and may have unpaved surfaces, reinforcing the need for lighter, modular systems.

THW operational logistics typically rely on multifunctional trailers with a payload of up to 12 tons (suitable for two 10-foot or one 20-foot container) and swap bodies capable of up to 15 tons.

Regarding handling and deployment of the containers, participants discussed the available options within THW for lifting and lowering 10-foot and 20-foot units. While various cranes are available for such operations, it was noted that these must be requested separately, which increases logistical effort and complexity during deployment.

Finally, participants suggested the use of portable lifting devices or container support systems that can be transported together with the unit and do not require additional vehicles. Furthermore, the possibility of employing roll-off containers instead of standard container types was considered as a means to simplify on-site handling. Another option mentioned was to operate the system on the chassis, allowing them to remain mobile without the need to be set down, thus enhancing flexibility in field operations.

2.2.2. System Performance

According to the requirements defined in the project call, the system must be capable of providing a minimum continuous output power of 50 kW. However, participants emphasized that with relatively little additional design effort, the system could also be configured to deliver up to 100 kW of output for at least one hour. This extended capacity would make the system compatible with most THW operational use cases, including BoO sites and the feed-in of electricity to building infrastructures. It would also significantly increase the operational flexibility of the unit, enabling its use across a broad range of deployment scenarios where currently 100 kW diesel generators are typically employed.

The design of the inverter system was discussed in this context, particularly regarding the overload capacity required to start heavy equipment such as large pumps. Participants noted that although individual THW devices rarely demand such high-power levels, the additional capacity would provide valuable operational safety margins and enhance overall system robustness in demanding field conditions.

2.2.3. Runtime and Fuel Storage

The runtime and tank volume requirements were derived from realistic operational scenarios. For disaster deployments, a two-week operational autonomy was defined as the target. Based on a typical load profile of a 50-person BoO (average 13.5 kW), a tank volume of approximately 5 m^3 methanol-water-mixture would be sufficient. Commercially available 10-foot methanol tank containers (10–12 m^3) could provide up to 35 kW of continuous power for two weeks. (Values regarding a methanol-water mixture, for an internal water mixing process these values will change.)

Participants noted that most THW operations last less than 24 hours, meaning that full two-week autonomy is rarely needed. Therefore, a modular fuel storage concept was favoured — combining larger tanks stationed near the operation site with smaller mobile fuel containers (0.35–1.2 m^3) for flexible transport. Readily available solutions such as IBC containers or pallet-sized units were identified as practical and field-tested options.

2.2.4. Dangerous Goods and Safety Considerations

The workshop also addressed the transport and safety regulations applicable to methanol, hydrogen, and battery systems. It was emphasized that compliance with dangerous goods transport rules must be ensured, including the potential for operation within ADR 1000-point limits or by other regulations to maintain deployment flexibility. The participants raised the question of whether methanol-based systems could be used safely in water protection areas, which will require further assessment during the design phase.

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2.2.5. Electrical Integration and Load Management

Another key topic was electrical integration and load balancing. The system should include appropriate sockets and cables capable of supporting loads up to 100 kW, with standard 125A CEE sockets being sufficient for most cases. The generator should support unbalanced load operation, a standard requirement for THW systems, which can be achieved using three parallel inverters phase-shifted by 120 degrees.

Participants proposed integrating load prioritization functions, allowing lower-priority consumers to be automatically disconnected during overload or low battery conditions. This feature would be particularly relevant for BoO sites and emergency infrastructure feed-ins.

2.2.6. Integration into Energy Networks and Parallel Operation

The system should be designed to support feed-in to island grids, including configurations integrating renewable energy sources such as photovoltaics. Parallel operation with existing power generators (e.g., diesel units) should also be possible. If feasible, the inverters should support four-quadrant operation, enabling both, energy import and export, within microgrid systems and allowing existing energy storage units to be utilised effectively. Participants regarded this as a significant added value for operational resilience.

2.2.7. Additional Functionalities

Finally, participants discussed several additional system functions to improve usability and monitoring. These include integrated data logging, remote monitoring capabilities, and adaptive control systems with configurable sampling frequencies. Different operational modes were proposed, such as Eco Mode for efficient low-load operation, Turbo Mode for maximum power demand, and Intelligent Adaptive Mode, which adjusts output dynamically based on detected consumption patterns. Handling and refuelling were also identified as crucial aspects. Participants recommended user-friendly refuelling solutions, such as automotive-type hydrogen filling nozzles, to ensure safe and intuitive operation in the field.

2.3. Conclusion of Workshop1

The workshop successfully defined the preliminary user requirements and application scenarios for the mobile fuel-cell-based power generator. Through active discussion, participants emphasized the importance of modularity, transportability, operational safety, and flexibility in deployment. The findings provide a solid foundation for the subsequent design phase, ensuring that the system meets both, the technological ambitions of the project and the practical needs of THW field operations.

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3. User Workshop2

Workshop 2 was held from 30.06.-01.07.2025 as a two-day event in Bonn, Germany. The on-site participants included four expert THW volunteers, one staff member from the THW Technical Department, one representative each from the THW International Affairs and THW Research Departments, one person from the Federal Office of Civil Protection and Disaster Assistance (BBK), and two members of the DLR. Further members of the consortium joined online for the appropriate thematic sections. The workshop goal was gathering, discussing and reaching consensus on the technical and operational requirements for the mobile H2/methanol RESCUE power generator. As part of the workshop, a visit was arranged to a similar container-based system for mobile energy supply that uses direct methanol fuel cells at the Federal Office for Civil Protection, in order to refine the requirements for the RESCUE power generator based on a real-world example and identify relevant topics that were overlooked so far.

Figure 3: Group photo Workshop 2 with BBK energy containers in the background.

3.1. Executive Summary

The two-day workshop gathered representatives from THW, Advent, DLR, and additional PROACT partners to refine operational and technical requirements for the fuel-cell power system. The meeting built upon insights from the first workshop while incorporating new elements, including PROACT's presentation of the integrated Safety Plan, updated perspectives on container logistics, and consolidated user requirements.

A summary of the current status of the design phase was presented by Advent to align participants on the current technical development. Attendees who had participated in the first workshop were invited to add any missing points, ensuring all participants had a shared understanding of project goals and expectations. Advent clarified that the system shown reflects a mature commercial baseline that will be adapted into the dual-fuel, hybrid configuration required in the project. The presentation detailed the placement and interaction of the fuel cell stacks, the methanol reformer, the hydrogen distribution and pressure-reduction units, as well as the cooling circuits and electrical cabinet. This framing helped participants identify which design aspects were fixed by physical or safety constraints and which were still adaptable.

PROACT began by presenting the project-wide Safety Plan, which defines the overarching safety framework for all technical developments. The presentation addressed risk categorization, incident prevention measures, and required documentation for each subsystem. A particular focus was placed on hydrogen management, methanol storage, venting strategies, ignition protection, and compliance with operational safety standards. The Safety Plan emphasized the need for clear separation between high-pressure hydrogen components, electrical distribution units, and fuel reforming equipment, as well as robust detection and fail-safe routines. These guidelines directly framed later workshop discussions on layout and container configuration.

Advent provided a full walkthrough of the fuel cell system architecture. This included a demonstration of the fuel cell stacks, the methanol reformer, hydrogen pressure regulation modules, exhaust handling, cabinet design, and safety elements. Participants examined how both – hydrogen and methanol operation modes – influence spatial layout, maintenance access, and safety distances. While THW expressed preference for a compact 10-foot container for ease of deployment, Advent demonstrated that a 20-foot container is necessary to meet safety clearances and separation of the electrical cabinet from the fuel cell cabinet and to integrate the complete hybrid system and to ensure manageable thermal and airflow conditions.

Container logistics became a major topic, with THW describing the practical challenges faced during deployment. Units in the field often operate with limited equipment, meaning that overly heavy or complex handling procedures can slow response times. Several issues were addressed:

- Lifting and placement: Many THW units lack cranes capable of lifting a 20-foot container; therefore, ground-level operability, integrated forklift pockets, and compatibility with THW loading systems were identified as crucial. Operability on the trailer was identified to have advantages of quick deployment.
- Transport restrictions: ADR rules for transporting methanol and hydrogen were reviewed in detail. Not all THW drivers hold ADR certification, which means mission planning must incorporate logistics units or designated transport staff. The risk classification of the fuels and the containerized battery system could require structured planning rather than ad hoc deployment.
- Fuel resupply and autonomy: The system should support extended operation — ideally up to two weeks. Refuelling procedures must be simple and safe, even under low-light, cold, or stressful conditions.

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- Terrain and accessibility: The system must be fit to operate on uneven ground, muddy terrain, or partially obstructed locations, which are typical conditions in emergency scenarios.

These logistical insights directly shaped the requirement refinement process.

The workshop also expanded the user requirements section, which now reflects a coherent and agreed-upon set of operational needs:

- Power output: A minimum of 50 kW continuous output is required, but THW underlined that the system should at least provide 85 kW continuous for one hour, especially to increase the application possibilities for feed-in into buildings and power grids and the efficient supply for BoO.
- Peak management: Because many THW tools generate substantial inrush currents to overcome the motor inertia, the integrated battery system must buffer peaks reliably without tripping system protection or compromising long-term battery health. Furthermore, when feeding power into buildings or power grids, it is also important to have sufficient power reserves, because the actual peak power required is often unknown in advance.
- Dual-fuel capability: The system must operate using both methanol (with reformer) and hydrogen, allowing flexibility depending on availability, safety constraints, and mission context.
- Robust automation: Given that many THW operators are volunteers without deep technical training, the system must include automated monitoring, error detection, and safe-shutdown routines, minimizing the need for manual troubleshooting.
- Environmental resilience: The system should be fully functionable under realistic environmental conditions in Germany (Instead of extreme laboratory temperature tests (e.g., –40 °C), realistic operational temperature windows and real-world cold-weather testing are preferred).
- Safety integration: System behaviour must align with PROACT's Safety Plan — including hydrogen venting, leak detection, cabinet airflow, and flame arrestors.
- Usability and accessibility: Clear labelling, intuitive interfaces, safe placement of connectors, and ergonomic layout were identified as essential for night time or adverse-weather operation.

During Day 2, additional emphasis was placed on electrical integration. The system must primarily supply AC output compatible with standard THW equipment. The workshop addressed synchronization with external grids, grounding and earthing concepts.

In addition to these topics, several more detailed system-level considerations were discussed:

The emergency-stop concept was examined in depth. Participants emphasized that an emergency stop must safely isolate voltage to the outside

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without forcing a complete shutdown of all subsystems unless absolutely required. The logic of indicator lights (green for operation, yellow for warning, red for fault) was discussed. Generator behaviour under isolation faults was reviewed, particularly the risk of back-feeding or unintentional synchronisation. It was agreed that the final safety concept will require expert assessment and must comply with the PROACT Safety Plan.

Air intake and filtration were discussed extensively, especially regarding dust, pollen, or gas-contaminated atmospheres typical in disaster scenarios. Several examples were given of past equipment failures due to blocked or insufficiently filtered intake air, reinforcing the requirement for robust and easily replaceable particle filters.

Participants discussed requirements for safe electrical connections according to VDE standards. A distinction was made between busbar systems (requiring specialized personnel) and standard plug connections (32 A, 63 A, 125 A) that can be safely operated by trained THW volunteers. Ensuring correct fuse protection and preventing unintentional back-feed into other networks were identified as essential.

The workshop further addressed building feed-in, cable routing, and island-operation requirements. Automatic synchronisation capabilities were highlighted as valuable, though limitations exist when interfacing with older diesel-generator networks. Participants emphasized the need for a reliable and safe interface for connecting to buildings, including grounding and isolation monitoring.

The workshop concluded with the clear identification of core requirements that must steer the prototype design: a 20-foot container for the fuel-cell system, a substantial and intelligently integrated battery subsystem, dual-fuel capability, intuitive operation suitable for volunteers, realistic environmental testing, and strict compliance with the PROACT safety framework. The workshop provided an in-depth discussion of technical, electrical, and safety requirements for a fuel-cell-based energy system in THW operations. Key topics included performance (85–100 kW), handling load peaks, and safe electrical connections according to VDE standards. Safety concepts, emergency stops, indicator logic, and fire suppression strategies were central. Practical issues such as air quality, filtration, thermal management, and heat utilization were thoroughly discussed. All requirements will be consolidated, structured, and prioritized to form a comprehensive specification for the prototype.

3.2. Assessment of technical feasibility on Workshop1 Requirements by Advent

Advent confirmed that several key requirements from Workshop 1 can be implemented, while others present constraints due to current technology limits. The fuel container can be accommodated in a 10-foot container, but the fuel-cell (FC) generator module must remain in a 20-foot container, as downsizing is not feasible with current balance-of-plant, redundancy, battery integration, and maintenance-access needs. Advent acknowledged concerns about larger volume compared to diesel generators but highlighted the inherently higher system complexity and modularity requirements of a fuel-cell system. The requirement for 100 kW peak load for 1 hour is technically achievable using a 100-kWh battery bank combined with continuous 50 kW fuel-cell output, pending final agreement on operational scenarios. Regarding power electronics, the inverter will support PV input, and three inverters will be integrated to enable phase balancing and provide overcapacity. For output connections, Advent proposes 2×125 A CEE sockets. A load prioritisation feature via relay-controlled sockets is feasible but categorized as "nice to have." For refuelling, Advent recommends placing the transfer pump on the fuel delivery truck rather than integrating it into the container. Requested operating modes — Eco, Turbo, and an intelligent adaptive mode (see Chapter 4) — are all technically feasible and can be integrated.

3.3. Logistics

The discussion about optimal container logistics was also extensively covered in the second workshop. The logistical options at THW for transport, loading, and operation are presented here as options 1-5:

The discussion on optimal container logistics was extensively addressed during Workshop 2. THW experts evaluated several handling and deployment options for the fuel cell container, with a focus on operational flexibility, setup time, safety, and compatibility with the existing fleet. All insights summarised below are based directly on THW operational expertise. The five logistical options for transport, positioning, and operation are presented in Figure 3.

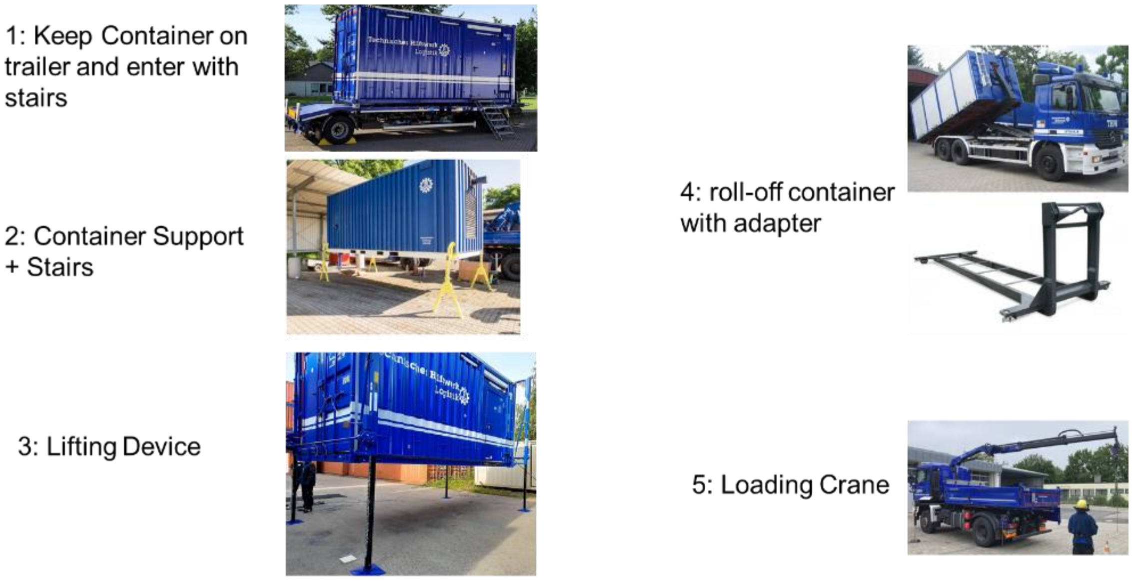

Figure 4: Logistical options for transport 1-5.

In order to clearly identify the best solution, the advantages and disadvantages were compiled in Table 1.

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Table 1: Pros and Cons for each transport option.

	Option	Pro	Contra
1	Keep Container on trailer and enter with stairs	• Very flexible and easy handling, as the trailer just has to be parked and the system can be used immediately • Faster operational readiness • No need to unload the container onto the ground • Avoids additional equipment and personnel • Simplifies positioning and repositioning	• This might be problematic on uneven terrain, as it could lead to significant tilting.
2	Container Support + Stairs	• Very simple	• Very unflexible, may be not stable on muddy terrain
3	Lifting Device	• It replaces e.g. a loading crane • Can level the container	• Takes some time to unload the container-> in case of emergency too time-consuming
4	Roll-off Container + twist-lock Adaptor	• No additional loading device necessary • Very flexible	• Inclined position during loading may be problematic • Very few vehicles in the THW fleet -> limited availability • ADR equipment status unknown
5	Loading Crane	x	• Not enough cranes/lifting capacity; • additional vehicle required

During workshop 2 discussions option 1 was chosen as the preferable option as it reduces setup time, avoids the need for cranes or lifting equipment, and aligns better with typical THW deployment workflows.

Furthermore, it is desirable to also integrate a lifting device so that the container can be set down without having to request additional units. This ensures that the container can be set down on ground level when the deployment situation requires it, for example, for specific maintenance tasks that cannot be safely performed on the trailer, or when the ground conditions do not allow use of the trailer as a stable operational platform. The lifting device serves as a fallback capability that does not interfere with the primary logistics approach but significantly increases operational flexibility.

3.4. Dangerous Goods - ADR considerations (three scenarios)

The consideration of ADR scenarios — regulations governing the transport of hazardous materials on European roads — is critical for the RESCUE system, because both, primary energy carriers, methanol and hydrogen, as well as the required battery storage, fall under dangerous goods legislation. Depending on the quantities of these materials integrated into the system, transport may remain within the simplified regime of the ADR 1000-points rule or may require full ADR compliance, which significantly increases logistical complexity. Since the regulatory status directly affects the system's operational flexibility, three scenarios were developed to assess the trade-offs between transport restrictions and achievable system performance.

The components influencing ADR classification are primarily the internal methanol buffer tank and the size and weight of the battery system. Their dimensioning determines the maximum output power of the generator, the duration for which the system can sustain outputs above 50 kW, and whether—and for how long—the generator can operate without relying on additional external fuel storage.

1. Scenario 1 represents the fully ADR-exempt configuration. In this case, no internal methanol tank is installed, and the battery capacity is limited to 333 kg to remain beneath ADR exemption thresholds. While this scenario is simple on the regulatory side, the system has minimal onboard energy and can only provide limited peak outputs and needs an external fuel tank to be operated.
2. Scenario 2 permits an internal methanol tank, but it must be completely emptied before transport to remain within the ADR 1000-points exemption. The battery capacity remains restricted to the ADR-exempt range. Once refuelled on-site, the system can operate autonomously, but this configuration also limits speed of deployment since additional handling and refuelling are required before operation.
3. Scenario 3 is a fully ADR-regulated configuration. Here, the internal methanol tank may be transported fully filled, and the battery capacity may be increased up to 100 kWh, enabling significantly higher system performance. This scenario supports extended autonomous operation, higher peak loads, and longer periods above 50 kW output. However, it requires ADR-certified vehicles, trained personnel, and full compliance with dangerous goods transport regulations.

In summary, the three ADR scenarios define a spectrum between transport simplicity and operational capability. Scenario 1 minimizes regulatory burden but offers the least usable onboard energy; Scenario 2 maintains ADR exemption but requires an empty internal tank during transport. It was still an open question if an empty fuel tank is a viable option. Scenario 3 unlocks full system performance at the cost of full ADR compliance. Choosing between these scenarios is therefore a key strategic decision in balancing mobility, autonomy, and power output for the RESCUE system.

The workshop participants discussed which scenario would be most suitable for operational deployment. All responders agreed that the performance limitations inherent in Scenarios 1 and 2 are too significant compared to the added logistical burden of ADR compliance. Consequently, Scenario 3 was identified as the preferred configuration, as it offers the necessary operational capability and autonomy required for realistic field use. Importantly, the group emphasized that further investigations and research are needed to determine whether the Scenario 3 configuration might be transportable without full ADR restrictions, exploiting regulatory frameworks or exceptions that have not yet been examined.

3.5. Autonomy and Tank size

3.5.1. Buffer Tank

It was noted that most THW deployments last less than 24 hours; therefore, the buffer tank must be sized to ensure continuous operation for at least this duration without refuelling. Table 2 presents the fuel consumption required for 24-hour operation at different continuous power levels. For a constant output of 50 kW, the system would consume approximately 0,7 m^3 of pure methanol, or 1,2 m^3 of a methanol–water mixture, or the equivalent of 4,5 bundles of 300-bar hydrogen gas cylinders.

Table 2: Fuel consumption within 24 hours.

Fuel Consumption in 24 Hours at different Power levels							
Use Case	Continuous Power (kW)	24 Hours	Total Electrical Energy amount in 24H Field Test (kWh_el)	HT-PEMFC Methanol consumption l/kWh_el	Methanol Volume m^3	Fuel:Water 60:40 Mixture Volume m^3	300bar Gas Cylinder Bundles
50kW Continuous	50	24	1200	0,6	0,7	1,2	4,5
35kW Continuous	35	24	840	0,6	0,5	0,8	3,1
25kW Continuous	25	24	600	0,6	0,4	0,6	2,2
15kW Continuous	15	24	360	0,6	0,2	0,4	1,3

During the workshop, it was discussed that this 50 kW scenario should be used as the basis for determining the internal buffer tank size. In most deployment situations, this would mean that the external fuel container would either not be required during the initial phase of the operation, or would only need to be transported after the first 24 hours. This would significantly reduce logistical burden during the “hot phase” of the mission, where logistics are often constrained: transport capacity is limited, infrastructure may be impaired, and on-site refuelling is undesirable or not yet possible. As a result, the system must be capable of bridging the first 24 hours without external refuelling using only the internal buffer tank.

Consequently, the buffer tank should have a minimum volume of 0,7 m^3 if the system uses an internal water circuit (internal mixing), or 1,2 m^3 if the system relies on a premixed methanol–water fuel (external mixing).

Furthermore, the amount of hydrogen required for the same 24-hour operational period would result in substantial additional logistical effort. The volume and weight of the 300-bar cylinder bundles are several times higher than those of methanol, and at least five bundle exchanges would be necessary within a 24-hour period. For these reasons, methanol should be considered the primary fuel wherever possible.

3.5.2. Fuel Container

Workshop 2 emphasised that the external fuel container must be dimensioned to ensure the required two-week autonomous operation under realistic field loads. For a continuous output of 50 kW, this corresponds to roughly 10 m^3 of pure methanol or 16,8 m^3 of methanol–water mixture (Table 3). Since this represents an unusually high and unlikely consumption level, participants agreed that more realistic scenarios should guide the sizing approach.

Table 3: Fuel consumption within two weeks.

Fuel Consumption in 2 Weeks at different Power levels							
Use Case	Continuous Power (kW)	2Weeks in Hours	Total Electrical Energy amount in 2 Weeks Field Test (kWh_el)	HT-PEMFC Methanol consumption l/kWh_el	Methanol Volume m^3	Fuel:Water 60:40 Mixture Volume m^3	300bar Gas Cylinder Bundles
50kW Continuous	50	336	16800	0,6	10,1	16,8	62,9
35kW Continuous	35	336	11760	0,6	7,1	11,8	44,0
25kW Continuous	25	336	8400	0,6	5,0	8,4	31,4
15kW Continuous	15	336	5040	0,6	3,0	5,0	18,9

Typical use cases involve varying loads with a two-week average of around 30 kW, while lower-intensity scenarios — such as supporting a BoO for approximately 50 people — are expected to average around 15 kW. Based on these profiles, a suitable tank size for systems with internal fuel mixing should be in the range of 3–6 m^3, while systems that rely on external methanol–water mixing require approximately 5–10 m^3. These ranges align well with the standard market availability of 10-foot tank containers, which commonly offer 10–12 m^3 usable volume that would even surpass the operation time of 2 weeks at 50 kW in case of internal fuel mixing.

However, ADR regulations may restrict the maximum methanol quantity that can be transported without route planning or additional administrative measures. As a result, the final fuel container size must be determined by carefully balancing operational autonomy, logistical feasibility, container availability, and regulatory constraints.

3.6. BBK EnergyContainer Visit

During the Workshop, an on-site visit was conducted to a container-based mobile energy system at the Federal Office for Civil Protection, which utilizes direct methanol fuel cells instead of HT-PEM technology that was chosen in the RESCUE project to implement the dual-fuel functionality. The visit provided practical insights to refine the RESCUE power generator specifications and identify additional requirements not previously considered.

Based on observations and follow-up discussions, the following additional requirements for the RESCUE system were derived:

1. Shock Protection: Critical components must be mounted with shock dampeners to ensure operational reliability under transport and deployment conditions.
2. Energy Integration: Where feasible, a photovoltaic (PV) system should be incorporated to supplement energy supply.
3. Monitoring and Communication: The system must include a communication interface to remotely monitor key operational parameters.
4. Water Management: Condensate water must be properly collected and drained, and doors and openings must have drip edges to prevent water ingress.

5. Container Compliance: All components, including air conditioning units, must fit within the container cube dimensions.
6. Operational Simplicity: Startup procedures must be straightforward and intuitive to minimise user errors.
7. Mobility: The system must remain mobile and deployable in various locations.
8. Sensor Reliability: Sensors must be robust and calibrated to prevent unnecessary shutdowns.

Figure 5: Features that stood out during the inspection included shock absorbers, drip edges, maintenance doors, and external components like air conditioning.

These requirements ensure the RESCUE power generator is robust, mobile, water-resistant, and user-friendly, aligning with lessons learned from a proven real-world system.

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4. Requirements

The following chapter presents the consolidated user requirements for the RESCUE system. These requirements were developed through a multi-stage process combining the outcomes of Workshop 1 and Workshop 2, the partial integration of the THW standard requirements for 100 kW diesel generators, and iterative technical discussions with Advent, DLR, PROACT, CERTH and the THW practitioner team.

This collaborative approach ensured that the requirements reflect the operational needs of emergency response organisations while considering technological feasibility, system integration constraints, and the characteristics of a fuel-cell–based mobile power system. As a result, the requirement set forms a jointly validated foundation for subsequent design and development activities within the project. It should be noted that most safety-related requirements are not included in this list, as they are addressed separately in the Safety Plan elaborated by PROACT.

4.1. Transport, setup concept & operability

Table 4: Transport, setup concept & operability requirements.

1.1	Transport concept: The system shall be designed for preferred operation on the trailer without unloading and only be unloaded with lifting supports, if necessary, which can be carried along in the container or chassis	Must
1.2	Container corners at the bottom and top for twist-lock	Must
1.3	Container crane-loadable (any superstructures on the roof must not obstruct the lifting equipment, or special crane lugs must be provided if the upper container corners are not accessible for craning)	Must
1.4	Forklift pockets for safe loading of the container with forklifts	Must
1.5	Lifting supports to allow the container to be set down from the trailer and reloaded	Must
1.6	Purchase custom trailer chassis from container supplier - depending on budget	Should
1.7	Lifting supports stowable in the chassis or in the container	Must
1.8	Cables and distribution equipment stowable for transport in storage boxes under the trailer or inside the container	Must
1.9	System operable directly on the trailer	Must
1.10	Operation and connection of consumers must be possible from outside via a control panel	Must
1.11	Foldable stair and platform to provide access to the control panel and connections when the system is operated on the trailer	Should
1.12	Portable access stair to be carried along for doors and access points that must be occasionally reached during operation on trailer	Should
1.13	Control panel flap designed as a rain cover	Should
1.14	External and internal lighting integrated into the container	Must
1.15	Positionable as close as possible to the consumers due to limited cable length	Must
1.16	Total height trailer + container + possible roof superstructures such as heat exchangers < 4 m	Must

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1.17	The system must be robust enough to withstand vibrations and shocks during transport.	Must
1.18	The main access points to the container should be positioned in such a way that at least one of the long sides of the container can be placed against a wall during operation, thus saving space at the deployment site.	Should
1.19	The container's center of gravity should be positioned as centrally and, above all, as low as possible.	Must

4.2. **Electrical power & connections & operating modes**

Table 5: Electrical power, connections & operating modes requirements.

2.1	50 kW continuous power	Must
2.2	85 kW power up to 1 hour	Must
2.3	100 kW power up to 1 hour	Should
2.4	150 kW power up to 1 second	Should
2.5	System startup times: warm start < 10 min, cold start < 70 min	Must
2.6	The system must be 100% unbalanced-load capable - System must support single-phase loads up to the full phase rating without functional degradation	Must
2.7	The installed inverters support four-quadrant operation, enabling seamless integration of existing photovoltaic systems that are connected to the grid while allowing the use of existing grid storage capacities. Four-quadrant operation includes both active and reactive power control in all operating conditions	Should
2.8	The electrical design shall be compliant with VDE-AR-N 4105 and VDE 0100-551; conformity evidence shall be provided during FAT	Must
2.9	Insulation monitoring must be implemented in two stages (50 kΩ warning / 23 kΩ shutdown), fast, robust, grid-compatible, and suitable for modern consumers with electronics/converters; Warning has to be audible e.g. with a warning horn	Must
2.10	Neutral conductor must be designed robustly; current measurement and monitoring may be necessary, since high current can flow under unbalanced load conditions	Must
2.11	Ensure that each socket outlet does not exceed its maximum current rating	Must
2.12	Residual current protection concept in accordance with IEC 60364-4-41 and applicable VDE standards (e.g., VDE 0100-410, VDE 0100-530). The system shall ensure protection against electric shock for all AC output circuits and internal auxiliary circuits	Must
2.13	Control Panel Switch for frequency increase to 52 Hz to disconnect photovoltaic systems from the grid	Must
2.14	Battery chemistry: select a battery type with high intrinsic safety against fire in case of fault (LFP > Li-ion)	Must
2.15	The system should achieve a Total Harmonic Distortion (THD) of < 5%, approaching grid-quality levels and voltage and frequency stability should follow EN 50160 characteristics as closely as possible (grid-like behaviour)	Should

4.2.1. Operating modes (regarding electrical connections)

Table 6: Required operating modes (regarding electrical connections).

2.16	**Operating mode 1 – Direct supply (protective isolation with insulation monitoring)**	Must
2.17	Protective measure: protective disconnect switch with multiple consumers and insulation monitoring (according to VDE 0100-551)	Must
2.18	Four-pole disconnection in case of fault (overload, short circuit, insulation fault)	Must
2.19	**Operating mode 2 – Grid feed-in**	Must
2.20	Supply system TN-C and TN-S network	Must
2.21	Feed-in only into previously disconnected networks (voltage-free) – necessary protective devices must be provided	Must
2.22	**Operating mode 3 – Parallel operation**	Must
2.23	Synchronised parallel connection with an existing TN-C network (Grid-following or Grid-forming)	Must

4.2.2. Sockets & protection

Table 7: Socket protection requirements.

2.24	All CEE connectors according to EN 60309, 5-pole, IP x7, with nickel-plated contacts, bayonet locking and captive cover on strap, 20° downward tilt, clockwise phase sequence, protected with 4-pole circuit breaker, C-characteristic	Must
2.25	Terminal block (L1/L2/L3/N/PE) for connection of solid, stranded and flexible conductors, cross-section 70 mm^2 - **OperatingMode 1-2-3**	Must
2.26	1x CEE panel socket 125 A / 400 V / 1 h – **OperatingMode 2**	Must
2.27	1x CEE panel socket 63 A / 400 V / 1 h – **OperatingMode 2**	Must
2.28	1h CEE panel socket outlets for OperatingMode 2 shall be mechanically/electrically interlocked to ensure that only one socket outlet can be utilised at any given time	Must
2.29	1x CEE panel socket 125 A / 400 V / 6 h – **OperatingMode 1-2-3**	Must
2.30	2x CEE panel sockets 63 A / 400 V / 6 h – **OperatingMode 1**	Must
2.31	2x CEE panel sockets 32 A / 400 V / 6 h – **OperatingMode 1**	Must
2.32	4x CEE panel sockets 16 A / 400 V / 6 h – **OperatingMode 1**	Must
2.33	6x Type-F panel sockets 16 A / 230 V, according to VG 96926 or equivalent, 3-pole, IP68, bayonet locking, captive cover, protected with 2-pole circuit breaker 16 A, C-characteristic **– OperatingMode 1**	Must

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4.2.3. System operating modes (regarding system behaviour)

Table 8: Required system operating modes (regarding the system behaviour)

2.34	**Eco mode**: system optimised for efficiency, no sudden increase in average power demand expected	Must
2.35	**Turbo mode**: system optimised for maximum power → all fuel cells kept at operating temperature	Must
2.36	**Adaptive mode**: intelligent mode that recognises energy consumption patterns and optimises the system accordingly	Should

4.3. Display & control

Table 9: Requirements concerning display & control

3.1	Display integrated in control panel	Must
3.2	Display daylight-readable	Must
3.3	Display provides access to all main functions	Must
3.4	Display of all key parameters	Should
3.5	Error messages displayed in plain text with detailed description (no error codes)	Should
3.6	Separate page for current/voltage/power factor/active power/system status/operating mode/direction of electrical power	Must
3.7	Separate gauges for current and voltage	Should
3.8	Signals: light signal – e.g. (1) operating, (2) warning, (3) system stop/fault; acoustic signal	Should
3.9	Robust and fault-tolerant sensor evaluation - No false shutdowns during 100 h continuous operation	Must
3.10	Create Data-Logs on all relevant system parameters	Must

4.4. Operating conditions & environment

Table 10: Requirements concerning the operating conditions & the environment

4.1	System robust against tilt during 1. loading/transport 2. operation → tilt angle in all directions > 30°	Should
4.2	Operational range from -20 °C to +45 °C, IP65	Must
4.3	Air pollution: dust, exhaust gases from combustion units, operation near biogas plants etc. → appropriate filter system must be provided to prevent operational restrictions due to polluted air at deployment site	Must
4.4	System designed to minimize operational restrictions in environments with potentially flammable materials	Must
4.5	Noise emissions: system should operate as quietly as possible. Sudden increases in noise level must be avoided. Rate of change of noise level limited (< 70 dB(A) at 7 m distance @ 100% load;< 60 dB(A) at 7 m distance below 50% load; A silent mode shall limit acoustic emissions primarily by limiting maximum output power)	Should

4.5. Fuel & tank

Table 11: Requirements concerning fuel and tank

5.1	Methanol tank volume for at least 12 hours effective operation (after warm-up) at rated power	Must

5.2	Methanol tank volume for at least 24 hours effective operation (after warm-up) at rated power	Should
5.3	Refuelling possible directly from tanker truck into buffer tank while the required pump is part of the tanker truck.	Should
5.4	Fuel Container: Methanol tank volume 10 m^3, if route planning required < 6 m^3	Should
5.5	Methanol refuelling designed as simple as conventional fuels such as gasoline/diesel; equipped with drip-free safety couplings and an overfill protection system (e.g. 4"Camlock)	Must
5.6	Hydrogen fuelling system designed in a way that it can be connected to an external hydrogen tank in a safe and easy way (e.g. 12mm OD hylok connector)	Must

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4.6. Operational safety & self-protection

Table 12: Requirements concerning the operational safety & self-protection

6.1	Self-preservation mode for batteries to protect fuel cell components from freezing (possibly via grid connection, bidirectional charging for storage preservation)	Must
6.2	Transport mode – all systems must be switchable off or brought into a safe mode for transport. Frost protection must also be ensured in this mode	Must
6.3	Remote access via LTE/5G module, web interface, remote maintenance and assisted troubleshooting capability - A reasonable cyber security protection measure must be included	Must
6.4	ISAA-compatible Situational Awareness Integration - status information, and alerts to external command-and-control platforms using ISAA-compatible data formats and communication protocols. The system shall provide machine-readable emergency management standards (e.g., OASIS EDXL-SITREP, EDXL-RM, EDXL-CAP) to ensure seamless integration into national and international situational awareness systems	Should
6.5	Key/locking concept – two authorisation levels secured by different keys: (1) general operation; (2) only authorised personnel access to interior (trained specialists)	Must
6.6	Emergency stop/shutdown procedure defined for 1. operator 2. complete system, forced external shutdown possible	Must
6.7	Hydrogen sniffer integrated on board	Must
6.8	Operator training should include basic troubleshooting	Should
6.9	Maintenance and repair / troubleshooting during test phase – responsible contact person must be defined	Must
6.10	System availability ≥ 99 % during 2,000 h (planned maintenance not included)	Must
6.11	The system must be designed in such a way that it complies with the regulatory requirements for its intended use.	Must
6.12	Design of the system in such a way minimising transport restrictions through the ADR regulations (make use of ADR special provision 363 and others) - ADR with special tank for methanol separately regulated e.g. stainless steel IBC - Clarify whether permanently installed tanks may be exempt under 1000-point ADR rule - Clarify when batteries are considered part of the container and not counted towards the 1000-point rule - Determine methanol quantities requiring route planning. Tunnel categories D/E must not be entered	Should

Implementation example for Requirement 6.4: ISAA-Compliant Telemetry and Alarms: The RESCUE Power Generator shall provide real-time telemetry and alarms to an ISAA-compatible situational awareness dashboard, enabling remote monitoring and coordinated deployment in disaster scenarios. Key parameters — including voltage, current, fuel level, battery state-of-charge, operating mode, GPS location, and fault conditions — must be transmitted at regular intervals (5–60 s) or immediately for critical events such as generator faults or emergency stop commands. Alarms must trigger automatically on threshold violations (e.g. overcurrent, low fuel, low battery) and be visible on the dashboard within ≤1 s. Telemetry data must match onboard measurements within ±2 %, and remote commands (e.g., shutdown, mode change) must be executed within ≤1 s to ensure safe and reliable operation.

5. Development of the End User Evaluation Protocol

The Key Performance Indicators (KPIs) defined in this chapter are agreed upon with the system developers and provide the quantitative foundation for evaluating the RESCUE system throughout its development, prototype validation, and field deployment phases. They translate the comprehensive set of functional, operational, and regulatory requirements into measurable and verifiable criteria that enable consistent assessment of system performance, safety, usability, and compliance. As such, the KPI framework serves multiple purposes within the project: it supports engineering decisions during system design, enables structured testing and verification during factory and site acceptance procedures, ensures traceability toward the consolidated requirements catalogue, and provides clear evidence of progress and compliance for project-internal reviews and external stakeholders.

The KPIs have been derived directly from the final requirements list of the RESCUE system (Chapter 4). Particular emphasis has been placed on mandatory (MUST) requirements, complemented by selected high-impact (SHOULD) requirements where they significantly strengthen system evaluation. The resulting KPIs cover all major technical and operational domains relevant to the RESCUE concept, including transport and deployment, electrical power supply and quality, operational modes, user interface and data handling, environmental robustness, acoustic performance, fuel and tank systems, and system-level safety and situational awareness integration.

Each KPI is formulated as a measurable statement with a clear pass/fail criterion to ensure objective verification. Where applicable, optional performance targets have been included to support design optimisation and comparative assessment without imposing mandatory compliance thresholds. Furthermore, the chapter includes an exemplary validation and test plan, outlining how each KPI will be verified through inspection, measurement, testing, or operational demonstration during prototype and field evaluations.

By establishing a coherent, transparent, and testable KPI structure, this chapter ensures that the RESCUE system can be evaluated consistently across all development phases and provides the basis for comprehensive, repeatable, and auditable performance assessment.

5.1. KPI List

KPI ID	KPI Description	Minimum Requirement (Pass/Fail)	Performance Target (Optional)	Root Req.
1. Transport, Setup & Operability KPIs				
KPI-01	System operable on trailer without unloading	Pass	–	Req. 1.1, 1.9
KPI-02	Multi-handling capability (twistlock, crane, forklift, lifting supports)	Pass	–	Req. 1.2–1.5, 1.7
KPI-03	Total height of trailer + container + rooftop components shall be < 4.0 m	< 4.0 m	3.90 m	Req. 1.16
KPI-04	Vibration & shock compliance (System remains functional after off-road transport)	Pass	–	Req. 1.17
KPI-05	Accessible control & cable connection from outside	Pass	–	Req. 1.10, 1.15
KPI-06	Internal and external lighting must enable operation at night and in low-visibility conditions.	Pass	–	Req. 1.14
2. Electrical Power, Inverters & Performance KPIs				
KPI-07	Continuous power output	≥ 50 kW	55–60 kW	Req. 2.1
KPI-08	1 h peak power capability	≥ 85 kW for ≥ 1 h	100 kW for ≥ 1 h	Req. 2.2, 2.3
KPI-09	Extreme peak load	≥ 150 kW for 1 sec	≥ 165 kW for 1 sec	Req. 2.4
KPI-10	Startup times	Warm < 10 min, Cold < 70 min	Warm 5 min, Cold 60 min	Req. 2.5
KPI-11	Unbalanced load capability (100% single phase without degradation)	Pass	–	Req. 2.6
KPI-12	Compliance with VDE electrical standards VDE-AR-N 4105 and VDE 0100-551	Pass (FAT verified)	–	Req. 2.8
KPI-13	THD < 5% and frequency/voltage stability following EN 50160 as closely as possible.	THD < 5%	THD < 3%	Req. 2.15
3. Operating Modes & Electrical Protection KPIs				
KPI-14	Supported operating modes (Direct, Feed-in, Parallel (grid-forming or grid-following))	Pass all 3	–	Req. 2.16–2.23
KPI-15	Four-pole disconnection must occur for overload, short circuit, and insulation faults	Pass	Reaction < 50 ms	Req. 2.18
KPI-16	Two-stage monitoring: warning at 50 kΩ, shutdown at 23 kΩ with audible alarm.	Warn at 50 kΩ, shutdown at 23 kΩ	Shutdown reaction < 2 s	Req. 2.9

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KPI ID	KPI Description	Minimum Requirement (Pass/Fail)	Performance Target (Optional)	Root Req.
4. Display, Control & Data KPIs				
KPI-17	Display must be daylight-readable and provide all main functions and parameter monitoring.	Pass	800+ cd/m² brightness	Req. 3.1–3.3
KPI-18	Meaningful Error messages	Error Codes	Errors in plain text	Req. 3.5
KPI-19	Continuous data logging	Pass	≥ 1 Hz logging frequency	Req. 3.10
KPI-20	No false shutdowns during 100 hours of continuous operation.	100 h continuous	250 h continuous	Req. 3.9
5. Environmental & Acoustic KPIs				
KPI-21	Operating conditions	−20°C - +45°C, IP65	−25°C - +50°C	Req. 4.2
KPI-22	Tilt capability	≥ 10° in all directions	≥ 30°	Req. 4.1
KPI-23	Noise level emission	< 70 dB(A) @100% / < 60 dB(A) @< 50%	Silent mode < 55 dB(A)	Req. 4.5
6. Fuel & Tank KPIs				
KPI-24	Methanol buffer autonomy	≥ 12 h at rated power	24 h	Req. 5.1, 5.2
KPI-25	Methanol refuelling safety	Pass (drip-free couplings, overfill protection)	–	Req. 5.5
KPI-26	Hydrogen external connection safety	Pass	–	Req. 5.6
7. Safety, ISAA & System Availability KPIs				
KPI-27	Remote access and cybersecurity	Pass	–	Req. 6.3
KPI-28	ISAA-compatible situational awareness interface	Pass	–	Req. 6.4
KPI-29	System availability	≥ 99% over 2,000 h	99.5%	Req. 6.10
KPI-30	Emergency shutdown (operator & full system)	Pass	Reaction < 2 s	Req. 6.6

5.2. KPI Test Plan

This section defines the procedures to verify KPI compliance. Each KPI is assigned to one of the following validation methods:

- **T** – Test (laboratory or field)
- **I** – Inspection (visual / documentation check)
- **M** – Measurement (instrumented)
- **D** – Demonstration (operational scenario)

KPI ID	Test Method	Test Description
KPI-01	D	Operate system on trailer for 4 h under load
KPI-02	I/D	Verify all handling interfaces
KPI-03	M	Measure total height
KPI-04	T	Vibration test per IEC 60068
KPI-05	D	Connect all sockets and operate control panel externally
KPI-06	I	Verify lighting functionality
KPI-07	T	Load bank test at 50 kW for ≥ 2 h
KPI-08	T	Load bank test at ≥ 85 kW for 1 h
KPI-09	T	Peak load pulse test
KPI-10	T	Cold/warm start measurement
KPI-11	T	Single-phase full-load test
KPI-12	I	Review certification documents
KPI-13	M	THD measurement with power analyzer
KPI-14	D	Demonstrate all three operating modes
KPI-15	T	Fault event injection → verify 4-pole disconnection
KPI-16	T	Insulation fault simulation
KPI-17	M	Display brightness measurement
KPI-18	D	Inject errors and verify human-readable messages
KPI-19	D/M	Verify data log completeness and sampling rate
KPI-20	T	100-h endurance test
KPI-21	T	Operation in extreme weather & IP65 spray test
KPI-22	T	Tilt test at ≥ 30°.
KPI-23	M	Acoustic measurement at 7 m distance
KPI-24	T	Run ≥ 12 h at rated load from internal tank
KPI-25	D	Demonstrate methanol refuelling
KPI-26	D	Connect external H_2 source and test leak-free operation
KPI-27	D	Remote access exercise and cybersecurity scan
KPI-28	D	Export ISAA-compatible datasets
KPI-29	M	Runtime availability analysis
KPI-30	T	Emergency shutdown test

6. Conclusions

The consolidated requirements and KPI framework presented in this document forms the foundation for the structured evaluation of the RESCUE system throughout its development and deployment. Based on the operational needs, constraints, and priorities defined by end users in WP2, the requirements catalogue specifies in detail the expected functional, technical, and safety-related characteristics of the system. Building on this foundation, the KPI set translates these requirements into measurable, verifiable indicators that enable transparent assessment of performance at both component and system level.

The requirements and KPIs, together constitute the core of the end-user evaluation protocol, which provides the methodological basis for validating whether the system fulfils the expectations and operational demands of practitioners. This protocol not only defines what must be achieved but also how achievement will be demonstrated, offering a unified framework for verification through laboratory testing, controlled trials, and real-world field exercises in RESCUE Project's WP6 and WP7. Its development has benefited directly from the contributions of the practitioner team, ensuring that the evaluation criteria remain grounded in realistic operational contexts and reflect the practical challenges encountered in emergency response.

By delivering a complete and traceable set of requirements, KPIs, and associated validation procedures, this document establishes a robust and coherent foundation for monitoring the performance and maturity of the RESCUE system. It ensures that system development is aligned with end-user needs, supports objective performance measurement, and provides a consistent reference for all subsequent testing, integration, and assessment activities. By delivering this evaluation protocol to the consortium (D2.3), the project is after one year duration well-positioned to systematically demonstrate compliance, guide iterative improvements, and ultimately validate the operational effectiveness of the RESCUE solution.