Safety is for life.™

BESS Explosion Safety Series by REMBE®

Reliable. German. Safety.


ENERGY
Storage System

Content

Battery Energy Storage Systems (BESS) are transforming our energy landscape – and REMBE® is pushing the boundaries of their protection. **No two BESS are identical, and each requires its own tailored approach.** Drawing on over 50 years of explosion protection expertise, we're leading the way in developing protection solutions that balance safety requirements with commercial objectives. **Our integrated approach** leverages multiple layers of safety, combining options for early detection and combustible concentration reduction with optimized deflagration vents to safeguard next-generation BESS installations.

REMBE® offers a comprehensive range of products that help safeguard BESS against explosions. Three distinct product series enable optimal solutions for any BESS installation, each bringing unique advantages to your project:

- The **BESS Core Venting Series** delivers **efficient roof venting** through our proven EGV products. Engineering excellence meets customization – each product is precisely tailored to customer specifications, from size and burst pressure to insulation materials and properties. This series offers proven protection with attractive volume pricing.
- Innovation takes center stage in the **BESS Smart Venting Series** with BESS.TGV, our revolutionary deflagration vent for BESS enclosure sides. The patented TargoVent principle deflects explosion effects upward to a safe location. By moving explosion protection from roof to container sides, BESS.TGV **eliminates concerns about snow loads and hail impact while freeing up valuable roof space**. This creates new possibilities for BESS configuration, such as **vertically stacked installations**. With a uniquely slim profile, BESS.TGV seamlessly integrates into any BESS enclosure.
- The **BESS Premium Venting Series** represents our latest breakthrough in explosion protection. As pioneers of flameless venting technology, REMBE® has developed BESS.Q.Vent – the **first flameless vent** specifically engineered for BESS applications. By eliminating external flames and minimizing thermal and pressure effects, BESS.Q.Vent enables safe installation of **BESS in indoor locations and other sensitive environments**.

Enhancing this comprehensive protection portfolio, REMBE®'s advanced detection systems provide an extra layer of safety. **Our Hotspot and GSME sensors** detect critical faults before they escalate: Hotspot through precise thermal monitoring, and GSME through multi-gas detection. This **early warning capability** enables early intervention before potential issues develop into thermal runaway events, completing our integrated approach to BESS safety.
Beyond our products, REMBE® is your global **consulting** and engineering **partner** throughout your entire project. Our explosion protection experts and external **engineering partners** work closely with you to determine the optimal safety solution for your specific requirements.

What contribution can we as REMBE® make to improving safety?

REMBE® is an independent, owner-managed family business with approx. 340 employees worldwide and can draw on over 50 years of experience as the market leader in the fields of explosion safety and explosion venting. Our expertise covers the following range of services:

Consulting.

- Support in developing adequate, project-specific safety concepts for battery systems
- Explosion-related calculations (e.g. calculation of venting areas) according to national and international standards

Engineering.

- Testing and validation of protective measures at the accredited testing laboratory REMBE® Research+Technology Center GmbH, e.g.:
  - Fire and explosion tests with prototypes under practical conditions
  - Testing of explosion pressure resistance or flame penetration tests for battery housings
  - Development of flameless venting systems to prevent explosive flames and flying debris

More information about the REMBE® Research+Technology Center GmbH can be found at: www.rembe-rtc.de

Products.

Explosion Vent Panels

- Accredited according to national and international standards
- Special solutions available as series products

REMBE® Consulting & Engineering for BESS

REMBE® delivers specialized consulting and engineering expertise to develop customized safety solutions for your BESS installation. Our technical team supports clients through risk-appropriate assessments, ranging from analytical modeling to Computational Fluid Dynamics (CFD) simulations and Finite Element Analyses (FEA). With our proprietary analysis tools, validated methodologies, and extensive explosion protection expertise across a vast range of industrial sectors, we provide custom BESS safety solutions featuring proven and innovative products that exceed standard compliance requirements while optimizing commercial viability—a comprehensive approach unmatched in the industry.

Layer-of-Protection Approach for Risk-Appropriate BESS Protection

REMBE® implements a comprehensive layer-of-protection framework for safeguarding BESS installations, providing an effective methodology for integrating complementary safety systems into a holistic solution. This proven approach, successfully applied across numerous industries handling hazardous materials, has been specifically adapted to address the unique needs of battery energy storage systems as illustrated in Figure 1.

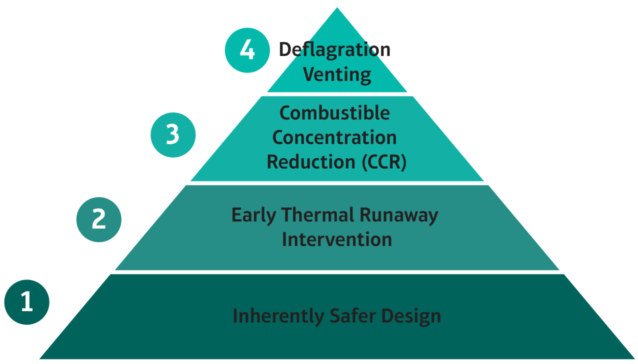


Figure 1: REMBE® layer-of-protection approach for risk-appropriate BESS protection.

Multiple layers of protection are essential for effectively managing BESS explosion risks. While active systems like ventilation provide significant benefits, they have inherent limitations—such as vulnerability to power loss—that must be addressed in comprehensive safety design. By strategically combining multiple protection layers, REMBE® solutions effectively minimize risk, optimize commercial objectives, and ensure compliance with rigorous safety standards and regulatory requirements.

Based on detailed analysis of individual BESS characteristics, REMBE® engineers work closely with clients to determine the optimal combination of the following protection layers:

1. Inherently Safer Design: Leverages safer technologies such as battery chemistries with reduced thermal runaway susceptibility or passive thermal barriers to contain thermal runaway propagation.
2. Early Thermal Runaway Intervention: Incorporates detection and intervention systems to identify and interrupt incipient thermal runaway before flammable atmospheres form.
3. Combustible Concentration Reduction (CCR): Deploys mechanical ventilation systems designed to reduce flammable gas accumulation during thermal runaway events. Controlled ignition systems using distributed spark ignitors can provide an alternative, effective CCR method.
4. Deflagration Venting: Constitutes the critical final protection layer, recognizing that even the most effective CCR systems cannot completely eliminate all flammable gas accumulation risk. Our passive deflagration vents reliably mitigate residual explosion hazards while requiring no power or external activation.

REMBE® specializes in mitigating explosion hazards after thermal runaway onset, with particular expertise in engineering optimized combinations of Combustible Concentration Reduction (CCR) systems and Deflagration Venting solutions. This integrated approach provides superior protection against the full spectrum of failure scenarios, from single-cell failures to cascading thermal runaway events.

Battery Vent Gas Analysis

Effective explosion protection for BESS installations demands precise characterization of thermal runaway vent gases. REMBE® analyzes comprehensive gas property data obtained through standardized UL 9540A testing protocols. Figure 2 presents a representative composition profile from NMC cell testing, illustrating the complex mixture of flammable and non-flammable components. Advanced analytical capabilities can often identify additional trace components.

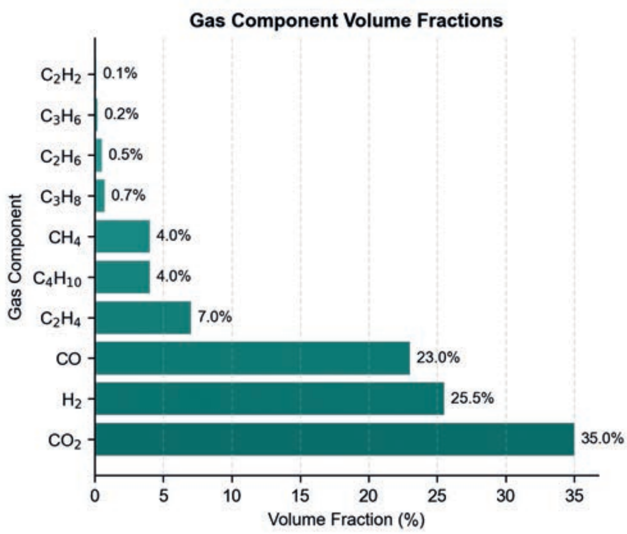


Figure 2: Battery vent gas composition (generalized example for representative NMC cell).

Beyond composition analysis, REMBE® evaluates gas quantity and release rate dynamics—critical parameters for comprehensive explosion safety engineering. We develop credible thermal runaway scenarios (single-cell failures, cascading propagation events, etc.) based on multi-level UL 9540A test results from cell, module, and unit testing. Our proprietary thermochemical modeling techniques transform raw test data into precise gas property specifications that drive subsequent CCR system design and deflagration vent sizing calculations, ensuring protection systems match real-world hazard conditions.

Ventilation Analysis – Combustible Concentration Reduction (CCR)

The forthcoming release of NFPA 855:2026 mandates implementation of CCR systems to limit battery vent gas accumulation within BESS enclosures. While properly engineered CCR systems significantly reduce flammable gas concentrations, REMBE® recognizes that residual gas volumes can still generate dangerous overpressures if ignited. Our comprehensive ventilation studies serve two critical functions: (1) quantifying the effectiveness of proposed ventilation systems in reducing combustible concentrations under various failure scenarios, and (2) providing precise input data for subsequent partial volume deflagration analyses to ensure complete protection system integration.

REMBE®'s multi-tiered ventilation analysis begins with analytical modeling based on NFPA 69 methodologies, providing rapid preliminary assessment using conservative assumptions. These calculations deliver early predictions of ventilation system performance capabilities and identify potential residual deflagration hazards requiring additional mitigation. Figure 3 presents results from our analytical ventilation modeling, simulating accumulated vent gas volumes over time during a cascading thermal runaway scenario under multiple ventilation rates—clearly demonstrating the critical relationship between ventilation system capacity and hazard reduction.

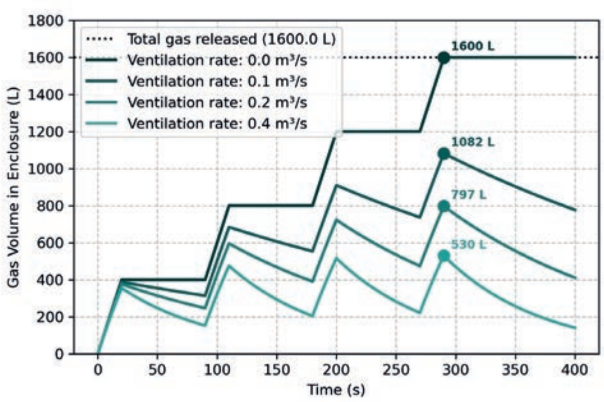


Figure 3: Gas accumulation predicted by analytical ventilation calculations.

Advanced CFD Analysis Reveals Critical Ventilation System Performance Details

While analytical methods provide valuable initial insights, REMBE® delivers detailed ventilation studies using advanced computational fluid dynamics (CFD) simulations. CFD modeling represents the gold standard for ventilation system evaluation, revealing complex gas flow patterns impossible to detect through simplified calculations. These detailed simulations assess ventilation performance against the stringent requirements of safety standards such as NFPA 855, incorporating the specific three-dimensional BESS geometry, precise thermal runaway gas release dynamics, and comprehensive ventilation system specifications.

Figure 4 illustrates a generic BESS geometry with a simplified ventilation configuration featuring a single air inlet with diagonally opposed exhaust—a baseline case we use to demonstrate ventilation optimization opportunities.

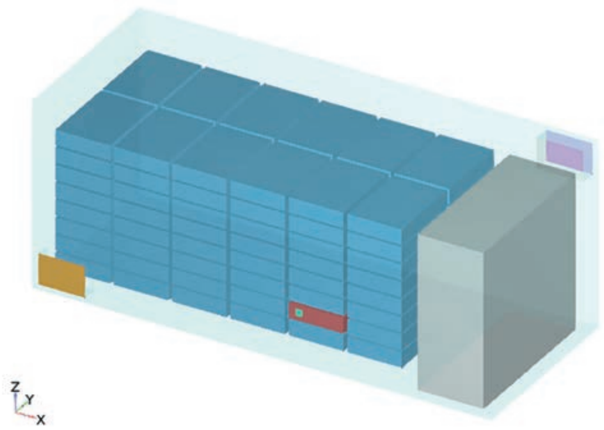


Figure 4: Simplified BESS geometry for sample CFD ventilation study (CONVERGE CFD software).

For this sample geometry, a steady-state ventilation simulation revealed significant regions of stagnation and recirculation, indicating opportunities for design improvements:

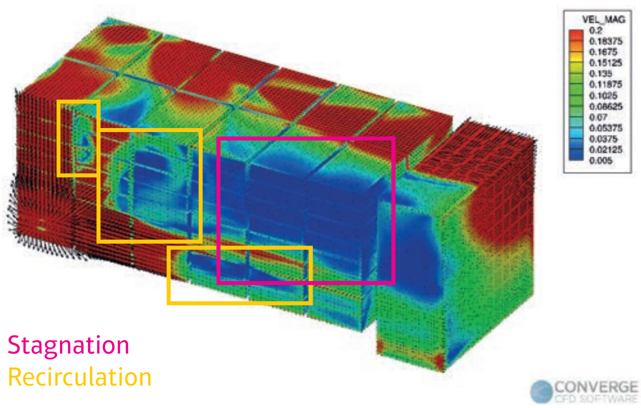


Figure 5: Stagnation and recirculation regions identified by steady-state CFD ventilation simulation (CONVERGE CFD software).

To validate ventilation system performance, we simulated a thermal runaway event within the identified stagnation region, among several other locations. Using gas release rates derived from UL 9540A tests, the CFD model captures the three-dimensional dispersion pattern of battery vent gases throughout the BESS enclosure, as shown in Figure 6.

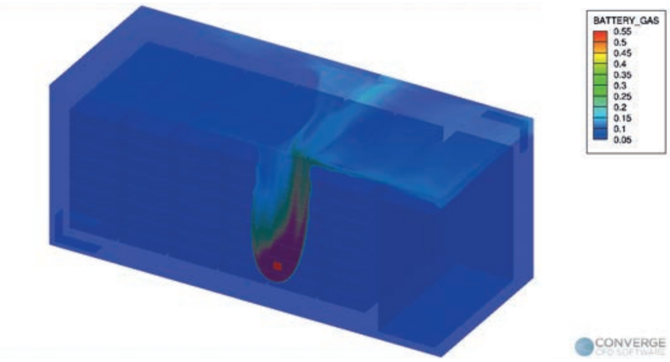


Figure 6: CFD simulation of battery vent gas release, showing gas dispersion considering mechanical ventilation (CONVERGE CFD software).

The CFD analysis demonstrates that in this ventilation configuration, average vent gas concentrations exceeded 25% of the lower flammability limit throughout the enclosure—a maximum allowable threshold specified in NFPA 855 and UL 9540A. CFD simulations can be used to optimize ventilation design and meet performance objectives. This analysis furthermore identified that localized gas concentrations present deflagration hazards requiring mitigation. Based on ventilation studies, REMBE® performs partial volume deflagration (PVD) analysis—an advanced engineering methodology that predicts internal explosion pressure effects. This critical analysis forms the foundation for designing optimally-sized deflagration venting systems that serve as the final, failsafe layer of protection in our multi-layered safety approach.

Precision Engineering in Deflagration Vent Sizing

Deflagration venting is considered the most effective method of mitigating the effects of a deflagration in BESS. As a completely passive protection measure requiring no power or activation systems, properly designed deflagration vent panels provide unparalleled reliability. When an explosion occurs, these engineered panels instantly respond to pressure rise, opening precisely at predetermined set points to rapidly relieve pressure before the structural integrity of the BESS enclosure would be compromised.

Figure 7 illustrates an implementation of deflagration venting on a standard 20-ft BESS container, featuring six deflagration vents installed on the roof—sized based on partial-volume deflagration (PVD) analysis.

Figure 7: Example of deflagration venting installed on BESS roof.

REMBE®'s deflagration vent sizing incorporates multiple critical parameters, including precise BESS geometry specifications, maximum credible flammable gas volumes, gas reactivity characteristics, and enclosure strength limitations.

Figure 8 demonstrates our VENT.iNG software in action, performing deflagration vent sizing calculations in accordance with NFPA 68 or EN 14994 requirements.

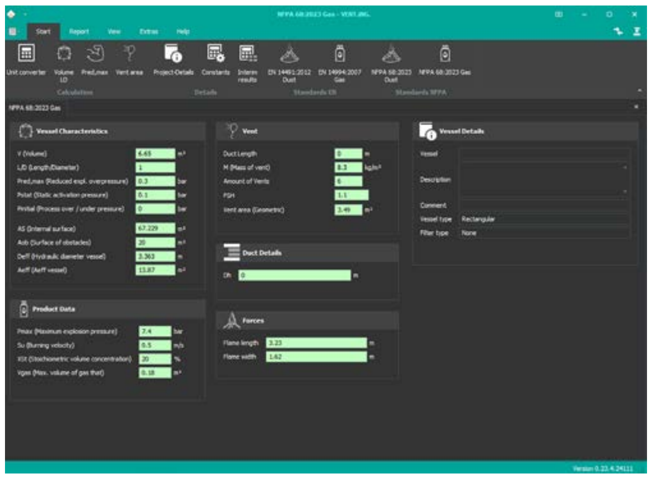


Figure 8: VENT.iNG software used for standardized deflagration vent sizing.

While we employ standardized calculation methodologies as a baseline approach, our engineering capabilities extend to advanced performance-based design techniques using CFD deflagration simulations and data from our extensive physical testing program. This performance-based approach delivers optimized protection solutions precisely matched to realistic gas release patterns and deflagration scenarios specific to each BESS installation.

REMBE®'s holistic protection philosophy enables optimal integration between protection systems. Our deflagration vent sizing methodologies precisely account for the mitigating effects of properly engineered ventilation and other CCR systems when implemented within our comprehensive layer-of-protection framework. For BESS installations with reliable, well-maintained ventilation systems operating to design specifications, this integrated approach can optimize deflagration vent sizing while maintaining protection integrity.

Large-Scale Testing: Validating Protection Performance in Real-World Conditions

While modeling and simulation form the foundation of REMBE®'s engineering approach, we recognize that nothing validates protection system performance like rigorous physical testing under realistic conditions. The REMBE® Research+Technology Center—our dedicated state-of-the-art testing facility—provides comprehensive explosion testing capabilities.

Rigorous Product Certification and Custom Testing Capabilities

All REMBE® explosion protection products undergo exhaustive testing under precisely controlled conditions that replicate real-world hazard scenarios. Figure 9 illustrates our controlled explosion testing environment, where we validate protection system performance under credible worst-case conditions.

For clients with unique requirements or specialized applications, our Research+Technology Center offers custom testing programs that evaluate protection solutions under specific conditions relevant to their BESS installations—providing unparalleled confidence in system performance before deployment.

Figure 9: Explosion testing under controlled conditions to validate protection design, performed at REMBE® Research+Technology Center.

Beyond Explosion Protection: Comprehensive Environmental Performance

Understanding the diverse operating environments of BESS installations, REMBE® conducts extensive additional testing beyond explosion protection functionality. Our deflagration vent panels undergo rigorous evaluation for environmental protection ratings (IP), fire resistance, and extreme operational challenges.

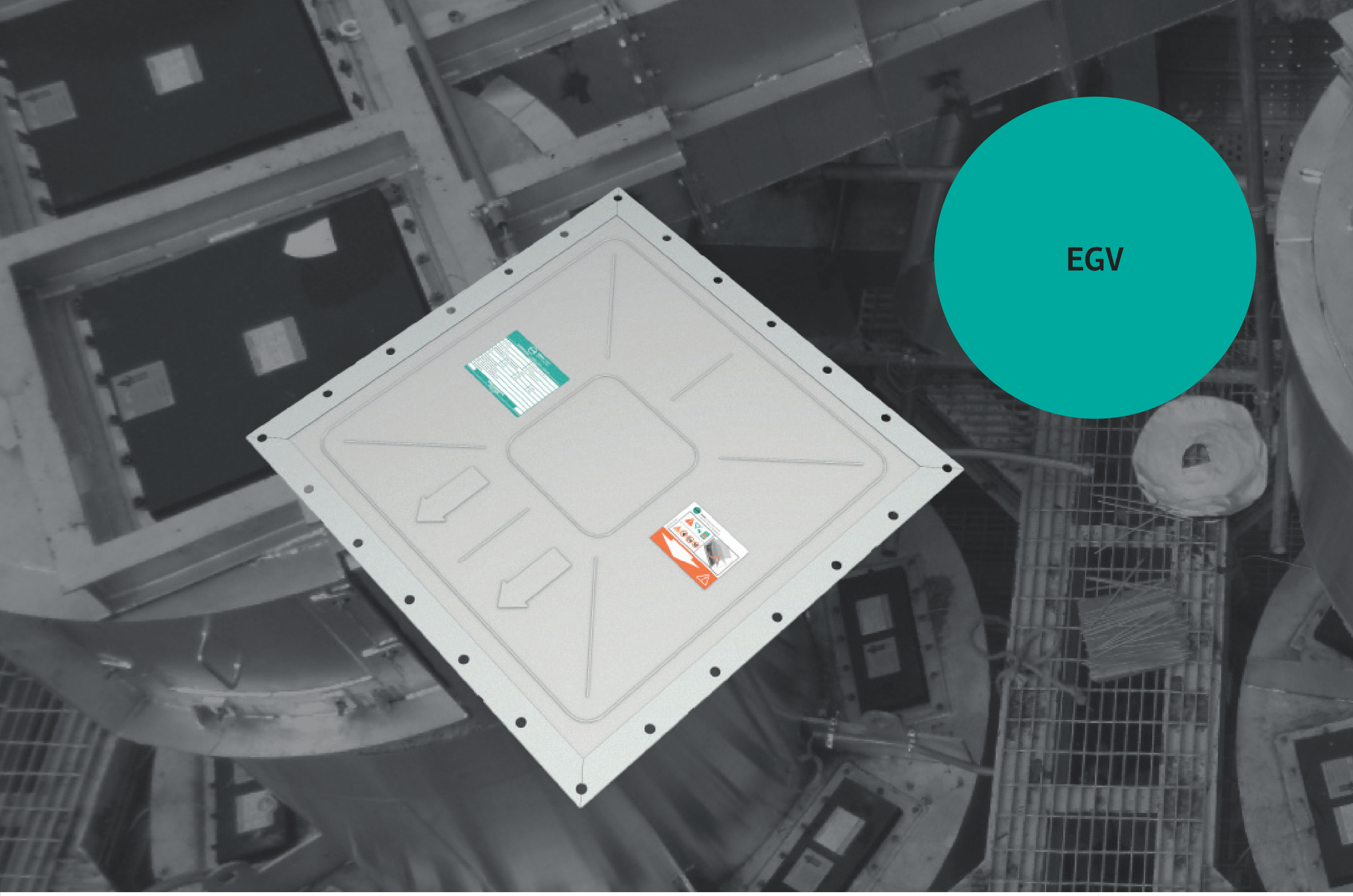
Figure 10 demonstrates the exceptional fire resistance capabilities of our BESS.IKLIEGV deflagration vents as evaluated in severe furnace tests. Figure 11 illustrates the robustness of our BESS.TGV panels even when inadvertently subjected to high-pressure fire hose streams during emergency response activities.

Through this comprehensive testing program, REMBE® ensures that our protection systems maintain their critical safety functions and full integrity under all foreseeable conditions throughout their service life.

Figure 10: BESS.IKLIEGV maintaining full integrity in furnace test. Sample shown prior to test (left) and after 120 min at 1050 °C furnace peak temperature (right).

Figure 11: BESS.TGV maintaining full integrity under severe fire hose impact.

The BESS
Core Venting Series



Advantages

- ✓ **High venting capacity and full bore opening** due to low surface weight.
- ✓ **High stability and opening speed** through integrated bionic structure.
- ✓ **Adapts perfectly to your BESS** due to the wide range of EGV geometries available.
- ✓ **Quick and easy installation** as EGV is torque independent. No additional counter frame required.
- ✓ **Significant space savings** due to the integrated gasket and frame in the explosion vent.

Technical data*

Burst pressure P_{stat}	25 - 500 mbar
Max. permitted operating pressure	50 % of P_{stat}
Temperature	- 40 to +180°C (– 40 to + 356 °F)
Material	Stainless steel
Gasket material	FDA approved silicon gasket
Tolerance	± 20 % at standard burst pressure
Recommended torque for M10 screws	20 Nm

* Our specialists will be pleased to assist you in finding a solution that matches your specific operating conditions.

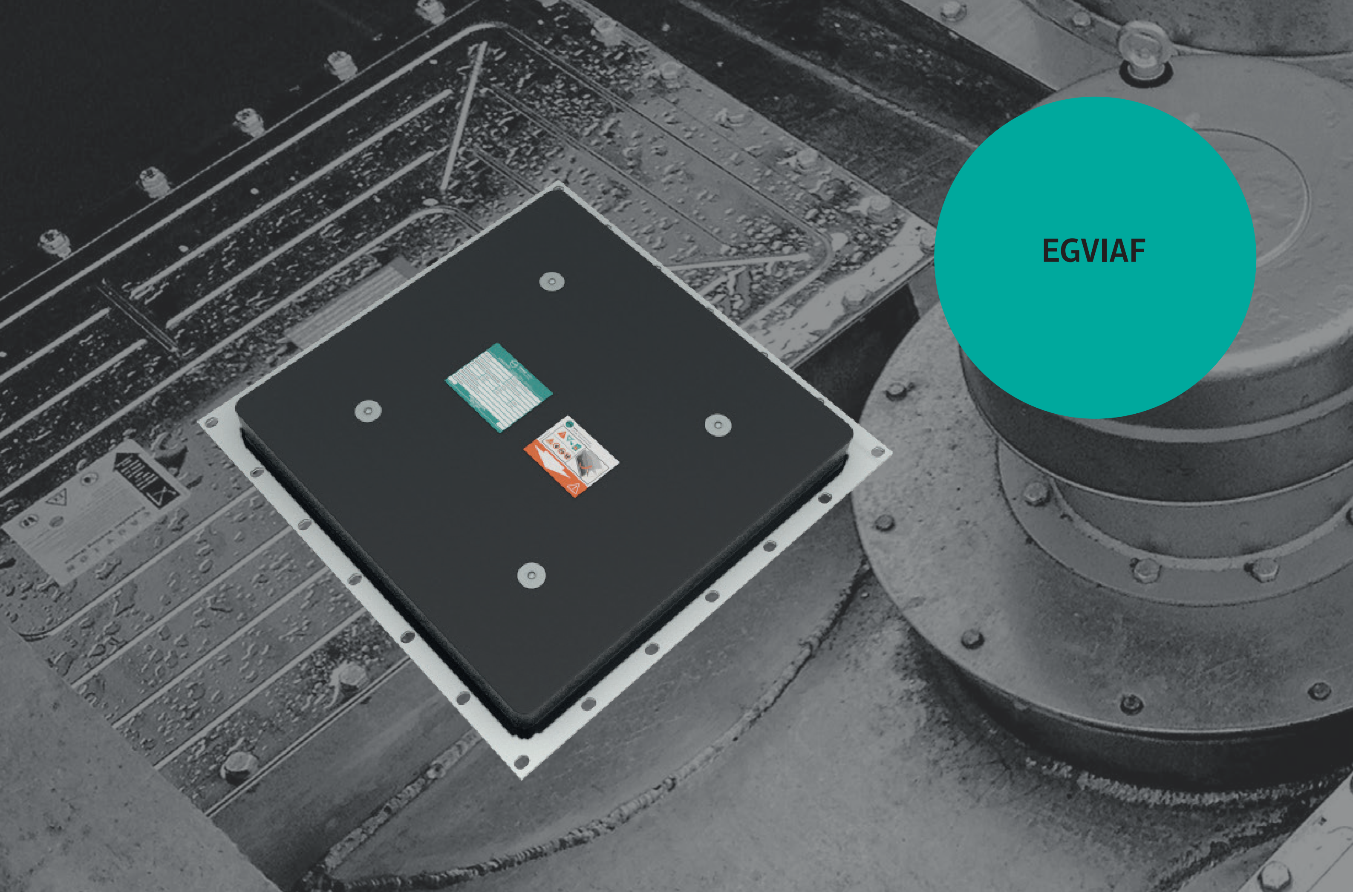
Certifications

Meets the requirements of **NFPA 68**

ATEX
EU-type examination certificate no.
FSA 04 ATEX 1538 X

SIL equivalent

SIL 4



Advantages

- ✓ Insulation inside and / or outside possible
- ✓ Lightweight

Technical data *

Burst pressure P_{stat}	25 - 500 mbar
Max. permitted operating pressure	50 % of P_{stat}
Temperature	-40 to +180°C (–40 to +356 °F)
Material	Stainless steel
Gasket material	FDA approved silicon gasket
Tolerance	± 20 % at standard burst pressure
Recommended torque for M10 screws	20 Nm
Insulation	FEF
Fire rating of insulation	UL 94 V 0
Insulation thickness	25-100 mm
Insulation properties	λ=0.035 W/m*K

* Our specialists will be pleased to assist you in finding a solution that matches your specific operating conditions.

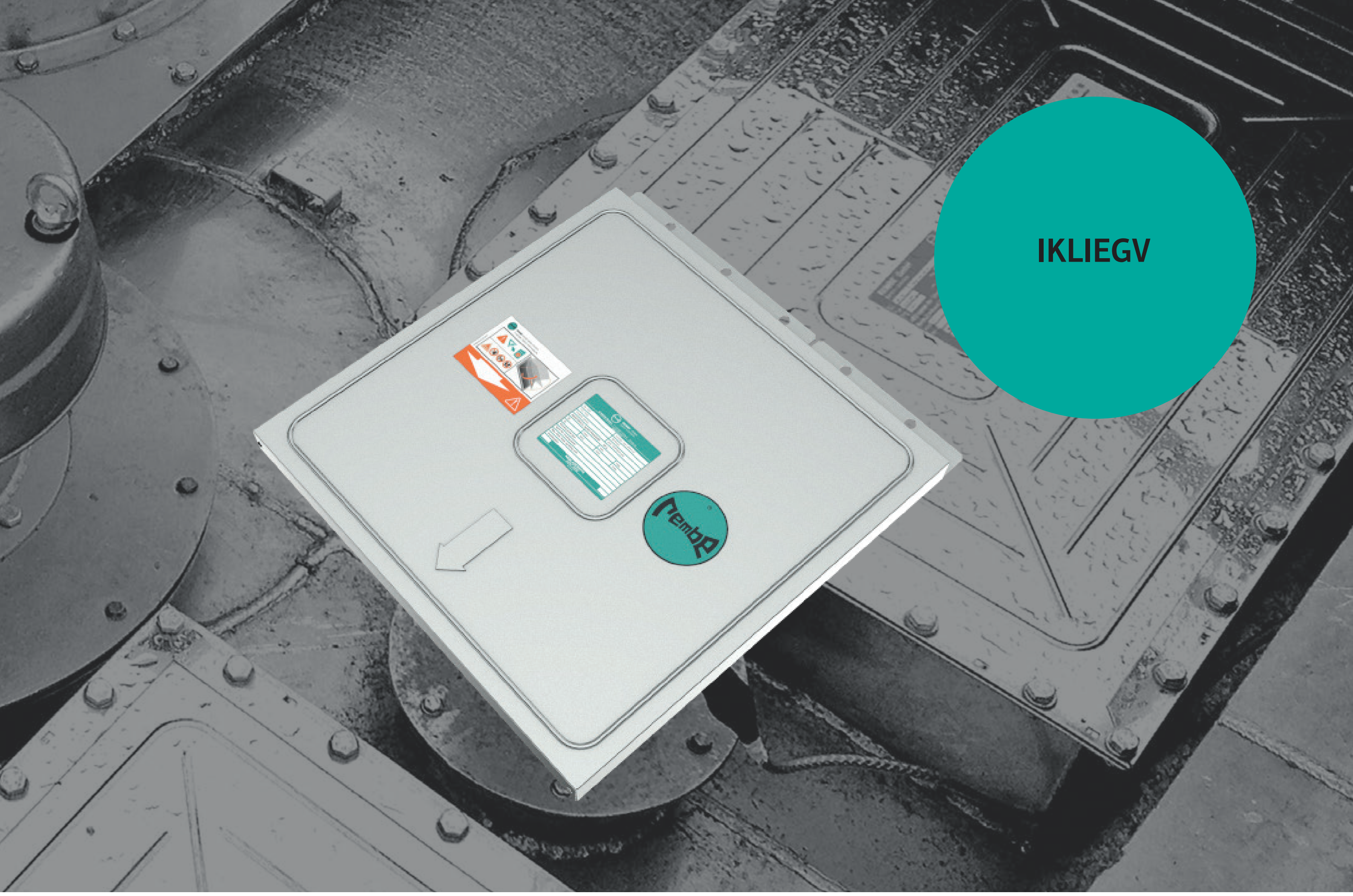
Certifications

Meets the requirements of **NFPA 68**

ATEX
EU-type examination certificate no.
FSA 04 ATEX 1538 X

SIL equivalent

SIL 4



Advantages

✓ Insulation protected
✓ Outside insulation
✓ Lightweight

Technical data *

Burst pressure P_{stat}	25 - 500 mbar
Max. permitted operating pressure	50 % of P_{stat}
Temperature	- 40 to +180°C (– 40 to + 356 °F)
Material	Stainless steel
Gasket material	FDA approved silicon gasket
Tolerance	± 20 % at standard burst pressure
Recommended torque for M10 screws	20 Nm
Insulation	Rockwool
Fire rating of insulation	Non-combustible
Insulation thickness	40-100 mm
Insulation properties	λ= 0.040 W/m*K

* Our specialists will be pleased to assist you in finding a solution that matches your specific operating conditions.

Certifications

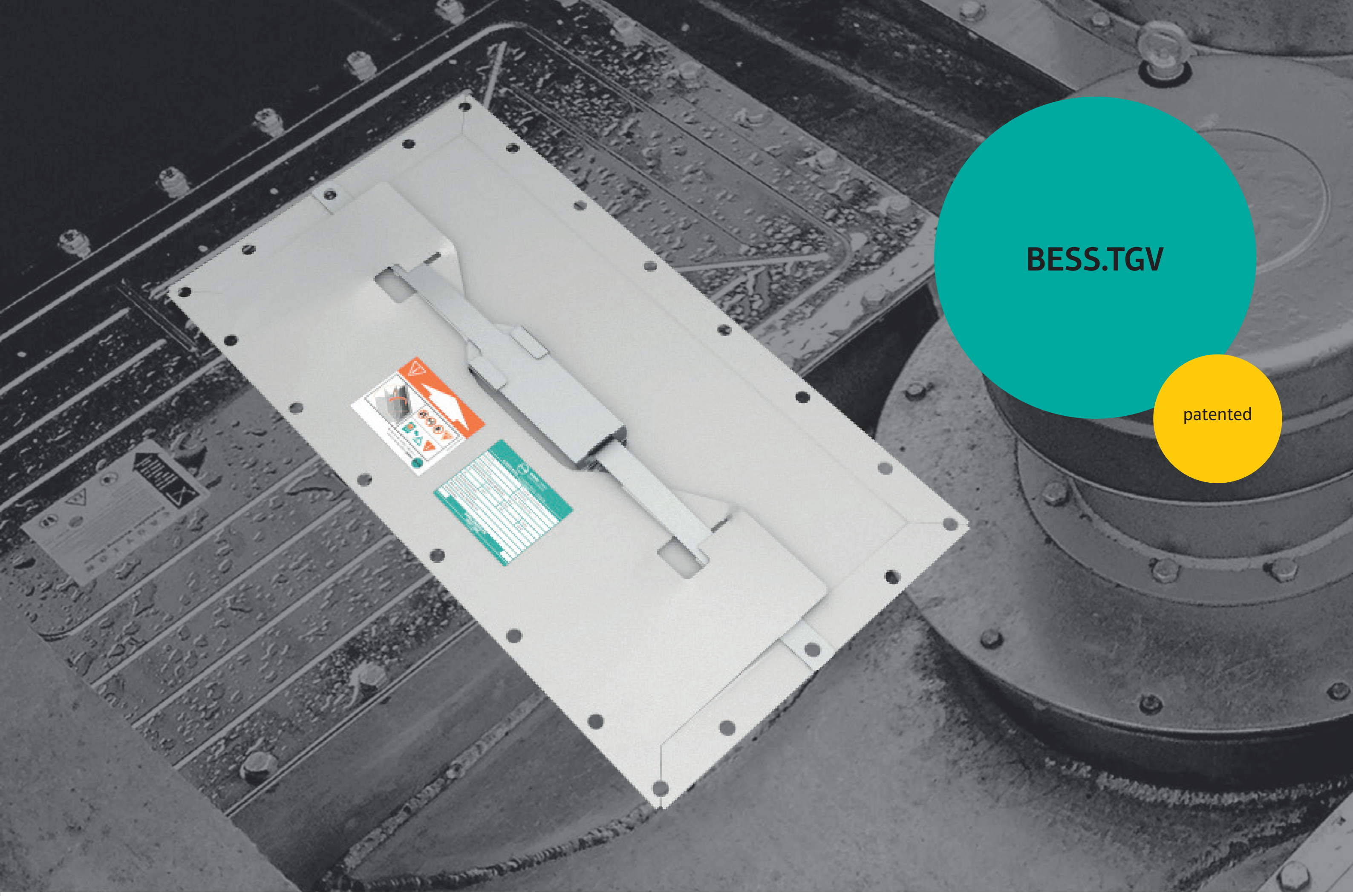
Meets the requirements of **NFPA 68**

ATEX
EU-type examination certificate no.
FSA 04 ATEX 1538 X

SIL equivalent

SIL 4

The BESS
Smart Venting Series



Advantages

✓ Limits opening angle to 45 °
✓ Reduced safety area
✓ Wall installation at BESS
✓ Uniquely slim profile < 15 mm
  • Blends in with the container walls
  • Allows container to be stacked

Technical data *

Burst pressure P_{stat}	25 - 100 mbar
Max. permitted operating pressure	50 % of P_{stat}
Temperature	- 40 to +180°C (– 40 to + 356 °F)
Material	Stainless steel
Gasket material	FDA approved silicon gasket
Tolerance	± 20 % at standard burst pressure
Recommended torque for M10 screws	20 Nm
Insulation	FEF
Fire rating of insulation	UL 94 V 0
Insulation properties	λ= 0.035 W/m*K
Opening angle	45°

* Our specialists will be pleased to assist you in finding a solution that matches your specific operating conditions.

Certifications

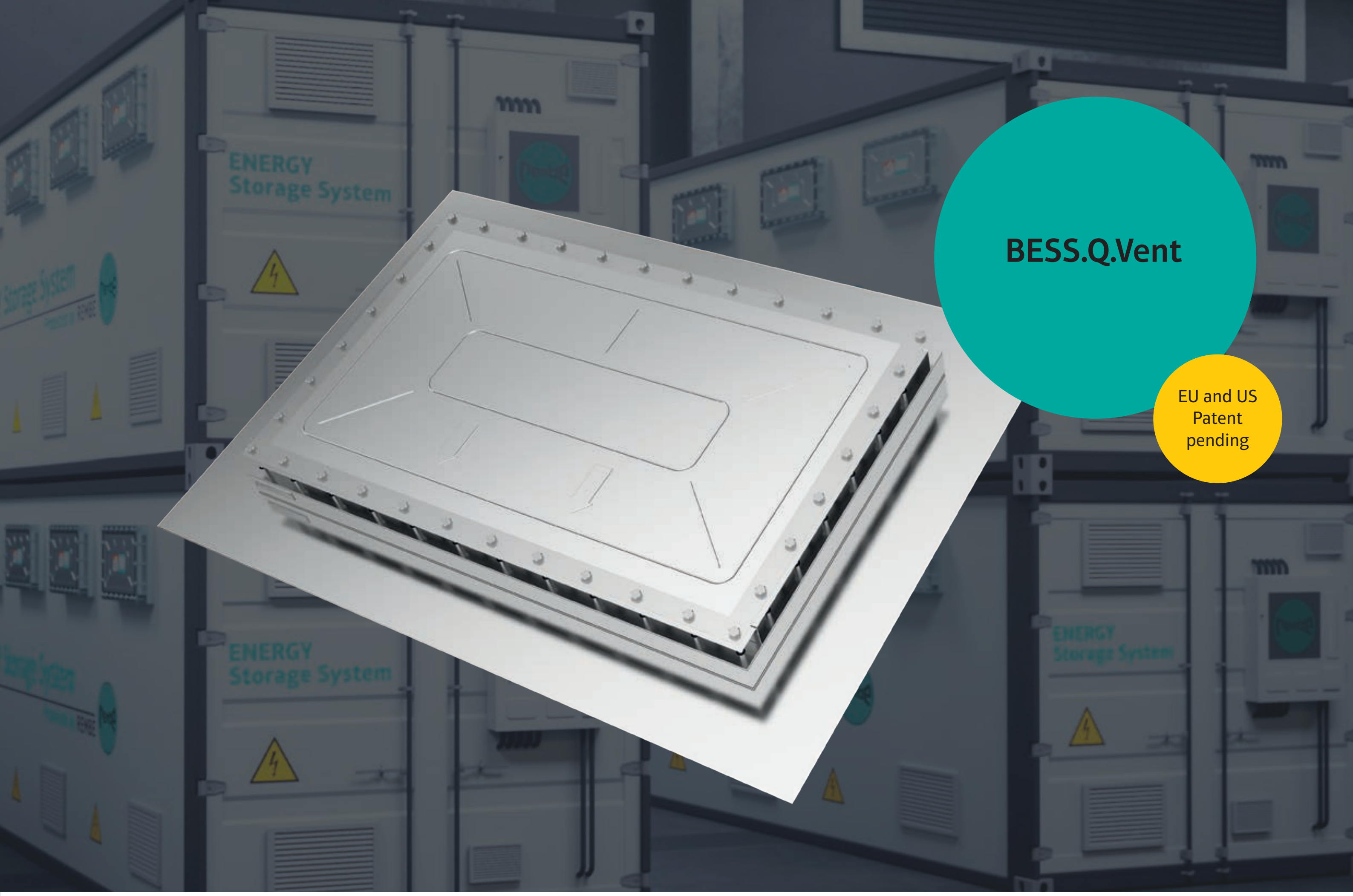
NFPA®

Meets the requirements of **NFPA 68**

SIL equivalent

SIL 4

The BESS
Premium Venting Series



Advantages

- ✓ Flame absorber
- ✓ Reduced safety area
- ✓ Wall or roof installation at BESS
- ✓ Uniquely slim profile
  - Blends in with the container wall
  - Allows containers to be stacked
- ✓ Maintenance-free
- ✓ Reduction of external explosion pressures
- ✓ Suitable for indoor installation of the BESS

Technical data *

Burst pressure P_{stat}	25 - 100 mbar
Max. permitted operating pressure	50 % of P_{stat}
Temperature	- 40 to +180°C (– 40 to + 356 °F)
Material	Stainless steel
Gasket material	FDA approved silicon gasket
Tolerance	± 20 % at standard burst pressure
Recommended torque for M10 screws	20 Nm
Insulation	FEF
Fire rating of insulation	UL 94 V 0
Insulation thickness	25-100 mm
Insulation properties	λ= 0.035 W/m*K

* Our specialists will be pleased to assist you in finding a solution that matches your specific operating conditions.

Certifications

NFPA

Meets the requirements of **NFPA 68**

SIL equivalent

SIL 4

BESS
Explosion Prevention

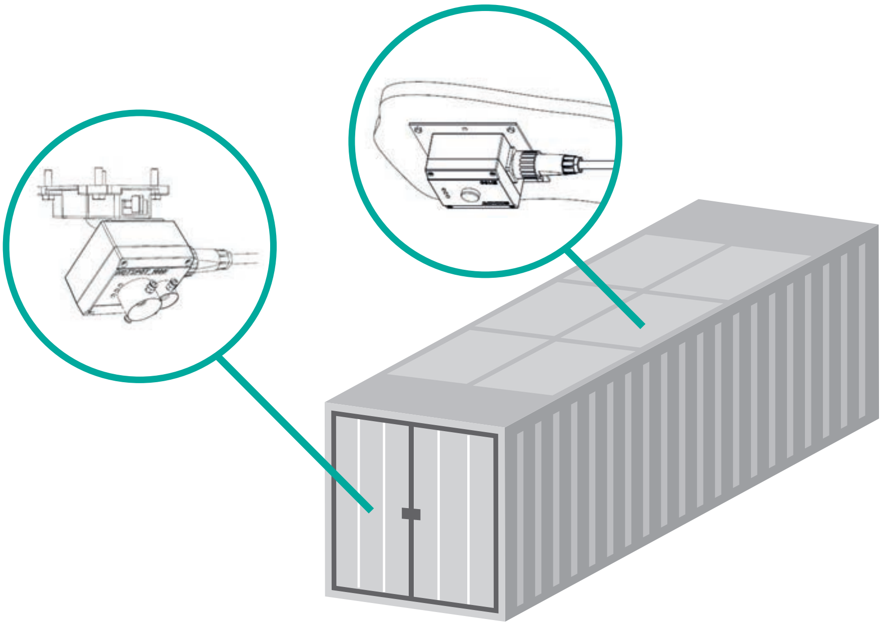
Detection of thermal runaway

GSME gas detector
Gas detector sensitive to hydrogen, carbon monoxide and hydrocarbons

Advantages
- ✓ Monitoring of relevant gas concentrations (multi-component detector 0-100 ppm) that arise during thermal runaway
- ✓ Early alarm

HOTSPOT temperature detector
Infrared camera to monitor the temperature of individual storage systems or facilities

Advantages
- ✓ Monitoring of surface temperatures ranging from 0 to 200 °C
- ✓ Identification of the smallest temperature increases



Service.
Maintenance and testing by
REMBE® Advanced Services+Solutions GmbH.


REMBE

Safety is for life.™

Consulting. Engineering. Products. Service.

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