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<< D6.2 – Safety analysis results >>

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Publishable summary

One of the main results of the HIGREEW project is to build up and demonstrate a fully functional 5 kW / 20 kWh prototype AORFB. The prototype will be integrated in a demonstrator test site in La Plana, Spain where it will interact with renewable generators as well as other energy storage technologies.

The AORFB prototype obtained in the project has to fulfil sustainability and safety issues to become a future energy storage solution for the transition path to the future grid. To ensure that the prototype developed fulfils these requirements a specific task has been devoted to executing a Safety analysis.

The activities covered in this report are among others:

- Identify potential hazards associated with the battery prototype related to the following:
• Energy: fire, burns, explosion.
• Electrical: electric shocks, electrical arcs, electrical burns.
• Mechanical: moving parts, pressure, noise, sharp edges.
• Chemical: toxic or hazardous substance exposure, leakage of electrolyte.
• Workers.
- Create a plan showing potential cause of failure, potential modes of failure, severity, expected effects and recommended actions to be taken

The Safety analysis consisted of a HAZOP analysis and a SWIFT analysis.

In both cases the scope of the analysis is the flow battery installed in La Plana for the HIGREEW project.

Firstly, HAZOP analysis was done, this methodology is applied in all cases where the change affects the process or operator/process interaction. Most of the recommendations from the HAZOP analysis were then introduced in the project before the commissioning. Afterwards, SWIFT analysis was done. Finally, most of the recommendations from the HAZOP analysis were then introduced in the project before the commissioning and during the commissioning the recommendations from the SWIFT analysis were considered and corrected.

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1 Introduction

HIGREEW project will end up with the installation of a fully functional 5 kW / 20 kWh prototype AORFB installed in a renewable energy plant, La Plana. This one of the main outcomes of the project. The sustainability and safety requirements of the prototype are also a target themselves.

In order to assess the safety risks of the prototype a hazard analysis methodology was defined, this methodology consists of a HAZOP analysis plus a SWIFT analysis.

On the one hand, Hazard and Operability Analysis (HAZOP) is a *structured and systematic technique for system examination and risk management. HAZOP is often used as a technique for identifying potential hazards in a system and identifying operability problems likely to lead to nonconforming products. HAZOP is based on a theory that assumes risk events are caused by deviations from design or operating intentions. Identification of such deviations is facilitated by using sets of "guide words" as a systematic list of deviation perspectives. This approach is a unique feature of the HAZOP methodology that helps stimulate the imagination of team members when exploring potential deviations.*

On the other hand, the structured what-if technique (SWIFT), is *a high-level and less formal risk identification technique that can be used independently, or as part of a staged approach to make bottom-up methods such as FMEA more efficient. SWIFT uses structured brainstorming in a facilitated workshop where a predetermined set of guidewords (timing, amount, etc.) are combined with prompts elicited from participants that often begin with phrases such as "what if?" or "how could?". At the heart of a SWIFT is a list of guidewords to enable a comprehensive review of risks or sources of risk. At the start of the workshop the context, scope and purpose of the SWIFT is discussed and criteria for success articulated. A SWIFT Analysis allows participants to look at the system response to problems rather than just examining the consequences of component failure. As such, it can be used to identify opportunities for improvement of processes and systems and generally can be used to identify actions that lead to and enhance their probabilities of success.*

Firstly, HAZOP analysis was done, this methodology is applied in all cases where the change affects the process or operator/process interaction. In this way, the study is useful in those cases in which the changes imply:

- P&IDs modifications
- Changes in process service parameters (level, pressure, temperature, flow, etc.)
- Pipelines layout with changes in P&IDs
- Installation or modification of new equipment with a modification in process service parameters
- Control Loop changes

An important benefit of HAZOP studies is that the resulting knowledge, obtained by identifying potential hazards in a systematic manner, is of great assistance in determining appropriate safeguards.

The practical application of the method is based on several sessions of multidisciplinary team meetings. The multidisciplinary team includes project and process engineers and operation engineers.

In a second stage, the SWIFT analysis was carried out. Different operations on site were defined for evaluation, such as commissioning, operation and maintenance.

Each SWIFT recommendation must be studied and applied correctly or rejected. In order to guarantee traceability, the entire process must be followed and recorded, as proposed in the following points:

- Include in the documentation a "SWIFT recommendations follow-up" document based on the list of recommendations.

- Write down the date and the person responsible for closing the recommendation.

- Register the application document and the revision number.

- Explain or justify the choice of each open recommendation.

- Adequately justify any rejected recommendation.

In this deliverable are described the results and recommendations of these safety analyses.

2 HAZOP analysis

The purpose of this section is to document the methodology, applied criteria and results of the Hazardous & Operability (HAZOP) sessions for the facilities described in the scope.

2.1 Scope

The scope of the HAZOP is the flow battery installed in La Plana for the HIGREEW project.

2.2 Description of work

The HAZOP (HAZard and OPerability study) is a systematic technique for identifying potential hazards and operational problems, especially adapted to continuous processes, providing fluid transfer through pipes and equipment which may be represented in piping and instrumentation diagrams (P&ID).

This methodology will be applied in all cases where the change affects the process or operator/process interaction. In this way, the study will be useful in those cases in which the changes imply:

- P&IDs modifications
- Changes in process service parameters (level, pressure, temperature, flow, etc.)
- Pipelines layout with changes in P&IDs
- Installation or modification of new equipments with a modification in process service parameters
- Control Loop changes

The HAZOP method is focused on analyzing any variable's deviations with respect to the intention of the process. The technique uses key words (no, more, less, etc.) applied to the process parameters (flow, pressure, temperature, etc.) which lead to deviations (more flow, less pressure, etc.).

Thus, the HAZOP study starts with the subdivision of the facilities in a number of subsets called "nodes" which later on have to be analyzed the possible deviations by a team that shall be composed by a heterogeneous group of technicians from different specialties. The HAZID study includes only one "node".

The analyzed nodes are as follows:

1. Flow battery in charging mode
2. Flow battery in other modes (discharge, waiting (pump on), stand-by (pump off), off, alarm, maintenance)

At the beginning of each node, the appropriate Discipline Engineer describes briefly how the system equipment is intended to operate. Then, the process deviations are examined for each node using the appropriate guideword (more, less, no, etc.) in relation to the process aspects (flow, pressure, temperature, etc.). For each deviation, the HAZOP team will suggest causes and possible consequences and will identify all existing safeguards to prevent, detect, control or mitigate each situation.

An important benefit of HAZOP & HAZID studies is that the resulting knowledge, obtained by identifying potential hazards in a systematic manner, is of great assistance in determining appropriate safeguards.

The practical application of the method is based on several sessions of multidisciplinary team meetings. The multidisciplinary team includes project and process engineers and operation engineers.

The procedure can be summarized in the following steps:

1. Start with the subdivision of the facilities in a number of subsets called NODEs
2. Define the node boundaries and identify the node with colours on the P&ID

3. Describe node intention and set-point of each PARAMETER

4. Select a PARAMETER in combination with a GUIDEWORD and study a DEVIATION

5. Look for credible CAUSEs

6. Figure out possible CONSEQUENCEs

7. List existing SAFEGUARDS

8. Suggest RECOMMENDATIONs when not satisfied with the existing safeguards

9. Repeat steps 4 to 8 with the following deviation until all the deviations have been studied

10. Repeat steps 3 to 9 until all the nodes have been covered

The following limitation and assumptions have been considered during the HAZOP workshop:

- HAZOP is not a design or P&ID review. The design represented in the P&IDs was considered fixed. (i.e., no design alterations occurred during the HAZOP study unless a specific recommendation is proposed).

- Commissioning, start up, shut down, maintenance and other special operation are not considered in detail during the brainstorming due to the lack of details in the P&IDs and the human interaction with the plant is higher.

- Double failure scenarios (double jeopardy) are not considered credible. The hazard identification is focused on single point failure events. Anyway, as can be understood through incident investigations, real accidents happen as a result of multiple failure scenarios. For this reason, the list of consequences must not be understood as a list of fully developed scenarios of major accidents.

- Deliberate malpractice, sabotage and intentional misunderstanding of plant instructions are not considered.

- Human factors did not receive a specific treatment and are considered only when this is the only credible cause for a parameter deviation or is especially relevant.

- External non-process hazards (e.g. airplane crash, collision with a vehicle, etc.) are not considered, except in the HAZID, where credible ones have been taken into account.

- Pipe rating is not checked for each pipe in the project.

- Listed safeguards have been chosen among the most reliable, applying the “layers of protection criteria” included in the standard IEC 61511-1. This means that safeguards are studied in the following order: Basic Process Control System, operator supervision, mechanical protection system, process alarms, Safety Instrumented System (SIS), mechanical mitigation systems (PSV and others), etc. Operator supervision and some type of preventions are always present, but their reliability is not ensured. For this reason, only the most reliable are listed in the HAZOP worksheets: when an interlock or Safety Instrumented System is present, this is considered the most reliable safeguard, so that no other safeguards are listed.

- Lack of (or improper) maintenance is not considered; correct maintenance of all equipment is expected.

- The sentence “no credible causes” that appears in many deviations means that the team have not identified causes associated with failure of control loop, instrumentation and process supervision or human failure, limiting the study to the normal operation.

- The sentence “not relevant in this node” that appears in many deviations means that the deviation is not directly controlled by the process inside the analyzed node (i.e. More / Less Flow when the process is controlled by Pressure).

2.3 Results

Table 1: Parameters, deviations and guidewords

PARAMETER	GUIDEWORD	DEVIATION	OBSERVATIONS
Level / Interphase	More	Higher Level / Interphase	Parameter, guideword and deviation included in the study
	Less	Lower Level / Interphase	Parameter, guideword and deviation included in the study
	No	Inhibition of level / Interphase	Deviation already considered in Lower Level
Pressure	More	Higher Pressure	Parameter, guideword and deviation included in the study
	Less	Lower Pressure	Parameter, guideword and deviation included in the study
	No	Inhibition of pressure	Not physically possible.
Temperature	More	Higher Temperature	Parameter, guideword and deviation included in the study
	Less	Lower Temperature	Parameter, guideword and deviation included in the study
	No	Inhibition of temperature	Not physically possible.
Flow	More	Quantitative Higher Flow	Parameter, guideword and deviation included in the study
	Less	Quantitative Lower Flow	Parameter, guideword and deviation included in the study
	No	No Flow	Parameter, guideword and deviation included in the study
	Reverse or misdirected	Reverse Flow	Parameter, guideword and deviation included in the study
	Part of	Qualitative Lower Flow	Deviation already considered in Less Flow
	Other than	Substitution of flow	Deviation already considered in Composition.
Viscosity	More	More Viscosity	Only applicable for HFO. Already studied in Temperature
	Less	Less Viscosity	Only applicable for HFO. Already studied in Temperature
Composition	Other	Other Composition	Parameter, guideword and deviation included in the study
Relief / Emissions	Other	-	Not relevant
Instrumentation	Other	-	Parameter already considered in utilities
Sampling	Other	-	Not relevant
Utilities	No	No Utilities	Parameter, guideword and deviation included in the study
Operation	Other	Other Operation	Parameter, guideword and deviation included in the study
Reaction	-	-	No chemical reaction processes in the plant
Corrosion / Erosion	-	-	Parameter already considered in Containment
Service failures	Other	-	Parameter already considered in utilities
Maintenance	Other	-	Not relevant
Static	Other	-	Not relevant for this products
Outside conditions	Other	-	Analysed in HAZID
Other	-	-	No additional parameters to consider

In the following table, a list of possible causes for each deviation is presented, together with a list of consequences and possible equipment where the deviation may occur.

Table 2: Possible causes for each deviation

DEVIATION TO STUDY	POSSIBLE LOCATIONS	POSSIBLE CAUSES	POSSIBLE CONSEQUENCES
More Level	Vessel to be filled Vessel normally empty Separators Flash drums Condensers Hot wells Steam traps	Failure of level control loop Non equilibrated inlet and outlet	Overflow → spillage if open Liquid to gas phase in steam/condensate systems Liquid to heat exchangers / compressor / ejectors / turbine → damages
Less Level	Vessel to be emptied Any vessel upstream a pump	Failure of level control loop Non equilibrated inlet and outlet	Pump running dry → damages No level, no siphon → equilibrium of pressure → possible overpressure downstream through the pump
More Pressure	Pressure coming from pipes entering the node or leaving the node Any blocked valve Any filter / separator Downstream any pump Any blocked exchanger	Failure of pressure control loop External causes Human error in closing valves Air failure High temperature	Overpressure → damages Shutoff conditions → damages to pumps Displacement of level → communications of phases Pressure gradient → reduction of equipment life
Less Pressure	Same as above but downstream	Same as 'more pressure' but downstream Unexpected opening of vent valves	Operational problems →Plant trip Depressurization → boiling of condensate / sudden vaporization → explosion
More Temperature	Any line entering the node being studied can come hotter Heat exchangers	Failure of temp. control loop No cooling	Over-temperature → damages Excessive vaporization → overpressure Steam when not expected → vibration and damages Pumps running dry → damages Temp. gradient → thermal shock (in heat exchangers, turbine)
Less Temperature	Any line entering the node being studied can come colder Heat exchangers	Failure of temp. control loop No heating Extreme weather	Liquid condensation where not expected → damages Temp. gradient → thermal shock (in heat exchangers, turbine)
More Flow	Only when relevant and controlled	Failure of flow control loop	Misadjustment in other parameters
Less Flow	Only when relevant and controlled	Failure of flow control loop	Misadjustment in other parameters → over-temperature if minimum flow is required
No Flow	Only when relevant and controlled	Blockage or closure of valves	

DEVIATION TO STUDY	POSSIBLE LOCATIONS	POSSIBLE CAUSES	POSSIBLE CONSEQUENCES
Reverse Flow	Every node inlet and outlet	Opening of valves not normally operated Pumps stop depressurization	Overpressure in upstream / downstream sections
Other Composition	When the node is open to the outside When accumulation or scaling or fouling is possible	Impurities Oil on water Water on oil Sulphur Non condensable Oxygen Leakages in heat exchangers	Scaling in boilers and heat exchangers Fouling in pipes Blockage in filters
No Utilities	Each node, limit to effects on the node	Failure of power supply Failure of instrument air Failure of cooling water Failure of heating / tracing Failure of nitrogen Failure of oxygen / hydrogen / CO2	Pumps stop, motor valves stop, valves to air failure position, no cooling, no heating, no inertization,
Other Operation	When special operation are required:	Put in service a line not normally used Clean a filter Change pump / compressor /ejector / line / by pass	No flow, more pressure, reverse flow, composition problems

Session: (1) 15/02/2022 Revision:
Node: (1) Flow battery in charging mode
Intention: Charge the battery with maximum peak 6.5kW power, with level below the overflow pipe (aprox 1,34 m), flowrate for pumps below 84 l/min and controlled to have minimum pressure difference in the stack, temperature range between 10 to 45 ºC. Total pressure below 1.1 bara. Design pressure for stack is around 1.1 bara. Chiller in service over 40ºC (approximated value, to be defined), blanketing maintained with a oil level to be defined (a few mmwc)

DEVIATION	CAUSES	CONSEQUENCES	SAFEGUARDS	REF#	RECOMMENDATIONS	BY
Higher Level	1. Leakage in the cooling system inside one of the compartments (higher pressure in the cooling side)	1.1. Entrance of cooling water from the cooling circuit, increase in the level, potential overflow to the other compartment. Dilution of electrolyte. In charging mode, this means earlier cutoff of the charging. No heating and no side reactions expected. No consequences for safety.	1.1.1. Level instrument in each compartment.	1.1.1	Implement an alarm at max filling level	
		1.2. Overfill of the 2 compartments with potential overflow through the exhaust pipe. Potential spillage of electrolyte outside the battery and to environment. Potential local environmental damage and exposition to workers to a potentially hazardous chemical.	1.2.1. same as 1.1.1 1.2.2. Cooling circuit is a closed system.	1.2.1	Check that the total volume of cooling water is allowed to be stored in the electrolyte tank vapor space and ensure the cooling circuit is closed. Otherwise adjust the level of electrolyte to allow enough free space.	
	2. Heating up of the electrolyte (not expected to be relevant during charging)	2.1. No consequences expected.				
	3. Leakage in the stack	3.1. Overfill of one of the compartment up to the overflow pipe. Dilution of electrolyte. In charging mode, this means earlier cutoff of the charging. No heating and no side reactions expected. No consequences for safety.	3.1.1. same as 1.1.1			
	4. Leakage in a 3way valve	4.1. same as 3.1.	4.1.1. same as 1.1.1			
	5. Human error aligning the valve to the other circuit.	5.1. Overfill of one of the compartment up to the overflow pipe. Dilution of electrolyte. In charging mode, this means earlier cutoff of the charging. In this case the effect is much quicker than other cases, but still no heating and no side reactions expected. No consequences for safety.	5.1.1. same as 1.1.1	5.1.1	Consider the implementation of constraints on the manual operation of 3way valves during charging mode (not possible at all or protected by password)	
Lower Level	6. Leakage in a tank compartment.	6.1. Low level in a tank compartment with...	6.1.1. Level instrument in each...	6.1.1	Implement an alarm at min...	

Session: (1) 15/02/2022 Revision:
Node: (1) Flow battery in charging mode
Intention: Charge the battery with maximum peak 6.5kW power, with level below the overflow pipe (aprox 1,34 m), flowrate for pumps below 84 l/min and controlled to have minimum pressure difference in the stack, temperature range between 10 to 45 ºC. Total pressure below 1.1 bara. Design pressure for stack is around 1.1 bara. Chiller in service over 40ºC (approximated value, to be defined), blanketing maintained with a oil level to be defined (a few mmwc)

DEVIATION	CAUSES	CONSEQUENCES	SAFEGUARDS	REF#	RECOMMENDATIONS	BY
Lower Level (cont.)	6. Leakage in a tank compartment. (cont.)	...no consequences for the stack as long as the level is above the pump suction.	...compartment. 6.1.2. Double wall tanks provided with leakage detection (liquid detection) with alarm		...filling level (safety purpose)	
		6.2. Low level in a tank compartment with pump running dry in case the level is below a minimum level. Pump cavitation on centrifugal pumps, no damages expected on the short term.				
		6.3. No flow to and through the stack. Resistance up and cutoff voltage. Risk of side reaction, such as hydrogen generation	6.3.1. Differential pressure sensor reducing speed of the other pump up to complete stop	6.3.1	Implement a complete stop of both pumps in case the differential pressure is over a certain value (to be defined) over a certain period (to be defined)	
	7. Leakage in a pipe (all elements expected to be screwed in, except pumps)	7.1. same as 6.1, 6.2 and 6.3	7.1.1. Level instrument in each compartment.			
		7.2. Spillage on the room pavement or on other pieces of equipment. Potential damage to some parts of equipment and/or floor due to corrosion on the long term.	7.2.1. Basin below the chiller and stack 7.2.2. Leakage sensor under the stack	7.2.1	Include regular visual inspection by operator	
	8. Leakage in the stack	8.1. same as 6.1, 6.2 and 6.3 and 7.2	8.1.1. same as 7.2.1 and 7.2.2			
		8.2. In case of undetected leakage on the long term, corrosion can lead to rupture of mechanical bolts and major rupture of the stack, leading to a major spillage of the electrolyte over the equipment with the voltage still applied. Potential for the generation of gases. Dangerous to operator if present inside the room.	8.2.1. Bolts designed to withstand corrosive environment 8.2.2. Basin below the chiller and stack 8.2.3. Leakage sensor under the stack 8.2.4. Differential pressure sensor reducing speed of the other pump up...			

Session: (1) 15/02/2022 Revision:
Node: (1) Flow battery in charging mode
Intention: Charge the battery with maximum peak 6.5kW power, with level below the overflow pipe (aprox 1,34 m), flowrate for pumps below 84 l/min and controlled to have minimum pressure difference in the stack, temperature range between 10 to 45 °C. Total pressure below 1.1 bara. Design pressure for stack is around 1.1 bara. Chiller in service over 40°C (approximated value, to be defined), blanketing maintained with a oil level to be defined (a few mmwc)

DEVIATION	CAUSES	CONSEQUENCES	SAFEGUARDS	REF#	RECOMMENDATIONS	BY
Lower Level (cont.)	8. Leakage in the stack (cont.)	8.2. In case of undetected leakage on the long term, corrosion can lead to rupture of mechanical bolts and major rupture of the stack, leading to a major spillage of the electrolyte over the equipment with the voltage still applied. Potential for the generation of gases. Dangerous to operator if present inside the room. (cont.)	...to complete stop			
	9. Evaporation of water (normally expected)	9.1. same as 6.1	9.1.1. Level instrument in each compartment.	9.1.1	Implement an alarm based on differential level of compartments, adjusted on temperature, to warn operator to schedule a refill (not for safety purposes) - move to stand-by mode	
		9.2. Precipitation of salt, leading to clogging. To be studied in Less flow.				
	10. Cooling down of the electrolyte (not expected to be relevant during charging)	10.1. No consequences expected.				
	11. Human error aligning the valve to the other circuit.	11.1. same as 5.1	11.1.1. same as 5.1.1	11.1.1	same as 5.1.1.	

Session: (1) 15/02/2022 Revision:
Node: (1) Flow battery in charging mode
Intention: Charge the battery with maximum peak 6.5kW power, with level below the overflow pipe (aprox 1,34 m), flowrate for pumps below 84 l/min and controlled to have minimum pressure difference in the stack, temperature range between 10 to 45 °C. Total pressure below 1.1 bara. Design pressure for stack is around 1.1 bara. Chiller in service over 40°C (approximated value, to be defined), blanketing maintained with a oil level to be defined (a few mmwc)

DEVIATION	CAUSES	CONSEQUENCES	SAFEGUARDS	REF#	RECOMMENDATIONS	BY
Higher Pressure	12. Failure of the pressure control loop based on the PS-01 and PS-02 and controlling variable pump speed	12.1. Pressure inside the stack increase over 50 mbar leading to potential rupture of the membrane when exceeding 100 mbar, with subsequent potential for stack leakage, with consequences already mentioned.	12.1.1. None identified	12.1.1	Consider the possibility of implementing some internal check in the differential pressure value to detect potential failure of one of the...	

Session: (1) 15/02/2022 Revision:
Node: (1) Flow battery in charging mode
Intention: Charge the battery with maximum peak 6.5kW power, with level below the overflow pipe (aprox 1,34 m), flowrate for pumps below 84 l/min and controlled to have minimum pressure difference in the stack, temperature range between 10 to 45 ºC. Total pressure below 1.1 bara. Design pressure for stack is around 1.1 bara. Chiller in service over 40ºC (approximated value, to be defined), blanketing maintained with a oil level to be defined (a few mmwc)

DEVIATION	CAUSES	CONSEQUENCES	SAFEGUARDS	REF#	RECOMMENDATIONS	BY
Higher Pressure (cont.)	12. Failure of the pressure control loop based on the PS-01 and PS-02 and controlling variable pump speed (cont.)	12.1. Pressure inside the stack increase over 50 mbar leading to potential rupture of the membrane when exceeding 100 mbar, with subsequent potential for stack leakage, with consequences already mentioned. (cont.)	12.1.1. None identified (cont.)		...two transmitters (i.e. value must be near zero when in stand-by mode or similar)	
	13. Clogging due to precipitation of salts, decomposition of ferrocyanide or due to evaporation or external parts	13.1. Potential precipitation of some cells. Full clogging of the stack is highly unlikely. Pressure increase is expected to be minimum. Lower electrical efficiency. Potential generation of gases due to side reaction in clogged areas: hydrogen on the negative side, chlorine or oxygen on the positive side, all vented through the exhaust pipe to the atmosphere. In the worst case, generation of explosive atmosphere inside the tank due to the combined effect of oxygen and hydrogen/chlorine	13.1.1. None	13.1.1	Implement measures to avoid clogging during commissioning and minimize precipitation during the charging.	
				13.1.2	Consider the possibility of redesigning the overflow pipe between compartments, with one deep pipe and one short pipe in the other side to separate the vapour spaces and duplicate the blanketing system, to avoid mixing the gases.	
	14. Clogging of exhaust pipe due to precipitation of salts in the walls	14.1. No flow of nitrogen out of the tank with potential to exceed the design pressure (around 50 mbar) and potential rupture when purging the tank.	14.1.1. None	14.1.1	Setup the nitrogen regulating valve to a maximum of 50 mbar	
		14.2. Pressure can build up in the tank due to changes in temperature of the electrolyte. Potential for tank rupture releasing gases to the room.	14.2.1. Hydrogen and chlorine detectors inside the room	14.2.1	In combination with recommendation no. 13.1.2, use the deep pipe to ensure the overpressure is delivered to the other compartment (the deep pipe should not exceed the 50mbar or 500mmwc)	
		14.3. Pressure can continue to build up in case gases are generated by the process. Potential for tank rupture releasing gases to the room.	14.3.1. same as 14.2.1	14.3.1	same as 14.2.1	

Session: (1) 15/02/2022 Revision:
Node: (1) Flow battery in charging mode
Intention: Charge the battery with maximum peak 6.5kW power, with level below the overflow pipe (aprox 1,34 m), flowrate for pumps below 84 l/min and controlled to have minimum pressure difference in the stack, temperature range between 10 to 45 ºC. Total pressure below 1.1 bara. Design pressure for stack is around 1.1 bara. Chiller in service over 40ºC (approximated value, to be defined), blanketing maintained with a oil level to be defined (a few mmwc)

DEVIATION	CAUSES	CONSEQUENCES	SAFEGUARDS	REF#	RECOMMENDATIONS	BY
Higher Pressure (cont.)	14. Clogging of exhaust pipe due to precipitation of salts in the walls (cont.)	14.4. Purging not effective and undetected when no gases are generated. Potential for side reaction to happen if oxygen is not purged. Loosing capacity on the long term. Potential alkalinization of the electrolyte. Increased corrosion, thus reduced lifetime. Generation of ammonia in the other compartments. Very unlikely. No consequences for safety.				
	15. Clogging of exhaust pipe due to external reasons	15.1. same as 14.1, 14.3, 14.4	15.1.1. None	15.1.1	same as 14.2.1	
	16. Closing a hand or automatic valve in the pump discharge by human error	16.1. Pressure build up in the pipe up to maximum.	16.1.1. Differential pressure sensor reducing speed of the other pump up to complete stop			
	17. Closing a hand or automatic valve in the stack	17.1. More or less flow across the stack. to be studied in Flow				
Lower Pressure	18. Failure of the pressure control loop based on the PS-01 and PS-02 and controlling variable pump speed	18.1. same as 12.1		18.1.1	same as 12.1.1.	
	19. Failure of the nitrogen supply (failure of the inlet valve or no nitrogen in the bottle)	19.1. Potential for the tank to be at negative pressure in case of cooling. Potential for damages to the tank below -50 mbar.	19.1.1. Oil trap may allow air to enter depending on design	19.1.1	Confirm design of the oil trap allows air inside the tank below -50mbar but not oil (deep tube longer than 50mmwc)	

Session: (1) 15/02/2022 Revision:
Node: (1) Flow battery in charging mode
Intention: Charge the battery with maximum peak 6.5kW power, with level below the overflow pipe (aprox 1,34 m), flowrate for pumps below 84 l/min and controlled to have minimum pressure difference in the stack, temperature range between 10 to 45 ºC. Total pressure below 1.1 bara. Design pressure for stack is around 1.1 bara. Chiller in service over 40ºC (approximated value, to be defined), blanketing maintained with a oil level to be defined (a few mmwc)

DEVIATION	CAUSES	CONSEQUENCES	SAFEGUARDS	REF#	RECOMMENDATIONS	BY
Other Operation	20. Refill during charging					

3 SWIFT analysis

The purpose of this section is to document the methodology, applied criteria and results of the Structured What if Technique (SWIFT) sessions for the facilities described in the scope.

3.1 Scope

The scope of the SWIFT is the flow battery for the HIGREEW project.

3.2 Description of work

The project P&ID had already been analyzed with the HAZOP methodology. Most of the recommendation from that analysis were then introduced in the project. In this phase, close to the commissioning, a new study is required to analyze the risk of commissioning, standard operation and special maintenance operations at the La Plana facilities. Given the type of production processes and facilities, and the type of process risks to be analyzed, the best analysis technique, recommended by experts in the sector, internationally and commonly implemented in the process industry, it is the Structured What if Technique (SWIFT).

The analyzed subsystems are as follows:

1. Commissioning
2. Operation
3. Sampling
4. Emptying
5. Exchange of electrolyte
6. Exchange of stack
7. Other maintenance tasks (replacing an instrument / pump / pipe / valve / electrical parts / auxiliary devices)
8. Installation (excluded from OH)

The SWIFT or Structured What if Technique is a hazard identification technique based on brainstorming and aimed at discontinuous processes or with a high percentage of non-automated operations. The technique achieves the best results when there is a clear and detailed work procedure, since all possible deviations from them can be analyzed, forming the pertinent questions, such as: what would happen if the task of… ? or What would happen if you did the task of... on the contrary? or What would happen if you did the task of… twice? In this sense, the technique is ideal for manual operations or with strong possibilities of human error, by omission or by commission.

The SWIFT study can be developed by analyzing the tasks carried out by a group of equipment, such as reactors, mixers, centrifuges, filter-presses, fillers, loaders, etc. As an example, we can cite the manual addition of different liquid reagents or solids to a batch reactor through the manhole. In these cases it is very useful that the subdivision into sets of equipment is compatible with what is usually done in a HAZOP study, where subsets called "nodes" are recognized. In this way, you can quickly supplement SWIFT with questions regarding the deviation of process parameters, whenever necessary.

The advantages of the “SWIFT” method are remarkable. Among other:

- it can be done with a relatively low level of technical knowledge. The typical SWIFT is a basic brainstorming session, where all sorts of topics can be discussed at random. Combined with a checklist format, the session can be developed using simple questions to answer, so that all process personnel can participate, contribute day-today situations and problems, and train themselves in the identification of dangerous situations.

- it is able to analyze a combination of failures. The option to address continue sequential failure can be investigated for the final result.

- it is flexible. It is easily adaptable to any type of process or installation flow. The questions can focus on the possible specific failures, making a previous selection of the points to verify.

On the other hand, among the limitations it can be said that it is a method based on experience, so that the dangerous situations identified depend directly on the people who take part in the sessions. Likewise, the method is not systematic in the identification of hazards, which is why it is often complemented with checklists so as not to forget to include certain aspects.

3.3 Results

Table 3:Commissioning analysis

Session: (1) 06/03/2023 Revision: (0) 06/03/2023
System: (1) Flow battery Container to be installed in La Plana
Subsystem: (1) Commissioning

What If...	Consequences	Safeguards	REF#	Recommendations	BY
1. eye wash solutions and any other mean needed for corrosive product protection and emergency first aid are not provided?	1.1. Potential hazards to workers if not available close in case of spillage and / spray with impact on people	1.1.1. Eyewash station available in the area 1.1.2. Absorbent material provided with container			
2. the fans are not started up 10 min before the opening of doors?	2.1. No consequences before first filling.				
3. doors are not left open?	3.1. Doors need to be open for first filing, no way to do the operation without opening.				
4. nitrogen is not connected (argon no longer used)	4.1. No consequences for people. Potential degradation of the electrolyte when in contact with oxygen.				
5. nitrogen bottle are not properly served or installed?	5.1. Delay in the commissioning in case nitrogen cage is not provided in time 5.2. Potential leakage in the nitrogen network leading to nitrogen cloud.				
6. nitrogen connection fails and leaks outside the container?	6.1. Nitrogen loss, but no safety issue foreseen because of the open area.				
7. nitrogen connection fails and leaks inside the container?	7.1. Potential hazard to personnel due asphyxia	7.1.1. Portable personal oxygen sensor in the container (available to some workers, not mandatory, not documented)	1	Ensure anybody entering the container will wear the required PPEs and the portable gas detector or apply LOTO as per recommendation no. 24 (advice on the door)	SGRE La Plana
8. the purge is not properly done (opening NV-N-01, PCV-n-01 and PRV-N-01)?	8.1. No consequences for people. Potential degradation of the electrolyte when in contact with oxygen.				
9. the oil trap is filled after the nitrogen purge?	9.1. No nitrogen containment into the compartments, with lower effect. No possibility to ensure the nitrogen is flowing.		2	Include in the commissioning instructions in the Operations Handbook (OH) that the oil trap must be filled with glycol before the nitrogen purge	FH

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System: (1) Flow battery Container to be installed in La Plana
Subsystem: (1) Commissioning

What If...	Consequences	Safeguards	REF#	Recommendations	BY
10. the barrels (or IBC) with electrolyte is not properly located close to the container and/or over the portable bund	10.1. Potential need for IBC/barrels moving with no forklift available in La Plana.	10.1.1. Area close to the container is open enough for allowing truck maneuvering and unloading	3	Include in the OH to locate the portable bund in the correct position for operation, ensuring the chemicals are unloaded over the bund	FH
	10.2. Potential spillage in the area, if the bund is not available.	10.2.1. Bund provided with container			
11. the product is received in barrels instead of IBC?	11.1. Need for supporting the barrel when doing the transfer, to avoid spillage. Need for the 2 operators. Potential spillage of electrolyte in the area.		4	Include in the OH the use of means to secure the barrel when unloading with the pump (straps or similar).	FH
12. the hose connection to the tank compartment is the wrong one?	12.1. Potential overfilling of one compartment in the worst case scenario. No possibilities of filling other vessels, compartments.				
13. the level is exceeded?	13.1. Potential overflow through the exhaust pipe. Potential spillage of electrolyte outside the battery and to environment. Potential local environmental damage and exposition to workers to a potentially hazardous chemical.	13.1.1. Max level alarm			
14. the compartments are not filled at same rate?	14.1. Potential relevant level differences in the compartments, leading to liquid in one side forcing the wall between compartments. Already considered in the design, but not desirable. Potential wall break.	14.1.1. Level transmitter	5	Include in the OH that compartments must be filled alternating the level increase to ensure no relevant level differences.	
15. the pump is not clean after unloading operation?	15.1. Potential hazards to the operator when doing the next filling using the contaminated pump.	15.1.1. Included in the OH			
16. water is not available (water container must be located close the electrolyte container for cleaning purposes)	16.1. same as 15.1		6	Include in the OH that water container and residual water tank must available in specified quantity	FH
17. a spillage takes place during filling?	17.1. Potential spillage inside the container, leading to spillage outside the container...	17.1.1. Absorbent material available.			

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System: (1) Flow battery Container to be installed in La Plana
Subsystem: (1) Commissioning

What If...	Consequences	Safeguards	REF#	Recommendations	BY
17. a spillage takes place during filling? (cont.)	...and to the ground, to a partially paved area. Potential soil contamination in small quantities (effect on environment not foreseen up to the moment).	17.1.1. Absorbent material available. (cont.)			
18. the tanks are not inerted during 20 minutes?	18.1. No consequences for people. Potential degradation of the electrolyte when in contact with oxygen.				
19. valves to stack are open during first fill with electrolyte?	19.1. Potential break of a stack cell if loading is done only from one side	19.1.1. Differential pressure interlock will stop pumps			
20. valves to the vent V-BY-01 and V-BY-02 are closed?	20.1. Potential pressure build up in the pipes but below the design pressure. Not ideal condition for first fill, but not hazardous to the battery.	20.1.1. Differential pressure interlock will stop pumps 20.1.2. High pressure interlock			
21. electrolyte is not within the temperature range?	21.1. Potential precipitation and clogging of stack during start up below 10ºC. Also,reduced tightness of the stack.	21.1.1. Container provided with heater 21.1.2. Temperature transmitter in the compartments			
22. pump speed is not limited to 30% (speed value must be filled manually by the operator into the PLC)?	22.1. Pump at max flowrate, quicker filling. Any leak or problem cannot be detected on time. No consequences for the process.	22.1.1. High pressure interlock			
23. a leakage happens and is not detected?	23.1. Potential hazards to personnel. No spray foreseen. Hazardous leakages are very unlikely.	23.1.1. PPEs	7	Include in the OH that potential leaking points must be checked before commissioning (list of them may be useful)	FH
24. a leakage happens and is detected?	24.1. Need for the operation to stop and battery and/or stack empty for repair or fixing. Delay in commissioning.				

Table 4:Operation analysis

Session: (1) 06/03/2023 Revision: (0) 06/03/2023
System: (1) Flow battery Container to be installed in La Plana
Subsystem: (2) Operation

What If...	Consequences	Safeguards	REF#	Recommendations	BY
25. some manual valve is left closed /open after commissioning (wrong position)?	25.1. Electrolyte cannot flow. Pressure / flow setpoint not reached. Charging operation not possible. Need for accessing again the container. Delay in operation.	25.1.1. Pressure interlock stop pumps			
26. doors are not secured?	26.1. Potential unauthorized access. Very unlikely because container located within electrical facility, where all operators are trained to be authorized to access any electrical cabinet.	26.1.1. Doors secured with lock. Lock available to control room operator			
27. operator open the doors with the battery in any working mode?	27.1. Potential electrical hazard to operator.	27.1.1. Access only allowed in "maintenance mode" and operator already trained to ensure cabinets are in maintenance mode before access.			
28. operator open the doors and access the container without waiting for the air to be renewed (10 minutes)?	28.1. Potential hazard due to chlorine. Chlorine is detected but the alarm is only visible in the panel. No local audible alarm. The opening of the doors will help renewing the air. High concentration of chlorine is very unlikely.	28.1.1. Fans are activated by gas detection and by maintenance mode activation.			
29. operator is not wearing the correct PPEs?	29.1. Potential splash and hazards to the operator.		8	same as 1.	
			9	Ensure disposable PPEs (protective suit coveralls and nitrile safety gloves) are available in the control room or appropriate place to avoid the operator entering the container without them.	SGRE La Plana
30. personnel may walk close the container walls where gas outlet and nitrogen bottles are located?	30.1. No particular hazards are foreseen for gas outlet, considering the location of outlet above 2,2 meters.		10	Consider the possibility of limiting the access to the container surroundings (1-2m around) using standards means already in place at La Plana if any (painting pavement, fencing, signaling, etc.)	SGRE La Plana
	30.2. No hazard of asphyxia expected close...				

Session: (1) 06/03/2023 Revision: (0) 06/03/2023
System: (1) Flow battery Container to be installed in La Plana
Subsystem: (2) Operation

What If...	Consequences	Safeguards	REF#	Recommendations	BY
30. personnel may walk close the container walls where gas outlet and nitrogen bottles are located? (cont.)	...to the nitrogen bottles as they are located in open area.				
31. remote connection is lost?	31.1. Operation stopped due to alarm condition. No need to access the container. No hazards foreseen.				
32. leakage takes place during normal operation?	32.1. Leakage may go undetected until some instrument detect low level or low pressure. Spillage may be extended over the container and outside through the door and to the paved ground.	32.1.1. Stacks provided with bund and leakage detector. 32.1.2. Tank not provided.	11	Consider installing a camera inside the container for continuous supervision by remote operator and/or implement regular inspection plan with variable frequency (can be reduced after ensuring operation is stable)	SGRE La Plana
33. spillage has to be collected from the stack bund?	33.1. The bund may be removed from the right side of the rack and as far as the leakage sensor allow movement. Potential spillage from the bund in case of quick movement	33.1.1. Bund is supported by a rail and movement is allowed in one direction only.			
34. any electrical fire takes place in electrical components inside the container (AC/DC converter or others)?	34.1. Potential fire extension. Electrolyte not combustible, but piping and equipment in general may burn.	34.1.1. None available.	12	Confirm smoke detector is not mandatory for this facility or implement one.	SGRE La Plana

Table 5: Sampling analysis

Session: (1) 06/03/2023 Revision: (0) 06/03/2023
System: (1) Flow battery Container to be installed in La Plana
Subsystem: (3) Sampling

What If...	Consequences	Safeguards	REF#	Recommendations	BY
35. operator open the doors and access the container without waiting for the air to be renewed (10 minutes)?	35.1. same as 28.1				
36. operator is not wearing the correct PPEs?	36.1. same as 29.1				
37. pumps are in service at higher pressure?	37.1. Potential splash with hazards to operator.		13	Update the OH to the new sampling mode, where pumps are no longer...	FH

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System: (1) Flow battery Container to be installed in La Plana
Subsystem: (3) Sampling

What If...	Consequences	Safeguards	REF#	Recommendations	BY
37. pumps are in service at higher pressure? (cont.)	37.1. Potential splash with hazards to operator. (cont.)			...required and sample is taken only by liquid head.	
38. samples are not properly taken / discarded?	38.1. Potential contamination of samples. the first one shall be discarded and disposed off in the laboratory , while the second shall be used for testing.		14	Update the OH to the new sampling mode: the first sample shall be discarded and disposed off in the laboratory , while the second shall be used for testing.	FH
39. sampling valves are left open?	39.1. Potential spillage. Already mentioned.				

Table 6:Emptying analysis

Session: (1) 06/03/2023 Revision: (0) 06/03/2023
System: (1) Flow battery Container to be installed in La Plana
Subsystem: (4) Emptying

What If...	Consequences	Safeguards	REF#	Recommendations	BY
40. the electrolyte is not completely discharged?	40.1. Potential degradation of electrolyte in contact with air if not completely discharged. Corrosion characteristics may also vary with charge. No hazards to personnel in case of incomplete discharge.				
41. the electrolyte cannot be completely discharged (battery is charged and has to be stopped for maintenance without possible discharge)?	41.1. Potential warm up of the electrolyte when mixing liquid from one compartment with liquid from the other in the same IBC. No exothermic reaction foreseen. No specific hazards foreseen.		15	Include in the OH that in case of emptying of charged electrolyte, two different IBCs should used for each compartment in order to prevent warming the product	FH
42. the pumps are not completely stop?	42.1. Potential leakage with hazards to personnel. Already mentioned.				
43. operator open the doors and access the container without waiting for the air to be renewed (10 minutes)?	43.1. same as 28.1				
44. operator is not wearing the correct PPEs?	44.1. same as 29.1				
45. empty IBCs or barrels are not available for unloading?	45.1. Delay in operation. In case of leakage, no possibility to stop the leakage removing...		16	Consider the need for storing the empty IBCs or barrels (they can be...	SGRE La Plana

Session: (1) 06/03/2023 Revision: (0) 06/03/2023
System: (1) Flow battery Container to be installed in La Plana
Subsystem: (4) Emptying

What If...	Consequences	Safeguards	REF#	Recommendations	BY
45. empty IBCs or barrels are not available for unloading? (cont.)	...the electrolyte			...the original from the supplier or others), as well as the portable bund and pump for emptying purposes.	
46. portable bunds are not available for unloading?	46.1. Delay in operation. In case of leakage, no possibility to collect the leakage		17	same as 16.	
47. valves are not properly aligned to ensure emptying?	47.1. Potential for leaving electrolyte in some spot of the pipes, even if the drain point is at lowest stack Potential hazard to operator opening the equipment.				
48. the system is not completely drained?	48.1. same as 47.1	48.1.1. instruction to open the vent valves V-V-01/02 to help draining at end of operation			
49. the 3way valve is not directed to the cap that has to be removed?	49.1. Potential leakage in the cap when opening. Potential leakage with hazards to personnel. Already mentioned.	49.1.1. PPEs 49.1.2. Visible sign on the 3 way valve (not always visible from the operator position)			
50. pumps are in service when hose are not yet connected and secured to the IBC or barrel?	50.1. Potential spillage as mentioned for filling due to movement of the hose	50.1.1. 2 operators			
51. barrels are used instead of IBCs?	51.1. Potential overfilling of barrels due to small volume versus high flow from pumps.		18	Consider the possibility of using IBC only for emptying purposes or using a portable pumps at low flowrate for barrels.	SGRE La Plana
52. product is left inside the tank?	52.1. Potential hazard to operator opening the equipment.	52.1.1. Use of portable pumps through manhole to remove the maximum quantity of electrolyte 52.1.2. Use of buckets to empty the 3 ways valves			
53. vent valves are left open?	53.1. Potential splash after new filling during the first pump start up, with leakages inside the container. Potential hazard to personnel.	53.1.1. Valve are visible and position is also visible.	19	Include in the OH to check that vent valves and caps are closed / installed before starting pumps (start-up chapter)	FH

Session: (1) 06/03/2023 Revision: (0) 06/03/2023
System: (1) Flow battery Container to be installed in La Plana
Subsystem: (4) Emptying

What If...	Consequences	Safeguards	REF#	Recommendations	BY
54. 3ways valve caps are left not installed?	54.1. same as 53.1	54.1.1. Caps are partially visible	20	same as 19	
55. the electrolyte has to be destroyed?	55.1. Treatment as waste is required inside and outside La Plana facilities. No hazards foreseen.				

Table 7: Electrolyte exchange analysis

Session: (1) 06/03/2023 Revision: (0) 06/03/2023
System: (1) Flow battery Container to be installed in La Plana
Subsystem: (5) Exchange of electrolyte

What If...	Consequences	Safeguards	REF#	Recommendations	BY
56. there's no space for locating the full and empty containers (IBCs or barrels) in the same space in front of the container doors (al least 4 pallet positions?	56.1. Need for a forklift or pallet-track for containers exchange during the operation. Need for paved surface under the containers and space for maneuvering.		21	Consider the need for a forklift to be in La Plana for any foreseen change of electrolyte	SGRE La Plana

Table 8:Exchange of stack analysis

Session: (1) 06/03/2023 Revision: (0) 06/03/2023
System: (1) Flow battery Container to be installed in La Plana
Subsystem: (6) Exchange of stack

What If...	Consequences	Safeguards	REF#	Recommendations	BY
...hoisted and/or secured to the lift tools used?	...potential consequences to personnel, leading to major injures.	61.1.1. none identified (cont.)		...stack removal should not be done with forklift without a proper lifting hook tool and securing the load through the holes in the upper part. The stacks must be removed from the top to the bottom	
62. installing and/or filling the new stack not following the instructions in details?	62.1. Potential leaking points as already mentioned in the filling chapter.				

Table 9: other maintenance tasks analysis

Session: (1) 06/03/2023 Revision: (0) 06/03/2023
System: (1) Flow battery Container to be installed in La Plana
Subsystem: (7) Other maintenance tasks (replacing an instrument / pump / pipe / valve / electrical parts / auxiliary devices)

What If...	Consequences	Safeguards	REF#	Recommendations	BY
64. an instrument is to be replaced in line or a line tube or a valve (i.e. pressure transmitter in line)? (cont.)	64.2. Air ingress when removing the instrument with potential degradation (cont.)			...open while waiting for the part)	
	64.3. Same As 63.1		27	same as 24.	
65. an instrument or pump is to be replaced in a tank i.e. (level transmitter)?	65.1. Air ingress when removing the instrument with potential degradation.		28	same as 26.	
	65.2. Same As 63.1		29	same as 24.	
66. an electrical part or auxiliary device has to be replaced (converter or cabinet or heater or light)?	66.1. Maintenance mode is designed to prevent liquid spillage and electrical discharge from stack. Standard electrical hazards are still present.		30	Implement LOTO procedure to lockout the container for any electrical maintenance inside if not already included in standard procedures in La Plana	SGRE La Plana

Table 10: Installation analysis

Session: (1) 06/03/2023 Revision: (0) 06/03/2023
System: (1) Flow battery Container to be installed in La Plana
Subsystem: (8) Installation (excluded from OH)

What If...	Consequences	Safeguards	REF#	Recommendations	BY
67. installation requires working at height for connecting some parts?	67.1. No working at height foreseen for this installation as the maximum height for passing pipes or cables is 2,2 m, which requires a standard ladder and working at 1m height over the ground. Common risk of fail.				

4 Recommendation

1. Ensure anybody entering the container will wear the required PPEs and the portable gas detector or apply LOTO as per recommendation no. 24 (advice on the door)

2. Include in the commissioning instructions in the Operations Handbook (OH) that the oil trap must be filled with glycol before the nitrogen purge.

3. To locate the portable bund in the correct position for operation, ensuring the chemicals are unloaded over the bund.

4. The use of means to secure the barrel when unloading with the pump (straps or similar).

5. Potential leaking points must be checked before commissioning (list of them may be useful)

6. Implement LOTO procedure to lockout the container for any electrical maintenance inside if not already included in standard procedures in La Plana

7. To check that vent valves and caps are closed / installed before starting pumps (start-up chapter)

5 Risk Register

Risk No.	What is the risk	Probability of risk occurrence[1]	Effect of risk[2]	Solutions to overcome the risk
1	A major risk was overlooked during the safety analyses and no mitigation plan could be proposed by the risk analysis	3	1-3	A multidisciplinary team has revised each step of the risk analysis so as to consider all possibilities and to include all possible perspectives

No further internal or external risks linked to this work/report to be reported.

[1] Probability risk will occur: 1 = high, 2 = medium, 3 = Low

[2] Effect when risk occurs: 1 = high, 2 = medium, 3 = Low

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Project partners:

#	Partner	Partner Full Name
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2	GAMESA	GAMESA ELECTRIC SOCIEDAD ANONIMA
3	UAM	UNIVERSIDAD AUTONOMA DE MADRID
4	CNRS	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS
5	C-TECH	C-TECH INNOVATION LIMITED
7	UWB	ZAPADOCESKA UNIVERZITA V PLZNI
8	PFES	PINFLOW ENERGY STORAGE, S.R.O.
9	UNR	UNIRESEARCH BV
10	SGRE	SIEMENS GAMESA RENEWABLE ENERGY
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