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LUWEX: Validation of Lunar Water Extraction and Purification Technologies for In-Situ Propellant and Consumables Production

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Abstract

Sustainable space exploration necessitates advancements in In-Situ Resource Utilization (ISRU) technologies, particularly those utilizing local resources to generate products essential for robotic and human exploration. The ability to harness local resources, such as water, not only addresses the logistical challenges of transporting supplies from Earth but also significantly reduces the cost associated with space missions. Water, deemed by Leonardo da Vinci as the driving force of nature, is a pivotal resource in space exploration. Serving as consumable for astronauts, radiation shielding, and being electrolyzed into hydrogen and oxygen—a highly effective rocket propellant combination—describes its versatile application. However, in-situ water extraction remains technically challenging, demanding further development. The LUWEX project addresses the challenge by developing and validating a complete in-situ water process chain, covering extraction, purification, and quality monitoring. It envisions harnessing water from lunar regolith for propulsion and for astronauts to consume thus enabling sustainable space exploration. The integrated test setup, designed to simulate lunar conditions using an icy lunar dust simulant inside a thermal-vacuum chamber, intends to elevate the Technology Readiness Level (TRL) of the overall process chain from level 2 and 3 to level 4 – i.e. functional verification and some subsystems even up to TRL 5 – i.e. verification in relevant environment.

The paper discusses the project's objectives and corresponding methodology, emphasizing the development and validation of advanced water extraction, capturing, purification, and quality monitoring technologies. Through these technologies, LUWEX seeks to contribute innovative lunar water extraction and purification systems for future European-led space exploration missions. An overview of the system design is presented and in addition to detailing the technical project development roadmap, the paper lays out LUWEX's adaptability towards future exploration missions, underscores its projected potential and long-term goals, and outlines potential terrestrial application strategies. The shift towards sustainable practices enhances our capability for long-duration missions by minimizing reliance on Earth-bound resources, thereby fostering the viability and affordability of space exploration.

Keywords: In-Situ Resource Utilization (ISRU), Lunar Water Extraction, Sustainable Technologies, Lunar Regolith, Water Purification

1. Introduction

1.1 Background and Motivation

Long-term manned lunar exploration requires in-situ resource utilization (ISRU) to enhance the capabilities of future missions by minimizing mass, cost and risk [1] ISRU technologies aim to use local resources to generate essential products for both robotic and human missions, reducing the dependency with Earth. The most important resources that can be extracted from the lunar surface are O^2, and H^2O for life support and O^2 and H^2 for fuel and propellant, which can be extracted from the water ice present in the permanently shadowed and near polar craters of the Moon [2]. ISRU technologies can radically change mission concepts, i.e. reducing the required landed mass on Mars by 75% by producing ascent propellant on Mars. Consequently, Earth launch requirements can be reduced by 300 metric tons [3].

Water present on the lunar surface is currently the focus of the planetary science and space technology communities. Not only can they provide information about the formation of the Solar System, but also they represent an opportunity to make space travel more inexpensive, opening the way for commercial activities on and around the Moon. Concentration of water in the permanently shaded craters of the South polar region was already hinted at by the Clementine mission in 1996 [4]. Subsequently, both the Lunar Crater Observer and Sensing Satellite (LCROSS) Shepherding Spacecraft [5], as well as Chandrayaan-1 Moon Mineralogy Mapper M(3) [6] have provided indications of water ice deposits in polar PSRs. Recent developments of lunar water prospecting indicate that its presence might be not limited to PSRs sites and might include both sunlit areas [7] as well as micro cold-traps [8].

1.2 Importance of Water in Space Exploration

Lunar water holds significant potential for lunar exploration. In particular, it can be broken into molecular hydrogen and oxygen via electrolysis. Hydrogen can be used in fuel cells for electricity generation, while oxygen can be used for life support. Furthermore, the recombination of hydrogen and oxygen is used for spacecraft propellant, which can facilitate more affordable travel to Mars and beyond by providing a refueling station on the Moon. The demand for lunar-derived propellant is estimated at 450 metric tons annually, equivalent to the processing of 2,450 metric tons of lunar water, with the potential of fueling a future lunar economy [9].

Sustainable food production can be achieved on the lunar surface by utilizing lunar water. Hydroponic systems can be adapted to lunar conditions in order to cultivate plants in a controlled environment. This approach not only fulfills crew dietary needs but also improves psychological well-being [10, 11]. Lunar water can also fulfill the radiation protection needs of future habitats. By lining habitats with water, astronauts can benefit from its ability to absorb harmful radiation, including cosmic rays and solar particles. This would be especially beneficial during solar storms or prolonged exposure to space radiation [12].

The extraction and processing of lunar water comes with its own set of challenges. As previously stated, water ice is expected to be found mostly in the permanently shadowed regions near the poles, hindering the extraction and transportation efforts. The harsh lunar conditions, characterized by a lack of atmosphere and extreme temperature fluctuations require technologies that allow the drilling and extraction of ice without losing it to sublimation [14]. A series of contaminants, such as CO2 and methanol is expected to be present in the lunar ice, which together with the presence of lunar dust, justifies the use of water purification technologies [11, 15].

1.3 Addressing Technical Challenges

The LUWEX (Validation of Lunar Water Extraction and Purification Technologies for In-Situ Propellant and Consumables Production) project is dedicated to addressing these challenges by developing and validating a comprehensive in-situ water process chain, encompassing extraction, purification, and quality monitoring. By advancing the Technology Readiness Level (TRL) of these technologies from levels 2-3 and to levels 4-5, the LUWEX project aims to enable sustainable lunar exploration through the use of local icy regolith. This paper discusses the project's objectives and methodology, focusing on the development and validation of advanced technologies for water extraction, purification, and quality monitoring. It covers the system design and implementation, including the water extraction and capturing system, the water purification system, and the water quality monitoring system. The paper also details the project's progress, particularly the design of an integrated test setup designed to simulate lunar conditions using a lunar dust-ice simulant within a thermal vacuum chamber. Additionally, it addresses the system's adaptability for terrestrial applications and future missions.

2. LUWEX Project Overview

The specific objectives of the LUWEX project are:

- Development of Water Extraction, Purification, and Quality Monitoring Technologies: The primary objective is to develop robust technologies for extracting, purifying, and monitoring the quality of water from lunar regolith. This in-situ raw water process chain is essential for ensuring the availability of consumable water for astronauts and for generating hydrogen and oxygen for propulsion.
- Design and Manufacture of an Integrated Experimental Setup: To accurately simulate lunar conditions, the project includes the design and manufacture of an integrated validation test setup. This setup will provide a controlled environment to test the operational capabilities of the developed technologies, using a lunar dust-ice simulant.
- Validation of In-Situ Raw Water Technologies in a Laboratory Environment: The validation phase involves testing the developed technologies in a laboratory setting that mimics the lunar environment.
- Advancing European Excellence in Space Exploration: By developing and validating ISRU technologies, LUWEX aims to enhance the scientific and technological capabilities of Europe in the field of space exploration. This advancement supports Europe's innovative space research and technology development.

- Improving Interdisciplinary Collaboration and Leveraging Synergies: The project fosters collaboration across various sectors, including industry, academia, and institutional research. This interdisciplinary approach leverages synergies and promotes the sharing of knowledge and expertise, ultimately contributing to the success and impact of the project.

These objectives align with international and European space exploration goals. The ISECG Lunar Surface Exploration Scenario foresees demonstrating ISRU capabilities for crew transportation and surface needs, targeting 50 tons of propellant per year by the mid-2030s [15] LUWEX is one step of many to achieve this goal. It also addresses ESA's Space Resources Strategy priorities, including maturing key technologies and demonstrating in-situ production from lunar materials [16] as emphasized in the 'Terrae Novae 2030+ Strategy Roadmap' [17].
By achieving these objectives, the LUWEX project will provide innovative solutions for sustainable and affordable long-duration space missions, significantly impacting future European-led space exploration and enhancing the competitiveness of the European space sector.

3. System Design and Implementation

3.1 System Overview

The LUWEX experimental system resembles a future lunar water process chain and is composed of the Water Extraction and Capturing Subsystem (WECS), the Water Purification Subsystem (WPS), the Water Quality and Condition Monitoring Subsystem (WQCM), the Data Acquisition, Control and Power Subsystem and the Thermal Vacuum Chamber (TVAC), including the surrounding laboratory infrastructure.
Figure 1 shows the material flow between the different LUWEX subsystems. The WECS is mainly located inside the TVAC and is filled with an ice regolith simulant for the experiments. The captured and liquified water is collected in a storage tank outside the TVAC (Storage I). This tank is still built vacuum rated, because it has an interface to the components inside the TVAC. All components following Storage I downstream are not vacuum rated. The water from Storage I is pumped to Storage II. Storage II is placed on scales to measure the amount of water extracted. From there the water is pumped through a series of water purification processes, which are accompanied with water quality and condition monitoring devices. All components are connected to the centralized Data Acquisition Control and Power Subsystem. The following subchapters explain each subsystem, except for the Data Acquisition Control and Power Subsystem, in detail.

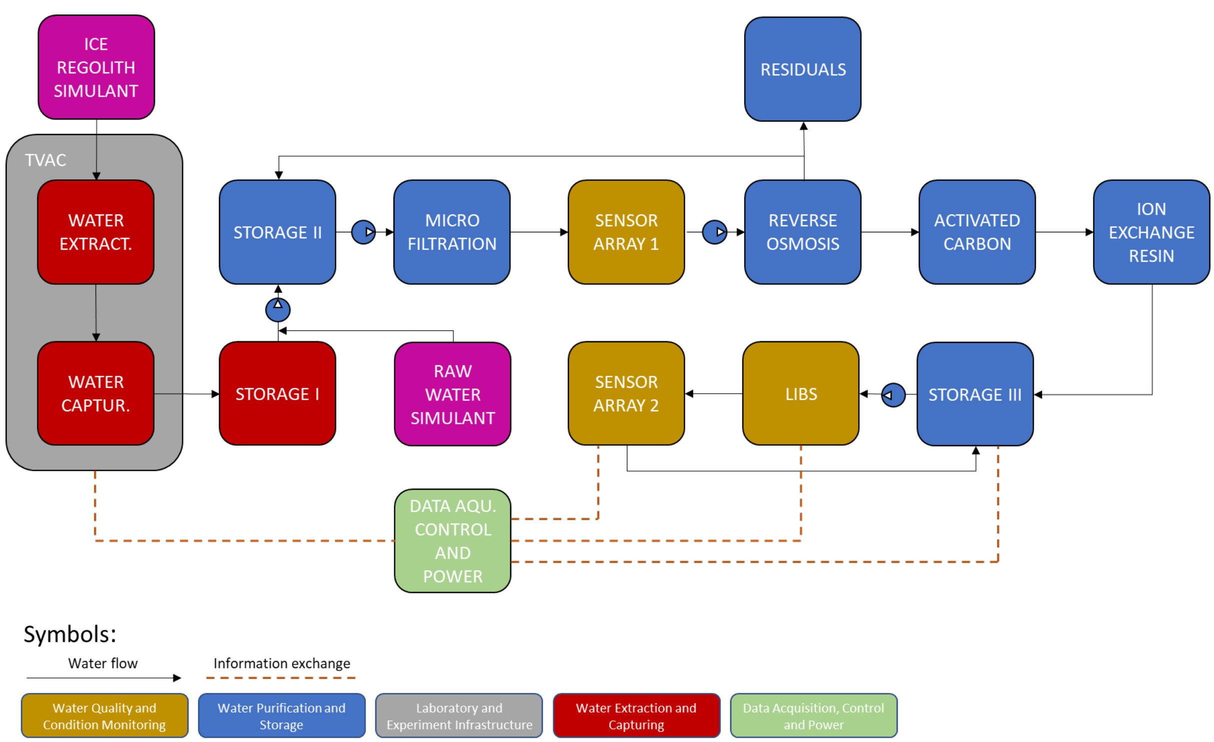


Fig. 1. System block diagram of all subsystems of the LUWEX experimental setup. Dashed arrows indicate signal interfaces. Solid arrows indicate water (solid, liquid or gaseous state) flow.

3.2 Water Extraction and Capturing Subsystem

In this section, an overview of the WECS is presented. The design can be split into two distinct sections, the extraction subsystem, and the capturing subsystem, which consists of the water capturing mechanism and the liquefaction chamber. The design of the subsystems is the result of an investigation using trade-off tables and simulations. In Figure 2, a schematic overview of the entire WECS system is depicted, as well as the boundaries of the vacuum chamber in which it is placed, and the tube used for filling the crucible with the icy regolith simulant. The different colored lines show the lines between the different subsystems and their boundaries. Figure 3 shows how the assembled WECS system looks inside the TVAC after complete integration. The main function of the extraction subsystem Is to sublimate the ice that is in the icy regolith simulant to create water vapor and allow the water vapor to flow towards the capturing subsystem. A large issue with lunar regolith is its extremely low thermal conductivity, meaning that it will take a lot of time and energy for the ice to reach a temperature where it could sublimate. To improve the way heat disperses in the regolith by the heaters, we decided to implement a stirring mechanism that continuously stirs the regolith around by having the heating rods rotate around. The heating rods are all mounted at a different radius from the center, which ensures that there are no empty paths created in the icy regolith simulant. The stirring also makes it easier for the generated water vapor to escape the dried-out parts of the regolith simulant.

The capturing subsystem Is the cold trap and the liquefaction chamber. The cold trap works by providing a surface cold enough for water vapor to freeze and be collected on it. Once enough ice has deposited on the cold trap, heaters inside the cold trap will activate, and cause the connecting layer of ice to once again sublimate, dropping the ice into the liquefaction chamber. The liquefaction chamber is then sealed off from the rest of the systems by a slider. Heaters inside the liquefaction chamber then cause the ice in there to melt, and this liquid water then flows into the storage I, that is outside of the chamber. From Storage I, it can be transported to the purification system.

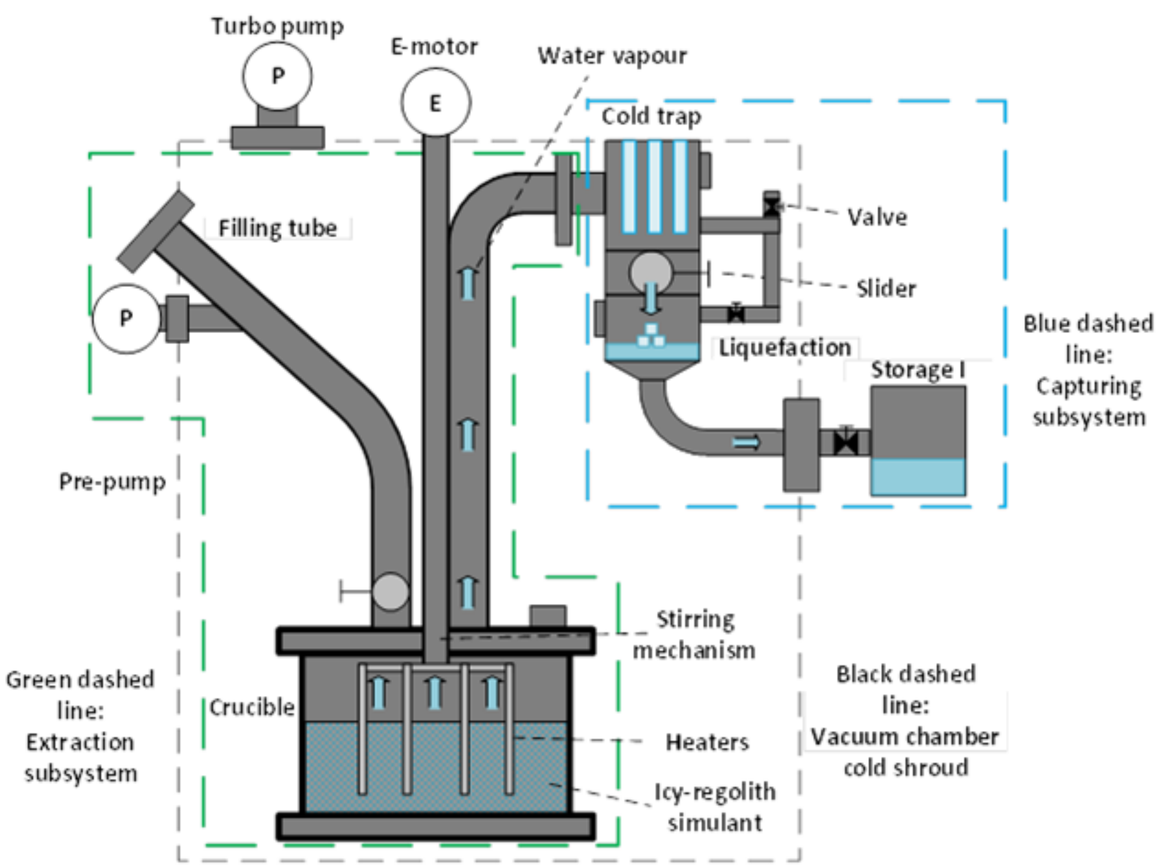


Fig. 2. Schematic overview of the WECS inside and partially outside the TVAC. The parts inside the green dashed line are the extraction subsystem, and the components encircled by the blue dashed line are the capturing subsystem.

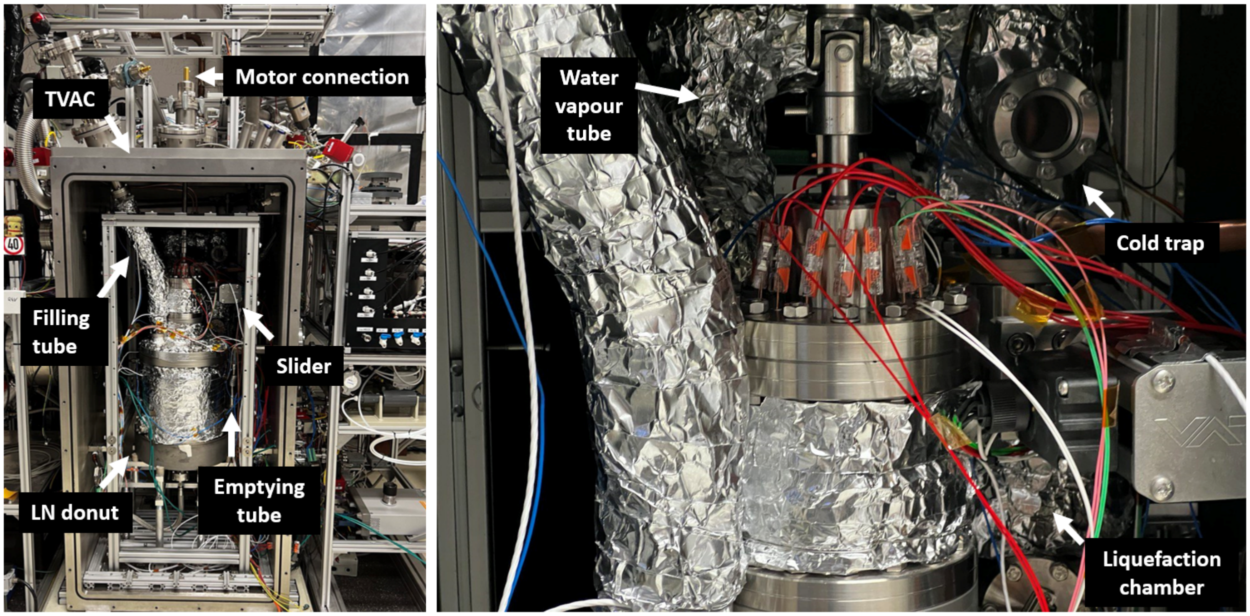


Fig. 3. Photos of the assembled WECS inside the TVAC.

3.3 Water Purification Subsystem

The WPS treats water coming from the WECS, which will contain different amounts of various contaminants. The goal of the WPS is to treat this polluted raw water to achieve water quality requirements for water electrolysis as those are more restricting than the requirements on potable water. The selection of contaminants and their concentration in the water used for the experiments is based on literature [5, 18]. However, not all of the contaminants can be added in the LUWEX experimental campaign, because some are not safe to use in the present laboratory infrastructure. Figure 4 shows the WPS as integrated next to the TVAC.

3.3.1 Techniques used for water purification

The choice of the technologies selected for the removal of contaminants was driven by the requirements of consuming less than 1g of filter and cleaning consumables per kg of product water and of achieving product water to feed water ratio >95%, maximizing system reliability and maintainability. The selected technologies are also chosen for their scalability, from demonstration on a lunar lander to a final productive scenario. Contaminants to be removed were divided into three categories: particulate, organics and inorganics. For each category the major removal technologies used are briefly described in the following section.

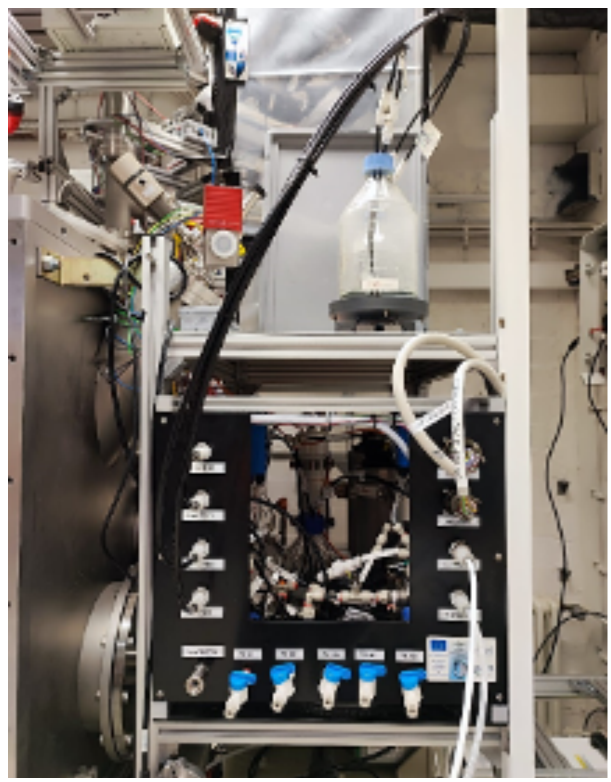


Fig. 4. WPS (black rack insert) integrated in a rack on the right-hand side of the TVAC. Storage II (glass bottles) on top of the rack.

3.3.2 Detailed design and operational principles

The water purification technologies used in LUWEX WPS are listed below. A microfiltration membrane is used to remove particulates bigger than 0.45 µm, expected in the form of lunar dust particles. Smaller dust particles are expected to not reach the WPS. The approach is considered conservative, since it is in general not clear whether and in which quantity these particles will actually reach the WPS. Indeed, the lunar dust dynamics within the previous WECS is not yet known.

For organics removal activated carbons (AC) are used. The quantity of organic contaminants is low so the associated consumables mass is low. However, the option of regenerating AC using steam generated by product water to reduce subsystem consumables was considered. The AC are challenged by methanol as a critical contaminant that is still expected in the feed flow, although it should be mostly removed by the WECS when still in the gas phase. In the case that the LUWEX system test will highlight that the quantity of methanol to be expected is higher than the current assumptions, further methods for TOC reduction will be implemented and are currently being studied.

Reverse osmosis (RO) as a first step for inorganic material removal is chosen because of the high removal efficiency of all the present species, especially for ammonia, without the use of consumables.

The RO concentrate is recirculated, allowing minimal process wastewater generation. This is possible given the low concentration of inorganic contaminants in the feed flow. Ion exchange resins are used as final polishing technology to achieve purity requirements for the required technical water.

3.3.3 Test results

The WPS has been tested separately before integration into the experimental setup using different combinations and concentrations of contaminants dissolved in water. Some of the results are explained in the following.

Figure 5 and Figure 6 show the average value on the runs of monitored parameters for each type of water at the outlet of the WPS subsystem. In Figure 5 it is visible that TOC, the total amount of organic carbon present in outlet water, reaches the required level according to Figure 6 for W1, W2, W4, W5 and W6, which does not contain methanol inside. Methanol, due to its affinity with water, is the most critical contaminant to remove, as it is shown in Figure 6, W3, W7, W8, have higher TOC levels. As per Performance Qualification Test of the ISS Water Processor Assembly (WPA) Expendables [19], ISS potable water limit for TOC is 0,5 ppm, this means that WPS can purify water containing methanol up to potable water level.

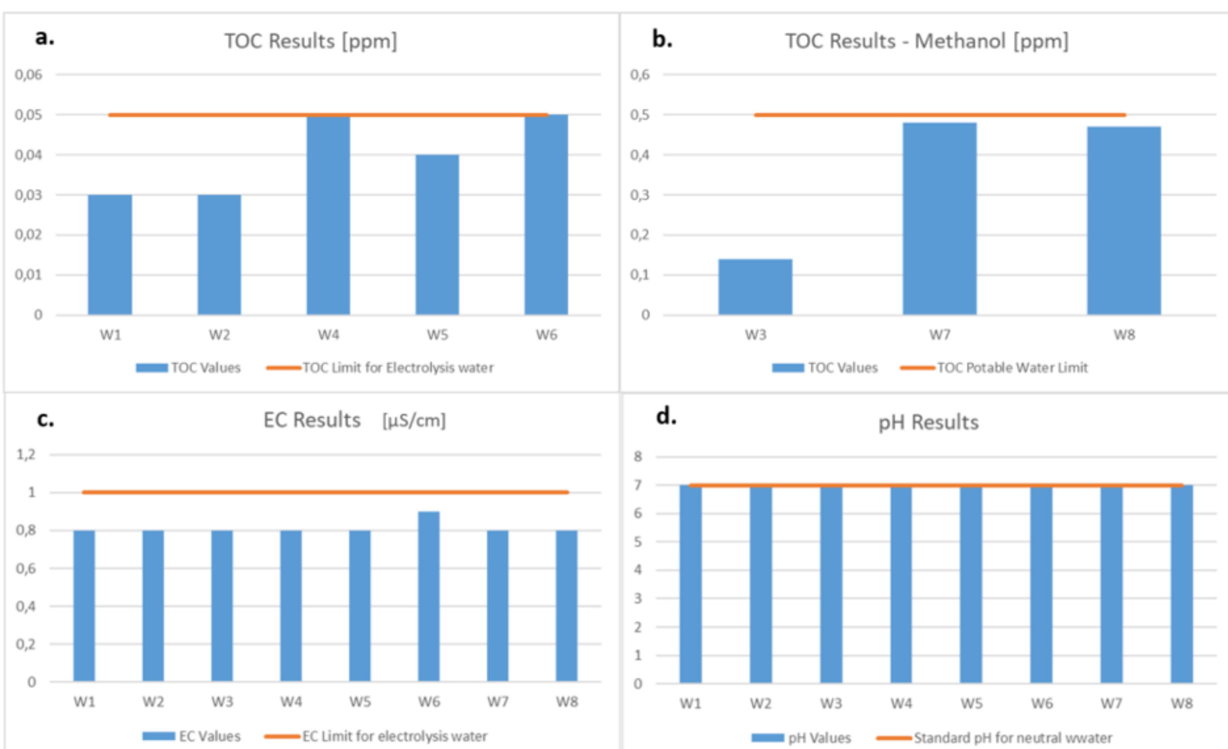
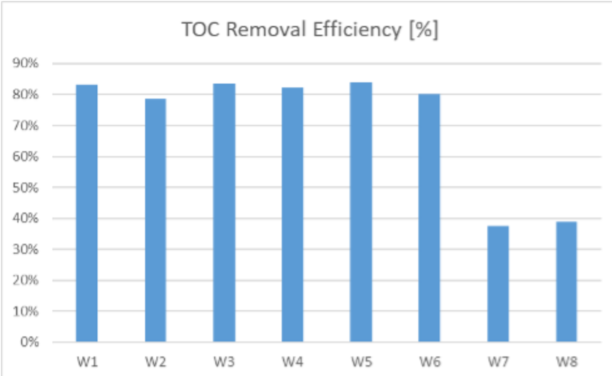


Fig. 5. Average TOC results for Ws without methanol, b. Average TOC result for Ws with methanol, c. Average EC results for all Ws, d. Average pH results for all Ws.



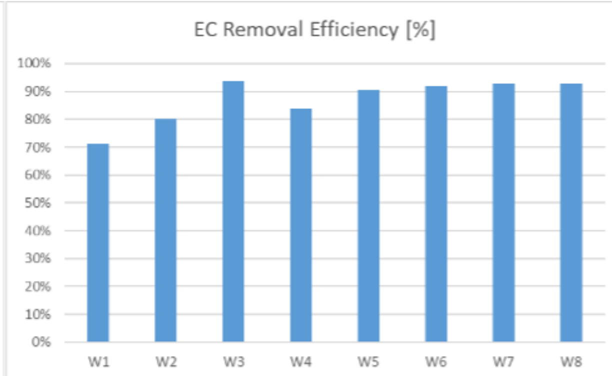


Fig. 6. TOC and EC removal efficiency calculated starting from the measurements of contaminants in inlet water.

Furthermore, NASA SWEGs (Spacecraft Water Exposure Guidelines) set methanol limit in potable water at 15 ppm, which is well above the quantity present in LUWEX product water. Even if TOC level for water containing methanol is slightly above the value required from ASTM D1193 for high purity water type II, the quantity of TOC is considered acceptable. Further studies are being carried on to improve WPS TOC removal technology. Electrolysers require water with low electrical conductivity to improve efficiency, reliability and longevity. All the tested waters have EC values < 1 µS/cm after WPS as it is shown in Figure 5 c.

In electrolysers pH may influence reaction kinetics, ion transport and overall performances. Most electrolysers (e.g. those based on proton exchange membranes – PEM) work with neutral pH values (pH = 7), which is compliant with LUWEX product water (Figure 5 d.). Some types of electrolysers (e.g. those using Static Feed Electrolysis – SFE) work with alkaline water (pH = 13) and pH can easily be enhanced by adding potassium hydroxide (KOH) to water.

3.4 Water Quality and Condition Monitoring Subsystem

The Water Quality and Monitoring Subsystem (WQCM) is designed for in-line monitoring of water quality and located upstream and downstream of the WPS. It consists of two sensor arrays and a LIBS (Laser Induced Breakdown Spectroscopy). The two sensor arrays include each one conductivity, one turbidity and one pH sensor. One sensor array is upstream and another one downstream of the WPS. The LIBS is located downstream of the WPS and upstream of the second sensor array, see also Figure 1.

The ’conductivity probes provide Information about the presence and concentration of ions in the water, while the turbidity probes relate to the amount of suspended and colloidal particles.

The measurement of pH can be used to verify conductivity measurements and to detect possible process impurities during the production of pure water. Simultaneous measurements of conductivity, turbidity and pH allow to determine water quality and identify potential anomalies in the water treatment processes within the WPS. The utilization of two sensor arrays allows to determine the degree of removal of pollutants from the raw water.

The LIBS Involves focusing a laser on a sample to create a plasma, which emits light that is analyzed to determine the sample’s composition. This approach is beneficial, as one setup can detect a number of different pollutants without the need to implement a huge number of pollutant-specific sensors. The same time, it causes no harm to the water, so it can be performed in-line. The LIBS subsystem is based on the CNI-LPS-1064-S 300mJ laser, Ocean FX OFX01102 spectrometer and custom-built measurement chamber. The laser light is being focused inside the transparent quartz cuvette and after passing through tested water it is terminated in a beam trap. Perpendicularly mounted optical system allows a spectrometer to observe the water turned into plasma with no risk of destruction of the device. Spectrometer acquisition is synchronized with laser activity. Upon successful acquisition of spectrum, the data is downloaded to the PC and analyzed with an algorithm to determine presence of pollutants.

In addition to the in-line measurements, sample ports on the WPS allow the taking of small amounts of water for testing in a standard water analysis laboratory. Typically, the laboratory test equipment has higher accuracy compared to the in-line measurements. The results of the laboratory tests can be used to validate the results of the in-line WQCM subsystems and also can provide further insights beyond what is capable with in-line measurements.

4. Project progress

4.1 Simulating Lunar Conditions

The WECS are placed inside the thermal-vacuum chamber of the Comet Physics Laboratory at TU Braunschweig described in [20]. To recreate a relevant lunar environment, the so-called L-Chamber is evacuated to a pressure of around 5×10^{-6} mbar utilizing the combination of a turbo-molecular pump and two forepumps and then cooled down to an ambient temperature of around 110K. This cryogenic environment is realized with the two active liquid-nitrogen cooling systems. The crucible is placed directly on the main cooling system such that it is cooled through conduction simulating the crucible to stand directly on the moon.

4.2 Sample Preparation

The granular water ice used to create the icy regolith simulant is produced by the ice machine detailed in Kreuzig et al. 2021 [20]. There, a mist of fine water droplets of distilled water is carried by gaseous nitrogen into an environment of liquid nitrogen, where the tiny droplets swiftly freeze, resulting in a suspension of water ice and liquid nitrogen. The fine water droplets are created by a piezoelectric water atomizer sitting in the distilled water. This ice machine is capable of autonomously producing around 150g of granular water ice per hour. For further usage of the water ice, it must be separated from the liquid nitrogen in a cryogenic desiccator. The resulting granular water ice consists of spherical shaped particles with median radii of (2.4±0.1) µm and has the appearance of powdered sugar. It can be stored in storage cans or directly utilised for the sample production. Throughout the whole production process, the temperature of the water ice is kept below 110K.

The icy regolith is produced by mixing the granular water ice with the lunar regolith simulant bought from Lunex Technologies GmbH in Berlin, Germany. The simulant is made from a mixture of 75% anorthosite (TUBS-T) and 25% basalt (LX-M), resembling the bedrock of the terrae and mare regions of the lunar surface near the south pole. It consists of highly angular particles with a particle size distribution in the range of < 0.01 – 1 mm. Approximately 50 % of the total weight is distributed among the smallest particles < 50 µm. The simulant has a bulk density of 1.24 g/cm³.

For the sample production, the needed amount of regolith simulant is dried as small amounts of humidity are absorbed by the material during storage. Under stable laboratory conditions the water content in the regolith simulant is <0.5 wt. % and is reduced to <0.01 wt.% of bound water by heating the simulant in an oven at 110°C for at least 12 hours without changing the simulants' properties. This process removes physically absorbed (non-bound) water as stated in NASA-STD-1008, 2021. The removal of non-bound water ensures the realization of an icy simulant with well-determined water ice fraction.

After drying the simulant, it is cooled below -160°C. Then, the simulant is mixed with a specific amount of granular water ice so that the intended mixing ratio is realized. When mixing, the water ice is added in small quantities and the mixture is stirred in between to achieve the most even distribution possible. This is done in the steel tube used for the cooling of the lunar regolith simulant. The resulting mixture is shown in Figure 7 and graphically represented in Figure 8.

Fig. 7. The icy regolith simulant just after mixing in the ice particles. This process is done under cryogenic temperatures.

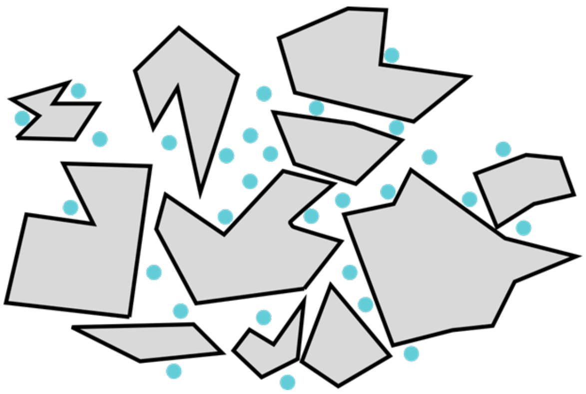


Fig. 8. A graphical representation of the unfused discrete icy-regolith. The high porosity of this specific sample means that even though ice is added, the thermal conductivity remains low.

4.3 Functional Verification and TRL Advancement

Each subsystem has been individually tested for functioning and performances before integration into the experimental setup. After integration, the overall LUWEX system is tested as a whole singular system resembling a complete water process chain. In Figure 9 the overall effort towards the increase of the TRL levels per subsystem are presented.

The water extraction and water capturing subsystems are inside a cryogenically cooled vacuum chamber, as presented in section 4.1 and 4.2. Considering the low temperatures, vacuum, and the use of high-fidelity lunar regolith simulants, the environment can be considered relevant enough toward lunar conditions, justifying the achievement of TRL 5. The other subsystems have been tested in a controlled laboratory environment, reaching TRL 4.

The fully Integrated system reached TRL 4 after the completion of the system level test campaign, meaning the lunar water value chain is proven from extraction till the end product, clean water.

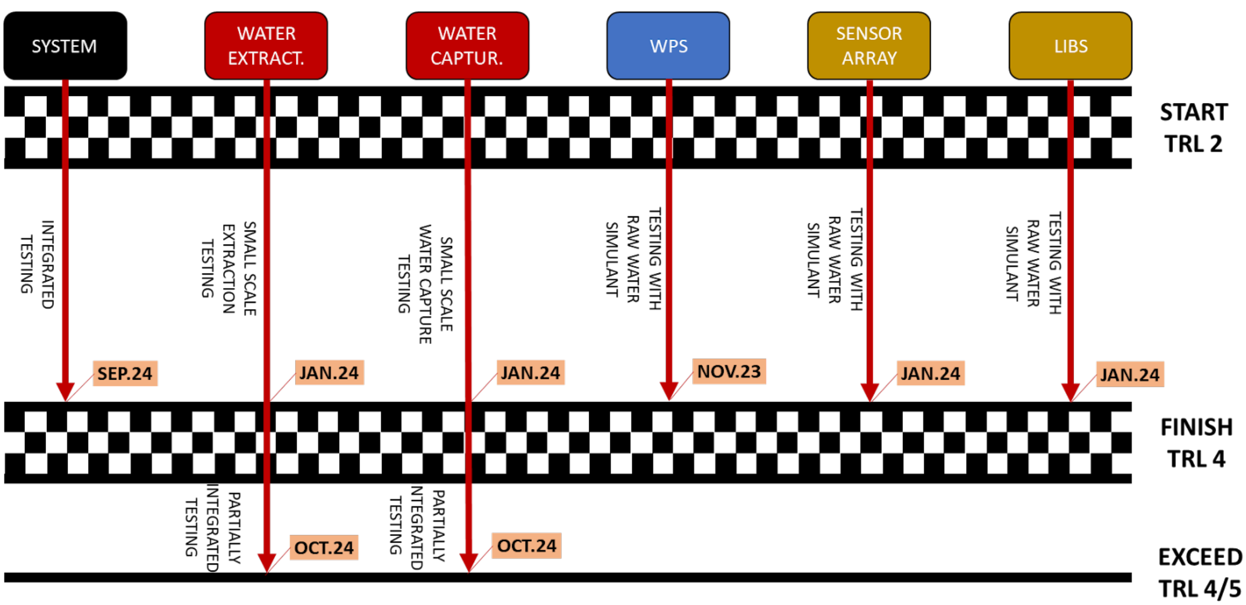


Fig. 9. TRL Roadmap for the LUWEX subsystems.

5. Adaptability and Future Missions

5.1 Application to Future Space Missions

LUWEX was developed from the beginning with the aim of integration into future European-led space exploration missions, from its demonstration phase, to the final utilization one. The technology demonstration phase is aimed to strongly rely on the European Large Logistics Lander (EL3) availability. Integrating a demonstrator for lunar water extraction and purification technologies within EL3 represents a transformative step in space exploration and resource utilization. The harsh lunar environment, characterized by extreme temperatures, vacuum conditions, and abrasive dust, poses significant challenges for any technology. Demonstrating water extraction and purification technologies in this setting provides a rigorous testbed, validating the robustness an efficiency of these systems. This not only mitigates risks for future missions but also drives innovation in engineering solutions tailored to extraterrestrial conditions. The EL3 project, designed to deliver cargo and logistics to the Moon, provides an ideal platform for integrating the water extraction demonstrator. The

lander's capabilities can support the deployment, operation, and monitoring of the extraction and purification systems. A modular design for the demonstrator ensures flexibility and adaptability, allowing it to be a seamless addition to the EL3 mission. Initial missions can be used to demonstrate single LUWEX subsystems and processes, like water sublimation and freezing, raw water ice liquefaction, icy-regolith management, water purification. Later missions can then include a scaled down version of the complete system.
Looking ahead, the ability to extract and purify water on the Moon is fundamental to establishing a sustainable human presence. Water is not only essential for life support but also for producing breathable air and rocket propellant. The current Global Exploration Roadmap [14] includes transforming the Moon into a hub for scientific research, commercial activities, and as a stepping stone for missions to Mars and beyond. Europe is strongly involved in all endeavors of manned presence on the Moon, from various Lunar base concepts to the wider Moon Village concept [12], all relying on ISRU. LUWEX would represent a key technological element in all these scenarios. The system's design includes considerations for integration with habitat life support systems and power grids, making it suitable for both short-term missions and long-term bases. By leveraging LUWEX technology, lunar bases can reduce their dependence on Earth-based resupply missions, thus lowering mission costs and increasing self-sufficiency.

5.2 Terrestrial Applications

5.2.1 Water Purification Module

Technology aims to meet basic human needs, with water being the most essential resource for sustaining life. As global freshwater supplies continue to diminish, the need for advanced water purification technologies is expected to grow significantly. Increasing demand is driven by the ongoing depletion of water resources, coupled with the critical need for clean water in various sectors.
Market and social trends also highlight the importance of such developments, with initiatives like the European Green Deal and the Fit for 55 Package underscoring the need for sustainable water solutions. A substantial gap is projected between humanity's rising demand for freshwater and the declining availability of clean water sources.
The water purification module of LUWEX offers innovative solutions for regions facing limited access to clean water. Its advanced filtration and purification technologies could significantly enhance existing systems or function as a standalone solution in areas experiencing severe contamination. As water demand rises globally and contaminants like pharmaceuticals become more prevalent, LUWEX's ability to purify water from diverse sources—ranging from municipal supplies to polluted natural water—positions it as a vital technology. Furthermore, by integrating cutting-edge solutions like hydrophobic nanostructured membranes and solar-powered desalination systems, LUWEX could provide efficient, cost-effective water purification options for the future.

5.2.2 Water Quality Monitoring Module

Innovations for determining water quality, joining the trend of monitoring water for harmful substances. There are many ongoing works on the (legal) requirement to monitor the water for harmful substances such as pharmaceuticals, or even virus derivatives like for example COVID. Adaptation of the water quality module according to the LUWEX Technology for a given element/spectrum seems feasible. This is one of the key advantages of the Technology.
The LUWEX water quality monitoring module is designed to detect and analyze a range of contaminants, including pharmaceuticals and other harmful substances. This module's capabilities could be instrumental in regions where water quality monitoring is inadequate or outdated. By employing advanced sensors and analytical tools, LUWEX can help ensure compliance with increasingly stringent regulations on water safety. The ability to provide real-time data on water quality could aid in early detection of contaminants, enabling timely interventions and enhancing overall public health and safety.

5.2.3 Storage Module

Effective storage solutions are crucial for managing water resources, especially in regions with fluctuating water availability. The LUWEX storage module offers innovative approaches to storing purified water, ensuring that it remains safe and accessible for extended periods. This capability is particularly relevant in areas prone to seasonal water shortages or in disaster-stricken regions where immediate access to clean water is critical. By incorporating efficient storage technologies, LUWEX could support both emergency response efforts and long-term water management strategies.

5.2.4 Addressing Global Water Issues

The global water crisis, characterized by increasing demand and limited freshwater resources, underscores the need for innovative solutions like LUWEX. With 36 countries projected to experience water deficits by 2040 and significant water stress evident in many European Union countries [21] the LUWEX system's technologies could play a vital role in alleviating these challenges. Its modular nature allows for flexible implementation, whether in large-scale municipal systems or localized setups in remote areas.

5.2.5 Integration with Existing Technologies
LUWEX's modules are designed to be compatible with existing water treatment systems. The adaptability of LUWEX technologies to integrate with current infrastructure could enhance their practicality and acceptance. For example, combining LUWEX's advanced purification methods with established water treatment facilities could optimize performance and extend the life of existing equipment.

5.2.6 Pilot Projects and Future Development
To realize the full potential of LUWEX technologies in terrestrial applications, pilot projects and further research are essential. Demonstration projects in diverse environments, such as mountain resorts facing water scarcity or regions with high levels of water pollution, will provide valuable insights into the system's effectiveness and feasibility. Additionally, collaboration with local stakeholders and adaptation of technologies to specific regional needs will be crucial for successful implementation.

6. Conclusions
Within the LUWEX project technologies and components for a lunar ISRU water process chain have been developed. Part of the process chain are the processes water extraction and capturing, water purification and water quality and condition monitoring. All subsystems have been integrated into an experimental setup to validate their functionality in a relevant environment in order to reach TRL 4 respectively TRL 5 of individual subsystems and TRL 4 for the complete process chain.
To perform the validation a thermal vacuum chamber has been reoutfitted to simulate lunar environmental conditions. Additionally, an icy lunar regolith simulant has been developed to resemble raw material as close as possible to one potential option for water ice occurrence on the Moon.
The validation of the subsystems is only partially completed and some experiments still need to be performed at the time of publication of this paper. At this point one can say, that the validation of the subsystems to the target TRL is finished. The validation of the complete process chain is still in progress. The final experiment results will be published elsewhere.

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