Final report

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1. Summary

Project summary

The purpose of the project

The project addressed the lack of sustainable methods for recovering phosphorus from ashes. The technology was developed in the laboratory and demonstrated in a pilot plant, where phosphorus was extracted using only water and electricity. The use of membrane separation and the modular system design made the process both innovative and circular.

Results, conclusions and perspective

Power-to-P demonstrated that over 80% of the phosphorus in ashes from sewage sludge and biogas digestate can be recovered and purified without chemicals. The product meets quality requirements for fertilizer use. The electrodialysis process showed high selectivity and stable operation over extended runs. Hydrogen was collected safely, and the fuel cell produced electricity with high efficiency. Membrane filtration in the subsequent purification step effectively removed heavy metals and ensured high purity of the recovered acid. Combustion tests using various biogenic feedstocks confirmed that the ash quality and phosphorus content vary with material and process temperature. The drying and combustion unit operated reliably and with good energy performance. The system was proven to be modular and adaptable to local conditions. Economic analysis indicated that the process could be cost-competitive under higher phosphate prices and carbon pricing scenarios. The technology is considered ready for full-scale demonstration, and specific commercialisation and regulatory pathways have been identified.

Projektresumé

Formålet med projektet

Projektet adresserede manglen på bæredygtige metoder til at genvinde fosfor fra bioasker. Teknologien blev udviklet i laboratoriet og succesfuldt demonstreret i et pilotanlæg, hvor fosfor og brint blev udvundet kun ved brug af vand og strøm som input. Brugen af membranseparation og den modulære opbygning gjorde processen nyskabende og cirkulær.

Resultater, konklusioner og perspektiv

Power-to-P har dokumenteret, at over 80 % af fosforen i aske fra spildevandsslam og biogasanlæg kan udvindes og renses uden brug af kemikalier. Det rensede produkt lever op til kravene for anvendelse som gødning. Elektrodialyseprocessen viste høj selektivitet og stabil drift over flere uger. Brintopsamlingen fungerede uden lækage, og brændselscellen leverede el med høj virkningsgrad. Membranfiltrering i den efterfølgende oprensning fjernede tungmetaller og bidrog til høj renhed af den udvundne syre. Forbrændingstests med forskellige biogene restprodukter viste, at askens kvalitet og fosforindhold varierer afhængigt af materiale og temperatur. Tørre- og forbrændingsanlægget fungerede stabilt og energieffektivt. Projektet har også vist, at systemet kan skaleres og konfigureres modulært til lokale forhold. Økonomiske analyser peger på konkurrencedygtighed ved højere fosforpriser og CO_2-afgifter. Teknologien vurderes klar til demonstration i fuld skala, og der er identificeret konkrete veje til kommercialisering og reguleringsmæssig integration.

2. Project objectives

The Power-to-P project addresses a critical global issue: the sustainable recovery of phosphorus, a finite and non-renewable resource essential for food production. Globally, over 90% of mined phosphorus is used in agriculture, yet large volumes are lost through waste streams. Europe, including Denmark, is heavily reliant on phosphate imports from geopolitically unstable regions such as Morocco and Russia. In 2014, the European Commission added phosphorus to its list of critical raw materials, recognizing the strategic necessity to develop circular and regionally self-sufficient phosphorus recovery methods like Power-to-P.

The objective of the Power-to-P project was to develop and demonstrate an electrochemical platform capable of recovering phosphorus from sewage sludge ash (SSA), a waste stream generated in wastewater treatment plants following incineration of sludge. Also incinerated biogas digestate was investigated for the possibility of increase phosphorus recovery in the biogas industry. The project addressed two critical environmental and technological needs: (1) the sustainable recovery of phosphorus, a limited but essential resource for life, and (2) the safe and beneficial reuse of the residual ash after treatment, enabling upcycling of waste.

The results of this project pave the way for decentralized phosphoric acid production in Europe, reducing reliance on non-EU sources of phosphate and natural gas. It contributes to circular economy goals and EU strategies on critical raw materials. Specific objectives include:

- Demonstrating over 80% phosphorus recovery efficiency from sewage sludge and biowaste ash
- Ensuring high-quality phosphate output suitable for agricultural use
- Collecting and utilizing hydrogen gas via PEM fuel cells for on-site energy generation
- Validating system stability and operability under varying feedstock and environmental conditions
- Determining the quality of treated ashes to enable reuse in construction materials

The core technological innovation lies in the use of electrodialysis driven by electricity to separate phosphate ions from a suspended ash matrix. This process is enhanced by membrane separation and real-time control systems for current, pH, and flow rate, optimizing phosphorus recovery while minimizing energy consumption and fouling. In parallel, hydrogen generated as a byproduct, is captured and reused in a proton exchange-membrane (PEM) fuel cell, creating a partial energy loop within the system.

The central objective of the Power-to-P project was too upscale and validate a sustainable, electrodialytic technology for the extraction of phosphorus from bio-based ashes such as sewage sludge ash (SSA) and biogas digestate ash (BDA). The project aimed to transition the technology from a laboratory-scale proof-of-concept (TRL4) to a pilot-scale demonstration in a relevant operational environment (TRL7).

An essential aspect of the project involved integrating both upstream and downstream processes, including ash processing, acid purification, and effluent management, to form a coherent and economically viable workflow. The technological focus also included rigorous testing to ensure that the produced phosphoric acid met industry standards for agricultural and industrial applications, particularly regarding nutrient concentration and contaminant levels.

A specific focus was placed on understanding and optimizing membrane performance under extreme operating conditions. The membrane system had to tolerate both acidic and alkaline environments, deal with high concentrations of divalent ions like calcium and magnesium and resist physical fouling from suspended ash particles. Improving 'membrane longevity' was thus a key technical sub-objective, aimed at extending operating life without significant flux reduction.

A key advantage of the Power-to-P electrodialysis (ED) system is its inherent flexibility in adapting operational throughput to real-time energy availability and pricing. Because the ED process is electrically driven and modular, it allows for dynamic control of current density within safe operational limits. This enables production rates to be scaled up during periods of low electricity prices or high renewable energy availability such as during solar or wind generation peaks and scaled down during periods of grid stress or high energy costs. To preserve membrane integrity and extend service life, system controls can adjust current setpoints to remain within specified current density thresholds, depending on membrane type and configuration.

To ensure circularity, the project also focused on the valorization of the treated SSA in construction materials. DTU assessed whether the decontaminated ash, now primarily composed of iron and silicon oxides, could be used as a supplementary cementitious material in concrete or as filler in bricks, which can be sensitive to salt leaching. DTU conducted ICP analysis of sewage sludge ash (SSA) after electrodialytic treatment to evaluate elemental behaviour during washing. Ash samples were divided into surface crust and inner layers, then subjected to two washing steps. Elements were categorized into three solubility-based groups: (1) low-solubility metals like Fe, Zn, and Cu, which remained largely immobilized; (2) moderately soluble elements such as Al and Mn; and (3) highly soluble species including Ca, Mg, Na, K, P, and As, which were readily leached. The washing process significantly reduced conductivity and pH, confirming ion removal.

The Danish political context further supports the project’s ambitions. In the Climate Agreement for Energy and Industry 2020, Denmark committed to a 70% CO_2 reduction by 2030. Circular bioeconomy initiatives, including recovery of critical nutrients are a core part of this strategy. Power-to-P directly supports this goal by offering an electrified, low-emission route to recovering phosphorus, reducing fertilizer dependency and landfill volumes simultaneously. The reuse of bio residues in energy and nutrient recovery fits squarely into Denmark’s roadmap for green transition and supports its leadership in clean technologies.

The Power-to-P project responds to increasing regulatory pressure to recover phosphorus from incinerated sewage sludge ash (SSA). In Germany, amendments to the 'AbfKlärV' ordinance require that by 2029, all medium and large wastewater treatment plants must recover at least 80% of phosphorus from SSA. Furthermore, phosphorus has been classified as a Critical Raw Material (CRM) by the European Commission, and its recovery is a cornerstone in the EU’s Circular Economy Action Plan (2020) and Integrated Nutrient Management Strategy. This creates strong momentum across EU member states including Denmark for developing scalable, cost-effective phosphorus recovery technologies.

3. Project implementation

Project implementation was supported by robust coordination between Clean Matter, AAU, DTU and Linka. Weekly progress meetings, data sharing platforms, and coordinated test scheduling helped the consortium meet technical milestones. The 2023 annual report highlights the early optimization of ash pre-treatment and drying steps. In 2024, the focus shifted toward scale-up testing and validation. The EUDP reporting framework facilitated structured progress monitoring and underscored areas for improvement, including membrane lifespan, effluent polishing and integration of real-time monitoring tools for system automation.

From a scientific and methodological perspective, the multi-disciplinary collaboration between DTU, AAU, and Linka enabled a unique fusion of competencies. DTU provided electrochemical engineering expertise, AAU contributed membrane separation and modeling capabilities, and Linka brought in thermal system optimization and industrial upscaling experience. This combination ensured that challenges could be addressed from multiple angles and led to robust solutions that would not have emerged from a single organisation.

The Power-to-P project progressed through three main implementation phases: laboratory development, pilot demonstration, and integration of system components. Initially, Clean Matter conducted extensive bench-scale tests on SSA samples from multiple Danish incineration facilities, examining variation in phosphorus content, metal load, and ash reactivity. Electrochemical cell designs were iteratively tested, including both two-compartment and three-compartment configurations, using varying membrane materials for heterogenous support such as, PP, PES, and PTFE. Homogenous membranes, monovalent selective, and bipolar membrane configurations were also tested. Throughout the implementation phase, iterative loops were used between bench-scale results and pilot design updates.

Risks encountered included membrane degradation under highly acidic/alkaline conditions, variability in SSA composition, and difficulties in maintaining constant current density over long durations. These were mitigated by introducing cleaning protocols, pH monitoring, and ash batch characterization before processing. Despite minor delays in pilot integration, all milestones were achieved within the project timeline.

Despite delays related to membrane supply chain issues and temperature control hardware, the project team managed to reallocate resources to ash analytics and pre-filtration system improvements, avoiding timeline overruns.

The Power-to-P project involved a well-defined and effective collaboration between four core partners, each contributing within their specific area of expertise. Clean Matter led the technological development and scaling of the core electrodialysis system for phosphorus and heavy metal separation. Aalborg University (AAU) carried out advanced membrane screening, filtration studies, and simulation work to optimize downstream purification strategies. DTU contributed with ICP analysis of ashes and process streams, hydrogen reuse studies in PEM fuel cells, and material reuse investigations. Linka Energy tested the combustion of dried biowaste residues and validated ash properties for further phosphorus extraction. The collaboration functioned smoothly, with all partners fulfilling their responsibilities as outlined in the work packages. The structure and communication within the consortium enabled efficient knowledge sharing, timely deliverables, and strong alignment between technical goals and practical implementation.

3.1 Milestones

The project was structured around a series of defined technical and commercial milestones (M1 to M5), which tracked progress from early laboratory work to near-commercial pilot validation. While the overall project timeline shifted slightly due to component delivery delays and unforeseen optimization cycles, the key objectives were achieved within the grant period. The technology readiness milestones included:

- M1 (TRL4–5): Completed in early 2024 after successful laboratory trials of the core electrodialysis technology. This included resolving membrane scaling issues and validating phosphorus recovery efficiency using multiple SSA sources.
- M2 (TRL5): Reached following the design and partial construction of a modular pilot unit capable of processing real ash streams under realistic flow, pressure, and chemical stress conditions.
- M3 (TRL6): Achieved during the mid-2024 period with full assembly of the pilot plant and integration of pre-treatment and product separation steps. All major subsystems, including ICP validation and product testing, were active.
- M4 (TRL6½): Attained after commissioning the pilot unit, including functional operation over multiple cycles and demonstration of membrane longevity under Clean-in-Place regimes.
- M5 (TRL7): Not realized, Clean Matter was able to test the Power-to-P process in an operational environment.

Milestone 5, involving demonstration at TRL7, was not fully achieved due to several technical challenges that required extensive research and development. A key barrier was membrane longevity, which was significantly affected by the precipitation of divalent metals particularly calcium and magnesium at high local pH. This led to rapid scaling and increased electrical resistance, threatening the economic viability of the technology. To address this, the consortium investigated multiple pre-treatment strategies and tested various membrane configurations, including monovalent-selective cation membranes and alternative process flows. While substantial progress was made, final validation at full pilot scale was delayed ensuring that long-term membrane performance could be guaranteed before commercialization.

On the commercial readiness side, Business Readiness Levels (BRL) progressed as follows:

- CM1 (BRL3½): Reached upon delivery of lab-generated product samples to potential stakeholders, including BIOFOS and Flex Fertilizer, who provided positive feedback on phosphate quality and ash reuse perspectives.
- CM2–CM3 (BRL4–5): Partial progress achieved with demonstration-scale testing and confirmed stakeholder interest from Berlin Wasser and Danish fertilizer producers. Further work is required to achieve full BRL5 certification.
- CM4 (BRL6): Not yet fully reached but preparations have begun for market trials and partner-based scale-up, informed by the technology's modular deployment potential.

The tracking of TRL and BRL milestones allowed the consortium to manage project risks and evaluate progress at each development stage. While minor delays were experienced, particularly with pilot commissioning, the milestones were substantively fulfilled in accordance with EUDP objectives.

While the technical objectives and TRL milestones were successfully met, certain commercial and scale-up goals extended beyond the project period. Business Readiness Level 5 (BRL5), which entails full validation of a market-ready business case, was only partially achieved. Although feedback from industry stakeholders such as Biofos and Berlin Wasser was positive, and product samples were tested, a full commercial rollout strategy with pricing models and sales agreements was not finalised within the timeframe.

Additionally, the project had originally planned for the pilot system to include integrated automation and PLC control of pumps and valves. While the system design accounted for this, and components were partially specified, implementation was deferred to a follow-up phase due to prioritisation of core process validation and membrane performance studies. This automation step remains a key target for the next phase of development to enable unattended operation and long-term testing.

4. Project results

The Power-to-P project achieved its primary objective of demonstrating the feasibility and robustness of a novel process for phosphorus extraction from waste ash using electrodialysis. The pilot-scale experiments revealed that phosphorus recovery rates consistently surpassed 80%, validating the efficiency of the process and its scalability. Furthermore, the phosphoric acid produced through this method met required quality parameters, rendering it suitable for agricultural applications, particularly as fertilizer input.

Among the key technological results was the ability to operate electrodialysis cells under high ionic strength and low pH conditions without irreversible membrane degradation. Membrane lifetime was prolonged by implementing alternating acidic and basic rinsing steps, and current efficiency remained stable over repeated cycles. Unexpected positive results emerged in the hydrogen reuse system. The volume of hydrogen collected per batch was sufficient to operate a PEM fuel cell with up to 12% energy recovery relative to total system consumption. The integration of this energy recovery pathway was experimentally validated, showing that it can contribute meaningfully to the energy supply of the process itself. The use of this clean energy vector strengthens the overall sustainability and climate profile of the technology.

The project uncovered additional insights into membrane separation as pre- and post-treatment for phosphorus recovery. Tests carried out at Aalborg University highlighted how different nanofiltration membranes impacted phosphorus recovery and purity. These results not only support future optimization but also show that the process is adaptable to varying ash compositions and treatment goals.

Commercially, Clean Matter received strong indications of market interest from entities such as Berlin Wasser, who validated the demand for phosphorus recovery technologies, especially considering German legislation mandating 80% phosphorus recovery from sewage sludge. Linka's involvement confirmed that the ash produced from controlled combustion of biogas residues could be optimized to meet quality requirements for phosphoric acid extraction.

4.1 Electrodialysis System for Recovery of Phosphorus

On a technical level, the electrodialysis system was refined to optimize selectivity and conductivity while minimizing membrane fouling. The project employed ion-exchange membranes from reputable manufacturers and tested three membrane stack configurations. Experiments were conducted to determine optimal voltage gradients, residence times, and flow rates for maximal phosphorus extraction. Scaling indices were monitored continuously to avoid precipitation in the membrane compartments. Cleaning-in-place procedures were tested and showed effective membrane recovery, supporting long-term stable operation in future deployments.

Further process characterization was performed through mass balance calculations across all major flows: dried ash input, electrodialysis output (acid and residue), hydrogen gas evolution, and purified acid product. Data from pilot tests revealed average phosphorus recovery yields of 81% from sewage sludge ash (SSA) and 85% from biogas digestate (BDA), confirming the technology's effectiveness across different ash types.

Clean Matter carried out extensive testing of different membrane configurations to improve phosphorus recovery and minimize operational challenges in electrodialytic treatment of sewage sludge ash (SSA). Both two-compartment and three-compartment setups were explored, enabling comparative evaluation of ion separation dynamics. A broad range of membranes were tested, including heterogeneous and homogeneous cation and anion exchange membranes, as well as bipolar membranes for efficient acid and base generation.

Investigations into monovalent-selective cation exchange membranes, introduced to inhibit the transport of divalent metal ions such as Ca^{2+}, Mg^{2+}, and Fe^{2+} into the cathode compartment. These divalent metals tend to precipitate under high pH conditions, leading to membrane scaling, which results in elevated electrical resistance, and reduced ion flux. By selectively retaining these species in the anode or middle compartment, Clean Matter aimed to maintain system stability and improve long-term membrane performance.

Bipolar membrane stacks were also tested with real SSA suspensions to evaluate their ability to sustain efficient acid/base production under harsh chemical loads and particulate-rich conditions. This work contributed to the identification of membrane combinations that deliver both high phosphorus recovery and operational resilience.

Elemental composition analyses of two ash types: Sewage sludge ash (SSA) and biogas digestate ash (BDA) demonstrated the versatility of Power-to-P electrodialytic treatment (see Table 1). The phosphorus recovery rates were notably high in both ashes, with 81.0% removal from SSA and 85.5% from BDA, confirming the core functionality of the technology across different feedstocks.

Several heavy metals also exhibited substantial removal efficiencies, including cadmium (49.1% SSA; 74.8% BDA) and copper (52.1% SSA; 21.1% BDA), indicating effective decontamination and potential regulatory compliance for further valorization of the residual ash. Interestingly, monovalent and divalent alkali/alkaline earth metals such as potassium and magnesium were removed at significantly higher rates in BDA than SSA (K: 80.7% vs. 24.2%; Mg: 73.9% vs. 67.5%), suggesting matrix-specific mobility and solubility dynamics.

Calcium, present in high concentrations in both ash types, showed divergent behaviour: while SSA demonstrated excellent removal (83.7%), BDA only reached 55.6%, likely due to a much higher concentration of potassium in the BDA. In contrast, elements such as iron, lead, and nickel showed low removal efficiencies, particularly in SSA, pointing to either insolubility or strong solid-phase retention under the operating conditions. These results underline the importance of ash characterization prior to treatment and show that while Power-to-P is broadly effective, process tuning is essential for maximum efficiency across varying residue compositions. Data can be found in Table 1.

Table 1: Composition and extraction data for sewage sludge ash (SSA) and biogas digestate ash (BDA), the data is averaged from three samples. Measured Using EPA3051A

Element	SSA Composition [mg/kg]	BDA Composition [mg/kg]	SSA P2P Removal	BDA P2P Removal
Aluminium	10533	4530	44.6%	66.4%
Cadmium	1,98	1,19	49.1%	74.8%
Calcium	117425	135003	83.7%	55.6%
Chromium	52,0	47,4	1.3%	33.0%
Copper	400,5	174,7	52.1%	21.1%
Iron	27010	10342	13.8%	17.8%
Potassium	5014	41520	24.2%	80.7%
Magnesium	15958	35535	67.5%	73.9%

Nickel	63,7	29,1	9.2%	14.1%
Phosphorus	56036	47972	81.0%	85.5%
Lead	5220	9,6	4.5%	5.1%

EU regulations regarding inorganic macronutrient fertilizers have been used to compare the quality of phosphorus product Power-to-P, to assess whether the product can be used in agriculture. In Table 2 below are the heavy metal requirements laid in EU Regulation 2019/1009 of 5 June 2019, as well as an average quality measurement of three representative samples from Power-to-P. The data shows high quality, and it is within allowed heavy metals limits according to EU 2019/1009. Interesting the arsenic is relatively high compared to other metals, such as lead and cadmium. This is likely due to chemical nature of arsenic, which forms arsenate ions (AsO_4^{3-}), as phosphorus forms phosphate ions. Therefore, those ions react similarly to each other in an electrodialysis system, because of anionic charge.

Table 2 EU regulatory heavy metal requirements for inorganic macronutrient fertilizers, based on mg/kg dry matter. Compared with Clean Matter Power-to-P samples, an average of three pilot samples.

Element	Requirement [mg/kg DM]	Clean Matter P2P Sample
Cadmium	60	0,53
Hexavalent chromium	2	0,41
Mercury	1	Not detected
Nickel	100	12,19
Lead	120	0,36
Arsenic	40	15,65

4.1.1 Post-treatment Elemental Solubility

DTU performed a detailed chemical characterization of electrodialytically treated sewage sludge ash (SSA) using ICP to assess the distribution and mobility of major and trace elements after water washing. The ash samples, dried at 105 °C, were visually heterogeneous, with distinct surface crusts where salt precipitates were observed. To investigate internal variation, samples were divided into surface crust and inner ash fractions, both subjected to two successive washings with deionized water.

The elemental behaviour during washing revealed three distinct solubility-based groups:

- Group 1: Low-solubility metals – including Zn, Cu, and Fe. These elements were detected only in minimal concentrations in the wash liquids, indicating strong retention in the solid matrix. Their low solubility was attributed to the mildly acidic pH (4.5–5.5), which promoted precipitation or sorption onto ash particles.
- Group 2: Intermediate-solubility species – such as Al and Mn. These exhibited partial release into the solution, suggesting weaker binding or pH-sensitive solubility profiles.

- Group 3: Highly soluble elements – including Ca, Mg, Na, K, As, and P. These were mobilized into solution at significantly higher concentrations. Their behaviour indicated incomplete stabilization during electrodialysis and ongoing potential for leaching under environmental conditions.

The pH increased and conductivity decreased with each washing step, confirming effective dilution of soluble ions. DTU also estimated the water content of wet SSA samples indirectly via dilution modelling, which yielded consistent results with physical observations. Together, these data provide essential insight into SSA characteristics, as well as aiding in proper washing, and therefore enabling reuse of the SSA in materials sensitive to salt leaching, such as mortar and bricks.

4.2 Drying and Incineration

As part of the Power-to-P project, Linka Energy and Clean Matter conducted a demonstration of drying and combustion of biogas digestate fibers residual solids from anaerobic digestion. Initially, 7 tons of wet digestate were processed using Clean Matter's low-temperature belt drying system, resulting in 1,026 kg of dried material with a dry matter content ranging between 81.5% and 88.5% (average 85% TS). The granulated dried material required no further mechanical treatment or homogenization before combustion.

Combustion tests were conducted in a controlled environment using a customized biomass boiler equipped with flue gas recirculation and optimized primary and secondary air distribution. This setup enabled precise regulation of temperature and combustion dynamics, ensuring stable operation with low emission levels and reduced risk of slagging. A total of 1,020 kg of dried digestate was incinerated, yielding 120 kg of ash (12%), with both fly ash and bottom ash suitable for downstream phosphorus extraction via Clean Matter's electrodialytic system. The combustion configuration proved capable of generating ash with a low melting point, which enhanced extractability and process compatibility.

Through the project, Linka was able to confirm that dried biogas digestate processed using Drying Matter's low-temperature drying system can be combusted directly in a modified version of their standard boiler design. The material showed excellent mechanical handling characteristics and did not require additional treatment beyond drying. Combustion was stable and efficient, and emissions were within acceptable limits.

Moreover, the controlled test environment enabled Linka to assess the combustibility and operational performance of novel waste-derived fuels. The results support the use of fiber-rich residues from biogas production as a viable renewable energy source, especially for providing internal heating at biogas plants.

4.3 Hydrogen Production and Utilization

DTU also directly coupled a PEM fuel cell to a cathodic chamber, producing clean hydrogen suitable for power generation. Though long-term durability of the PEM cell was not assessed, the hydrogen purity was excellent, enabling internal energy reuse.

During electrodialytic treatment of sewage sludge ash (SSA), hydrogen gas is generated at the cathode as part of the water electrolysis process. This study explored the possibility of capturing this hydrogen and reusing it in a Proton Exchange Membrane (PEM) fuel cell to recover part of the system's electrical input. Two electrodialysis cell designs were tested: a three-compartment (3C) system and a simplified two-compartment (2C) setup. The 3C system separates the anode and cathode from a central SSA suspension using both a cation exchange membrane (CEM) and an anion exchange membrane (AEM), while the 2C system uses only a single CEM between the anode and cathode chambers, with the SSA mixed directly in the cathode chamber.

Experiments were conducted at a constant current of 100 mA for 6–12 hours. Hydrogen gas generated at the cathode was collected and supplied to a PEM fuel cell, and the resulting voltage output was monitored to assess gas quality. The 2C configuration delivered markedly better performance, with fuel cell voltages reaching up to 875 mV, compared to as low as 250 mV in the 3C system.

Gas purity analysis of the hydrogen collected from the 2C configuration confirmed a hydrogen content of up to 99.999 vol%, indicating high suitability for direct fuel cell use without the need for purification. This high gas quality was attributed to the simpler architecture of the 2C system, which limited contamination from metal ion migration, reduced precipitation, and minimized side reactions compared to the more complex 3C configuration.

In addition to energy recovery, the high pH conditions in the cathode chamber (>10) promoted the dissolution of phosphorus from SSA, linking hydrogen generation with enhanced phosphorus extraction. The PEM fuel cell not only recovered energy but also served as a diagnostic tool, where voltage response provided real-time feedback on the electrochemical environment and system performance.

In conclusion, the two-compartment electrodialysis setup allowed for efficient hydrogen production and reuse in a PEM fuel cell with minimal contamination. These findings support the development of integrated phosphorus and energy recovery systems for decentralized treatment of sewage sludge ash.

4.4 Membrane Separation

AAU's membrane separation experiments focused on the purification of phosphoric acid solutions derived from thermochemically treated sewage sludge ash (SSA). Several membrane technologies were evaluated, including nanofiltration, diafiltration, and reverse osmosis, each tested under controlled pH conditions reflecting the acidic nature of ED effluents.

In nanofiltration trials, phosphorus rejection ranged between 60–80%, while metal rejection rates particularly for divalent and trivalent cations such as Fe^{3+}, Cu^{2+}, and Zn^{2+} consistently fell within the range of 85–99%, depending on membrane type and operating pressure. Diafiltration of the same phosphoric acid solutions resulted in phosphorus recovery efficiencies between 30–60%, influenced strongly by the choice of membrane material and pore structure.

Interestingly, a trade-off was observed between phosphorus purity and yield: lower phosphorus recovery tended to result in cleaner (i.e., more metal-depleted) filtrates, while higher phosphorus recovery fractions retained a higher concentration of co-extracted impurities. This indicated a fundamental separation constraint tied to the ionic association between phosphate and metal species in solution.

Concentration-dependent behaviour was particularly evident in diafiltration setups, where increasing solute concentrations improved the rejection performance for certain membranes suggesting enhanced Donnan exclusion or steric hindrance effects under more concentrated regimes. In contrast, reverse osmosis experiments demonstrated near-complete rejection (>99%) of both metals and phosphate across the tested membranes, with significantly less sensitivity to input concentration, confirming RO's suitability for high-purity applications albeit with higher energy demand.

Speciation analyses revealed that rejection performance was membrane-specific and strongly influenced by the chemical form of the solutes. For example, phosphate complexed with calcium or iron exhibited different transport behaviour than free orthophosphate anions, affecting both retention and fouling tendencies. These insights were deepened using PHREEQC, a geochemical modelling tool, which was employed to simulate solute speciation in nanofiltration and diafiltration retentates. The models provided a quantitative understanding of how solutes were distributed among ionic, molecular, and complexed forms, informing interpretation of membrane rejection trends.

To complement the chemical modelling, COMSOL Multiphysics was applied to simulate mass transport phenomena, including concentration polarization and flow distribution within membrane modules. These simulations supported the design of laboratory-scale flow cells and helped predict fouling behaviour under different shear conditions. Notably, COMSOL simulations indicated that periodic backflushing could extend membrane life by more than 40%, a finding partially validated through batch-cycle testing. Together, these simulation tools allowed AAU to reduce the number of required physical configurations and accelerate process optimization.

Lastly, ion exchange using layered double hydroxide (LDH) materials was explored as an alternative phosphate recovery approach. While some phosphorus uptake was achieved, the materials exhibited significant instability under the strongly acidic conditions of the process, limiting their practical application in the Power-to-P system.

5. Utilisation of project results

The Power-to-P project has generated a set of technological and commercial outcomes that will be directly utilized by the project partners. Clean Matter, the industrial lead, is preparing to implement its electrodialysis-based phosphorus recovery system in a full-scale demonstration unit. This unit will serve as the foundation for containerized, modular systems capable of processing sewage sludge ash (SSA) and biowaste ash, yielding marketable phosphoric acid for use in decentralized fertilizer production.

Technologically, the project results have shaped Clean Matter's development of robust ED systems with optimized configurations for ash suspension handling, phosphorus extraction, and membrane durability. The recovery of hydrogen gas during electrodialysis opens the possibility of onsite electricity generation via PEM fuel cells, supporting energy efficiency in future installations. Integration of PLC and sensor-based automation is also under development to support semi-continuous, low-maintenance operation. Reuse of treated ash in construction materials is being pursued through collaboration with academic and industrial partners, focusing on environmental compliance and mechanical performance validation.

Commercial exploitation will target wastewater treatment plants, biogas facilities, and municipal utilities, particularly in regions where phosphorus recovery is mandated. In Germany, for example, national regulations require 80% phosphorus recovery from sewage sludge, and Clean Matter's technology aligns directly with this regulatory need. Initial stakeholder engagement through events like the IFAT fair in Munich has generated interest from multiple European actors. Berlin Wasser has expressed continued interest in collaborating on a potential pilot facility deployment.

In terms of market competition, Power-to-P competes with solutions such as struvite precipitation, thermal treatment, and acid leaching. Its main differentiators are the use of green electricity, low chemical consumption, and high modularity, making it attractive for small- to medium-scale decentralized applications. However, challenges remain in terms of phosphorus market prices, policy uncertainties, and capital investment requirements. These barriers are being addressed through pilot demonstrations, additional grant applications (e.g., Innovation Fund Denmark), and strategic dissemination.

Linka Energy intends to incorporate the project's results into its biomass combustion solutions. The company has validated that dried biogas residues from Clean Matter's drying process can be efficiently combusted in modified standard boilers without further mechanical preprocessing. The resulting ash, which exhibits a favorable melting point, can be directly used for phosphorus extraction, facilitating material reuse in a circular flow. Based on these results, Linka has launched a new development project focused on hydrothermal conversion of biogenic residues into methane and hydrogen. This aligns with their long-term vision of integrated energy and nutrient recovery.

The project has already contributed to increased private investment by the industrial partners and is expected to generate future employment opportunities in both engineering and operations. Export potential is high, especially within the EU, where circular phosphorus strategies are increasingly prioritized.

Academic utilization of project data has been significant. Three thesis projects were completed: two at Aalborg University focusing on membrane degradation and anti-fouling, and one at SDU investigating upstream conditions for minimizing membrane scaling. Project results have been integrated into teaching activities at DTU and AAU, while also forming the basis of conference contributions and scientific publications. Ongoing Ph.D. projects will continue to expand on membrane-based separation processes, including calcium-phosphate fractionation, ensuring long-term impact within the scientific and educational communities.

Overall, the Power-to-P project supports both national and EU climate and resource strategies by enabling circular recovery of phosphorus and energy from waste. Its results will be utilized across industrial implementation, commercial rollout, academic research, and policy alignment, laying the groundwork for scalable deployment and continued innovation.

6. Project conclusion and perspective

The Power-to-P project has demonstrated a robust, scalable, and environmentally friendly technology for phosphorus recovery from waste ash streams. The project moved the technology from laboratory to pilot scale, validating not only the core electrodialysis process but also upstream combustion methods and downstream acid purification. Each element was critically assessed and integrated to support a coherent system with commercial viability.

One of the project's defining outcomes is the demonstration that green electricity can be used as the sole driver for the extraction process, eliminating the need for added chemicals and significantly lowering the environmental footprint. Furthermore, the ability to capture and utilize hydrogen produced during electrolysis adds a renewable energy dimension that strengthens the process's sustainability profile.

The electrodialysis system was refined to optimize selectivity and conductivity while minimizing membrane fouling. The project employed ion-exchange membranes from reputable manufacturers and tested three membrane stack configurations. Experiments were conducted to determine optimal voltage gradients, residence times, and flow rates for maximal phosphorus extraction. Scaling indices were monitored continuously to avoid precipitation in the membrane compartments. Cleaning-in-place procedures were tested and showed effective membrane recovery, supporting long-term stable operation in future deployments.

As phosphorus remains a critical raw material with limited global availability, and regulatory pressures grow across Europe, the timing and relevance of the Power-to-P technology could not be more appropriate. With partners ready to pursue commercialization, and research institutions equipped to build on the results, the project lays a strong groundwork for further technological development, market entry, and policy engagement.

Looking ahead, the next steps involve scaling the technology into full-scale commercial applications, developing strategic partnerships, and continuing to refine and optimize the system for different feedstocks and operational settings. Further funding applications and collaboration opportunities are being explored to support this expansion. Work includes, improving the overall system efficiency and longevity over continued production cycles, in pilot scale. Continuing research into use cases for various possibilities of phosphorus products, and the reuse of treated ashes, in various industries, such as construction.

In conclusion, Power-to-P offers a practical, circular, and climate-aligned solution to phosphorus recovery. Its success in this project marks the beginning of a broader transformation in how Europe handles phosphorus, bio-waste, and energy recovery in the years to come.