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SaltGae
algae to treat saline wastewater

Demonstration project to prove the techno-economic feasibility of using algae to treat saline wastewater from the food industry

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WP7	**Integrated Sustainability and Business Viability Assessment**
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Glossary

The glossary of terms used in this deliverable can be found in the public document "SaltGae_Glossary.pdf" available at: http://saltgae.eu/downloads-public/

Abbreviations and Acronyms

Abbreviation / Acronym	Description
2-AD	2-step anaerobic digestion
AAO	Anaerobic-anoxic-oxic
AO	Anoxic-oxic
AP	Acidification Potential
BOD	Biochemical oxygen demand
CAS	Conventional aerated sludge
CBA	Cost benefit analysis
CAPEX	Capital expenditures
CHP	Combined heat and power plant
CO_2	Carbon dioxide
COD	Chemical oxygen demand
DAF	Dissolved air flotation
D7.2	Deliverable 7.2
DIC	Dissolved inorganic carbon
EP	Eutrophication Potential
ERD	Energy recovery device
F&B	Food and beverage
HRAP	High rate algae pond
HPH	High pressure homogenisation
IEA	International Energy Agency
LCA	Life cycle assessment
LCCA	Life cycle costing assessment
MCA	Multi-criteria analysis
NOx	Nitrogen oxides
NPV	Net present value
OPEX	Operational expenditure
ORP	Open raceway pond
PBR	Photobioreactor

Abbreviation / Acronym	**Description**
PLA	Polylactic acid
POCP	Photochemical ozone creation potential
PSILCA	Product social impact life cycle assessment
R&D	Research and development
RO	Reverse osmosis
SD	Sustainable development
S-LCA	Social life cycle assessment
SME	Small and medium-sized businesses
TRL	Technology readiness level
TBL	Triple bottom line
UV	Ultraviolet
VFA	Volatile fatty acids
WWTP	Wastewater treatment plant

1. EXECUTIVE SUMMARY

The objective of wastewater treatment plants is to remove pollutants in water and avoid adverse effects that untreated wastewater could have in water potability, aquatic life and agriculture. Besides producing clean water, wastewater treatment plants could also become energy and resource recovery facilities, contributing to a circular economy. The SaltGae project aims to support in the transition to a circular economy by demonstrating on an industrial scale the feasibility of wastewater treatment based on microalgae grown in high salinity wastewater.

This report presents the **sustainability assessment** for the SaltGae project. Three demonstration sites where installed in Slovenia, Italy and Israel. The cost and environmental impact of these systems were evaluated with a life cycle assessment (LCA) and a life cycle costing assessment (LCCA). A social life cycle assessment (S-LCA) was also performed for the Italian and Israeli sites. Further, the consortium carried out a set of lab-scale experiments to valorise algae into different products, including animal feed, platform chemicals for adhesives and coatings, composites and ceramic pastes. Some of these routes were also evaluated using life cycle-based methodologies. Results and conclusions of these analyses are presented in section 4.

This report also presents the **business feasibility assessment** of the SaltGae systems. This assessment evaluates the potential for the technology to be commercialized. First, the technology readiness level (TRL) of the system components was assessed based on performance, integration level and user satisfaction. Then the market readiness of the technology was evaluated by dividing the project into four routes: basic system functionality, valorization of solids and sludge, valorization of effluent and valorization of biomass. To estimate market readiness, issues and solutions were evaluated. Results and conclusions of these analyses are presented in section 5.

In the **sustainability assessment** section, the LCA hotspot analysis of the demonstration sites is presented. These analyses highlight two factors — extra nutrient requirements and energy consumption — contributing to more than 85 % of most of the environmental impact categories examined. In terms of nutrient requirement, the analyses revealed that the SaltGae system might require extra nutrients to maintain biomass yield. The amount of extra nutrients required depend on the inherent nutrient loads in the wastewater treated. To optimize the environmental benefits of the system, SaltGae should be targeted to treat nutrient-rich wastewater streams. In such a case, the addition of extra nutrients is minimized. However, from an economical point of view, the amount of nutrients added depends on the business case of each site. For instance, if high quality algae biomass is targeted, then extra nutrients might be required.

In terms of energy consumption, the energy related impact of the sites is different due to local conditions, including weather and accessibility to renewable energy sources. Despite the site-specific variability, a sustainable SaltGae system should entail the optimization of energy requirement and the securement of renewable energy supply. In Slovenia, the main energy related impact stems from the electricity used by the pumps circulating wastewater. This site has not yet optimized energy requirements, however its environmental impact results benefit from its access to renewable electricity from the adjacent biogas cogeneration plant.

The Italian and Israeli sites have minimized the pump energy use; however, their access to renewable electricity is not secured. Both sites use electricity from the national grid. The negative effect of restricted access to renewable energy exacerbates for the Israeli site. In other words, even if the amount of electricity per functional unit is similar for the Italian and Israeli sites, the electricity related environmental impact in the Israel site is significantly higher. This is attributed to the strong dependence on fossil fuels by Israel's national grid.

In terms of temperature regulation, both the Slovenian and the Italian sites require heat during the winter season. The environmental impact results for these sites have benefited by optimizing heat requirements and securing access to waste heat from renewable sources. On the other hand, for the Israeli site, the high temperature of the desert requires indoors cultivation of inoculum in photobioreactors (PBRs). This involves air conditioning cooling and light requirements. Therefore, the energy related environmental impact from the PBRs in Israel become a major contributor to the overall environmental impact of this site. Powering lights and the air conditioner with solar energy would significantly reduce the overall environmental of the Israeli site.

In terms of water consumption, the SaltGae system uses clean water to grow inoculum and to replenish evaporation from the algae ponds. Evaporation depends on local weather conditions. However, despite the different weather of the three sites, the analysis shows that managing evaporation in open cultivation is important for environmental sustainability. Scenario analysis demonstrated that recirculation of treated wastewater significantly reduced water consumption. Notice that this strategy could involve a trade-off between the environmental and social sustainability. Recirculating treated water reduces the availability of desalinated clean water for the local community and local ecosystems.

For the Slovenian site, evaporation is important; however, the two-step anaerobic system (2-AD) is utilizing more clean water than the algae ponds. A problematic trade-off between energy recovery and clean water consumption was identified. The 2-AD system allows for the recovery of energy from wastewater in the form of biogas. However, with the current state of technology development, the 2-AD needs significant amounts of desalinated water. To avoid burden shifting between these two impacts (i.e. water and climate change), further scientific and technological development is needed in terms of e.g. research on bacteria species with higher halotolerance.

The LCCA hotspot analysis of the three demo-sites highlights that most of the costs of the Koto system are associated with investment costs for the algae ponds, construction phase and financial/business categories. The Archimede demo site is a high-tech facility with high potential, where most of the costs are originating from labour. The investment and operating cost for Archimede are slightly higher than the benchmark; though after 6 years, the accumulated present value becomes better for Archimede than for the benchmark and the investment starts to pay off. The investment and operating costs for Arava are also slightly higher compare to benchmark, but the demo site will have a slightly better net present value (NPV) after 10 years. Notice production costs is strongly dependent on plant scale. According to Fasaei et al. [1], by increasing the cultivation size from 1 ha up to 10 ha, the cost impact from labour could decreased by 85%.

The implication of species selection was examined through a life cycle-based analysis that highlighted the differences between *Nannochloropsis* and Spirulina cultivation. Thanks to lower CO_2 consumption and higher CO_2 uptake efficiency, Spirulina cultivation shows a better environmental performance than *Nannochloropsis* in all impact categories, except for eutrophication. Spirulina has a higher EP than *Nannochloropsis* due to higher sodium bicarbonate and sodium nitrate requirements. In terms of cost, the cultivation of Spirulina is preferable. Further, technologies for valorizing Spirulina are more developed than for *Nannochloropsis*. With all this in consideration, the Italian and Israeli sites chose to cultivate Spirulina rather than *Nannochloropsis*. Profitable markets for *Nannochloropsis* are awaiting, however further research on optimizing culture conditions for this species and lipid extraction protocols is required.

Carbon dioxide (CO_2) consumption and leakage of the did not result a major contributor to the environmental impact of the SaltGae demo sites. However, when designing a SaltGae systems, special attention should be paid to the amount and source of CO_2, particularly for systems growing *Nannochloropsis*. Analysis of the Italian site show that food grade CO_2 bough from the market, might entail high environmental impact due its origin from the ammonia industry. Furthermore, this CO_2 is fossil; thus, any CO_2 leakage contributes directly to climate change.

The environmental implication of two distinct cultivation methods — batch versus continuous cultivation — were analysed for the Israeli site. Continuous cultivation shows improvements in terms of energy reduction, due to the reduction of PBR operating time. However, the water consumption increases due to an increment in the open pond operating time. To avoid shifting burden between water consumption and climate change, water recirculation of treated water is recommended to replenish evaporation in continuous cultivation.

The LCA on animal feed shows that the climate impact of the feed increased by a factor of 10 when replacing fish meal with algae. This assessment is very stringent, since data for anchovies and fish residues was used (i.e. anchovy fishing is very efficient). Parker et al. [2] suggest that high environmental benefits for society could be realized when directing greater proportions of fish catches to human consumption, instead of industrial uses (e.g. animal feed). Therefore, thorough research in this area is required to fully understand the consequences of the use of low-impact protein in different sectors.

The LCA of algae-based biocomposites shows that utilizing Spirulina debris in gluten thermoplastics yields small improvements of less than 10 %. Using the whole algae in the composite formulation is not recommended in terms of environmental impact, even when considering the increment in mechanical properties. In terms of ceramic pastes, the LCA shows that 4 % addition of algae debris does not entail significant improvements nor worsening of the cradle-to-gate environmental impact of 3-D printed ceramic pastes. However, the use of ceramic pastes to replace cement-based pastes yields significant environmental improvements.

The environmental impact of the protein extraction process for Spirulina was also assessed. The protein extraction process constitutes 30 % of the cradle-to-gate climate impact of the protein cream. The extraction process was performed at lab scale; therefore, process optimizations from technological improvements/upscaling can be expected. Further LCA research should focus on thoroughly assessing algae use for different applications, with e.g. protein as the functional unit.

The **business feasibility assessment** shows that effluent valorization and wastewater treatment for low/medium salinity and BOD wastewater are ready for a market introduction. In terms of biomass valorization, the production of lipids and proteins from algal biomass require more improvements in the extraction processes. The production of piglet feed and edible coatings are at TRL 7, however edible coatings have distinct smell which is a drawback for market penetration.

SaltGae has a good opportunity to enter markets where water scarcity is prioritized, and policies incentivise are established. In this case, biomass production in wastewater water has an important competitive advantage compared to a simple algae production site. In terms of algae valorization markets, although interest in algae based edible coatings has been growing, the competition is rather high with existing high-performance edible coatings on the market. For a successful market penetration, novel coatings must probably have a competitive edge concerning performance, costs or environmental profile.

Legislation and standardization in the area of biomass valorization are limiting factors of SaltGae, especially for the food applications such as dried algae, food supplements and edible coatings. The fact that there are no specific regulations for the SaltGae routes, besides existing insufficient standards, new instruments should be promoted on the EU level, especially for the use of algae as the wastewater treatment and the use of algal biomass grown in wastewater.

The basic assumption of the commercialization evaluation is the start-up of a wastewater treatment company using algae cultivation; the facility should be built close to a wastewater plant and the company would represent a technical solution which is an intermediate step between wastewater plants and buyers of biomass. The first step would be to understand the needs of the wastewater producer and optimize the plant according to those needs. The company has a potential to become a supplier of algae and produce the algae derivatives as well after satisfactory results of R&D of extraction processes. Gaps in the current legislation and suites of standards regulating all relevant aspects of the combined processes wastewater treatment-algae production-biomass valorization should be addressed by initiating and promoting the development of new such agreements. The legislative issues are relevant not only for the licensing the technology but also for establishing the standard quality guidelines. A timetable is proposed for the implementation of the business by to an early adopter/entrepreneur and the necessary resources are discussed in the business plan. Results and conclusions of these analyses are presented in section 5, the business viability assessment.

2. INTRODUCTION AND AIM

Wastewater treatment plants remove pollutants in water and avoid adverse effects that untreated wastewater could have in water potability, aquatic life and agriculture. Besides producing clean water, wastewater treatment plants could also become energy and resource recovery facilities, contributing to a circular economy.

There is a growing awareness of wastewater as source of nutrients and energy. The integration of algae production with wastewater treatment provides an opportunity to ensure economic and environmental sustainability of algae production through the provision of water and nutrient requirements [3]. Microalgae can recover the nutrients contained in wastewater. Using high productive systems such as high rate algae pond (ORPs), can lead to high rates of nutrient removal as well as high rates of biomass production [4]. Further, with anaerobic digestion technology, energy in the form of biogas can be recovered from wastewater.

The SaltGae project aim is to support in the transition to a circular economy through demonstrating at large scale the technological feasibility of sustainable treatment of high salinity wastewater from the food and beverage industry (F&B). Conventional wastewater treatments in this industry are often ineffective due to bacterial processes being inhibited by high salinity. Further, most of the commercial cultivation of algae is using freshwater. Therefore, a window for technological development in this area was identified.

The SaltGae technology is expected to provide an innovative way to treat high salinity wastewater while producing algae. In terms of environmental impact, the SaltGae technology aims at protecting natural water from eutrophication and facilitate the recovery of nutrients from wastewater through the assimilation of nitrogen and phosphorous during algae growth.

The scope of the SaltGae project includes the installation of three demonstration sites in Slovenia, Italy and Israel. In these sites a set of technologies have been tested and validated including high rate algae ponds (ORPs). The SaltGae project also includes a set of lab-scale experiments of technological routes to valorize algae into different products, including animal feed, platform chemicals for resins, adhesives and coatings, and composites and ceramic pastes.

The overall objective of work package seven (WP7) is twofold. First, the objective is to identify the environmental, economic and social effects of the technologies developed within SaltGae project. A life cycle perspective was used to identify these effects. Specifically, the methods of Life Cycle Assessment (LCA), Life Cycle Cost Analysis (LCCA) and Social Life Cycle Assessment (S-LCA) were used. Through these assessments, we provide feedback to the consortium on critical parameters for the development of the technologies. Finally, the results of the social, economic and environmental assessments were merged via an integrated assessment and provide a sustainability roadmap for future development of SaltGae technologies.

Second, the objective of WP7 is to evaluate the business feasibility of the technologies developed within the SaltGae project. This study provides information not only for scientists but also for technology investors or entrepreneurs who want to understand the algae production as a business idea for wastewater treatment. Together with the results from the integrated assessment, a technical assessment and a screening of the market not only for potential suppliers, competitors or customers but also for laws and regulations which also can affect the business case has been carried out in order to evaluate the business feasibility and develop business plans. The aim for the technology assessment was to evaluate the performance, level of integration, and level of satisfaction of the SaltGae system from a technical point of view.

Following the two overall objectives of WP7, this document is divided into two main sections: the sustainability assessment and the business feasibility assessment. The sustainability roadmap and the business plan summarize the conclusions of the different assessments.

3. OBJECTIVES AND SCOPE

The purpose of the study carried out under Tasks 7.2, 7.3, 7.4 and 7.5 is to assess the techno-economic feasibility as well as the environmental and social impacts of the SaltGae technology. The sustainability roadmap aim is to summarize the main findings of the social, environmental and economic assessment, discuss synergies and trade-offs and document the improvement possibilities and research and development challenges of treating wastewater with microalgae.

3.1. Sustainability assessment objectives

Together with deliverable 7.2 (D7.2), this deliverable provides an attempt to answer four questions:

1. Which steps in the process chain contribute most to the overall cost, environmental and social impact of the SaltGae wastewater treatment solutions?
2. What are the environmental and economic advantages or disadvantages of using algae grown in wastewater to replace existing raw materials in animal feed, composites and ceramic pastes?
3. Which trade-offs are there between the impacts of the SaltGae system on the three sustainability pillars?
4. What are the improvement possibilities and research challenges in the life cycle of the SaltGae wastewater treatment solutions?

3.2. System boundaries and functional unit

This section describes the processes included and excluded in the assessments performed. Figure 1 categorizes the processes into four groups: *wastewater pre-treatment, algae cultivation & harvesting, downstream processes and benchmark systems.*

The wastewater *pre-treatment processes, algae cultivation & harvesting* as well as the water valorization part of the downstream processes are specific for each demo sites. In other words, the processes selected for each site are specific to the wastewater characteristics (i.e. COD, salinity levels and volume of wastewater available). The parts of the process chain related to biomass valorization pathways of the *downstream processes* are the algae drying, refinement and its incorporation into algae-based products.

Table 1 summarizes the main differences between the three demo sites. Further description for each demo site can be found in the results section. For all demo sites the functional unit chosen is **1 m^3 of treated water**. Notice that all demo sites produce also algae biomass.

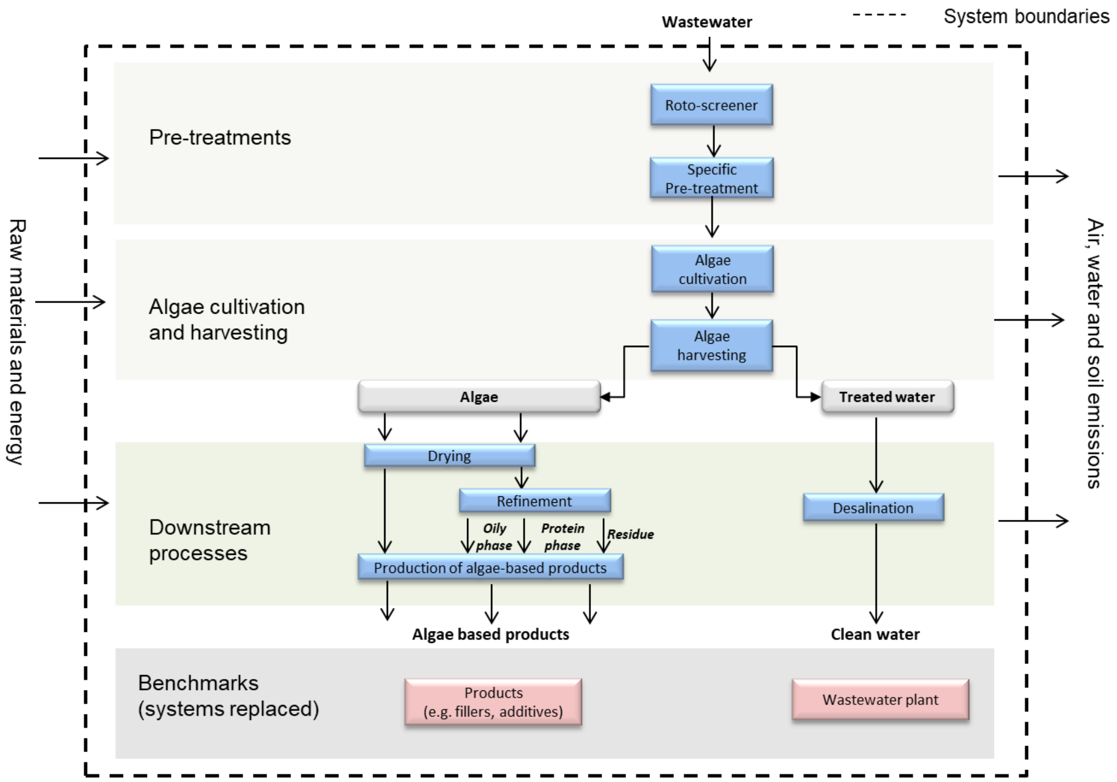


Figure 1. System boundaries of the SaltGae system assessment.

Table 1. Main differences between the three demo sites.

Demo site	Location	Wastewater type	Flowrate	Salinity	COD	Algae type	Algae production
Koto	Ljubljana, Slovenia	Tannery wash water	0,45 m^3/day	High	>10000	Mixed	1 kg/day
Archimede	Imperia, Italy	Dairy wash water	16 m^3/day	Medium	1000-10000	Spirulina or *Nannochloropsis*	19 kg/day
Arava	Arava desert, Israel	Aquaculture water	10 m^3/day	Low	< 1000	Spirulina	10 kg/day

The two organisms selected as main targets for the SaltGae processes lead to different biomass valorization routes, as shown in Figure 2. On one hand, the protein route for Spirulina which has high levels of protein content (about 65%). In this route, the algae can go to animal feed or the proteins can be extracted in order to produce edible coatings. The debris remaining from the extraction can be used for production of thermoplastic biocomposites and pastes for 3D-printed ceramics. On the other hand, the oil route for *Nannochloropsis*, in which EPA is first extracted for commercialization as a dietary supplement. The remaining oil is used for production of platform chemicals for production adhesives and coatings. Notice that mixed culture like the one in the Koto site could also be valorised, but not as aforementioned. It could be valorised instead, for example, as a feedstock for biogas production. Notice that no LCA or LCCA has been made for the valorization of Koto's algae.

Table 2 summarizes the biomass valorization products selected for analysis. In each case, the functional unit chosen for the assessment is **1 kg of product**.

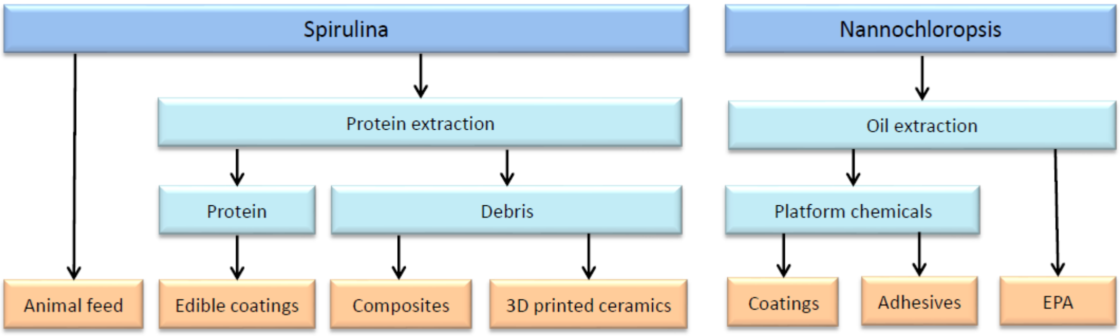


Figure 2. Biomass valorization routes

Table 2. Assessed algae valorization products

Product	Algae type	Benchmark	Partner
Animal feed with algae as additive	Spirulina	Animal feed with fishmeal as additive	Produmix
Gluten composites with algae as filler	Spirulina	Gluten composite without filler	Polimi
Ceramic paste with algae for 3D printing	Spirulina	Ceramic paste for 3D printing without algae Concrete paste for 3D printing	Polimi
Edible coatings with algae	Spirulina	Commercially available product	Funditec

The following aspects of the process steps have not been included in the environmental analysis (also called system cut-offs):

- Capital goods (i.e. the production of the equipment for the facility) are not included in the environmental assessment, as its environmental impact has been shown to be negligible compared to the operational phase (see D7.2).
- The construction and demolition of the demonstration facilities is excluded.
- The maintenance (e.g. chemicals used for cleaning) was not included as it is expected to have a negligible impact.
- Transportation of the wastewater to demo sites has been excluded, as it is assumed that the SaltGae technology will be located next to the industry producing the wastewater when the technology will be fully developed and implemented.
- The chemical load of the inflow and outflow water in the demo site was not included in the model since a high variability in the measurements where observed (D6.2). Hence, we assume that the wastewater treatment function of the demo sites is comparable to conventional wastewater treatment methods. The assessment focuses on the impacts of the process of treating water but does not judge the quality of its performance.
- The impacts related to the industrial process producing the wastewater to be treated are excluded, as these are considered outside the system boundaries.
- For the downstream processes, transportation for the harvested biomass to the final products were excluded.

3.3. Business assessment objectives and scope

The objectives of the business assessment are enlisted below.

- Technology readiness evaluation of all the parts of the system based on the partners feedback.
- Market readiness from the technical point of view based on the partners feedback.
- Production cost assessment of different based on the results from three demo-sites.
- Techno-economic system analysis based on the technical performance, production costs, influence

of legislative issues, SWOT analysis (Figure 47 - Figure 50).

- Business plans based on the TRL levels, market and SWOT analysis. Determine the strategy for the possible start-up activities. Providing roadmap for the future actions necessary for the commercialization of the technology. Identifying necessary resources for the technology to be commercialized. Identifying risks and lifecycle of SME. Identifying operations such as workflow, possible partners to cooperate, quality control and the production process.

In terms of scope, this business assessment is performed based on the current development of the project. The initial business plan will contain the information and recommendations available today. With the development of the technology and production trials, more detailed business plan should be presented. Therefore, the roadmap of the future actions towards the commercialization of the technology is made. The scope of this assessment is to show the strong and weak parts of the technology, and to provide possible solutions and advantages.

As the first step in any technical start-up the importance of the technical performance is significant therefore having the clear picture all the process steps and their technical readiness is significant (see Figure 39). The technical readiness and possibilities are the first issue to determine the potential of the future technology. The cost analysis is based on the market prices and possibilities of commercialisation in different demo-sites. The legislative issues analysis is general due to the difference in standards in different countries, but also due to the lack of existing standards for this technology.

4. SUSTAINABILITY ASSESSMENT

4.1. Methodology

This section presents an overview of the tools and methodologies used for the completion of tasks 7.2, 7.3, 7.4 and 7.5. It starts with the methods used to identify and quantify the impacts on the environment and society (i.e. LCA and S-LCA) as well as the method to account for the cost over the technology's life cycle (i.e. LCCA). Lastly, the method for integrating the results of these assessments into a single sustainability assessment is presented.

4.1.1. LCA, LCCA & S-LCA

Life cycle assessment (LCA) is a systems analysis tool used to quantify the potential environmental impacts associated with the entire life cycle of products, processes and/or services. By applying a holistic cradle-to-grave framework, LCA sheds light on the different environmental impacts of the product's different stages, as well as on the potential trade-offs of environmental impacts linked to its life cycle. The strength of this approach is to avoid shifting burdens between different stages or different types of impacts. The LCA in this study follows as closely as possible the basic principles and framework described in the ISO standard 14040. According to the standard, an LCA consists of four iterative phases: goal and scope definition, life cycle inventory analysis, life cycle impact assessment phase and results interpretation. The phases are described in more detail in D7.2.

Life cycle cost analysis (LCCA) is a tool designed to assist decision-makers to select among different alternatives by providing important data and guidance information in terms of economic figures. LCCA has been defined as "process of economic analysis to assess the cost of an item over its life cycle or a portion thereof" [5]. The LCCA should reveal the hotspots of the respective technology. The results are often presented as the net present value or the payback period if discounting is applied and the revenue is also considered. For a pure cost analysis, a comparison of life cycle costs per functional unit with other products could be conducted. It is important to bear in mind that by using these two methods, some difficulties can arise. This work strives after methodological consistency between LCCA and LCA, therefore these analyses have similar system boundary and functional unit. For further methodological description about LCCA, see D7.2.

Social Life Cycle Assessment (S-LCA) is a novel assessment tool that can be used to assess the social and socio-economic aspects of products and their potential positive and negative impacts along their life cycles. In this study, we consider social and socio-economic impacts along the supply chain (i.e. raw material extraction and manufacturing). The S-LCA complements and the environmental LCA with social and socio-economic aspects. Social phenomena have a "multi-layered" nature, this has resulted in a wide variety of assessment methods developed [6]. Multiple methodological approaches [3] [4], indicators [9], ways to account for positive impacts [10], databases [11] and even discussion about the relevance of certain chosen topics [12] are available in the literature. Consequently, the diversity in possible approaches has made it more challenging to standardise S-LCA practice. S-LCA can be quantitative, semi-quantitative or qualitative and can use site-specific or generic data.

4.1.2. Integrated sustainability assessment

Defining and assessing Sustainable Development (SD) is not a simple task. Many efforts to define the concept have been carried out ever since the Brundtland Commission made a first attempt to do so [13]. Different ways to define SD have been proposed through the years. Many of these definitions agree on a well-known "Triple bottom line" definition: people, economy and society must be developed while sustaining nature, life support and community [14]. In order to assure that human development follows sustainable pathways, substantial efforts are needed to ensure that all technologies can achieve an equilibrium between economic, social and environmental demands. Therefore, to asses sustainability one must include its three pillars: environmental, economic and social.

In this study, the LCA covers the environmental pillar, the LCCA encompasses the economic pillar, while the S-LCA examines the social pillar. Through the integrated assessment, the main findings of the life cycle-based assessments are outlined, then discuss synergies and trade-offs between the findings to reveal possible strategies to improve the performance of the SaltGae technologies from a wholistic sustainability perspective.

The integrated assessment consists of three steps. First, the most important findings in LCA, LCCA and the S-LCA were outlined during an internal workshop at RISE. After discussions on synergies and trade-offs, the workshop yielded a set of possible strategies to improve the SaltGae system. The strategies drafted are future oriented and valuable for use outside of the consortium, e.g. other organisations interested in investing in the technology or new research constellations interested in further research and development.

The second step consisted of presenting the set of strategies to algae and wastewater treatment experts within the SaltGae consortium. Based on expert judgement, the strategies and their implications were discussed and assessed in terms of relevance. Further, the discussion highlighted perceived factors that would hinder or enable the achievement of such strategies. The qualitative expert assessment was complemented with a quantitative life cycle-based assessment. In the third and final step, the expert and quantitative assessments are documented in the form of a sustainability roadmap for SaltGae technology.

4.1.3. LCA data

The software used to perform the LCA was GaBi, from Thinkstep. Generic data from Thinkstep and Ecoinvent v3.5 [15] were used to model the background system, i.e. parts of the process on which the SaltGae partners has no control, such as the electricity mix. Primary data was used as much as possible to model the foreground system, i.e. parts of the processes developed in the SaltGae project.

On the algae valorization side, the experiments carried out in the project mostly stayed at laboratory-scale, hence our analysis was based on laboratory-scale data (i.e. formulations and yields) combined with some industrial-scale data (i.e. energy demands for processes). Between D7.2 and D.7.3, a new data collection round was performed, and all the models were updated with the most recent information.

On the water valorization side, demonstration-scale data from the 3 demo sites were used. However, it should be underlined that it is challenging to collect data of good quality for algae cultivation as it requires consistent data acquisition over several years [16]. None of the demo sites was able to provide data for a complete year given the timeframe of the project, but effort was put into reviewing the data and updating it as the project moved forward.

4.1.4. LCCA data

The data used for the LCCA were preliminary based on site-specific data from the demo sites or from laboratory experiments. The study also included a combination of generic data from other work packages, discussions with partners, literature and databases. The data inputs of LCCA models are like the inputs into the environmental models described above: energy consumption cultivation and harvesting system, growth data, and site-specific parameters, such as location, daily dilution rate, mixing and operational days per year.

One major difference between the data needed for LCA and LCCA is that LCCA also business-related data like country specific taxes, production time, discount rates and labour cost. Production yields, raw material cost, equipment costs and estimations for labour costs were received from our partners. The economic performance was estimated with the net present value method based on estimated raw material and energy consumption. The input data were categorized into capital expenditures (CAPEX) and operational expenditures (OPEX). As mentioned in section 4.1.3, the data provided by the demo sites for this study are based on production data, provided on a shorter timeline than a year. Especially labour costs and maintenance costs were based on rough estimations. Output data as potential market prices was researched through a literature review and further discussed with partners. D7.2 includes a sensitivity analysis to the assumptions and their impact on other financial indicators.

Finally, business cases were developed and studied to analyze deeper whether the case could result in new business and what steps would need to be taken. The analysis included for example evaluation of the market size, analysis of business environment, barriers and opportunities.

4.1.5. S-LCA data

This assessment uses a quantitative approach for the evaluation of the Italian and Israeli demonstration sites. The quantitative assessment is based generic social impact data from the *Product Social Impact Life Cycle Assessment* (PSILCA) database developed by *GreenDelta* [17]. The assessment identifies possible impact hotspots of the technology in four stakeholder groups, namely workers, value chain actors, local communities and society. Notice that the S-LCA database is not predictive, it provides information about possible hotspots that need to be further investigated.

The PSILCA database contains data on life cycle social impacts of commodities in a wide array of countries and industry sectors and considers global supply chains. With this database and the product mass and energy flow, social hotspots can be identified in early stages of the development process of the value chains. PSILCA contains data for 54 qualitative and quantitative indicators in 18 subcategories, which relate to the four stakeholder groups. A subset of impact categories was evaluated to measure the impacts of the SaltGae technology. Given the broad range of indicators available, the S-LCA in this deliverable has focused on those identified as relevant for the technologies developed in SaltGae. The process for the selection of the social indicators is described in sections in the following section, section 4.3.3 and 4.4.3, as well as in D7.2.

PSILCA data uses worker hours per US dollar output for each process as “activity variable”. “Activity variables” are necessary to describe the relevance of a social impact caused by a process in a life cycle [18]. The activity variable is the measure of the process activity which can be related to the process output [19]. In order to use PSILCA in our assessment, price data for raw materials and energy used in the SaltGae process were collected. The sources of this price data can be found in Annex X and Annex XII.

Annex XIV outlines the PSILCA datasets used to assess the social risk for each process in the SaltGae system. The datasets selected assess the social risk of a specific sector in a specific region. For the Archimede S-LCA, datasets for Italy are primarily used and proxy data from other European countries is used to fill in missing regional data. For the Arava S-LCA, datasets are used exclusively from Israel.

4.1.6. Impact assessment methods

4.1.6.1. LCA impact assessment methods

Table 3 shows the environmental indicators used in the LCA study to characterise the environmental impact of the studied processes.

Table 3. Environmental indicators and assessment methods

Indicator	**Unit**	**Life Cycle Impact Assessment method**	**Description** [20]
Water consumption	kg water	Blue water consumption according to the water footprint assessment methodology [21]	Measure of the total average water volume that has been sourced from surface or groundwater resources and is either evaporated, incorporated into a product or taken from one body of water and returned to another, or returned at a different time, through all stages of the production of the unit output.

Acidification Potential, AP	kg SO_2 equivalent	CML-IA 2016	The main acidifying air emissions are SO_2, NOx, and NH_3. Acid deposition can occur through acid rains but also in fog, snow and dew. Additionally, dry acidic particles and aerosols are converted to acids when dissolved in surface water or when in contact with moist tissues as the lungs.
Eutrophication Potential, EP	kg P equivalent	CML-IA 2016	Eutrophication is linked to excessively high nutrient levels that lead to shifts in species compositions such as algae blooms. The impact assessment covers nutrients as well as degradable organic pollutants which lead to oxygen consumption by microorganisms in terrestrial and aquatic ecosystems.
Global Warming Potential, GWP	kg CO_2 equivalent	Global warming potential with 100 years perspective (GWP100), excluding biogenic CO_2 emissions. CML-IA (2016). In line with IPCC AR5 (2013)	Characterisation of greenhouse gases based on the extent to which they enhance radiative forcing in the atmosphere and thereby heat the atmosphere, over 100 years.
Photochemical Ozone Creation Potential, POCP	kg Ethane equivalent	CML-IA 2016	Photo-oxidants such as nitrogen oxides (NO_x) and volatile organic compounds (VOCs) can create ozone in the presence of sunlight in lower parts of the atmosphere, also called smog. This can have negative impacts on crops as well as human health.
Primary Energy Demand, PED	MJ	Renewable and non-renewable (net calorific value)	Measure of the total average energy necessary through all stages of production to produce the unit output. All types of energy sources included.

4.1.6.2. LCCA assessment methods

Table 4 presents the economic indicators used in the LCCA study to characterise the economic impact of the studied processes.

Table 4. Economic indicators

Indicator	Life cycle cost analysis (LCCA) method	Unit for characterization
Cost-benefit analysis (CBA)	Cost comparison between the costs for producing a commercially available product (benchmark) and the cost for producing algae-based products (with methods described in the SaltGae project)	€/kg product
Investment cost (CAPEX)	Purchasing cost	€/m^3 water treated
Operational cost (OPEX)	Operating costs, including utility costs such as maintenance, water use and energy costs	€/m3 water treated
Net-present values (NPV)	The net present value of the project, in today's euros	€
Pay-back time	The time it takes to pay back the investments in the project	Years

4.1.6.3. S-LCA assessment methods

Table 5 displays the social indicators used in the S-LCA and describes their attributes within the PSILCA database. To be able to compare processes and indicators in the assessment, the indicators are risk assessed. The indicator assessment uses an ordinal level of measurement. There are six levels: no risk, very low risk, low risk, medium risk, high risk, and very high risk. The assignment of level is based on e.g. international conventions, labour laws and standards.

Each of these levels is assigned a quantitative impact factor, or equivalence factor. The equivalent unit or reference unit for all indicators is medium risk hours. For example, for the indicator of fatal accidents in the workplace, the medium risk level is defined to be between 15 to 25 accidents per year. If a sector in a specific region has an amount of fatal accidents higher than 25 per year, this sector would be assessed to have a high risk or very high risk of fatal accidents and assigned an impact factor higher than 1.

The five indicators selected for this assessment are presented in Table 5. Four of these indicators relate to health and safety issues for workers, whereas one of these indicators assesses impact to local communities, specifically whether the access of local communities to material resources is restricted because of commercial or industrial activities in their regions.

Table 5. Social indicators

Indicator	Unit	Medium risk hour	Description
Disability-adjusted life years (DALY)	years/100,000 population	15 - 30	Assessing health and safety issues for worker. Assessment of health risks due to indoor and outdoor air and water pollution. Accounts for healthy years lost from the average life expectancy of the population.
Safety measures	#/100,000 workers	300 - 600	Assessing health and safety issues for worker. The number of safety protocol violations at the workplace per year and sample size.
Non-fatal accident rate at workplace	#/100,000 workers	1500 - 2250	Assessing health and safety issues for worker. Recorded workplace accidents per year and sample size.
Fatal accident rate at workplace	#/100,000 workers	15 - 25	Assessing health and safety issues for worker. The number of fatal workplace accidents per year and sample size.
Industrial water depletion	% use of total renewable water supply	20 - 30	Assessing material access for local communities. Indicator of level of industrial water use related to total withdrawal. This maps the process contribution to depletion of renewable water supply.

4.2. Koto results

The flowchart of the Koto demonstration site below, Figure 3, shows all processes included in our analysis of the *operational phase* impact and cost.

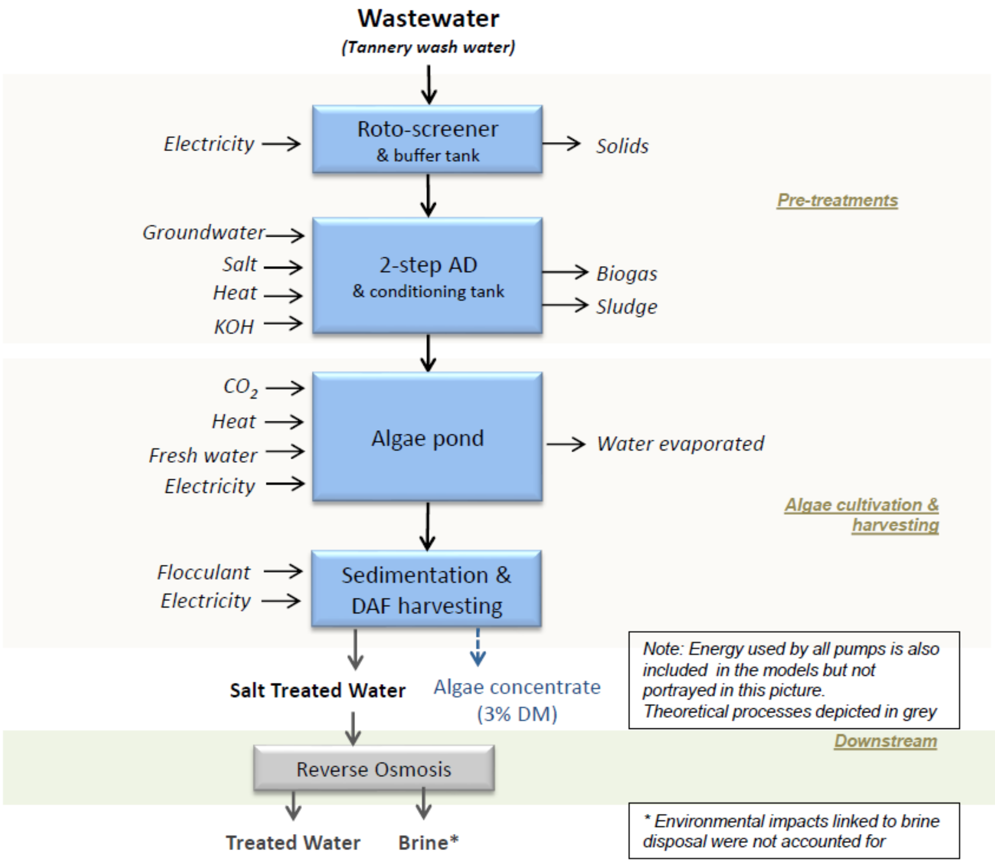


Figure 3. Koto demonstration site flowchart

The *pre-treatment processes* in Koto demo site consist of a roto-screener and a two-step anaerobic digestor (2-AD). The raw wastewater from the tannery industry enters the roto-screener where solids are removed, after which it goes into a buffer tank. The raw wastewater is then fed into the two-step anaerobic system. The SaltGae set up is designed for the treatment of high salinity wastewater while generating biogas. It consists of two phases: acidogenic and methanogenic. The biogas produced in this process is sent to the existing CHP plant where it is burned to produce heat and electricity. This step requires freshwater, some salts and heat.

The pre-treated water is then transferred to the algae pond where it is further treated with a mix of microalgae. In the algae pond, CO_2 sourced from the adjected biogas CHP plant is added. Heat is also added through a floor heat exchanger. No extra nutrients are added to the pond, as all the nutrients needed for algae growth are in the wastewater. Notice that possible nitrous oxide emissions from algae pond is not considered in the analysis since no sire specific data was available. Finally, the algae are harvested using sedimentation and dissolved air floatation (DAF). The Koto demo site does not include equipment for the drying of the algae. Therefore, the two flows coming out of the Koto demonstration site are: algae concentrate with on average 6 % dry matter and treated wastewater.

There are 14 pumps installed in Koto also considered in our analysis, see the list in Annex II. All energy (i.e. electricity and heat) for the site is sourced from the adjacent CHP plant. The data used to model the processes for Koto is presented in Annex III. Since D7.2, the energy data for the pumps has been updated, resulting in lower values for the 2-AD system and slightly higher values for the pond.

Since the tannery water treated at the Koto demo site has high levels of salinity, it is assumed that the water should be desalinated after algae harvesting even though it is not currently performed. Energy for a reverse osmosis process was added to the LCA model, inducing an outflow of 50 % brine and 50 % desalinated water. Estimations for the RO energy consumptions where determined by Greg McNamara with the DOW ROSA software used for water and process solutions modelling. Environmental impact of brine disposal was not considered. See section 0.

4.2.1. LCA results

The LCA performed is a hotspot analysis, shown in Figure 4 per sub-system (A) and per input/output (B). Here, the results are normalized in order to see the relative contribution of each sub-process or input to the total environmental impact of the categories assessed (Water consumption, acidification potential (AP), Eutrophication potential (EP), global warming potential (GWP), photochemical ozone creation potential (POCP) and primary energy consumption). The absolute results can be found in Annex I.

The sub-systems presented in Figure 4A are the following:

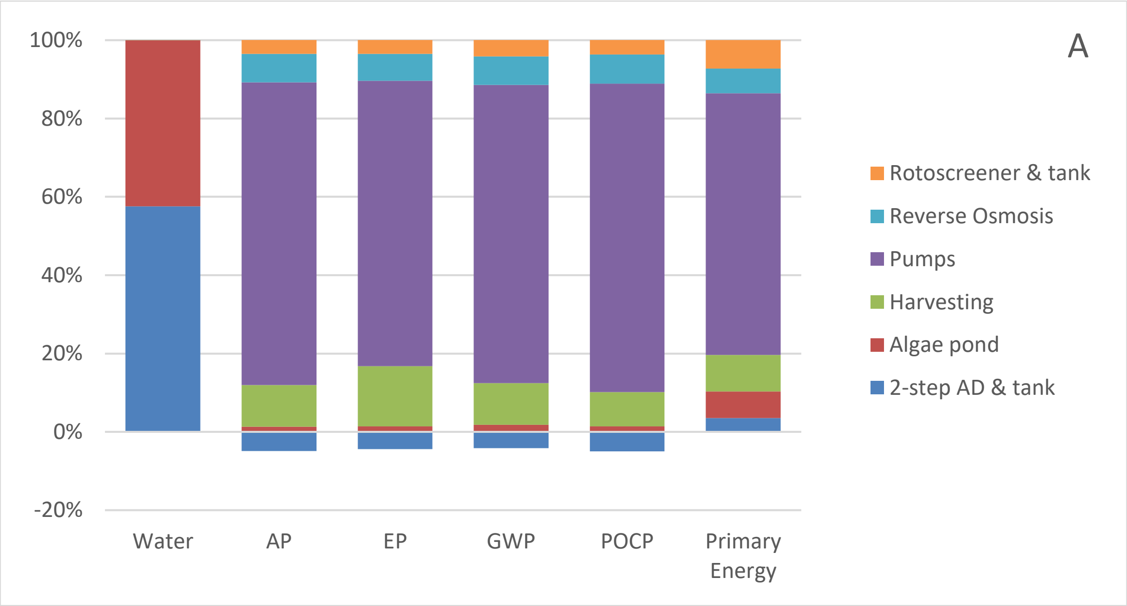
1. Roto-screener & tank
2. Reverse osmosis
3. Pumps
4. Harvesting
5. Algae pond
6. 2 step-AD & tank

The first four sub-systems include the direct energy used by the specify equipment only. For example, the 2 step-AD system & tank category includes the thermal energy used in the AD system and the electricity used for the tank mixer; meanwhile the pumps category includes the energy used for the feed pumps, recirculation pump and diluting pump to the AD system. Thus, the categorization is done for analytical purposes only.

The inputs and outputs presented in Figure 4B are:

1. Heat and power co-generation
2. Flocculant production
3. Ground water input
4. Biogas credits

These 4 categories were chosen because they summarize all the major inputs and credit that have a noticeable effect on the environmental impact results. Potassium chloride is also an input in the 2-AD system; however, its impact is too small to be observed in the results. The following section will discuss more closely the different aspects of the results, following the inputs and outputs perspective.



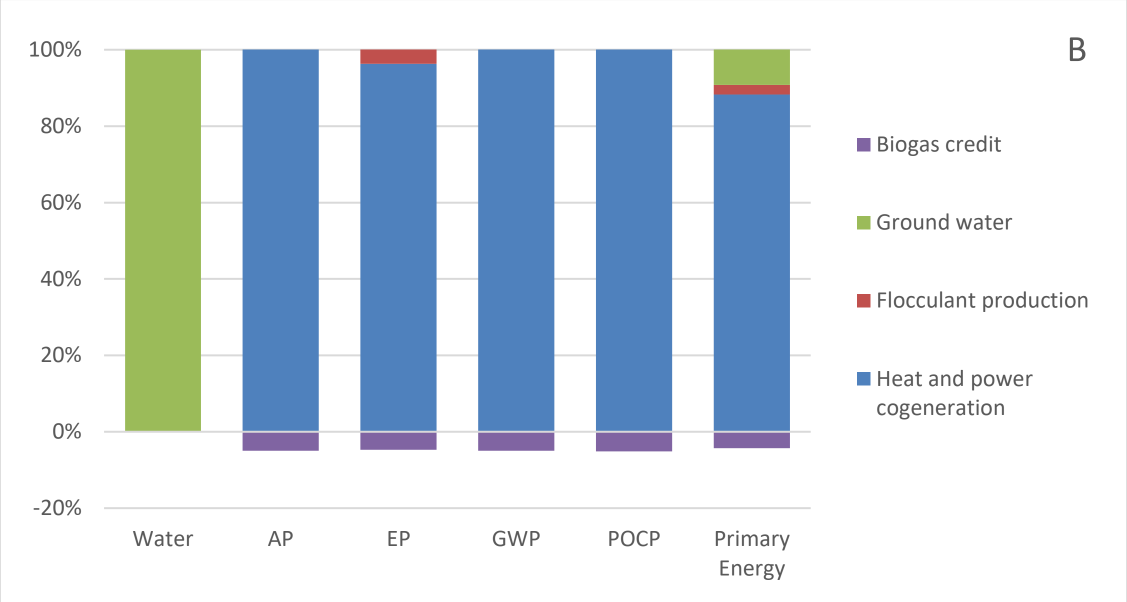


Figure 4. A and B LCA hotspot analysis of the Koto demo site, per sub-system (A) and per input/output (B)

Freshwater use. For each m^3 of water treated at Koto, 1.04 m^3 freshwater are needed, of which 60 % is in the 2-AD system and 40 % is used to compensate for evaporation in the open ponds (Figure 4A). This freshwater input is the sole contributor to water consumption (Figure 4B). The reason for this freshwater demand is the high salinity of the tannery water received at Koto, which is problematic for the non-halophilic bacteria used in anaerobic digestion. A scenario where final effluent is used as the clean water source is explored in section 4.7, and would be considered in the case of a full-scale SaltGae set-up. For more discussion around the water flows in the three demo sites, see section 4.8.2.

Heat and power used. The main input of the process is the electricity needed to run the plant. In this case, all the electricity comes from a CHP plant. The energy consumption contributes of at least 80 % of the impact for AP, EP, GWP, POCP and primary energy demand. Figure 4A shows that the pumps are overwhelmingly the biggest energy consumers in the system. The most energy consuming pumps in the system are the recirculation pumps of AD1 and AD2 as well as the electricity circulation pump and the heating water circulation pump of the pond (respectively 2.4; 2.4; 3.0 and 2.16 kWh/day, see Annex III), together accounting for 65-70 % of the pump energy consumption. One reason for the very high impact of the pumps in the case of Koto is the fact that the plant is oversized for the current water flow, 0.45 m^3 raw wastewater per day.

Biogas production. The biogas produced in 2-AD system give credits to the system for AP, EP, GWP, POCP and primary energy demand. Figure 4B shows that the credits equate to about 5 % of the overall impact of the system.[1]

Flocculant. The production of flocculant used, polyacrylamide, is responsible for about 8 % of the impact on EP but does not have a significant impact on other impact categories.

CO_2 addition. Two major aspects for algae cultivation LCA are not shown in Figure 4 since they have no impact in the case of Koto. First, the CO_2 input which is burden free because it is sourced from the adjacent CHP plant. Second, the impact of the CO_2 leaked by the system (discussed in section 4.3.1) is not accounted for, since the CO_2 used at Koto is biogenic.

[1] Theoretical biogas production calculations by NOVA in 2018 were used in this LCA. According to NOVA lab scale experiment, daily biogas production in Koto would be around 0.25 kg of methane equating to total energy recovery of around 3.8 kWh/day. By the end of the project an electricity production of 9 kWh/day and a heat production of 18 kWh/day was reported by Algen. The latter numbers were never confirmed. Following the precautionary principle, the lower biogas production value was used in the LCA. This avoids overestimating biogas credit and underestimating total GWP impact of the site.

Biomass production. No credits were given to the system for producing algae while treating water, for the reasons stated in section 4.5.1. The biomass produced at Koto is not a single microalgae species. Further, the biomass produced at this specific demonstration site would probably have to be used for lower value product than the ones presented in the biomass valorization routes. Additionally, no drying step was integrated at Koto and was therefore not accounted for in the model.

Even though the quality of the water treatment performed is crucial in terms of impact to environment, the chemical load in the tannery water and the treated water at Koto were not included in the model due to large variations on the measured data (D6.2). Therefore, no comment can be made on the quality of the treatment of the water other than that the demo site is compliant with the local regulations for water discharge limits. For more details, see D6.3.

4.2.2. LCCA results

The results presented in this section shows the operational economic impacts of treating 1 m^3 of wastewater at Koto. It is presented as a hotspot analysis. The *operational phase* results are analyzed using the five sub-systems presented in Figure 5 and additionally a category specific for all pumps installed throughout the system.

1. Roto-screener & tank
2. 2 step-AD & tank
3. Algae pond
4. Harvesting
5. Reverse osmosis
6. Pumps

As shown in Figure 5, the major operational phase cost expenditure encountered in Koto is labour cost. Since Koto is still on demo scale, labour cost has a high impact on the overall cost. Therefore, in order to show the impact, labour have been given its own stack and is presented on its own as shown in Figure 5. Salaries were taken from average labour costs in Slovenia (Annex X). The total annual labour time was based on data from the demo site and the total cost of labour amounts to 17,300 €/yr. Maintenance costs for each category is in average around 30 % of the category's total impact, which can be changed when the concept goes from demo to an industrial site.

For the pumps it is mainly the pumps connected to the anaerobic digesters (feed pumps, recirculation and diluting pumps) that contributes to the cost in the operational phase. They also contribute with the highest energy consumption for each of the sub-systems.

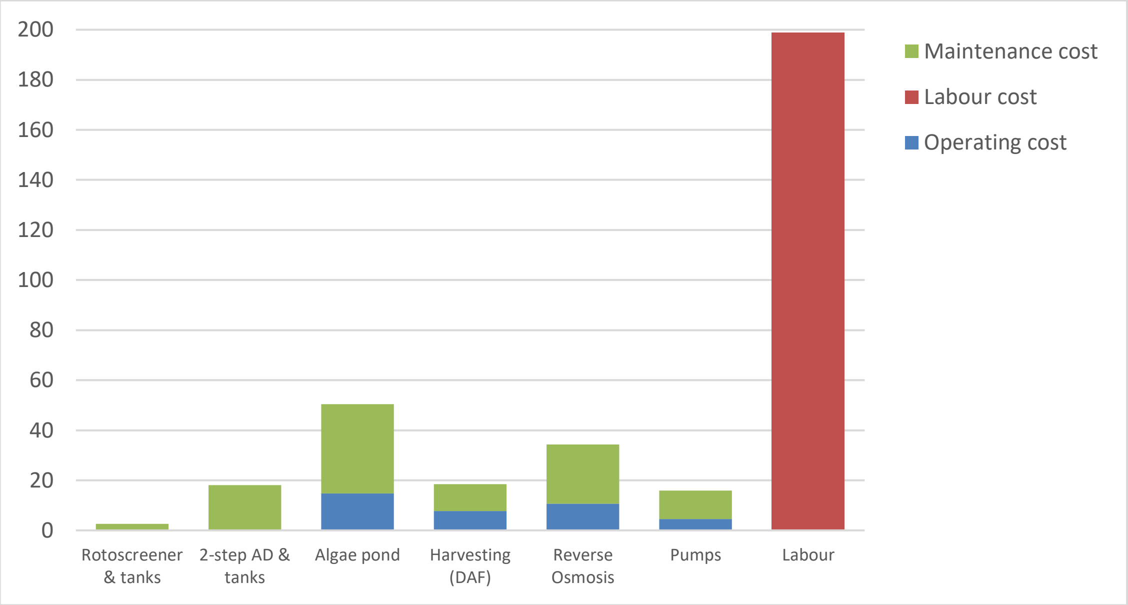


Figure 5. Koto cost distribution – operational cost (€/m^3)

The data series called O*perating costs* includes costs for purchasing raw materials like potassium and coagulants, but also costs like water evaporation and energy consumption; costs which are needed for the facility to be running properly. For this series it´s the algae pond and the Reverse Osmosis that represents the highest costs. In both cases the energy consumption stands for almost 30 % of the total operational cost per functional unit. But in absolute number, a change in electricity price do not influence the treatment cost to any large extent. The same applies for changes in the price of fresh water and chemicals; the cost of water constitutes a minor part of the total treatment cost and thus changes in the price of water is of minor importance for the operational costs.

4.3. Archimede results

The flowchart below, Figure 6, depicts all processes performed at the Archimede demonstration site. The processes included in the analysis of the wastewater treatment *operational phase* impact and cost are the activities for *water pre-treatment* and *algae cultivation and harvesting*, namely the roto-screener & tank, the DAF & tank, the algae ponds and the ultrafiltration & centrifugation used for harvesting. The impact for algae drying is only considered when the functional unit is 1 kg DW biomass produced.

Wash wastewater from the dairy industry is first stored in two existing storage tanks. It is then pumped to the roto-screener where solids are removed. From there, it goes into a transfer tank where the pH is balanced using phosphoric acid. The wastewater is then fed into the DAF where it is further pre-treated, and sludge is extracted. Following that, the pre-treated wastewater is pumped to a buffer tank where electricity is used for mixing.

The pre-treated wastewater is then transferred to the growth pond and then to the starvation pond, where algae growth and starvation is performed. Notice that inoculum is grown in photobioreactor (PBRs) using freshwater. Freshwater is also used to balance water evaporation from open ponds.

Sodium nitrate and a small amount of micro-nutrients is used to enhance algae growth in the pond. The main components of the micro-nutrient mix are sodium phosphate and phosphoric acid. Carbon dioxide (CO_2) is added in the photobioreactors for both *Nannochloropsis* and Spirulina. Spirulina cultivation requires addition of sodium bicarbonate to regulate the pH. *Nannochloropsis* cultivation requires additional CO_2 in the open ponds.

The CO_2 added in Archimede is food grade and is bought from the market in liquid form. There is CO_2 produced in the adjacent CHP; however, this CO_2 cannot be used in the ponds since it is not food grade CO_2. Amounts of micro-nutrients, sodium nitrate and CO_2 as well as the yield depend on the microalgae species, as shown in Table 6.

Waste heat sourced from the adjacent CHP plant is used to control the pond temperature, with no extra cost. Ultrafiltration and centrifugation process are used to separate the treated water from the algae (i.e. to harvest the algae). Out of the harvesting process treated water and algae concentrate with 20 % dry weight is obtained. The algae concentrate is further dried trough spray drying, producing an algae powder with less than 5 % water content. The spray drier uses heat from natural gas and electricity from the Italian grid.

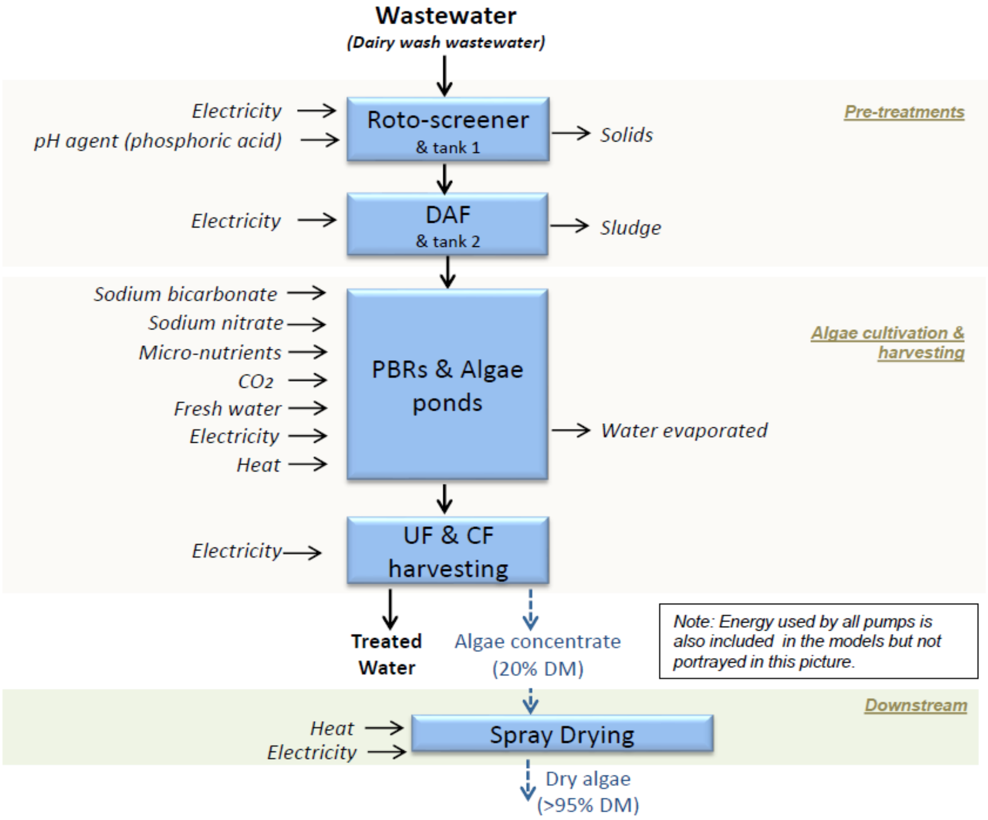


Figure 6. Archimede demonstration site flowchart

Note that all CO_2 not absorbed by the microalgae is assumed to be emitted to the air, i.e. no carbon is fixated in the water.

There are 15 pumps installed in Archimede demo site considered in the analysis, see the list in Annex IV. The data used to model the processes for Archimede is presented in Annex V. All electricity used is sourced from the Italian grid.

Table 6. Varying factors for *Nannochloropsis* and Spirulina cultivation in Archimede

	Algae produced, kgDW/day	**Micro-nutrients** L/kgDW	**CO_2,** kg/kgDW	**CO_2 uptake efficiency,** %	**Sodium nitrate,** kg/kgDW	**Sodium bicarbonate,** kg/kgDW
Spirulina	19.5	0.51	4.5; PBR only	40	0.17	0.56
Nannochloropsis	18.2	0.55	9; PBR & ORP	20	0.09	0

PBR: Photobioreactor, ORP: Open raceway pond

4.3.1. LCA results

Two LCA analysis were performed for Archimede:

- A hotspot analysis of the site, with the functional unit **1 m^3 water treated.**
- A comparison of the environmental impacts of *Nannochloropsis* cultivation vs. Spirulina cultivation, with the functional unit **1 kg DW biomass produced.**[2]

[2] Note that spray drying was not included in the wastewater treatment models but were included in the biomass production model. The energy demand for spray drying accounts for about 20 % of the overall GWP of producing 1 kg of Spirulina.

Hotspot analysis

Data for Spirulina cultivation was used throughout this section since it was found to perform better economically and for most of the environmental impacts, compared to *Nannochloropsis* (see section comparing *Nannochloropsis* and Spirulina). In order to see the relative contribution of each process component, results for each environmental impact category assessed (Water consumption, acidification potential (AP), Eutrophication potential (EP), global warming potential (GWP), photochemical ozone creation potential (POCP) and primary energy consumption) are normalized. The absolute results can be found in Annex I.

Figure 7A and B show the results of the hotspot analysis from two different perspectives. First per sub-system (Figure 7A) and second, per input/output (Figure 7B).

The sub-systems presented in Figure 7A are the following:

1. Roto-screener & tank
2. Pumps excluding pond
3. Harvesting
4. DAF & tank
5. Algae pond

The first four sub-systems include the direct energy used by the specify equipment only. For example, for the roto-screener category, only the energy used for the screen drum motor is considered, thus the energy used for pumping the water to the roto-screener is under the category pumps. Accordingly, the categorization is done for analytical purposes only. Notice also that drying is not included in this analysis.

The input and outputs presented in Figure 7B are:

1. Sodium nitrate production
2. Micro-nutrients production
3. Liquid CO_2 production
4. Freshwater input
5. Electricity production
6. CO_2 leakage

These 6 inputs and outputs were chosen because they summarize all the major inputs that have a noticeable effect on the environmental impact results.

The sub-system results show that overall, the algae pond have the largest environmental impact due to its large demand in energy for pumping and mixing, as well as the addition of sodium nitrate, freshwater, liquid CO_2 and micronutrients. The following paragraphs will go into more detail of each the inputs and outputs shown in Figure 7B.

Electricity. The energy consumption is a major importance in the LCA and impacts heavily all the categories. The impacts are dependent on the local energy mix. According to the IEA World Energy Balances 2018, the Italian electricity mix was composed of 39 % natural gas, 11 % renewable energies, 5 % nuclear energy, 7 % coal and 35 % primary and secondary oil in 2016. Resulting in an electricity mix GWP of approximately 0,41 kg CO_2-eq/kWh.

Sodium nitrate. Sodium nitrate is a hotspot in the system mainly for EP (70 %), GWP and POCP. The dataset used was modelled for Europe, combining stoichiometric calculations with data from a large chemical plant in Germany. Sodium nitrate is synthetized industrially by reacting tail gases from nitric acid plants with sodium hydroxide or sodium carbonate. Nitric acid production produces nitrous oxide which has 298 times higher global warming potential than CO_2.

Sodium bicarbonate. Sodium bicarbonate is produced in majority through the Solvay process, using salt brine and limestone from quarries. The process is energy intensive and can induce some losses of ammonia in the atmosphere. It also produces calcium chloride in amounts largely exceeding the market demand. Disposal of calcium chloride is therefore an environmental issue for the process. Sodium bicarbonate is used to regulate pH when cultivating Spirulina, since it grows at high pH levels. It contributes to 7 to 20 %

of the environmental impacts of the process (except water). Treated water recirculation could help reduce the sodium bicarbonate needs since the recirculated water would already have the required pH.

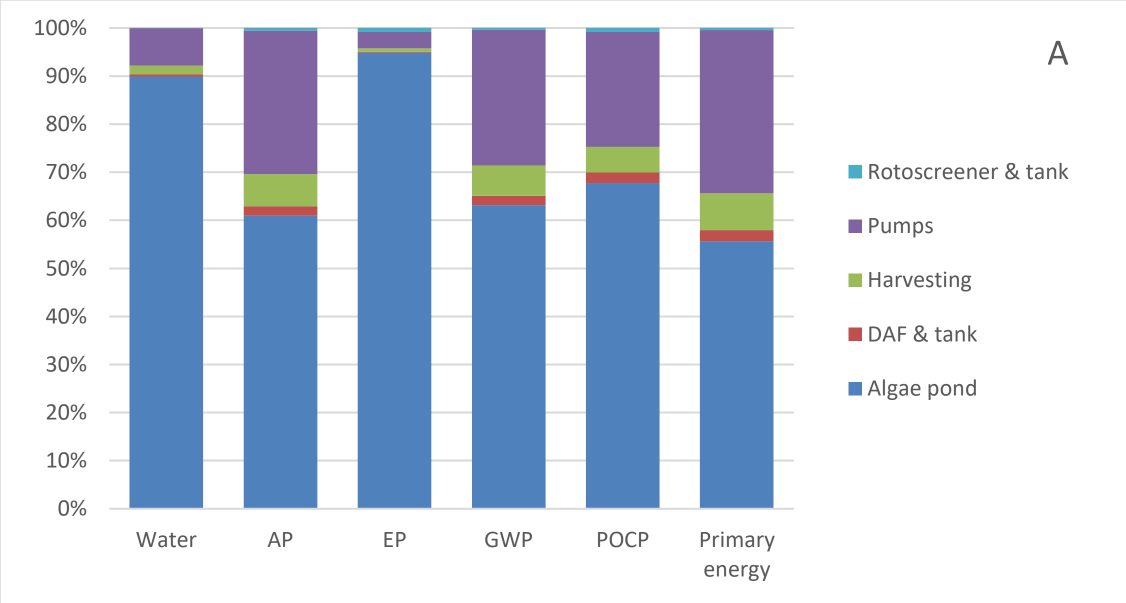
Liquid CO_2. Liquid CO_2 is traditionally produced as a by-product of ammonia production in Western Europe through the Haber-Bosch process which is a very energy intensive process. Even though the CO_2 is a by-product of the process, it carries a heavy environmental impact from its production. The use of liquid CO_2 rather than waste stream from a nearby CHP plant is necessary to ensure the level purity needed for food grade production, including animal feed. It could be argued that in Italy, liquid CO_2 could be produced in geothermal exploitations in central Italy where there is a presence of CO_2 rich fluids [22]. However, no further information about the availability on the market of CO_2 was found. Other sources of CO_2 should be explored, such as bioethanol production by-products.

CO_2 uptake efficiency and leakage. It was shown that when using bubble gases as a way to feed CO_2 to the microalgae, 50 % to 90 % of the input CO_2 is released into the atmosphere.[23] In the case of Archimede, we verified this claim by comparing the carbon content of the produced microalgae with the CO_2 input, and found losses of approximately 80 % for *Nannochloropsis* and 60 % for Spirulina. See the section comparing the two species for further details. This issue is particularly significant when cultivating *Nannochloropsis*, for which CO_2 must be blown in the shallow open pond which have the limitation of not allowing the gases to fully dissolve in the water.

Tap water input. Freshwater is used to grow the preculture in the photobioreactors as well as to compensate for evapotranspiration. For each m^3 of treated water, 0,15 m^3 of tap water is used. For more discussion around the water flows in the three demo sites, see section 0

Even though the quality of the water treatment performed is crucial in terms of impact to environment, the chemical load in the dairy wash water and the treated water at Archimede were not included in the model due to large variations on the measured data (D6.2). Therefore, no comment can be made on the quality of the treatment of the water other than that the demo site is compliant with the local regulations for water discharge limits. For more details, see D6.3.

The LCA results served as a basis for the propositions of scenarios for future developments, presented in section 4.7.1.



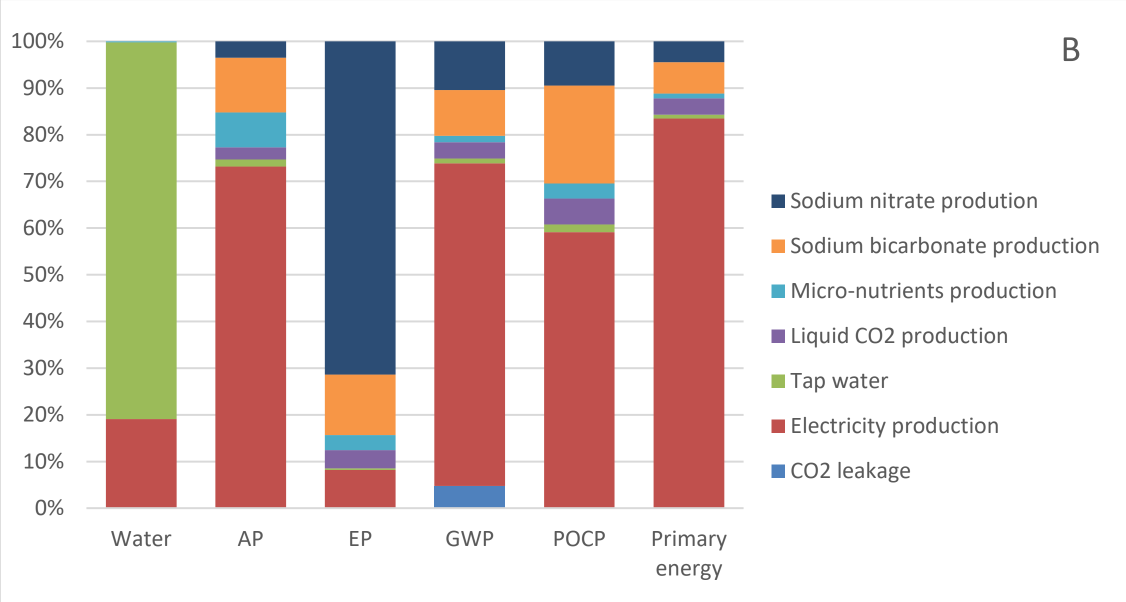


Figure 7. A and B LCA Hotspot analysis of the Archimede demo site using Spirulina, per sub-system (A) and per input/output (B)

<u>Comparing *Nannochloropsis* and Spirulina</u>

The main differences between *Nannochloropsis* and Spirulina are outlined in Table 6. The difference in CO_2 requirements and the CO_2 uptake efficiency of the two species is significant. Spirulina's CO_2 uptake efficiency is higher because Spirulina is an alkalophilic cyanobacteria capable of growing in high pH (9-10) while *Nannochloropsis* is a microalga growing at lower pH level (7-8). A higher pH switches the carbon dioxide – sodium bicarbonate equilibrium, inducing more carbon dioxide uptake. Therefore, less CO_2 is lost when growing Spirulina than *Nannochloropsis*.

Notice also that Spirulina requires sodium bicarbonate while *Nannochloropsis does not*. Spirulina grows at high pH levels, therefore sodium bicarbonate addition in the inoculum is necessary to increase pH levels in fresh water. Furthermore, growing at high pH gives cultivation of Spirulina the additional advantage of avoiding cross-contamination; however, this advantage could not be captured in this LCA.

Another difference between the two species is the optimal temperature for growth, which is around 28-30 ˚C for Spirulina and 18 ˚C for *Nannochloropsis*. This could have significant effects on the energy needs of a theoretical cultivation plant if heating or cooling is needed and should be taken into consideration when choosing the species to cultivate.

Figure 8 shows the relative LCA results of *Nannochloropsis* and Spirulina. In all impact categories, except for EP, Spirulina performs better than *Nannochloropsis*. Spirulina has a slightly higher growth rate than *Nannochloropsis;* therefore, water consumption for Spirulina is 6 % lower than for *Nannochloropsis*.

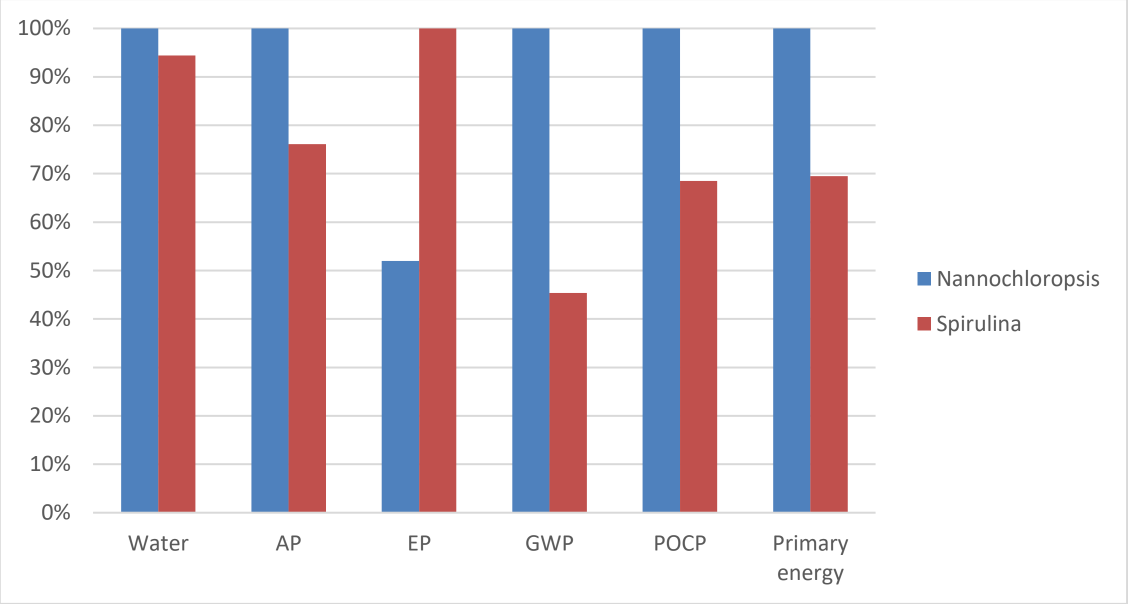


Figure 8. Normalized LCA results for Nannochloropsis and Spirulina produced at Archimede.

For AP and POCP, the impact differences can be attributed to the difference in liquid CO_2 consumption: *Nannochloropsis* needs a much larger CO_2 input than Spirulina. In terms of GWP, Spirulina is 55 % better than *Nannochloropsis* due to that liquid CO_2 input and CO_2 leakage are greater for *Nannochloropsis* than for Spirulina. For the primary energy demand, the 30 % difference stems from the combination of lower liquid CO_2 need and a higher growth rate for Spirulina compared to *Nannochloropsis*.

In terms of Eutrophication potential, *Nannochloropsis* performs better than Spirulina. The reason is the higher demand of sodium nitrate and sodium bicarbonate for Spirulina: both chemicals have a high EP impact during production. Except for EP, the results show that Spirulina cultivation is advantageous in terms on environmental impact compared to *Nannochloropsis* due to its alkalophilic properties.

4.3.2. LCCA results

The LCCA in this section is performed as a hotspot analysis where the results are normalized in order to see the relative contribution of each process and then compare it with the results from LCA and S-LCA. The *operational phase* results for Archimede are analyzed using the four sub-systems presented in Figure 9 plus a category specific for all pumps installed throughout the system.

1. Roto-screener & tank
2. DAF & tank
3. Algae ponds
4. Harvesting
5. Pumps

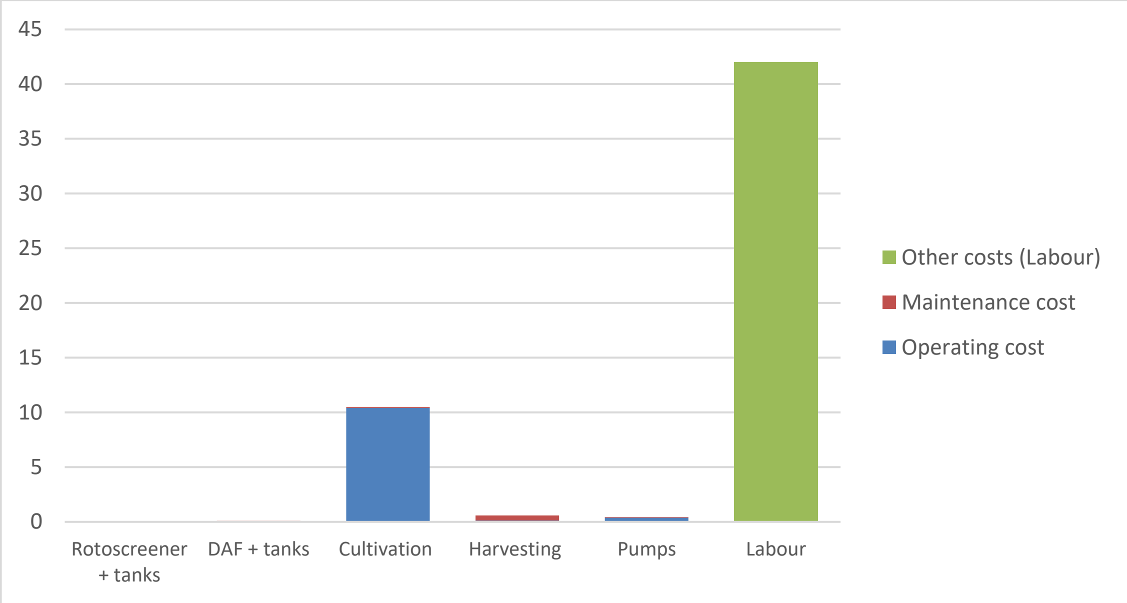


Figure 9. Archimede cost distribution – operational cost (€/m^3)

Figure 9 shows that most of the costs for Archimede are associated with labour costs, which are calculated using Italian salaries (Annex XI). Since Archimede is still on demo scale, labour cost has a high impact on the overall cost. Therefore, in order to show the impact, labour have been given its own stack and is presented on its own as shown in Figure 9. Except for that, cultivation has the main cost input, originating from operating costs, where electricity and nutrients stand for most of the costs. The CO_2 is currently bought from the market in liquid form, but this cost could be reduced by replacing it with the CO_2 produced by the adjacent CHP. But CO_2 cannot be used in the ponds since it is not food grade CO_2. It could be, technology for gas purification systems exists, but due to the scale of the plant it has not been justified. Further on, the cost input for the pumps is rather small in comparison to the other sub-systems presented in Figure 9, but they are a major contributor to the energy demand.

Comparing *Nannochloropsis* and Spirulina

In the following section, the economic impact from the two cultivation species are compared using the functional unit of 1 kg DW biomass produced. For more information, see section 4.3.1.

According to Archimede, assuming the same wastewater flow, *Nannochloropsis* grows 5-10 % slower than Spirulina and needs around 50 % more CO_2, since it uses CO_2 both in the ponds and in the PBRs. It also needs 7 % more nutrients, but 50-60 % less sodium nitrate and 100% less sodium bicarbonate than Spirulina. See **Table 6.** Altogether, this means that treating the wastewater using Spirulina instead of *Nannochloropsis* would improve the annual result with 5 %.

4.3.3. S-LCA results

The social impact assessment of Archimede is based on a series of indicators from the PSILCA database. The chosen indicators were identified according to a materiality assessment that reviewed common interests of stakeholders. The results presented below are normalized to aid the interpretation of results. The overall results show that the inputs for Archimede are all below the threshold of *medium risk*, lying in either *low risk* or *very low risk*. The absolute impact results are presented in Annex XV.

The five selected indicators were disaggregated into three processes. Most of the impact is weighted to the cultivation and harvesting process simply because the mass and energy inputs are far greater at this stage than of the others. About 86 % of the system's social impact is created by four inputs: electricity from the grid, liquid CO_2, micro-nutrients, and sodium nitrate.

Electricity. Electricity derived from the grid accounted for nearly 52 % of total occupational accidents (indicators 1-4). Hazards are related to the generation, distribution, and maintenance of electricity and infrastructure in Italy; thus, it is unlikely that safety accidents from electricity occur onsite at Archimede. Due to the high consumption of fossil fuels in Italy's electricity production, these impacts are more likely to occur outside of the facility (see section 4.3.1).

Liquid CO_2. The production of liquid CO_2 and sodium nitrate constitute the majority of DALYs and fatal accidents. Liquid CO_2 can cause respiratory hazards to workers at high concentrations as well as increasing fire hazard potential from use and storage.

Sodium nitrate. Production and use of sodium nitrate chemicals are perhaps the most threatening of the system inputs. Sodium nitrate is labelled with a warning from the European Chemicals Agency due to its potential as an irritant to workers and its flammability aspect in case of fire. Although, the impacts are not especially high overall, the fact the chemical impacts life quality years and fatality may be of greater concern.

Sodium bicarbonate. The additive of sodium bicarbonate has little effect on the social impacts for the system. Though the chemical is classified under PSILCA as inorganic and indeed capable of causing workplace hazards, the risk is very low when sourced from within the European Union.

Micronutrients. The micro-nutrients used have a large effect on non-fatal accidents, largely due to their classification as 'agrochemicals' within the PSILCA database. The specific chemicals that make up the micro-nutrients are known to be irritants to human health, although none are especially dangerous in the case of fatalities when compared to liquid CO_2 and sodium nitrate.

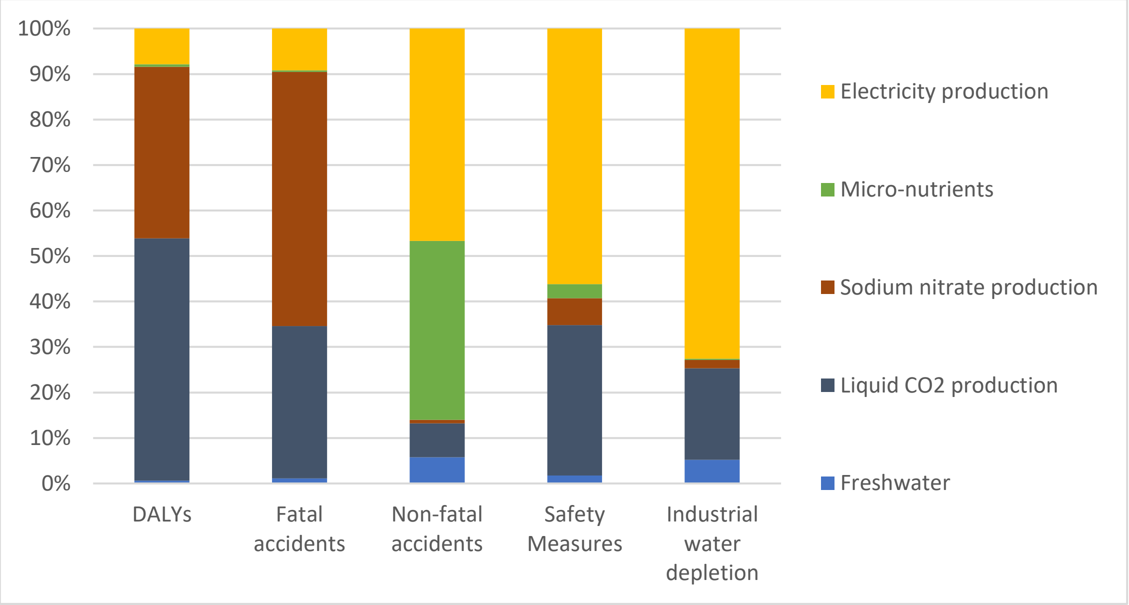


Figure 10. Analysis of social indicators for Archimede

The system's contribution to industrial water depletion was found to be *very low risk* based on reference values in PSILCA. This signifies that the water used in the processes and production of inputs has little impact on other industrial and societal usage. This indicator is important since a major benefit attributed to Archimede is wastewater treatment, thereby generating more water than used in the processes. However, a current limitation of the PSILCA data is the lack of options for examining positive impact. Most of the social indicators are focused on highlighting and measuring negative impacts. This makes it difficult to weigh positive versus negative social impacts, or in the case of Archimede to measure benefits of water treatment and microalgae harvesting against negative impacts from system inputs. Overall, the system shows itself to be socially equitable in terms of labour conditions and resource-use indicators analysed.

4.4. Arava results

The Arava demonstration site is situated in the desert in South Israel. The demo site has an aquaculture unit, for which brackish groundwater is used. The aquaculture enriches the water with nutrients, which is therefore a good candidate for treatment through the SaltGae technology.

The flowchart of the Arava demo site below, Figure 11, shows all processes included in our analysis of environmental impacts and costs of the demo site. The processes included in the analysis of the wastewater treatment operational phase are the activities for water pre-treatment and algae cultivation and harvesting, namely the drum filter, biofilter & transfer tank, the DAF & reservoir, the algae cultivation (in PBRs, small, medium and large ponds), harvesting with vibrating screen, reverse osmosis and solar oven drying.

Wastewater from aquaculture is pumped to the drum filter where large solids are removed. It is then transferred to the biofilter followed by a transfer tank. From there, it is pumped to the DAF system where it is pre-treated with soda, flocculants and coagulants for further solid removal. Sludge is extracted, and the pre-treated wastewater is pumped to a big reservoir tank equipped with a mixing system. This water is then transferred to the ORPs for algae cultivation.

Indoor PBRs are used to grow the Spirulina inoculum which is later introduced in the small ORPs. For optimal growth of the start cultures in the PBRs, air bubbling, air conditioning and light are required. Modified, cost reduced Zarrouk media made of freshwater and nutrients are used in the PBRs. The outdoor cultivation systems in net houses are made of three small, two medium and three large open raceway ponds equipped with paddle wheels. No heating or cooling of the ponds is performed, but shading nets are used to reduce irradiation and heat during the summer months. No additional CO_2 is supplemented to the culture. Potassium phosphate, iron sulphate, magnesium sulphate and sea salt are used to enhance the algae growth and sodium bicarbonate to determine the high pH level. The local evaporation rate is 5 mm/m^2/day.

Biomass harvesting is performed using a vibrating screen, which uses about 5 % of the total volume of harvested algae culture groundwater to wash the Spirulina. The harvesting results in an algae paste. Following that, the water is pumped to a collection tank from which it is pumped to the reverse osmosis unit, producing a flow of desalinated cleaned water and a flow of brine. The Spirulina paste is dried using a solar oven, for which only solar energy is needed. Hence, the three outflows of the systems are desalinated water, brine and dried Spirulina. The output water is of high purity but a pH of around 9.3-9.5. The water is meant to be used for local farmers for irrigation of agriculture crop, which today is performed with brackish water in the Arava desert. Use of desalinated water instead of brackish water on the field could improve crop yields and avoid a gradual accumulation of salt in the soil, which is detrimental for the soil fertility and therefore an imminent problem in the area. An alternative scenario could be recirculation of the harvest water to the algae ponds (section 0) and / or the aquaculture. Environmental impact of brine disposal was not considered. See section 0.

The cultivation method is a batch cultivation with a 2-week cycle, using 150 m^3 fish water in the ORP every cycle which equivalents the total volume of fish water produced by the aquaculture activity of the plant. The PBR volume necessary to produce the inoculum is 480 L per cycle (i.e. 960 L per month). The different ORPs operating in stages (between 3-10 days per cycle) using fish wastewater to increase the algae culture volume to produce at the end of each cycle about 150 kg DW Spirulina. At harvest about 3.5-5 % of the water is lost. The remaining water than goes to the RO for desalination, where 50 % brine and 50 % desalinated water is produced. On average, 35 m^3 water is evaporated every month which is compensated for with ground water.

There are 7 pumps installed in Arava demo site considered in the analysis. See list in Annex VI.

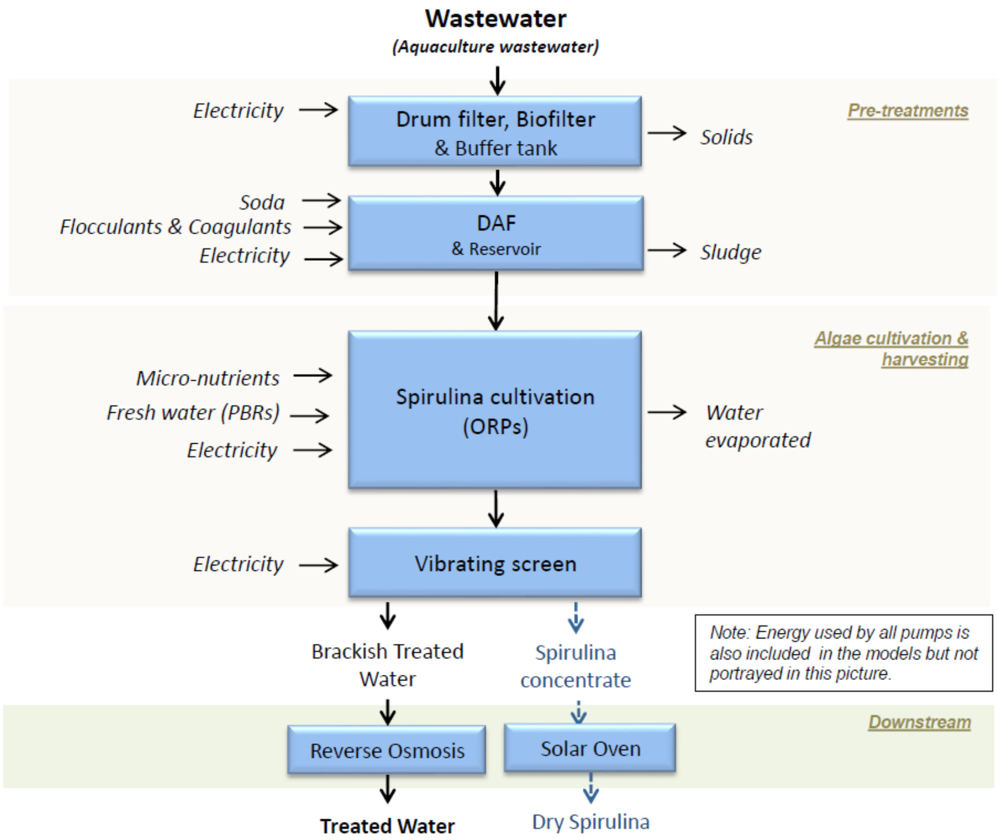


Figure 11. Arava demonstration site flowchart

4.4.1. LCA results

The datasets used to model this process is outlined in Annex VII. The LCA performed is a hotspot analysis, shown in Figure 12 per sub-system (A) and per input/output (B). Here, the results are normalized in order to see the relative contribution of each sub-process or input to the total environmental impact of the categories assessed (water consumption, acidification potential (AP), Eutrophication potential (EP), global warming potential (GWP), photochemical ozone creation potential (POCP) and primary energy consumption). The absolute results can be found in Annex I.

The sub-systems presented in Figure 12 A are the following:

1. Vibrating screen & tank
2. RO
3. PBRs
4. Drum filter, biofilter & tank
5. DAF & reservoir
6. ORPs

Each subsystem includes the direct energy used by the equipment as well and the pumping linked to the subsystem, see Annex VI. More precisely:

- The vibrating screen includes the pump to the vibrating screen and the vibrating screen activity
- The RO includes the pump to the collection tank, the pump to the RO and the RO energy demand
- The PBRs include the lights, bubbling blower and air conditioning
- The Drum filter, biofilter & tank includes the drum filter activity, the fish wastewater pump, the pump to the DAF and the buffer tank heating system
- DAF & reservoir includes the DAF activities, the pump to the reservoir tank and its mixer
- ORPs includes running the ORP and pumping between them

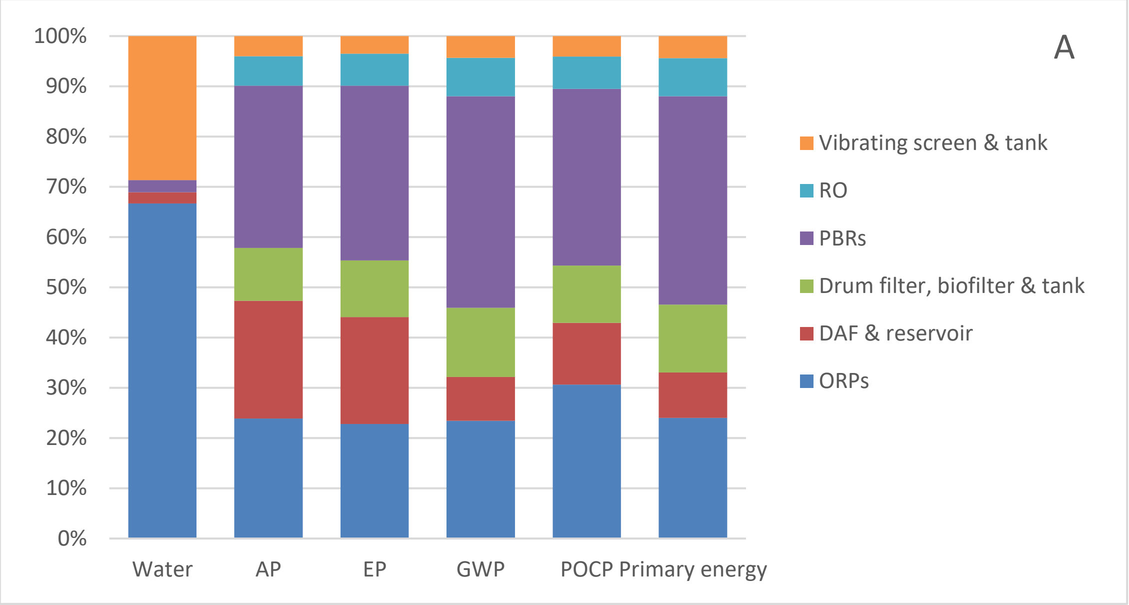
Notice that the drying is performed through a solar oven which consumes no electricity or other inputs and does not contribute to any environmental impact.

The inputs and outputs presented in Figure 12 B are:

1. Sodium bicarbonate production
2. Coagulant production
3. Groundwater use
4. Flocculant production
5. Electricity production
6. Dipotassium phosphate production

These 7 categories were chosen because they summarize all the major inputs and credit that have a noticeable effect on the environmental impact results. Other inputs such as magnesium sulphate and iron sulphate had no observable effect on the environmental impacts of the system.

The sub-system results show that the PBRs and ORPs are the activities with the biggest environmental impact. Except for the groundwater use, the PBRs have a 30-40 % share and the ORPs 20-30 % share on the environmental impact. This differs significantly from Archimede results where inoculum production does not contribute significantly to the impact of the overall process. The reason is the particularly high energy demand of the PBRs at Arava, which operate indoors under controlled growth conditions using T5 HO Cool daylight lamps for enough light supply and air-conditioning for optimal and stable temperature.



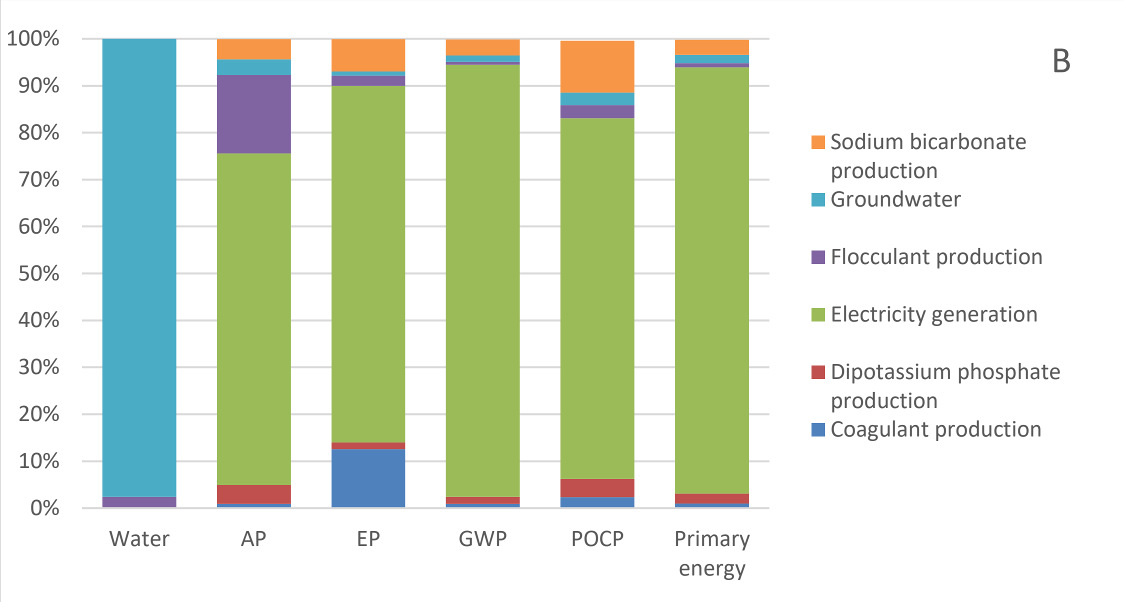


Figure 12. A and B LCA Hotspot analysis of the Arava demo site, per sub-system (A) and per input/output (B)

The following section will discuss more closely the different aspects of the results, going through the major inputs and outputs of the system.

Electricity. Not surprisingly, electricity is a major contributor to all the environmental impacts except water consumption, with a 70 to 90 % share on AP, EP, GWP, POCP and the primary energy demand (Figure 12 B). Except for the solar oven and the transfer of algae from the medium to the large HRAPs, all processes of the SaltGae set-up at Arava consume electricity, especially the PBRs and ORPs (Figure 12 A). According to the IEA 2018, the electricity mix in Israel is largely dependent on fossil fuels, predominately natural gas and coal. Renewable energy only accounts for about 2 % of the electricity mix. Hence, it has a high carbon footprint: 0.79 kgCO_2-eq/kWh which is the reason why the electricity consumption is the most important source of environmental impact of the system. A scenario in section 0 asses how use of solar energy would impact the results. The use of energy saving LED's for the PBRs could decrease energy consumption and costs significantly.

Sodium bicarbonate. As mentioned in section 4.3.1, sodium bicarbonate is produced in majority through the Solvay process, using salt brine and limestone from quarries. The process is energy intensive and induces some losses of ammonia in the atmosphere. It also produces calcium chloride in amounts largely exceeding the market demand. Disposal of calcium chloride is therefore an environmental issue for the process. At Arava, it is added in the ORPs primarily to regulate pH. A scenario analysis was performed where water recirculation prior to the RO is used to compensate for evaporation (section 0). This could help reduce the sodium bicarbonate demand of the system.

Flocculant and Coagulant. The coagulant, aluminium polychloride, has a 11 % contribution to eutrophication potential while the flocculant, a polyelectrolyte has a 15 % contribution to the acidification potential of the system.

Groundwater. For every treated m^3 of fish wastewater, 0.17 m^3 of groundwater is used, which is the lowest of the three demo sites. It is mostly needed to compensate for the high levels of evaporation in the desert (66 %) of the share, but also to wash the algae at harvest (28 %) and in the PBRs where the inoculum is grown in ground water with added nutrients. A scenario recirculating the non-desalinated outflow water instead of using groundwater to compensate for evaporation is explored in section 0. For more discussion around the water flows in the three demo sites, see section 4.8.2.

A scenario exploring another cultivation method, continuous cultivation, is presented in the scenarios section (0).

Even though the quality of the water treatment performed is crucial in terms of impact to environment, the chemical load in the fish wastewater and the treated water at Arava were not included in the model. Therefore, no comment can be made on the quality of the treatment of the water.

4.4.2. LCCA results

The LCCA performed in this section is as a hotspot analysis where the results are normalized in order to see the relative contribution of each process. The *operational phase* results for Arava are analyzed using the three sub-systems presented in Annex XII.

1. Water pre-treatments
2. Algae cultivation and harvesting
3. Effluent treatment

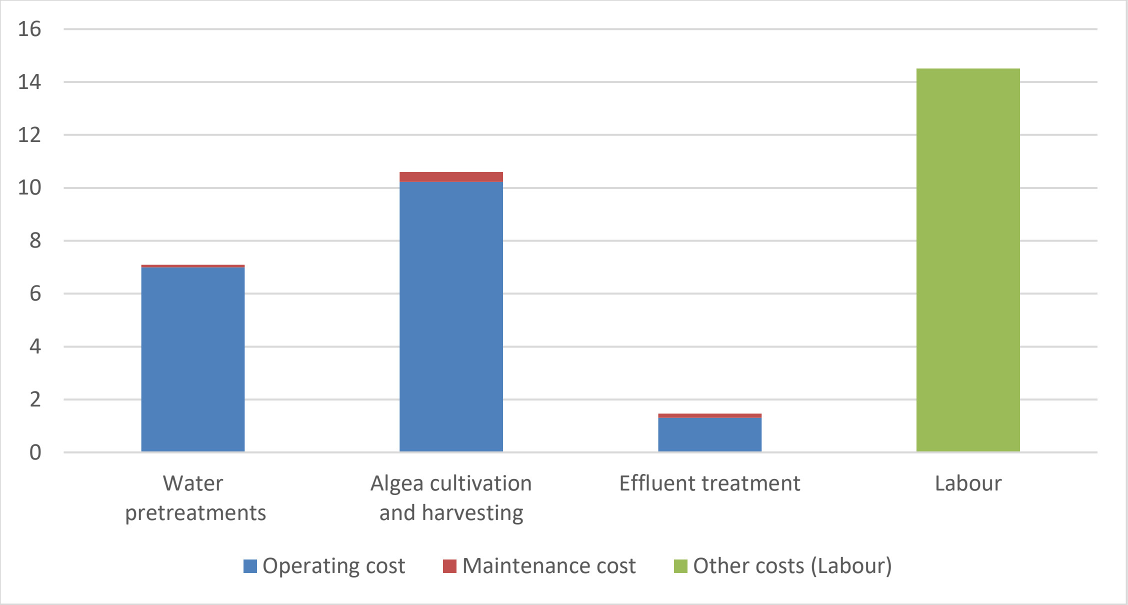


Figure 13. Arava cost distribution – operational cost (€/m^3)

The highest cost group is originating from labour costs, which are calculated using Israeli salaries (Annex XII). Since Arava is still on demo scale, labour cost has a high impact on the overall cost. Therefore, in order to show the impact, labour have been given its own stack and is presented on its own as shown in Figure 5 Figure 13. The second highest cost derives from algae cultivation and harvesting. Most of the cost are additives like coagulants and nutrients. Together they represent 65 % of the operational costs, and similar assessment can be made for the set *Water pre-treatment*. The second highest cost group is originating from labour costs, which are calculated using Israeli salaries (Annex XII).

4.4.3. S-LCA results

The indicators for the social impact assessment of the Arava system were selected in an identical process to the Archimede system. The materiality assessment of Arava produced the same central indicators. Notice that industrial water is directly required for replenishing evaporation and indirectly required for the industrial process for producing raw materials (e.g. sodium bicarbonate). This makes the social indicator for industrial water especially interesting in the water scarce Arava region.

The major contributors to social impact were grid electricity, sodium bicarbonate, and select nutrient additives. These contributors displayed impacts that were close in proportion to their mass inputs. This reveals that the system could see high benefit from the reduction of sheer mass inputs, aside from supply chain sourcing. The indicators fatal accidents, safety measures, and industrial water depletion are in the zone of *very low risk* and *low risk* for all inputs.

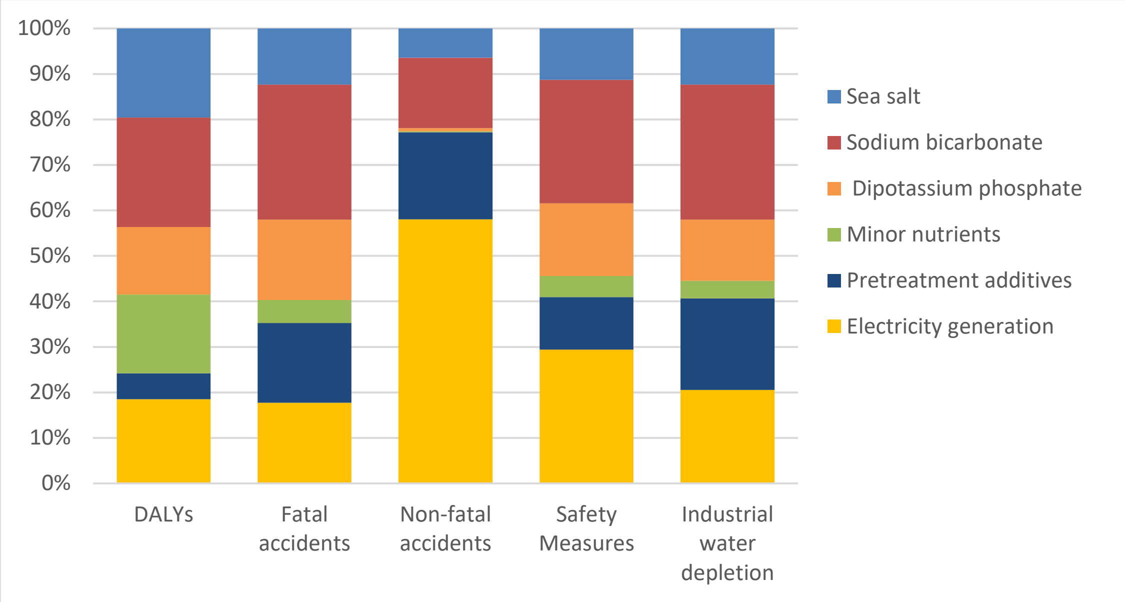


Figure 14. Analysis of social indicators from Arava

Electricity. Using electricity from the Israeli grid generates nearly 31 % of all impact to occupational safety (indicators 1-4). It also makes up the majority (58 %) of non-fatal accidents, which results indicate as being in the threshold of *very high risk*. According to the International Energy Agency 2018, the electricity mix in Israel is largely dependent on fossil fuels, predominately natural gas and coal. Renewable energy only accounts for about 2 % of the grid electricity supply.

Sodium bicarbonate. The production of sodium bicarbonate in Israel has a relatively high social impact when compared to other products in the PSILCA database. The chemical is slightly beyond the threshold of *medium risk* for non-fatal accidents and safety measures but is considered at *very low risk* for the other indicators. This could likely be derived from its classification as a product of mining, an industry which has had a problematic history with labour and environmental practices. The European Chemicals Agency does not classify sodium bicarbonate as a particularly hazardous substance in its solid form, aside from minor irritation on exposure to eyes and respiratory tracts. Fumes from the chemical can be toxic to human health if burned, but the substance does not present problems of flammability.

Nutrients. A portion of social impacts from additives can be based down to dipotassium phosphate. The input is of *low risk* to all indicators. While the chemical has low health impacts for common industrial use, potential long-term health impacts could arise from prolonged exposure and mishandling.

There are two recommendations for furthering the social assessment of Arava. The first would be to utilize a greater number of iterations, or data connections, within the PSILCA database for OpenLCA software. The cut-off used for iterations was $1x10^{-5}$, the minimum recommended for S-LCA in PSILCA. A deeper cut-off, such as $1x10^{-7}$, would produce results as to where the impacts upstream originate exactly. For example, it could be revealed with more certainty that the social impacts of sodium carbonate are derived mostly from mining activities rather than downstream uses. However, deeper cut-offs in OpenLCA require long compiling times and powerful computer hardware to complete.

The second recommendation is to analyse the Arava system with positive-impact indicators. This could be performed by comparing the products derived from Arava with similar product groups from other regions. It is assumed that goods produced in Arava would otherwise have to be imported, possibly from regions that display a greater negative social impact than goods from Arava. This would serve to capture the trade-off benefits of the system in a wider socio-economic context.

4.5. Wastewater treatment benchmark

An important aspect when having final LCA and LCC results is to compare them with results for existing technologies performing a similar function. This gives perspective to the results and helps grasp the order of magnitude of the different environmental impact results.

The system chosen as a benchmark for the SaltGae water treatment technology was conventional aerated sludge. Wastewater treatment will generally be a cost rather than an exercise generating profit. It is, therefore, difficult to gain an understanding of the economic and environmental benefits of the SaltGae Solution in a stand-alone system analysis. To gain a clear understanding of the SaltGae system performance, the LCCA/LCA includes a benchmark system for comparative assessment. The benchmark system used in this study is the anoxic-oxic (AO) configuration of the CAS system with the condition to desalinate for WW salinity > 2,000 mg/l (Figure 15). The anaerobic-anoxic-oxic (AAO) system was considered for the benchmark system in order to mitigate some of the cost of phosphorus removal; however, the AAO system requires a high level of expertise and is difficult to control with very small influent flowrates. Benchmark parameters, associated values, and data sources are provided in the appendix.

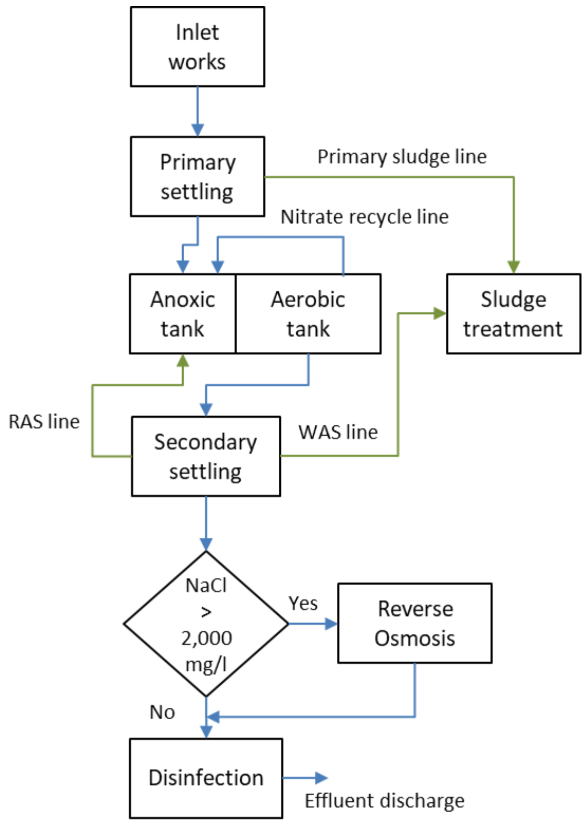


Figure 15. Anoxic-oxic configuration CAS benchmark system

4.5.1. LCA benchmark

In the specific case of the SaltGae water treatment technology, the system is multifunctional, i.e. it performs two functions: treating water and producing microalgae. Therefore, in order to be able to compare the water treating function of the system with a more traditional water treatment system, the multifunctionality must be solved by compensating for the microalgae production function in the calculations. Meaning, giving credits to model to account for the microalgae function. This method is called system expansion and requires reliable life cycle inventory data for a standard microalgae production.

However, finding reliable data for comparable microalgae production is problematic. While LCAs on new technologies can serve as a guide for more sustainable technology development, it comes with a series of challenges: pilot scale data may not be representative of large scale process and numerous assumptions such as system boundaries have to be made which are not always clearly reported [24]. Studies comparing lab-, pilot- and full-scale scenarios of life cycle energy and emission profile of algae biofuels showed the large uncertainty that arises from performing LCA on emerging technologies [25]. More specifically, numerous microalgae LCA have been performed with a lack of industrial data, producing a wide range of results [26]. For example, estimated GHG emissions for bio-oil derived from microalgae lipids range from -100 to 500 gCO_2eq/MJ [27]–[30]. The variability is due to different assumptions about the type of cultivation system, assumed lipid content in the strains, as well as methodological choices such as system boundaries or allocation methods.

Additionally, it is challenging to collect data of good quality for algae cultivation as it requires consistent data acquisition over several years [16], which adds an additional layer of uncertainty and variability in the assessments. Open pond cultivation systems like the ones used in SaltGae are subject to external factors such as weather conditions and potential contamination which makes the short-term data only partially reliable. This makes it extremely difficult to find a standard microalgae production system; the data should correspond to a series of criteria: coming from a similar cultivation system, situated in a region with similar weather patterns, producing the same species.

Nevertheless, 9 LCA studies for either *Nannochloropsis* or Spirulina cultivation were assessed [31]–[40], but no study transparent enough to combine all of these criteria was found. This observation was also made by the JRC in their report on biomass production, stating a lack of availability and quality on algae data [41]. Table 8, columns 5 and 6 show the results when system expansion trials were performed using data for the two LCA studies that were the closest to the SaltGae technology. Additionally, since Spirulina could replace fishmeal in animal feed, a system expansion trial was performed using fishmeal to account for Spirulina production in the Archimede wastewater treatment model. The results are shown in Table 8 column 7.

Overall, the results show how significant the choice of data for the system expansion impacts the results, which are meant to be compared with conventional aerated sludge results (Table 8 column 8). For this reason, it was decided to discard benchmarking for the water treatment part of the SaltGae project in this study.

4.5.2. LCCA benchmark

The CAPEX curve for the AO system was developed from the study conducted by Foes et al [42] (Figure 16). The costs were adjusted from 1998 to 2019 with the US construction cost index (1998 = 5952, 2019 = 11234), and the exchange rate on 26/03/2019 was $1 = 0.89 €. The CAPEX curve does not include the cost of land or the RO system. Desalination costs are added in the event RO is required.

The AO system OPEX includes the cost of energy, chemicals (Table 7), sludge management, labour, and an annual 5 % of CAPEX for maintenance. The approach adopted for labour hour estimations is based on the report published by the *New England Interstate Water Pollution Control Commission* (NEIWPCC) [43]. Sludge management costs are distributed between energy for pumping and dewatering, chemicals for thickening, and final disposal with a nominal value of 40 €/ton (sludge disposal specific costs apply to both benchmark and SaltGae systems). The primary energy sinks in the AO system are aeration, pumping, and sludge treatment; accounting for > 90 % of the total energy.

SaltGae SVT tech. manual is recommended for details related to the benchmark system modelling.

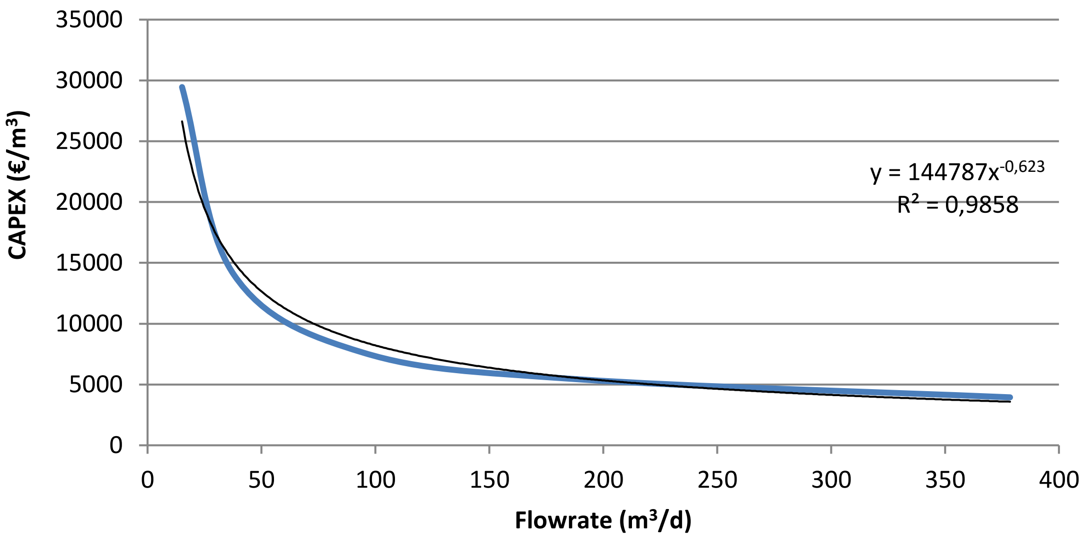


Figure 16. Anoxic-oxic system CAPEX curve

Table 7. Chemicals and specific costs

Chemical	Formula	Cost
Ferric chloride	$FeCl_3$	0.70 €/L[3]
Sodium hydroxide	NaOH	0.77 €/kg [44]
Calcium hydroxide[4]	$Ca(OH)_2$	0.20 €/kg [45]
Polymers (acrylic acid)	Variable	5 €/kg [46]
Calcium hypochlorite[5]	$Ca(OCl)_2$	1.53 €/kg [47]

[3] Estimated from personal communication, Acorn Water, Bandon, Co. Cork, Ireland
[4] Estimated cost is based on U.S values adjusted from 2013 to 2017.
[5] Original price was quoted for 65% available chlorine; price presented here has been adjusted to represent 100% chlorine.

Table 8. LCA results for 1 m^3 of water treated at Archimede with *Nannochloropsis* and Spirulina production, without system expansion and with system expansion with data from two different studies (*Nannochloropsis* model) and fishmeal (Spirulina model) and results for conventional aerated sludge.

Impact category	Unit	Results Archimede WWT, *Nannochloropsis* *	Results Archimede WWT, Spirulina*	Results Archimede WWT *Nannochloropsis* - system expansion with algae LCI 1 [31]	Results Archimede WWT *Nannochloropsis* - system expansion with algae LCI 2 [36]	Results Archimede WWT Spirulina - system expansion with fishmeal	Results conventional aerated sludge
Water	kg water consumed	251	237	-116	-200	237	14,9
AP	kg SO2 eq.	$3.5x10^{-4}$	$2.6x10^{-4}$	$7.9x10^{-5}$	$-1.63x10^{-3}$	$2.4x10^{-4}$	$1.2x10^{-4}$
EP	kg P eq.	0.006	0.011	$3.9x10^{-3}$	-0.07	$3.7x10^{-3}$	$2.5x10^{-4}$
GWP	kg CO_2 eq.	15.3	6.94	8.8	-224	6.06	1.83
POCP	kg Ethane eq.	$4.2x10^{-4}$	$2.8x10^{-4}$	$1.83x10^{-4}$	$-6.36x10^{-4}$	$1.89x10^{-4}$	$7.3x10^{-5}$
Primary energy	MJ	187	130	103	-581	128	40.3

*Results without system expansion or other allocation method, thus not separating the water treatment and biomass production function of the system.

Note that results from Table 8 should only be compared between *Nannochloropsis* models (columns 3, 5 and 6) and Spirulina models (4 and 7). The results for conventional aerated sludge are given for information, but no deterministic conclusions should be drawn from comparing the results to this benchmark. The table is meant to show the problems encountered when trying to find suitable data for impact allocation for multifunctional system such as SaltGae.

4.6. Spirulina valorization routes

4.6.1. Animal feed

Produmix has developed and tested the replacement of fish meal with dried Spirulina for animal feed. This should improve the piglet's health and reduce the use of antibiotics in the pork industry. The flowchart for the production is shown in Figure 17. Out of the different formulation developed and tested, one with 50 % replacement of the fishmeal (algae 2.5 %, fish meal 2.5 %) was the best performing.

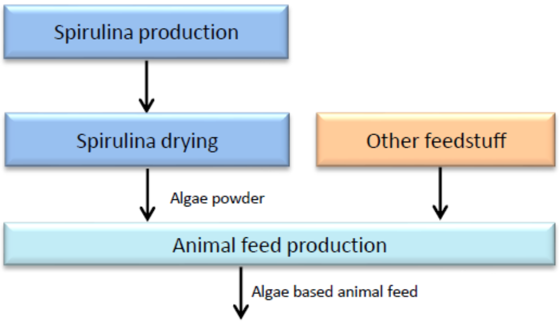


Figure 17. Animal feed production flowchart

4.6.1.1. LCA results

The benchmark is animal feed with no replacement of fishmeal by algae. It was assumed that the animal growth and food intake is not affected by the replacement of fishmeal by algae, and that the additional feedstuff remains unchanged. Therefore, the upstream impact of the feedstuff was not taken into consideration in the LCA. Furthermore, animals feed capacity to reduce antibiotic needs of the piglets could not be taken into consideration in the LCA calculations. Since D7.2, new more representative data has come for fishmeal produced in a co-production of fishmeal and fish oil from a mix of anchovy and fish residues, based on a study from Fréon et al. [48]. Furthermore, the algae production has been modelled with the models for Spirulina at Archimede. Absolute results can be found in Annex I.

Figure 18 shows the results for three impact categories: Acidification Potential (AP), Eutrophication Potential (EP) and Global Warming Potential (GWP). The results are normalized to the benchmark.

In terms of AP, the results are 10 times higher when replacing 50 % of the fishmeal by Spirulina then when using fishmeal only. The reason is the impact on AP of the production of Spirulina, see section 4.3.1. In the case of Spirulina from Archimede which was used to model the animal feed production, about 20 % of the energy demand comes from the drying step. Scenarios in section 4.7.1. explore possibilities for improvement of these results.

Notice that his assessment is very stringent, since data for anchovies and fish residues was used (i.e. anchovy fishing is very efficient). Further, the dataset used for fishmeal production comes from highly industrialized and therefore optimized processes, whereas the data for Spirulina production comes from pilot scale trials at Archimede. There is reason to believe that the production would have a lower energy demand if performed at large scale.

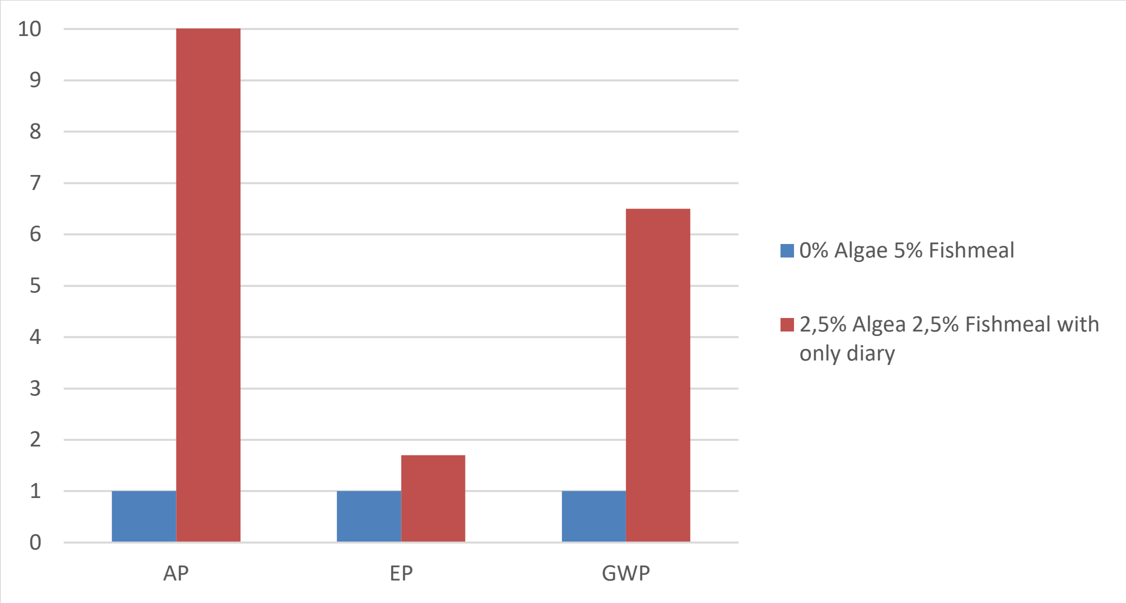


Figure 18. LCA results for animal feed for three impact categories, normalized to benchmark

In terms of EP, the results for animal feed with 50 % Spirulina replacement are about 70 % higher than when using fishmeal only. The reason comes from sodium nitrate and sodium bicarbonate used during Spirulina production.

Finally, the results for GWP are more than 6 times higher for animal feed with 50 % Spirulina replacement than when using fishmeal only. The reason are the combination of the energy demand and sodium nitrate use discussed previously.

Note that the therapeutic advantages of Spirulina cannot be shown in the LCA. If feeding the piglets with animal feed with Spirulina can significantly reduce the use of other drugs, it would probably be a considerable environmental advantage for the Spirulina based animal feed. Furthermore, the impact on ecosystem services cannot be assessed with LCA, which could be a downside of the fishmeal production.

Further, Parker et al. [2] suggest that high environmental benefits for society could be realized when directing greater proportions of fish catches to human consumption, instead of industrial uses (e.g. animal feed). Therefore, thorough research in this area is required to fully understand the consequences of the use of low-impact protein in different sectors and assess potential benefits for society from replacing fish catches with algae in animal feed.

4.6.1.2. LCCA results

In terms of animal feed, two different cases were assessed with different algae contents and a benchmark product with no algae. Three sets of results are presented for animal feed, namely a case with high algae content (2.5 % algae and 2.5 % fish meal), a case with low algae content (1.25 % algae and 3.75 % fish meal) and the benchmark with no algae.

Figure 19 shows the economical assessment of three types of animal feed. Since the market price of algae are also significantly higher than the market price of fish meal, it is more profitable from an economical point of view to invest in the benchmark case. For the low algae-case scenario (1.25 %) it is almost a 70 % increase in costs with the assumed costs as mentioned in Annex IX. From a cost sensitivity analysis, even a 50 % decrease of the algae market price would not make the low algae-based animal feed more profitable than the benchmark.

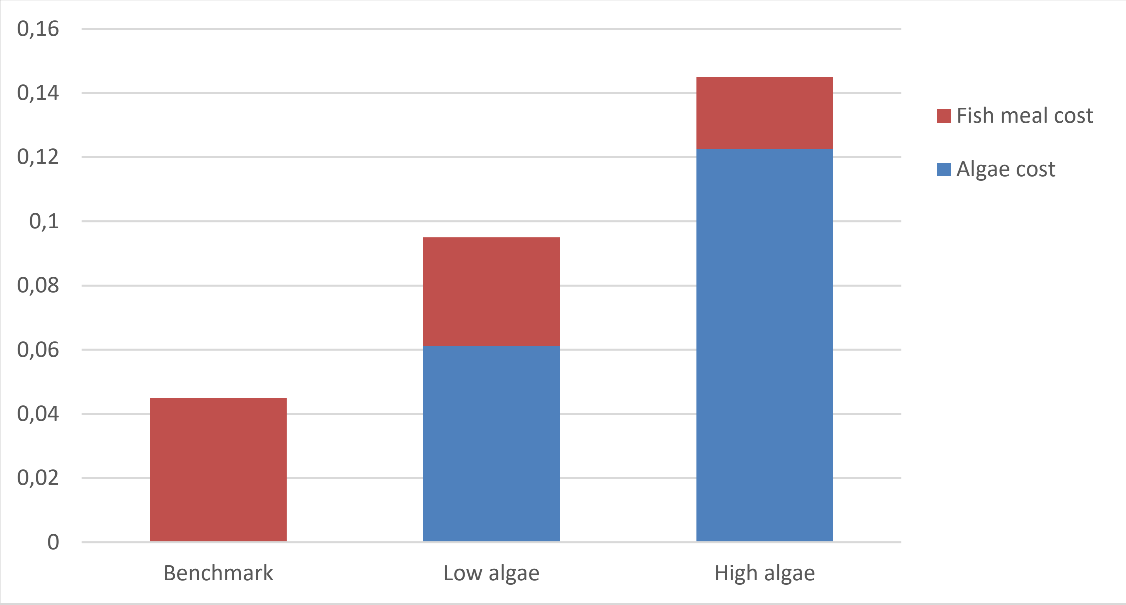


Figure 19. Animal feed – cost distribution (€/kg)

4.6.2. Gluten thermoplastic

Within the SaltGae project, Polimi has been working on incorporating the low value algae fraction, also called cell debris or algae residues, in thermoplastic biocomposites. The flowchart of the process is shown in Figure 20. Notice that this deliverable focuses in Gluten thermoplastics. Rubber thermoplastics was already evaluated in D7.2.

The production process for thermoplastics starts with mixing the different raw materials according to the recipes shown in Table 9. Then hot pressing is used to produce the final biocomposite. Gluten thermoplastics produce a material that can be used for packaging of dry things. The gluten thermoplastics with Spirulina were tested using whole cell and debris. Polimi showed that the gluten proteins interact with the proteins of the microalgae. Therefore, improved mechanical properties were observed only when using whole cells, not debris. In that case, the material is 50 % more resistant, which induces the possibility of using less material for the same function by approximately 20 %. When using debris, no mechanical improvement is observed, and the residues act as a filler.

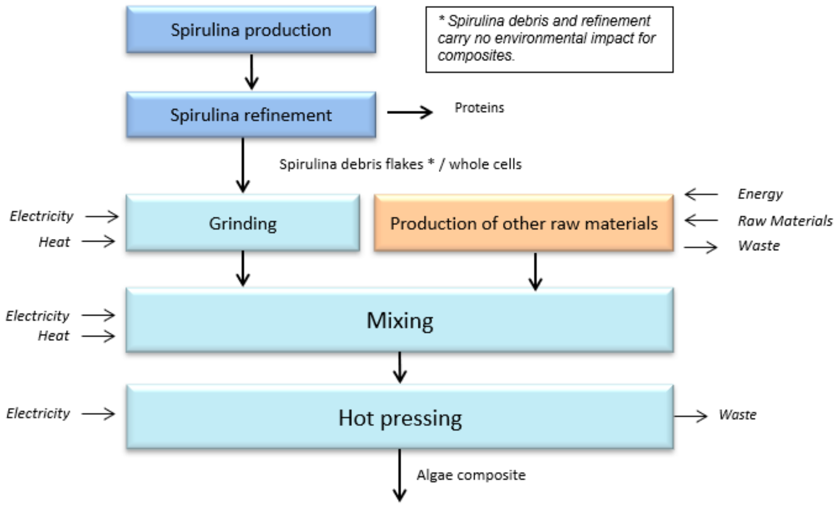


Figure 20. Gluten thermoplastic flowchart

Table 9. Gluten thermoplastic biocomposite formulations

Raw material	Benchmark (without algae)		Low algae content (9% algae)		High algae content (23% algae)	
Gluten	20 g	65 %	20 g	59 %	20 g	50 %
1,4-butandiol	10.8 g	35 %	10.8 g	32 %	10.8 g	27 %
Spirulina	-	-	3.1 g	9 %	9.2 g	23 %

4.6.2.1. LCA results

Microalgae debris are considered environmentally burden free since they are a waste by-product of the main protein and oil valorization routes. Absolute results can be found in Annex I.

Figure 21 presents the environmental impact hotspots for AP, EP and GWP, showing that the energy demand for hot pressing and mixing has the highest contribution to all categories: 81 % on AP, 40 % on AP and 50 % on GWP. The impact from the production of raw materials, gluten and 1,4-butnadiol, is 15 % for AP, 50 % for EP and 30 % for GWP. The relative results for the different alternatives presented in Figure 21 show that going from no microalgae to 23 % Spirulina debris in the thermoplastics reduces the impacts by 4 % for AP, 13 % for EP and 9 % for GWP. Hence, the major factor influencing the results is the Italian electricity mix, of which approximately 80 % is from fossil origins.

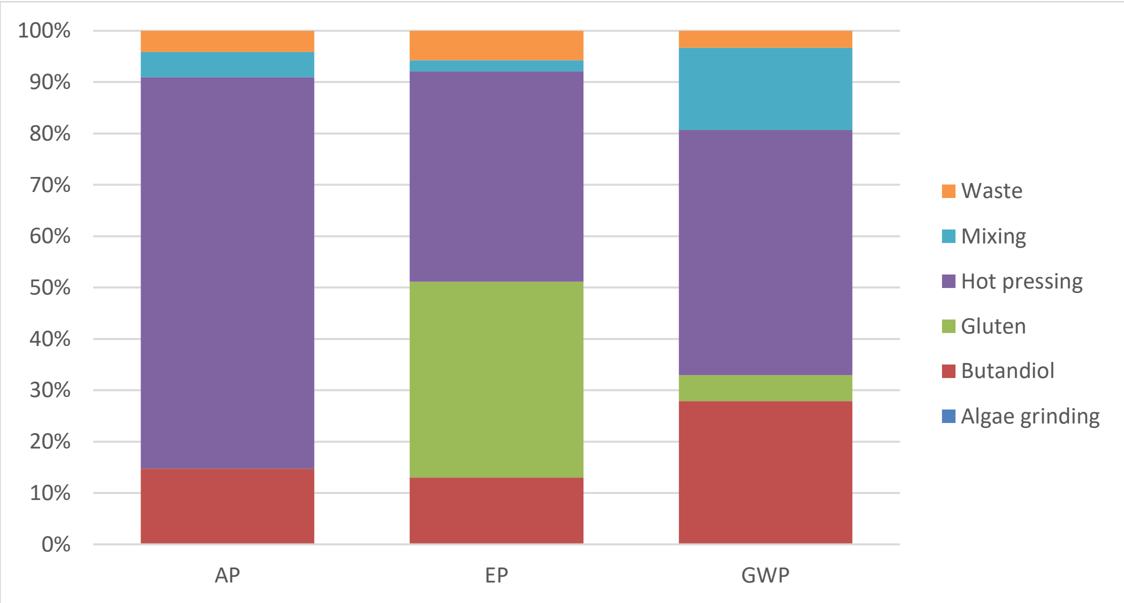


Figure 21. LCA Hotspot analysis of gluten thermoplastic biocomposite with 23 % Spirulina debris

Figure 22 additionally shows results for an alternative where and 23 % whole Spirulina from Archimede is used instead of debris. In that case, it was assumed that 20 % less production is required to achieve the same function. The results show that the material reduction of 20 % does not compensate for the environmental burden of producing Spirulina at Archimede.

This is especially noticeable for EP, where thermoplastics with whole algae have 6 times higher impact than thermoplastics without algae. This is mainly due to the impact of sodium nitrate and sodium bicarbonate production used in algae cultivation. The electricity for algae production is also significant due to its dependency on fossil fuels (section 4.3.1.).

The results show that using algae debris is considerably better in terms of environmental impact than using whole algae in thermoplastic production. This is because debris carries no environmental burden from the algae production since it is a waste from algae protein extraction. In contrast, thermoplastic with 23% whole algae carry the environmental burden of Spirulina production, which is significantly higher compared to the other raw materials in the formulation.

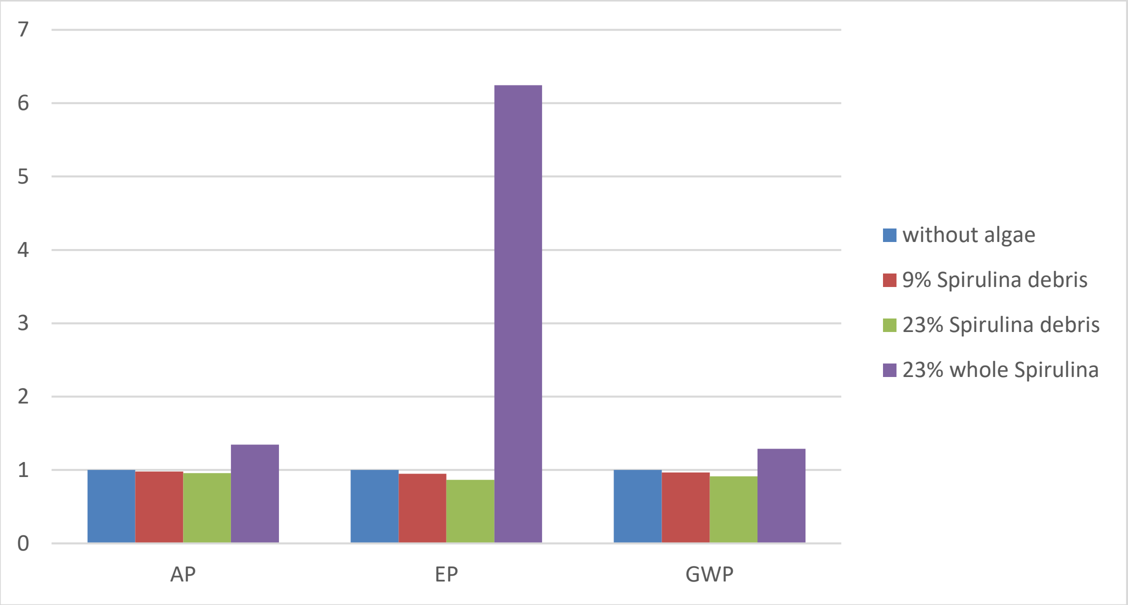


Figure 22. LCA results for four gluten thermoplastic formulations, normalized to the benchmark.

4.6.2.2. LCCA results

Three sets of results are presented for gluten composites, namely a case with high algae content (23 % algae), a case with low algae content (9 % algae) and the benchmark with no algae. For the economical part, instead of using data from the demo sites and our partner, a market value for the algae is used as data input (5 €/kg). In D7.2 and Annex IX more of the assumptions and data input are described.

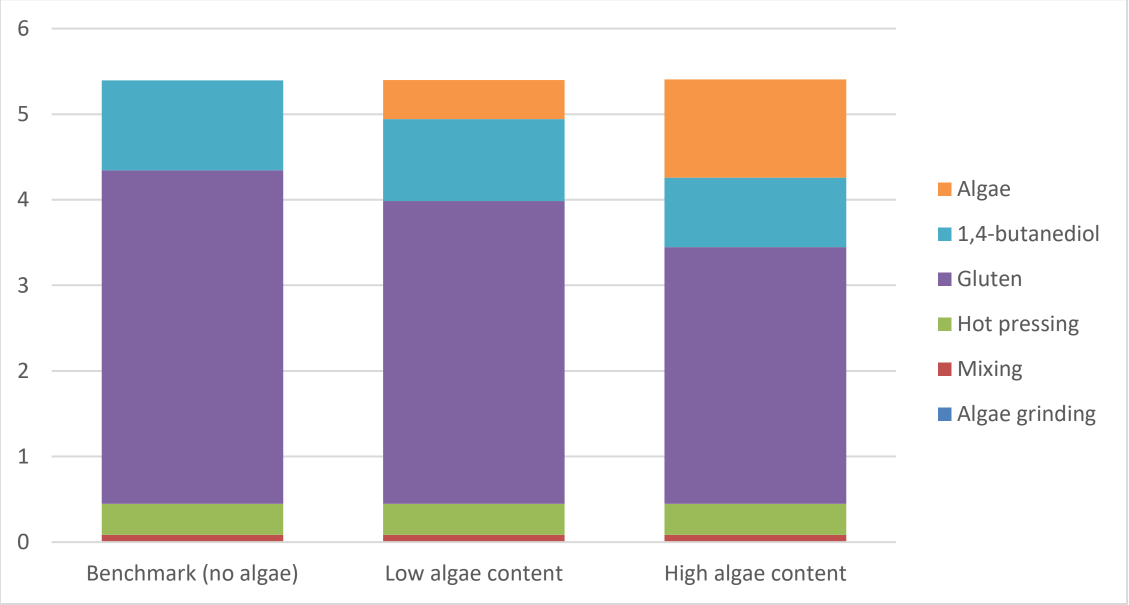


Figure 23. Gluten composites – cost distribution (€/kg)

Figure 23 shows that the algae-based gluten composites either in the high-case scenario (23% algae content) or in the low-case scenario (9%) have no improvement or deterioration in the economic assessment.

For the high algae-case scenario (23% algae), a 5% change in the algae price makes the price for the algae-based gluten composite around 3% lower than the benchmark scenario. It can thus be concluded that the algae-case scenario can defend its place on the market on the ground of profitability. On the other hand, if the gluten price would decrease with 5%, then the price for the algae-based gluten composite would increase, making the benchmark scenario more profitable.

4.6.3. Pastes for 3D-printed ceramics

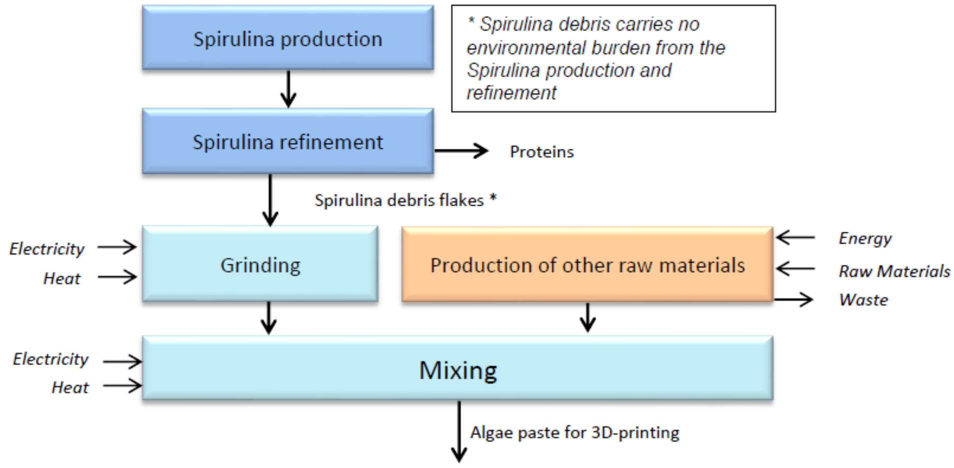


Figure 24. Paste for 3D-printed ceramics flowchart

Polimi also studied the incorporation of cell debris in pastes for 3D-printing (Figure 24). It would take the form partial substitution of bentonite clay in geopolymers for 3D-printed ceramics, using microalgae debris, according to the recipes shown in Table 10. Tests were performed with Spirulina, *Tetraselmis* and *Nannochloropsis* and showed no significant difference. Hence, both Spirulina and *Nannochloropsis* debris could be used for this application. The use of microalgae as a filler was shown to have no detrimental impact on the mechanical properties of the 3D-printed ceramics. The flowchart for ceramic paste is shown in Figure 24.

Table 10. 3D-printed ceramics paste compositions

Component	Baseline (g)	Baseline (%)	With algae (g)	With algae (%)
Metakaolin clay	23.6	47.3	23.6	47.8
Sodium silicate solution (62% water)	18.8	37.7	18.8	38.1
Bentonite	7.5	15	5	10.1
Microalgae debris	0	0	2	4

4.6.3.1. LCA results

Figure 25 shows the environmental hotspots of the LCA for 3D-printed ceramic paste with 4 % algae debris. Bentonite and algae grinding have an insignificant contribution to the environmental impact of the product compared to the other inputs: sodium silicate, metakaolin and electricity for mixing. Sodium silicate was consistently found in literature to be a major hotspot for geopolymers [49]–[51], which in this case was observed to have a contribution of 40-60 % of the impact for AP, EP and GWP. Metakaolin affects primarily the GWP with a 35-40 % share of the impact, and EP, 25-30 %. The electricity demand for mixing accounts for about 40 % of the impact on AP and 25 % on GWP.

Figure 25. LCA Hotspot analysis for 3D-printed ceramic paste with 4 % algae debris

The partial substitution of bentonite with algae induces the relative amount of sodium silicate to be slightly higher. Hence, the environmental benefit of reducing bentonite amounts – having a very low environmental impact on the studied categories – is lost in the environmental burden brought by sodium silicate. This is observed when comparing the baseline to the 4 % algae debris recipe LCA results in Figure 26. The figure also shows the results for cement paste from Portland cement, for which the environmental impact comes primarily from the cement production. The cement paste has almost 3 times higher AP than the geopolymers, and 2 times higher GWP. The EP is 50 % lower for cement than for geopolymer pastes due to sodium silicate's high EP contribution on the geopolymers.

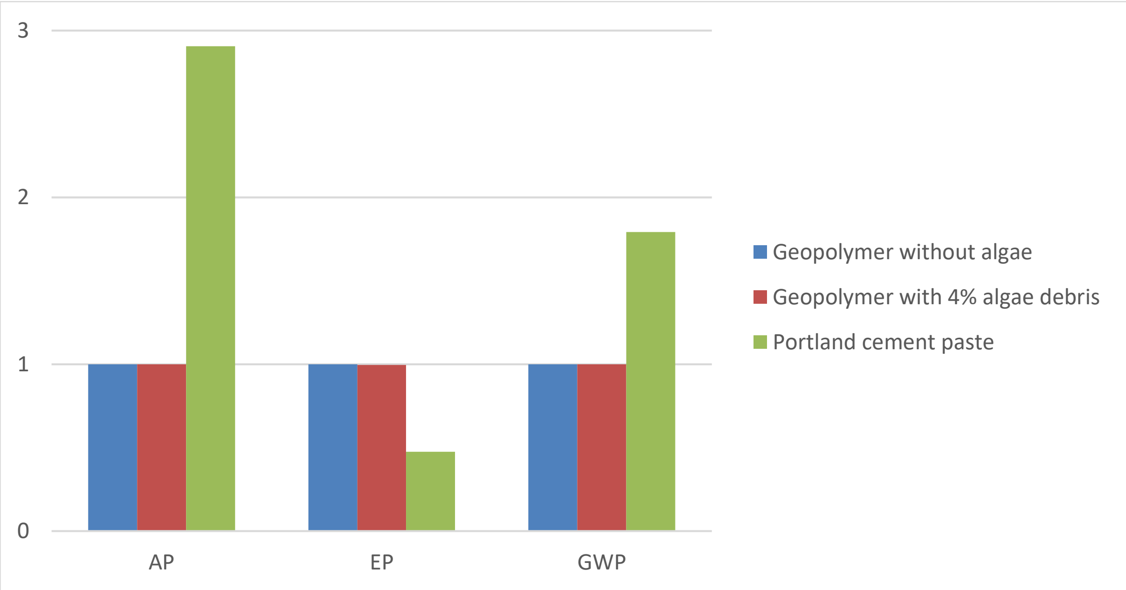


Figure 26. LCA results for 3D-printed ceramics pastes, normalized to the benchmark.

4.6.3.2. LCCA results

Figure 27 shows the economical CBA found in the LCCA performed for 3D-printed ceramic paste with 4 % algae debris. The set to the left represents the baseline, with only metakaolin, sodium silicate and bentonite, while the set to the right also includes 4 % algae. Since the microalgae are supposed to replace bentonite, the benefit of using algae from an economic point of view is connected to the difference in market prices for the two materials. For this scenario, they were calculated to almost be the same, meaning that reducing bentonite amounts by replacing it with algae doesn't impact the economical result.

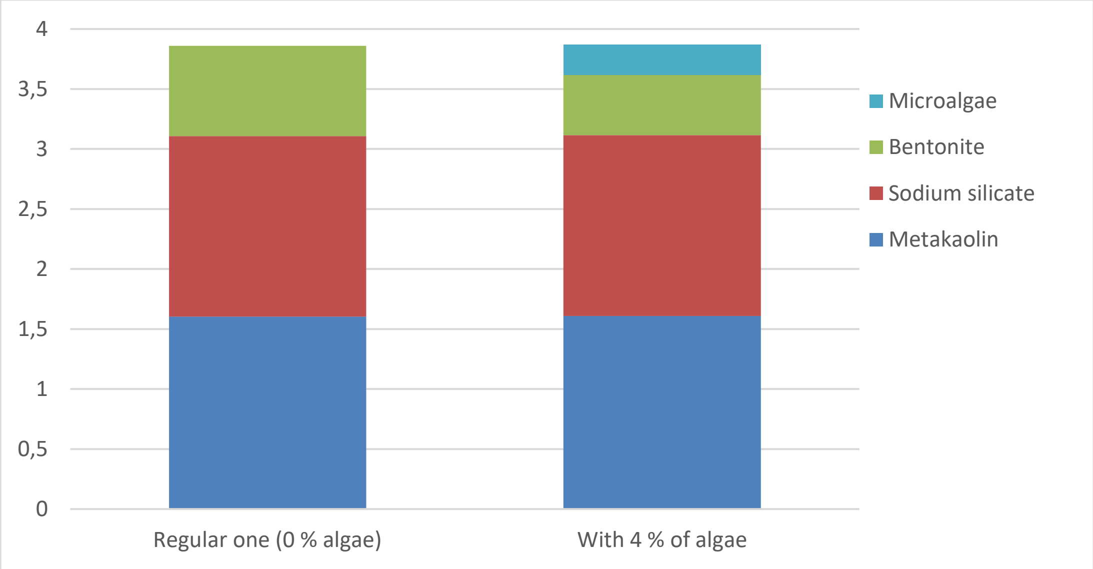


Figure 27. 3D-printed ceramics past – cost distribution (€/kg)

4.6.4. Protein extraction

The protein extraction protocol was developed by Extractis and is shown in Figure 28. It starts with a dilution and a two-phase high-pressure homogenization, producing a homogenized Spirulina dispersion. Since the process needs wet Spirulina, no drying would be required if the protein extraction would be performed on the micro-algae production site. Then, the dispersion is diluted and alkalized using sodium hydroxide (soda concentrated solution). A first separation is performed with a high-performance centrifuge, from which a more solid fraction (cream 1) and a liquid fraction (juice 1) are produced. The cream is spray-dried and can be used for the valorization pathways developed by Polimi using the low value fraction of the cells.

The juice is further processed through acidification with phosphoric acid and a second centrifugation, producing a second cream and juice. Juice 2 is a waste with only 3 % dry matter, sent for wastewater treatment. Cream 2 produced is the protein rich fraction of the microalgae, used for edible coating production. Each step requires stirring and pumping.

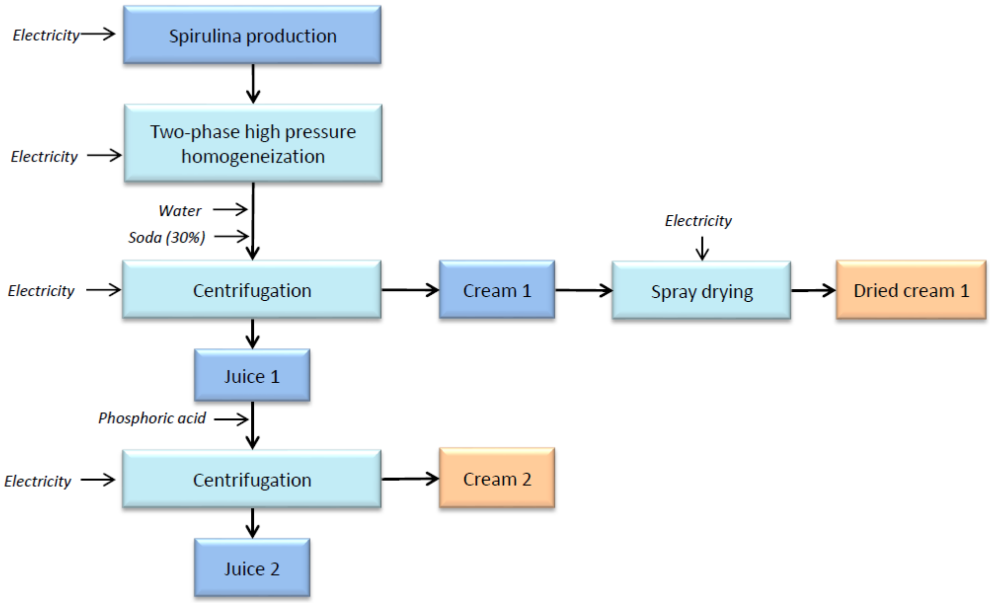


Figure 28. Protein extraction flowchart

Table 11 shows the results from the small pilot-plant scale trials performed by Extractis. The separation efficiency was lower than in laboratory scale, which resulted in lower amounts of cream 1 than expected, and with a higher protein content than expected. Similarly, the second centrifugation did not perform as well as expected, resulting in the same protein content in juice 2 and cream 2, with the overall yield of about 11 % of the initial protein content recovered in cream 2. Furthermore, the amount of starting material compared to the size of the equipment resulted in high losses in the dead volumes of the pumps and other equipment: 60 % of the initial protein content is lost. This scale issue also impacts the energy demands collected during the experiment, which are most probably not representative of an industrial, continuous process for this protocol. However, this data was the best available data for the assessments.

Table 11. Protein extraction process input outputs and yield from small pilot-plant scale trial

Process step	**Homogenized** Spirulina **dispersion production**	**Juice 1 & Cream 1 production**	**Juice 2 & Cream 2 production**
Inputs	49 kg 25% DW Spirulina	49 kg Spirulina dispersion 146 kg osmosed water 1,6 kg sodium hydroxide 30 %	155 kg Juice 1 2.1 kg phosphoric acid 75%
Outputs	49 kg Spirulina dispersion	0,94 kg dried cream 1 155 kg Juice 1 15.9 kg liquid losses, 24.8 kg evaporated water	22.3 kg wet cream 2 113.3 kg Juice 2 21.5 kg liquid losses
Yields	Spirulina dispersion: 25% DW, 13.5% protein, 6.6 kg protein	Cream 1: 96% DW, 55.2% protein, 0,5 kg protein Juice 1: 4.9% DW	Cream 2: 6.52% DW, 74.4% protein, 0.86 kg protein Juice 2: 3% DW, 24% protein, 0.79 kg protein

4.6.4.1. LCA results

It was assumed that the protein extraction would be performed at the Spirulina production site, hence no drying prior to the extraction is needed. Since the models are based on Spirulina from Archimede, the Italian electricity mix was used for the protein extraction process. The functional unit for this assessment is **1 kg of extracted high value** Spirulina **protein cream** ("cream 2").

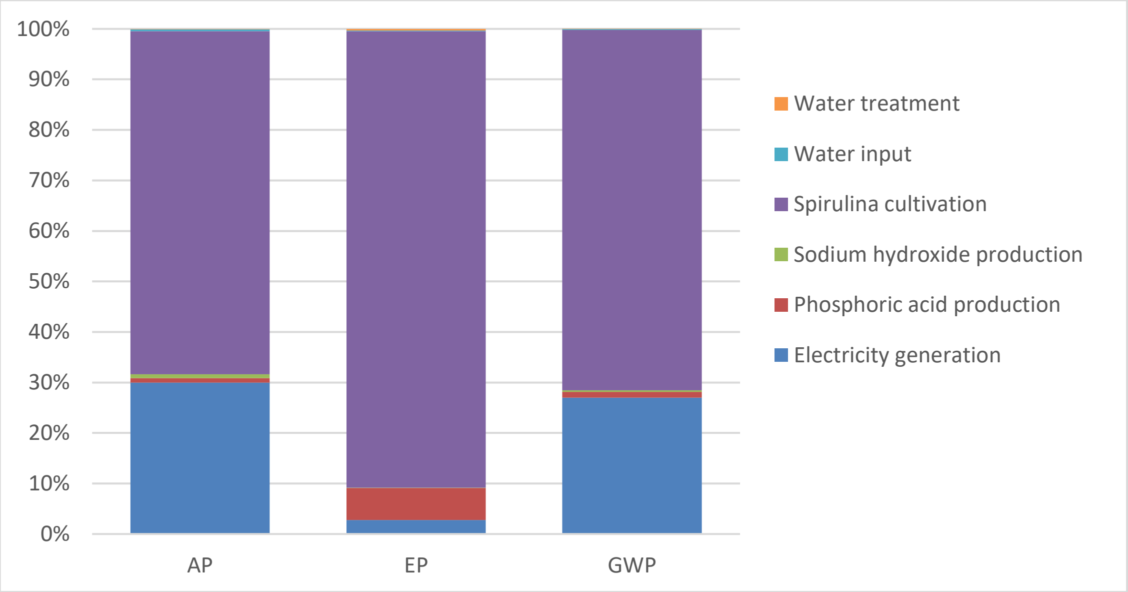


Figure 29. LCA hotspot analysis for 1kg of extracted high value Spirulina protein cream, for three impact categories

Figure 29 shows the results obtained for AP, EP and GWP. Absolut results can be found in Annex I. The main finding of the LCA analysis is that the two main contributors are the production of Spirulina and the energy demand of the extraction process.

The production of Spirulina is responsible for 90 % of the impact of the process on EP and 70 % on AP, which is mostly due to the use of sodium nitrate and sodium bicarbonate during its cultivation. Almost all the remaining impact on EP (8 %) comes from phosphoric acid used during the second part of the extraction process.

The production of the electricity consumed in the extraction process accounts for 30 % of the impact on GWP and 30 % on AP. Out of the stirring, pumping, HPH and centrifuging activities, the later accounts for about 50 % of the energy demand. Bear in mind that the energy demand is overestimated due the scale of the experiment.

4.6.4.2. LCCA results

Figure 30 shows the economical hotspots found in the LCCA performed for protein extraction. Similar to what was discussed in the previous LCA section about protein extraction, it must be noted that the values presented in this section are for scale reasons not representative of a fully optimised process, continuous and with large amounts. Both the operational and capital investment data for this part came mostly from our partners, except for the high-pressure homogenizer where they only could provide with capacities. Fortunately, a company called *Colley flowtech* could provide with that information for a similar equipment.

Since the algae at the production site includes water and that the protein extraction needs algae with moisture content, it was assumed for this part that the separation would be performed at the algae production site in order to remove the drying step. Treating fresh microalgae would therefore be more logical (rather than drying and then adding water).

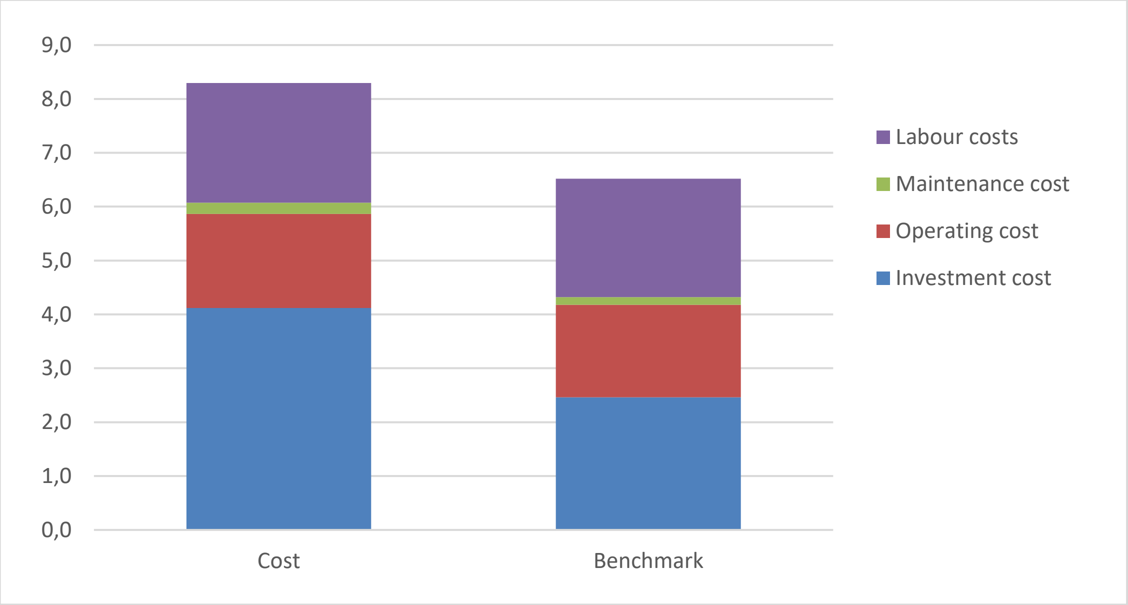


Figure 30. Protein extraction – cost distribution (€/kg)

Reporting the costs on a per unit basis shows which cost areas are contributing the most to the overall cost of production. The largest component for the extraction cost is from the investment cost, compared to the benchmark it is almost twice as high. But the operating cost are almost the same as for the benchmark, concerning energy consumptions. A well-adapted scale equipment will provide a better efficiency. But once again, it must be stressed that since the process at this point has not been optimized enough at the pilot scale in order to conclude the process parameters these numbers could also change.

In general, the separation parameters of centrifugation should be improved in order to produce higher concentration of proteins in the result product of the process. In order to improve the separation, a hydrohermetic seal option for the centrifuge could enable hermetic feeding of the product and decrease foaming. Another option would be to use centrifugation as a first step and then tangential filtration as the second (to filtrate the resulting juice). These options have not been tested yet and if they work well, they should be developed at the pilot scale. Moreover, the values of energy consumption and equipment of the present lab process cannot be representative of a fully optimised process, continuous and with large amounts, because of the semi-continuous operating mode used at the pilot scale (important dead volumes effects and underestimation of the positive recycling of some streams such as washing flushing).

4.6.5. Edible coatings

Edible coatings for fruits have been developed by Funditec using protein extracts from Spirulina (Figure 31). The protein extracts act as a replacement for proteins and polysaccharides of gum arabic, as shown in Table 12. The production process requires use of water at maximum 50ºC in order to emulsify the lipid fraction and mix it with the hydro-soluble fraction.

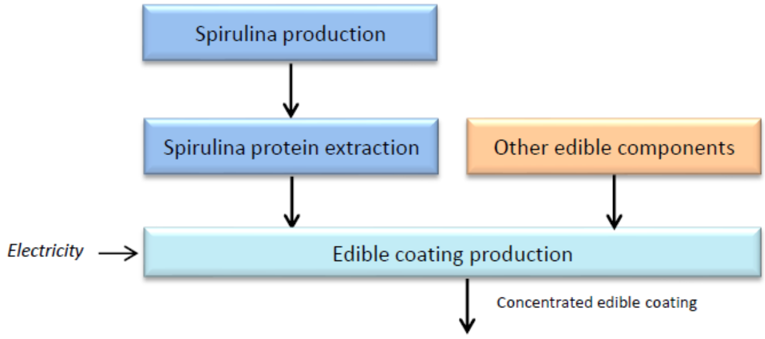


Figure 31. Edible coating flowchart

The final product is a concentrated solution meant to be diluted by the farmers to 1 % before application on the fruits. The use of Spirulina protein extract should improve the barrier properties against gases thanks to its hydro soluble properties.

Table 12. Edible coating formulation

Formulation	**Without** Spirulina	**With 10%** Spirulina
Gum arabic	46%	36%
Spirulina protein extract	0%	10%
Linseed oil	11%	11%
Clove oil	15%	15%
Natural extracts	15%	15%
Emulsifier	13%	13%

4.6.5.1. Environmental results

Since Spirulina act as a replacement for gum arabic in the edible coating product, the question around whether the new formulation has an improved environmental impact compared to the old formulation comes down to comparing the environmental impacts of gum arabic and Spirulina protein extract.

Gum arabic is a natural product derived from hardened acacia tree sap. It is produced in the so-called gum-belt in sub-Saharan Africa [52]. Unfortunately, no information could be found to be able to evaluate the environmental impacts of producing gum arabic. Hence, no conclusion can be made on which of the two bio-based products: Spirulina protein extracts or gum arabic has the lowest environmental impacts.

4.6.5.2. Cost results

The cost assessment for this part is based on a cost-benefit analysis. The costs are calculated on dry bases, and only represented by raw material costs. The final selling price of the edible coating prototype is calculated for a product with 30 % solvent content, which is packed in vessels of 5 litres and then diluted to 1 %. The data and the price for the benchmark *Naturecover* [53] for this section is received from our partners.

Compared to the benchmark, the edible coating in Figure 32 including algae proteins is approximately 1 €/L cheaper. The highest cost impact for the edible coating originates from the raw material cost from natural extracts and clove oil. Together they cover for 92 % of the production costs, but only represent 30 % of the raw material input. Therefore, in order to decrease the market price for edible coatings made with algae, it is advisable to decrease the amount of natural extracts and clove oil or trying to find materials for a lower price.

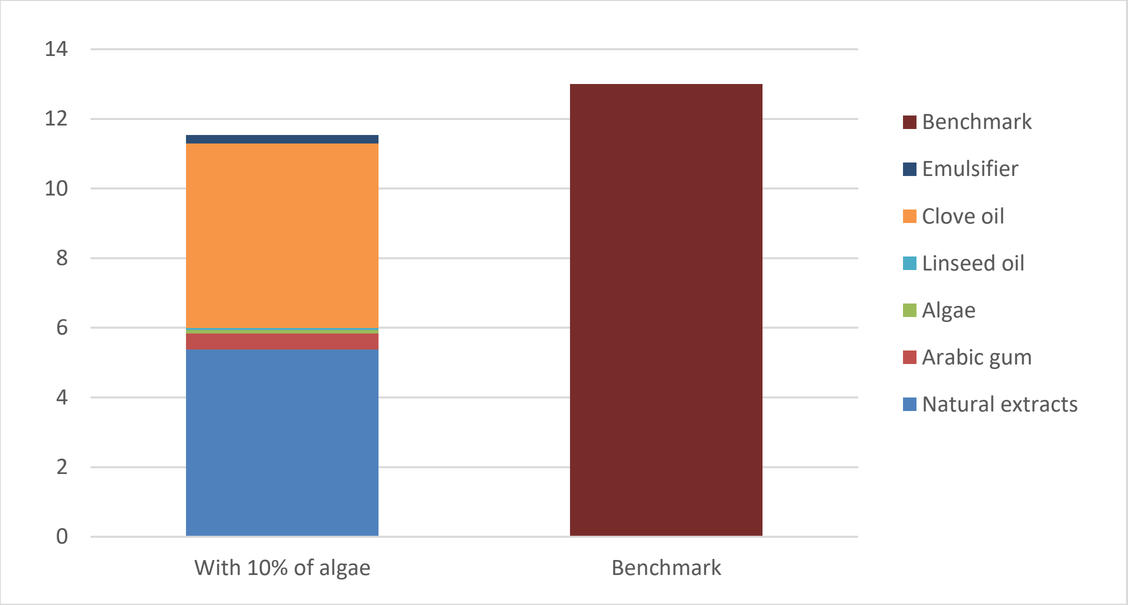


Figure 32. Edible coatings – cost distribution (€/L)

4.7. Scenario analysis – demonstration sites

4.7.1. LCA scenarios

In order to give perspective to the LCA results of the demo sites, a couple of scenarios judged to be realistic were tested for the three demo sites. They are presented and analysed in the following sections.

4.7.1.1. Koto LCA scenario

1. Water recirculation

For Koto LCA, a scenario was evaluated where the freshwater theoretically produced after reverse osmosis is recirculated to the 2-AD system (Figure 33). For that, the energy need for an additional recirculation pump was added. The results showed a reduction in water consumption of 60 %. The other environmental impact categories would increase by approximately 5 %.

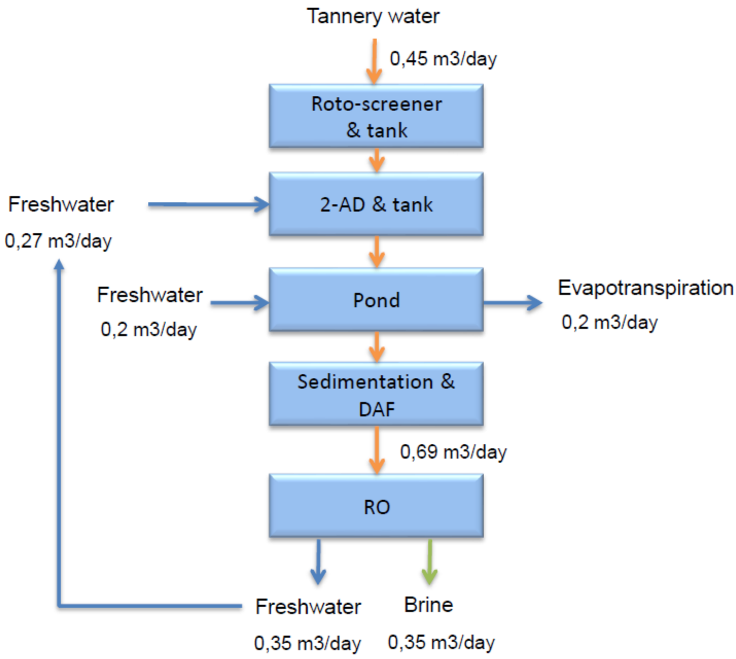


Figure 33. Koto scenario flowchart

4.7.1.2. Archimede LCA scenarios

The calculations performed in the Archimede LCA scenarios were based on the Spirulina cultivation data.

1. Biogenic CO_2

In this scenario, the main assumption was that waste CO_2 from the local vegetable oil CHP plant would be used instead of commercial liquid CO_2 from fossil sources. The environmental impact of cleaning the CO_2 from the CHP plant was calculated based on the use of activated carbon (0.01 kg/kg CO_2) to filter the waste gas, as well as energy (0.1 kWh/kg CO_2) to pump the gas to the ponds. Note that the implementation of such a scenario would require a study with a specialist since some microalgae inhibitors could remain after filtration. A combination of treatments might be needed to achieve a proper purification.

The results showed that this change would induce a reduction of 12 % in GWP, and 7 to 10 % change for the other impact categories. The combination of the impact of activated carbon reduction and additional electricity has an 80 % lower GWP than liquid CO_2, meaning that the filtrating and pumping local waste flue gas is better in terms of environmental impact than producing liquid CO_2 for ammonia production. Additionally, since the CO_2 from the local vegetable oil CHP plant is biogenic, the emissions are compensated by the carbon sequestration performed during the feedstock growth.

Note that the Spirulina model was used for this scenario. The amount of liquid CO_2 used and relative CO_2 leakage in *Nannochloropsis* production is significantly higher than for Spirulina production. Therefore, this strategy would be more beneficial for *Nannochloropsis* production.

2. Use of electricity from a biogas CHP plant

For this scenario, the Italian energy mix used for the electricity input was changed to electricity coming from a biogas heat and power cogeneration plant. LCI for a biogas CHP plant in Europe was used as a proxy to represent the impact of Archimede's adjacent vegetable oil CHP plant. This would imply that the CO_2 is sourced from biobased matter, called biogenic CO_2, which means the emissions are compensated by the absorption of the biomass. Note the source for vegetable oil is not waste, therefore the impact of vegetable oil CHP is expected to be higher, especially eutrophication impacts related to agriculture activities.

The results showed that replacing electricity from the Italian grid with electricity from biogas CHP plant could reduce the GWP by 30 %, the primary energy demand by 85 % and the AP by 70 %. The results are not significant for the other impact categories.

3. Use of filtration instead of UF for Spirulina

Use of ultrafiltration for harvesting is not necessary for Spirulina, and a conventional filtration system could be used instead. For this scenario, it was assumed that the energy needed for filtration is half the energy demand of UF. The results show that this solution would improve the GWP and primary energy demand results by 6 %.

4. Wastewater transportation

SaltGae concept entails the installation of a algae-based wastewater facility close to the wastewater source. To highlight the importance of this set-up a scenario for Archimede was calculated to evaluate the impact of wastewater transportation.

Currently, due to the experimental set-up, the dairy water treated at Archimede demo-site is shipped by truck to the site (which was not within the system boundaries of the main LCA study). Transporting 500 km by truck adds an additional 29 kg CO_2-equivalents per m^3 water treated at Archimede, which would represent almost 80 % of processes the impact on climate change.

Naturally, the closer the wastewater source to the treatment site, the better in terms of environmental impacts. The Arava set-up, where the SaltGae system lies next the aquaculture part of the site is an optimal set-up in terms of transportation.

4.7.1.3. Arava LCA scenarios

1. Continuous cultivation

This scenario explores an alternative cultivation method for Arava called continuous cultivation. It would need 176 m^3 initial input of fish water of 2-3 weeks - including compensation for evaporation - and one month of running before reaching a stable phase for continuous harvest and water treatment. The procedure would be performed 3 times a year. The remaining months of the year, the continuous phase would be a harvest of 10 m^3 algae culture replaced by 10 m^3 fish water every day. The concentration of algae at harvest being 1 g/L, this would result in a production of 10 kg DW Spirulina per day. The PBR volume necessary to produce the inoculum would be 480 L, 3 times per year. Then, the small and medium ORPs would run 10 and 6 days respectively, 3 times a year. Large ORPs would be running all year around. The average of 9 m^3/day evaporation would be compensated with brackish groundwater or with recycled harvest water.

The continuous cultivation scenario would use roughly the same amount of fish wastewater and would produce the same amount of Spirulina. The main differences between the baseline scenario (batch cultivation) and the continuous cultivation scenario concerns the energy demand and groundwater use, outlined in Table 13.

Table 13. Main input differences for Arava cultivation scenarios, averaged over a year

Scenario	Energy demand PBR kWh/day	Ground water demand PBR L/day	Energy demand ORP kWh/day	Ground water demand ORP L/day
Batch culture	93.4	30	40	1160
Continuous culture	26.7	3.9	57	9000

Figure 34 shows the relative results for the continuous culture scenario compared to the baseline scenario, batch culture. The main observation is that is reduces by 10 to 20 % the impacts on AP, EP, GWP, POCP and primary energy, since it reduces significantly the need for inoculum production in PBRs and thus the high energy demand that goes with it (see Table 13). On the other hand, since the ORPs are running more in the continuous culture cultivation, more water is lost to evaporation and almost 8 times more ground water is needed to compensate for it. This induces an 60 % increase on the water consumption impact of this scenario.

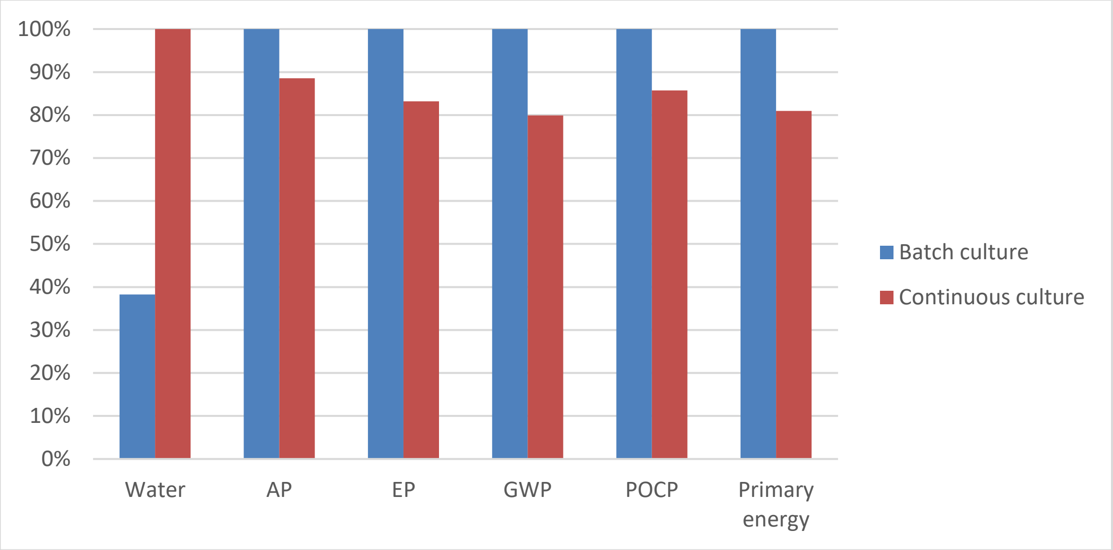


Figure 34. Batch cultivation and continuous cultivation LCA comparison for Arava demo site

2. Water recirculation

Here, the option of recirculating the water collected after the vibrating screen and before the RO to compensate for evaporation. The harvest water still contains some Spirulina filaments which should not pose problem for recycling in the ORPs. This would avoid using 1.16 m^3 per day of groundwater. Additionally, the pH of this water would be adapted to the culture and could reduce the sodium bicarbonate need by 12 %.

The results show that this would reduce the water consumption impact by 95 %. The groundwater demand going from 0.17 to 0.05 m^3 groundwater/m^3 water treated.

3. Solar energy

Since the Arava demo site is situated in a desert, one could imagine a scenario where all the electricity demand of the site is supplied through solar thermal energy. Figure 35 shows that this scenario would have no impact on the water consumption but lower the environmental impact on the other impact categories. It would reduce GWP and the primary energy demand by 85 %, which would reduce the process to around 3 $kgCO_2$-eq/m^3 treated fish wastewater which are promising results. It would also reduce the AP by 70 %, the EP by 50 % and POCP by 10 %.

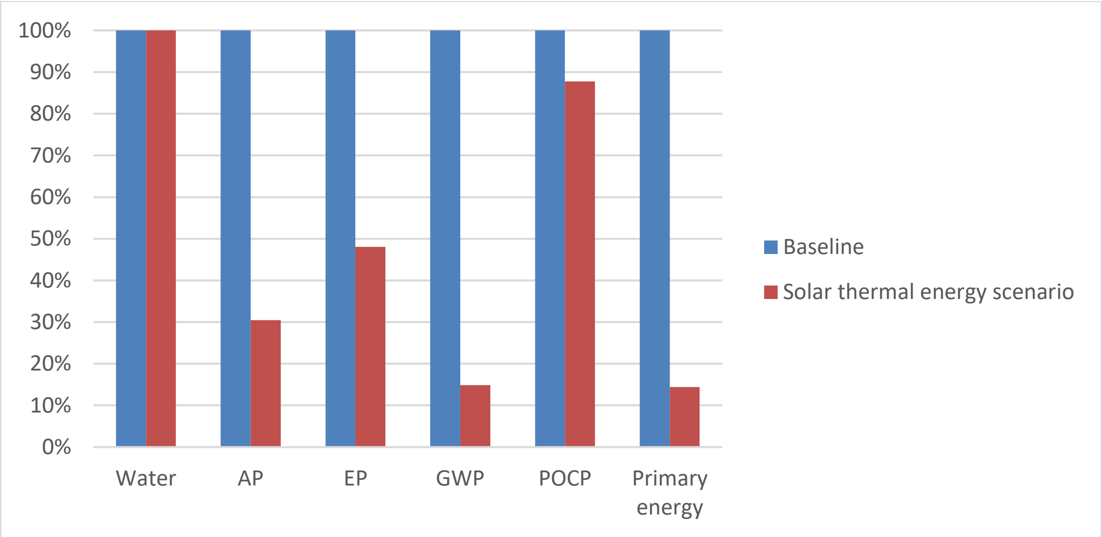


Figure 35. Baseline scenario and solar thermal energy scenario LCA comparison for Arava demo site

4.7.2. LCCA scenarios

Similar to the previous section 4.7.1 also a couple of calculations for LCCA results were made for all three demo sites. They are presented and analysed in the following sections. One difference from the LCA scenarios is that here also a transportation scenario is evaluated.

4.7.2.1. Koto LCCA scenario

1. Water recirculation

For Koto, a theoretically scenario was evaluated where the freshwater produced after reverse osmosis is recirculated to the 2-AD system (Figure 33). For that, the cost for installing an additional pump was added to the scenario, accomplished with cost for pipeline and the energy needed for recirculating water. Because of the relatively low flow rate which Koto currently has, the outcome from this scenario didn't show a large impact for the overall result, less than 1 % of the annual cost was reduced in absolute numbers.

4.7.2.2. Archimede LCCA scenario

1. Biogenic CO_2

According to Archimede, the CO_2 are currently bought from the market. By using biogenic CO_2 at a market price of 0,05 €/kg [54], which includes carbon, equipment depreciation and energy cost, the annual cost could be reduced with up to 10 %. In this scenario, it was taken under consideration that the demo site would need an additional pump, fully equipped with piping and investment/operational cost for pumping 0,1 kWh/kg CO_2 to the ponds.

2. Green electricity

In this scenario, the main assumption was that the demo site changed from buying electricity directly from the grid to electricity coming from the adjacent biogas plant. In the base case of Archimede, the electricity is bought from the Italian grid for market price. In the same site as Archimede is located, also a vegetable oil CHP plant is positioned. Since the two facilities are also subsidiaries to the same main company, they can cooperate and hopefully jointly benefit from each other's work. For instance, one opportunity could be that Archimede could use electricity from the CHP plant.

But in Italy, the price for selling green electricity to the grid is higher than the cost of buying the same amount. Due to subsidies for renewable energy production, the amount of money they get for selling the green electricity to the grid is in other words larger than the capital they spent on buying from the Italian grid. If we assume the CHP plant is giving the electricity required for running the SaltGae system for a year for free, then the green electricity scenario would imply an income loss of 0.14 €/kWh for the whole Archimede. This means that Archimede have no economic incentive to use the green electricity for themselves.

3. Use of filtration instead of UF for Spirulina

In Archimede, when producing Spirulina, a conventional filtration system could be used for harvesting instead of ultrafiltration. The investment cost for a demo site with Archimedes capacity (Annex XI) could be in the range between 40-50 000 € [55]. Since ultrafiltration is a more expensive technology, the cost in this scenario is reduced with 10 to 15 % and therefore more beneficial for the business.

4.7.2.3. Arava LCCA scenarios

1. Continuous cultivation

This scenario explores an alternative cultivation method for Arava called continuous cultivation. More information about the basic assumptions could be found in section 0. The baseline requires roughly 30 % more energy to produce the same amount of biomass. On the other hand, the calculation shows that this new scenario needs 8 times more ground water, mainly through an increase in evaporation. For a demo site located in a hot region like the Arava, the increase on the water consumption could be valued higher than the cost of decrease in electricity. By only comparing the operational costs (labour costs excluded) for Arava's case, the new scenario would increase the costs with 8 %.

2. Water recirculation

Recirculation of the water could reduce the water consumption with 1.16 m^3/day and sodium bicarbonate with 3.77 kg/day. From an economical point of view, this means that the operational costs (labour costs excluded) for Arava decreases with 1-3 %

3. Solar energy

Suppling all the electricity of Arava with solar energy, it would mean an increase for the investment costs since solar panels would to be purchased. Assuming a total cost of 50 €/MWh [56] to cover all the energy demand with solar power, increases the overall investment cost with 12 %. But since the panels are producing energy, they also save an annual cost corresponding to 7 % of the total operational costs. The solar panels have paid off after roughly 6 years.

4.7.2.4. Transportation LCCA scenarios

In this scenario, based on the project partner's needs, a couple of transportation scenarios were investigated. It is a common issue that when producing secondary products out of biomass, it creates a need for transportation since the production is separated geographically from the sources and the supply of biomass varies with the season. This study analyses the transportation costs for three types of cargo: wastewater, raw biomass and pretreated biomass. Based on literature and discussion with partners, trucks are the most feasible transportation of small volumes and for distances lower than 500 km [57].Therefore, the assumed transportation mode is using rented trailer trucks with load capacity of 30 m^3. The major components of truck transportation costs are the fixed cost (€/ton) which is independent of distance traveled, and the variable distance-dependent cost (€/ton/km). For this study Equation 1 is used to calculate the transportation costs, T_{tc} (€/ton).

Equation 1. $$\boldsymbol{T_{tc} = F_{tc} + d * V_{tc}}$$

where, F_{tc} represent the fixed transportation cost (€/ton), d the one-way trip distance (km), and V_{tc} is the variable transportation cost (€/ton/km) including cost related posts like loading and unloading time. More information of the different assumptions made for this section can be found in Annex VIII.

Water transportation

Figure 36 describes both the additional cost for transporting wastewater to be treated at the demo site, and the cost for transporting the enhanced water to another facility from the demo site. Transporting additional wastewater could be the case for Koto since the demo site does not receive enough volume of wastewater on a daily basis to utilize the installations optimally. For instance, optimizing the wastewater flow generates lower equipment cost per functional unit, since the pumps are designed for a higher flow and can therefore be producing at a higher level of efficiency. Therefore, similar to the discussions made for scenario 1 (Archimede), it could make economic sense to transport wastewater to ensure that the equipment capacity and other design decisions related to Koto's facility planning are met.

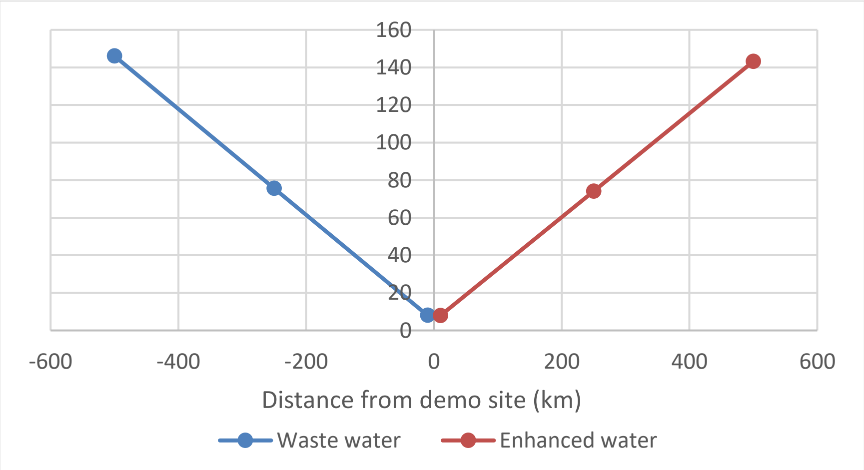


Figure 36. Additional water transportation - before and after demo site (€/m^3)

Biomass transportation

Since the potential wastewater treatment facilities are not necessarily located close to an algae valorization facility, there is a need to include the transportation in the cost assessments. Therefore, for transporting the biomass, three different logistics cases were developed as visualized in Figure 37 and analyzed based on production data from Archimede.

In the first case, the transportation is between the demo site (orange box) and a theoretical factory (green box). In this case it is assumed that the pretreatment (blue box) is located and already installed at the same site as the factory. Therefore, no pretreatment step, like drying, for the biomass is needed at the demo site. This case could offer valuable information for companies which would like to try the SaltGae system but decrease their initial investments.

For the second case, it is assumed that the pretreatment (blue box) is located and already installed at the demo site. Therefore, it is assumed that a lower amount of biomass is needed to be transported and a higher investment cost for the demo site is required.

And finally, for the third case, the pretreatment is assumed to be located somewhere in between the demo site and the factory. Here the pretreatment could be operated by a third party located at a terminal, which have both the equipment and the know-how to treat the biomass properly. Since the location of the terminal are dependent on the actual situation, the distance between the demo site and the terminal is analyzed in terms of the total distance from the demo site to the factory, in intervals of 20 %.

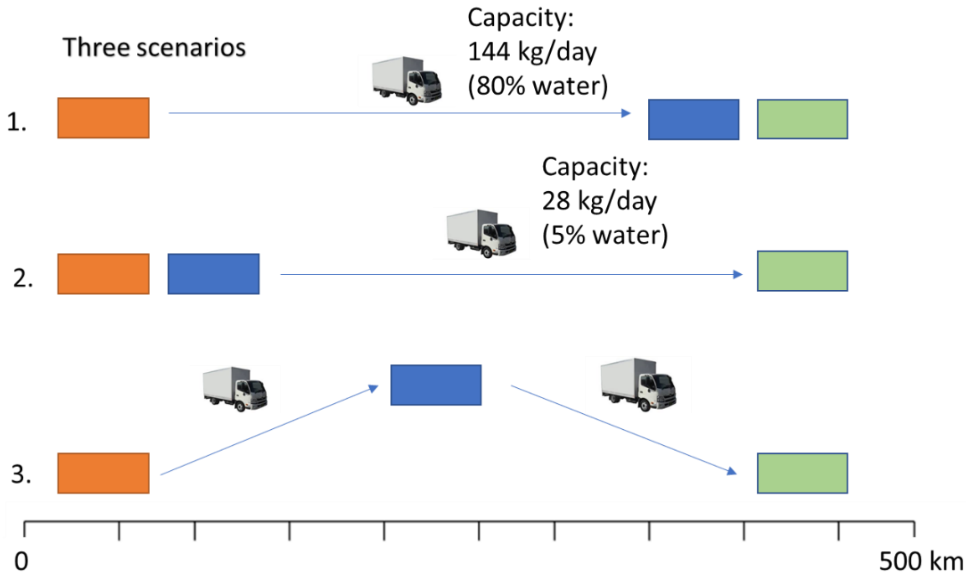


Figure 37. Three transportation cases

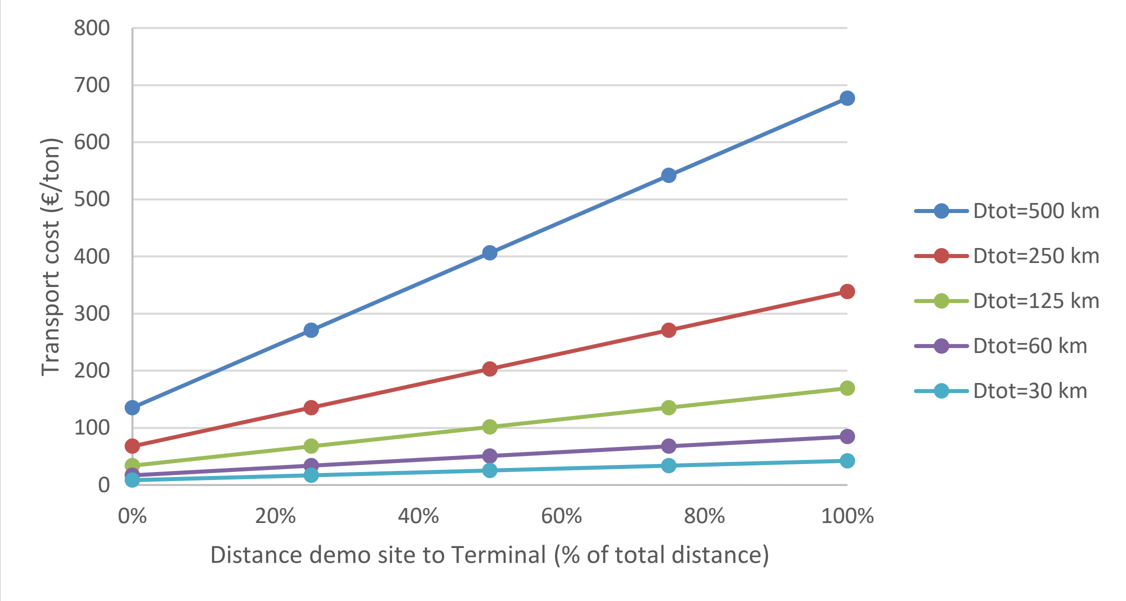


Figure 38. Transportation cost – terminal at different distances from demo site (€/ton)

Figure 38 shows the transportation costs for the different cases, when the total distance is varied between 500 km and 30 km. The transport cost at 0 % represents the results for Case 2, when the pretreatment is located at the demo site. The costs at 100 % is for the result from Case 1, when the pretreatment is located at the factory, maximizing the transportation costs. In between 0 % and 100 % could the results from Case 3 be found. At a total distance of 500 km, transporting the biomass to a terminal located in the middle of the demo site and the factory, the transportation costs are twice as high as for transporting it 250 km. For further cost assessment related to transportation and terminals, see Annex VIII where the transportation costs are related to investment and operating costs.

4.8. Integrated sustainability assessment

This section presents the results of the process of integrating environmental, social and economic assessment results and enlisting potential strategies to improve the SaltGae technology.

4.8.1. Strategy outline and assessment

The tables in this section present the list of strategies identified in the first step of the integrated sustainability assessment. Table 14 presents the strategies based on the Koto models, Table 15 present the strategies from the analysis of the Archimede models and

Table 16 presents the scenarios for the Arava demo site. The list of strategies presented is based on the hotspot analysis of the base cases presented in Sections 4.2, 4.3 and 4.4.

The strategies are drafted as actions to improve the base cases and assessed as scenarios using LCA and LCCA modelling. The assessment results are presented per sustainability pillar (i.e. environment, economy and society) the first column shows the environment implication (i.e. LCA results), the second column presents economic implications including LCC results and the last column presents the expected impact to society. See Section 4.7, for more detailed of quantitative results and analysis.

Table 14. Koto strategy list and assessment

Strategy	Environmental implications	Economic implications	Social implications
Increase amount of wastewater in 2-AD system	The technological bottleneck is that sodium salt concentration in water below 20 g/l inhibits anaerobic digestion. Not quantitatively assessed. If achieved, ceteris paribus, the total impact would significantly decrease.	Reduction in water consumption would make freshwater available to the community.	
Treated water recirculation back in 2-AD system	Reduce water consumption by 60 %. Slight increase of the rest of the impact categories (~ 5 % increase) due to extra electricity used[6].	Not significant change. Slight increase in total cost by 0.1 % since pumping/piping is required as well as energy for operation.	If desalination is installed and desalinated water is released to near ecosystems, more freshwater would be available for the local communities. If the desalinated water is instead used for enabling 2-AD system, less water would be available but slightly more energy (through CHP) would be available for the community.
Optimize equipment dimension to flowrate	Not quantitatively assessed. If flowrate increases, slight increase in energy for pumps is expected, but overall consumption of resources per functional unit is expected to decrease.	Not quantitatively assessed. This is expected to reduce CAPEX, OPEX and labour.	If resources and energy consumption is reduced per functional unit, then total S-LCA impact would be also reduced.
Reduce contaminating algae	Not significant. If not removed, this invasive biomass would inhibit light access for the productive specie. However, the former can be easily removed regularly.		

[6] The base case used for comparison includes reverse osmosis. Increase in energy, CAPEX & OPEX are due to extra pump/pipeline.

Table 15. Archimede strategy list and assessment

Strategy	Environmental implications	Cost implications	Social implications
Minimize CO_2 leakage in algae production	Difficult to assess quantitatively. According to Mayers et al. [58] to minimize CO_2 loss, it is important to optimize CO_2 addition through controlling flowrate and pH.		
Biogenic CO_2 from flue gases of adjacent CHP plant.	Reduction of 12 % in GWP, and 7 to 10 % change for the other impact categories. Note this numbers are representative for Spirulina production.	10 % reduction of total cost due to reduction on the cost of CO_2[7] Besides direct technology costs, there are also costs related to processing permit/certification to approve CO_2 from flue gases for food grade.	If CO_2 comes from the adjacent CHP plant, then the social impact from chemical production would be replaced by Archimede's CHP social impact. This is a possible positive adjustment since it allows more control over social factors affected (e.g. health and safety issues for workers).
Green electricity	LCI data for biogas CHP plant. A GWP reduction of 30 %, the primary energy demand reduction of 85 % and the AP reduction of 70 %. Note that if adjacent vegetable oil energy would be used, lower reductions are expected due to e.g. higher EP impact from agricultural activities.	In Italy, the market price for selling green electricity is higher than buying the same amount of electricity from the Italian grid. Therefore, if Archimede would use the green electricity by themselves, it would mean for them a loss of income with approximately 3-5 %.	If electricity comes from the adjacent CHP plant, then the social impact from electricity production would be replaced by Archimedes own CHP social impact. This is positive, since it allows Archimede to have more control and set policy/strategy to decrease any social impact encountered.
Filtration technology used for Spirulina harvesting	Both GWP and primary energy demand would be reduced by 6 %.	Replacement of UF & CF equipment with conventional filtration equipment equates to 10 to 15 % total cost reductions.[8]	The energy reduction is not expected to yield any significant S-LCA improvements. A detail assessment of working conditions for employees of these two technologies (i.e. UF vs simple filtration) could yield some information, but it is not expected to be very significant differences.

[7] This is based on Archimede models without sodium bicarbonate but less wastewater throughput.

[8] This is based on Archimede models without sodium bicarbonate but less wastewater throughput.

Table 16. Arava strategy list and assessment

Strategy	Environmental implications	Economic implications	Social implications
Continuous cultivation	Continuous cultivation implies higher operating time for the open ponds. This increases yearly evaporation equating to 60 % increase in water consumption. The rest of the environmental impacts are reduced from 20 to 30 % due to lower PBR energy demands.	Not analysed	Continuous cultivation implies more brackish water needed for replenishing evaporation. This implies less brackish water available for local communities. However, local communities cannot make use of brackish water directly, they need desalinated water. The SaltGae system is providing the desalination service.
Treated water recirculation to open ponds.	Replenishing evaporation with treated water (prior to RO) causes water consumption to be reduced 95 %. The production of sodium bicarbonate is avoided by 25 %, this equates to less than 5 % reduction of the environmental categories analysed.	Not analysed	If water is recirculated back to the algae ponds, less desalinated clean water would be available for the local community, e.g. for agricultural use.
Solar energy	The use of solar based electricity induces a reduction of 85 % GWP and primary energy consumption.	Not analysed	If electricity comes from installed solar power by Arava, then the social impact from electricity production would be replaced by Arava's own social impact. This is potentially positive, since it allows Arava to have more control and set policy/strategy to decrease any social impact encountered.

4.8.2. Land use

Land use and its corresponding cost has not been included in the LCA and LCCA. The land required for algae production is significant. However, in contrast to agriculture, algae can be cultivated in non-productive and non-arable land. Algae are highly efficient organisms that could exhibit twice the photosynthetic efficiencies and yields of terrestrial plants [3]. However, compared to other wastewater treatment processes, algae used for treating wastewater requires significant amount of land. For instance, around 1 hectare per 100 m3 of wastewater would be required for dairy wastewater treatment (S. Mangini, personal communication, September 2019).

In terms of environmental impact, it is important to avoid converting e.g. forest land into algae site. When converting productive land into algae sites in the United States, Handler et al. [59] estimate that land use change impact could be in the size of 6 to 12 % of the total GHG emission over the entire algae renewable diesel life cycle without considering the land use change. To avoid this impact, the use of marginal land unsuitable for agriculture or forest activities is recommended.

In terms of costs, the business case of algae production using wastewater treatment should consider land costs. The value of marginal land unsuitable for agricultural use is normally more economical than active agricultural land. However, specific land costs are very variable between regions and nations; therefore, an analysis to support decision makers should be region specific. Multicriteria models, such as the one presented by O'Neill [60] could evaluate the best location in a region based on stakeholders' preference e.g. proximity to CO2 sources, wastewater treatment plants and land costs.

4.8.3. Water efficiency index

The scenario analysis shows that clean water recirculation is an interesting strategy for the sites to reduce their water consumption. Table 17 and

Table 18 summarize wastewater and clean water flows in the baseline system (i.e. the SaltGae system without clean water recirculation) and scenario systems with clean water recirculation.

Table 17. Water flows in the three demo sites, baseline scenarios

	Wastewater inflow	**Water consumption**	**Water returned to environment**	**Water return per water consumption**
	m^3/day	m^3/day	m^3/day	m^3/m^3
Koto	0.45	0.47	0.35	**0.74**
Archimede	24	8	26	**3,25**
Arava	10	1.69	5	**3**

Table 18. Water flows in the three demo sites, recirculation scenarios

	Wastewater inflow	**Water consumption**	**Water returned to environment**	**Water return per water consumption**
	m^3/day	m^3/day	m^3/day	m^3/m^3
Koto*	0.45	0.20	0.10	**0.50**
Arava**	10	0.5	4.3	**8.6**

* For Koto the clean water treated after RO is returned to the 2-AD system.
** For Arava, water treated before RO is returned to the algae pond to replenish evaporation.

In the last column to the right an indicator is calculated to portray the water efficiency of the systems. The water efficiency index is defined here as clean water consumed per cleaned water returned to the environment or used by local community (e.g. agriculture in Israel). It indicates how efficient is the system in using clean water to produce clean water. A value greater than 1 implies net production of clean water.

The Archimede system is quite efficient already without water recirculation. Arava is also already a net producer of clean water in its baseline case, however water recirculation before reverse osomosis increases its water efficiency index significantly. Notice that Koto is not a net clean water producer in any of its two case. However, when wastewater after RO is returned to the 2-AD system, the efficiency index increases significantly.

4.8.4. Water desalination and brine

Desalination of the effluent after e.g. RO results - besides desalinated water - in another stream of brine. It must be considered whether this stream can represent an additional value or not. Brine, or solid salt, has a potential use for de-icing of roads or for dust-binding before sweeping dust and debris from hard surfaces.

It appears, however, that it is highly unlikely that the brine could be used for any such application and the reason is mainly the extremely low cost of the incumbent alternative, where salt is bought very cheaply in large quantities. Moreover, salts for treatment of roads must meet certain purity criteria, and the effluents from the SaltGae processes contain a variety of different salts, and with a potentially varying composition at that.

The other side of the coin is whether the brine incurs additional costs for its disposal. One method, which is an alternative for all sites located close to a coast, is to bring out into the sea. Since the salinity is unnaturally high, it is impossible to release the brine close to shore, which risks causing adverse effects on the marine flora and fauna. Thus, it must be released further out, which could be made by shipping out to sea or by sending it through long pipes to larger depths. Even that is not environmentally uncontroversial. Another alternative is injection in the rock bed (deep well injection), but this is seldom a viable option.

In the case of the Arava demo site, sunlight is an abundant and free energy source that quite conceivably could be used in an initial evaporation step, where the brine concentration is increased and the volumes to be transported are decreased. Hoque et al. (2010) investigated several methods for enhanced evaporation of seawater brine, but the eventual fate of the concentrated salts is not described. Economic calculations made by Hoque et al. have been used by Greg McNamara at DCU to estimate a disposal cost of 6 €/m^3.

There are several on-going projects to turn brine waste into valuable resource. For instance, direct electrosynthesis of sodium hydroxide from brine is being explored by Kumar et al. [61]. Desalination industry uses vast amounts of sodium hydroxide, therefore a business case and consequently, a scale up of this technology could be a possible future.

The availability of disposal options appears to be strongly variable, depending on the location and other specific preconditions. A detailed cost analysis is therefore very complicated to perform and must be made on a case-to-case basis. At any rate, the costs are significant, and it should be kept as a memento to take them into account.

4.9. Sustainability roadmap and conclusions

An important overall finding is that the performance and deployment of the SaltGae technology is very location and site specific. The technological configuration (i.e. the selection and arrangement of the different technologies that form the SaltGae system) and the sustainability performance of the three demonstration sites analysed is very different. However, these three assessments allowed to observe a wide range of factors that determine the sustainability performance of the treatment of industrial high salinity wastewater with microalgae. These factors are described below.

Our analysis of the Koto system highlights a trade-off between environmental impact categories, namely climate impact/energy vs water consumption. High organic carbon in water allows for the recovery of energy in the form of biogas, through an anaerobic process (i.e. the 2-AD system). However, anaerobic microorganisms are not very tolerant to the high salinity levels in wastewater, therefore requiring significant amounts of freshwater. In LCA, the recovery of energy brings environmental benefits from substituting other sources of energy production with higher impact. However, for the SaltGae system the use of freshwater to recover this energy entails a significant water consumption.

It is recommended to avoid any environmental burden shifting between energy and water consumption. To avoid this shift of burden, technological development is required. With the current state of technology development, the 2-AD system installed in Koto needs 0.6 m^3 of freshwater for every m^3 of wastewater treated. This is state-of-the art; therefore, further scientific and technological research and development is needed to reduce freshwater consumption in the 2-AD system through e.g. research on bacteria species with higher halotolerance. Further, the investment cost of the 2-AD system was assessed to be very high, so future research and development activities are expected to increase the TRL level of this technology and reduce the investment risks.

An alternative way to reduce the freshwater requirement in the 2-AD system is through recirculating effluents back into the 2-AD system. To recirculate this wastewater, the water salinity needs to be reduced. Assuming reverse osmosis as the desalination technology, theoretical requirements for extra pumps and desalination have been used to asses a scenario with water recirculation (see section 4.6.4.2). The results show that total water consumption of the system is reduced by 60 %. In economic terms, the installation of the extra equipment to allow recirculation (i.e. pumps and pipeline) is 1 % of the total cost and the cost related to the desalination represent around 10 % of total cost.

The scenario results for recirculation seem to be favourable for water consumption, however a deeper analysis raises further questions. The recirculating scenario shows that for the current flowrate of 0.45 m^3 in Koto, the energy obtained from the anaerobic system is 11 MJ, whereas the energy consumption of the two extra circulation pumps is 14 MJ. Thereby, at this point of technological development more energy is required to enable the energy recovery by recirculating wastewater, than the energy produced. These results raise questions about the suitability of the existing process (i.e. 2-AD system) to recover energy without compromising water consumption and with a favourable energy balance.

It is of course important to keep in mind that the 2-AD system is required to lower the COD load and allow for the following algae treatment. If the 2-AD is discarded, a much larger pond surface would be needed. Otherwise, another technology to reduce the COD load would be need. Further research to evaluate the system consequences of this changes is recommended.

Notice that the current Koto assessment is performed with a very low flowrate. An increase in flowrate would equate to significantly higher biogas production (i.e. energy credit) and higher energy consumption (i.e. energy debit). However, the increase in the energy credits and debits will not be linear. Therefore, we suggest future research to find the flowrate threshold with a favourable energy balance that allows recirculation of water and avoids burden shifting.

No direct N_2O emissions have been considered in the LCA of the SaltGae demonstration sites due to lack of experimental or site-specific data. Literature has shown that microalgae cultivation might exhibit direct nitrous oxide (N_2O) emissions. However, in the specific cases analysed by Kelly et al. [62] and Alcántara et al. [63] open pond operating under normal conditions have negligible N_2O emissions. Despite this, a sustainable SaltGae system should manage any possible N_2O emissions, through e.g. checking for the presence of denitrifying bacteria within the culture.

A question is also raised regarding the technology configuration for a SaltGae system to treat tannery wastewater. Assuming reverse osmosis is installed; then one could compare two scenarios. A scenario where water is recirculated within the site for production of biogas in the 2-AD system vs the selection of another technology to reduce COD (i.e. not 2-AD system) and the release of treated desalinated water back to the environment. The overall results depend on the selection of the technology replacing the 2-AD system. However, in this comparison one must not consider the social and environmental benefits of clean water availability for ecosystem and the community in the second case.

An observation from this study is that the equipment dimensioning for the Koto demonstration site is overestimated. As previously mentioned, Koto's flowrate is low; therefore, a low hanging fruit strategy for this site is to increase the flowrate. For LCA and LCC calculations, a significant increasing in the flowrate implies a larger reference flow. This increase in reference flow, ceteris paribus, result in a significant reduction of the overall environmental impact and cost.

Microalgae species selection is very important factor defining the deployment and performance of the SaltGae system. As presented in section 4.3.1, Spirulina has higher production yields and uses significantly less CO_2 and has than *Nannochloropsis*. This project also showed that the extraction protocol for Spirulina is technically feasible and that there are several technologically ready valorization routes for this species. On the other hand, *Nannochloropsis* valorization requires further research and development. Extraction of lipids from *Nannochloropsis* remains technologically challenging. This technological bottleneck does not allow for a complete life cycle-based comparison of both species. Future research suggested is a comparative LCA of both species, including emissions from the extraction protocols and system expansion (i.e. environmental credits) from e.g. eicosapentaenoic acid (EPA) replacement in the market. In terms of future economic evaluation, higher revenue is expected from valorising *Nannochloropsis* compared to Spirulina. Therefore, complementing LCA and LCCA research could highlight economic and environmental trade-off of Spirulina vs *Nannochloropsis* cultivation.

An increment of the wastewater flowrate in the system is the most significant improvement possibility for the SaltGae system. Due to project set up, Archimede demonstration site used freshwater in one of their two algae ponds. A scenario for the use of wastewater in both pods allowed us to demonstrate a significant reduction in water and nutrients used equating to 25 % to 40 % reduction of all environmental impacts. Economic benefits are aligned since this strategy reduces the total costs by 23 %. In the design of a commercial scale SaltGae site, when biomass yield is not compromised, maximizing the amount of wastewater treated is recommended.

To achieve economically feasible algae productivity targets, inorganic carbon in the form of CO_2 must be supplied to algae cultures to achieve high growth rates. CO_2 is soluble in water but when administered into a shallow algae pond, CO_2 bubbles reach the surface and leaks. The leakage depends on reactor geometry, mixing system, bubble size, temperature, water pH and biomass concentration [64]. The CO_2-use efficiency (i.e. percentage of CO_2 not lost) of 40 % was assumed for the cases of Spirulina, while 20 % was assumed for *Nannochloropsis*. To minimize loss, possible solutions include optimizing CO_2 addition through flowrate and pH control [64]. According to Mayers et al. [58], there are losses of carbon as dissolved inorganic carbon (DIC) in the media, therefore it is also important to recycle culture media to reduce the need for additional CO_2. Further, there are some companies offering specific external devices to optimise carbonic gas dissolution (e.g. INJECTOR-BICONE by Air Liquide) (P. David, personal communication, August 2019).

There is general recognition that microalgae are very productive systems that generate biomass and capture carbon. However, as shown with the CO_2-use efficiency above, not all carbon added is captured. The hotspot analysis showed that for Spirulina the impact related to fossil carbon production and fossil carbon leakage equate to 9 % of the GWP, while for *Nannochloropsis* it equated to 70 % of the total GWP. Replacing the added fossil CO_2 with biogenic carbon would reduce significantly this GWP impact, especially for *Nannochloropsis*. In the case of Archimede, the flue gases from the adjacent vegetable oil CHP plant could be used to supply this biogenic carbon. The economic analysis shows that using these flue gases imply a cost reduction. However, the costs and time required to process the permits and certify the CO_2 from the flue gases as food grade, hinders the implementation of this strategy.

In Archimede's base case (Spirulina), electricity consumption equates to around 60 to 70 % of GWP, POCP and AP impacts, and over 80 % of primary energy demand. It also equates to 60 % of operational cost (when labour costs are excluded). The electricity in the base case scenario is from the Italian grid with around 80 % of fossil fuels. Green electricity could provide a solution to reduce the environmental impact of the operations. Green electricity is produced from a range of different technologies and sources. In the Archimedes scenario quantified, electricity from biogas CHP is assumed. This equates to significant environmental improvements such as a reduction of the GWP by 30 %, the primary energy demand by 85 % and the AP by 70 %. However, this strategy implies a trade-off with the economic pillar. Green electricity is more expensive; therefore, the economic scenario showed a 3 - 5 % decrease in the annual income.

Further, an economic factor that hinders the use of green electricity from the adjacent CHP plant was observed. The revenue Archimede gets from selling their green CHP electricity to the grid is significant. The price for selling green electricity to the Italian grid is significantly higher than the cost of buying grey electricity from the grid. Therefore, Archimede has no economic incentive to use their green electricity for their own operations. Further research on incentives for the consumption of renewable energy is recommended to complement this strategy.

For Arava, the benefits of utilizing green electricity by installing solar power on-site is very large. About 85 % reduction in GWP and primary energy consumption could be realized. Further, installing solar panels could reduce acidification, eutrophication and POCP by 15 to 70 %. Investment cost of installing solar energy were not assessed, however it seems like the Arava desert is a good location for photovoltaics and a good business case could be realized.

The Slovenian site uses already green electricity from their adjacent biogas CHP plant. This is environmentally preferable than using Slovenian grid mix based on 33 % fossil fuels [65]. SaltGae system installed in Italy could do the same, namely use green electricity from their adjacent CHP plant. However, one must consider that green electricity from different sources have different environmental impact. Compared to electricity from biogas, the use of vegetable oil electricity is expected to decrease the environmental gains of using green electricity, as shown in the scenario for the Italian site (see section 4.7.1). The reason is that electricity from vegetable oil is expected to have a higher environmental impact than biogas electricity. In Italy, vegetable oil is produced from rapeseed oil and entails environmental impact of these agriculture activities also; whereas biogas is from waste and the upstream impact is lower.

A special scenario was calculated for the Arava where the environmental implication of two distinct cultivation methods — batch versus continuous cultivation — were analysed. Continuous cultivation shows improvements in terms of energy reduction, due to the reduction of PBR operating time. This equates to 20 to 30 % reduction of global warming, primary energy, eutrophication, acidification and POCO impacts. However, the water consumption increases by 60% due to an increment in the open pond operating time. To avoid burden shifting between these two environmental impacts, water recirculation of treated water is recommended to replenish evaporation in continuous cultivation. The results of water recirculation scenario for Arava showed that replenishing evaporation with treated water (prior to RO) induces a reduction of water consumption of 95%. This was evaluated for the batch cultivation method. The benefits would be even higher in a continuous method. An important social implication of recirculating clean water within the system could be that less desalinated cleaned water would be available for the local community, e.g. for agricultural use. In this case one must subjectively weigh the biomass production vs clean desalinated water production.

5. BUSINESS FEASIBILITY ASSESSMENT

5.1. Technological assessment

5.1.1. Aim

The aim of the technology assessment is to evaluate the performance, level of integration, and level of satisfaction of the SALTGAE system from a technical point of view.

5.1.2. Methodology

The business feasibility study starts with a technical assessment to identify the technical readiness level (TRL) and then it continues with a production cost assessment, integrated with work made from the earlier LCCA. These two assessments are then merged into one techno-economic system analysis, and finally integrated with market aspects for the business plans.

One tool that is used in the technology assessments is the Technology Readiness Level (TRL) scale. It can be used for planning and communication purposes, and as a supporting tool for decision making on investments [66]. It was developed during the 1970-80s as a seven-level scale to assess and communicate the maturity of new technologies. In the 1990s it was further developed to a nine-level scale that now is widely used, but often adapted to specific needs of an organization. The TRL scale used in Horizon 2020 work programs, and thus used in this project, is seen in Table 19.

Table 19. TRL scale used in Horizon 2020

TRL scale	Description
1	Basic principles observed
2	Technology concept formulated
3	Experimental proof of concept
4	Technological validity in a lab
5	Technology validated in relevant environment
6	Technology demonstrated in relevant environment
7	System prototype demonstration in an operational environment
8	System completed and qualified
9	Actual system proven in operational environment

In early 1970s, the prevailing view was that innovation was linear and this is reflected in the TRL scale [66]. One flaw of the tool is thus that it is not designed to capture and communicate the dynamics of the innovation process, were it is common with setbacks in maturity.

Another limitation is that the original TRL scale was developed for product oriented technologies and focused on a single component and not a whole system [66]. This is still reflected in the tool by a focus on one single technology in the lower levels of the TRL scale. The higher levels, however, are about integrating several individual technologies with diverse maturities. This means that it is possible that a product has a high TRL at the same time as some of its manufacturing technologies have low TRL levels. The shift in focus within the tool complicates the application in projects such as SaltGae which rather are about system development than component development. As an attempt to handle this limitation of the TRL scale, each component of the system is assessed individually and then the system is assessed.

Further, the EARTO reading [66] highlight that the TRL scale do not cover non-technological aspects, like the readiness of an innovation to go to market and the readiness of an organisation to implement the innovation, and as a solution they provide a broader reading of the scale including such aspects. However, since it is also valuable to evaluate the technology readiness from a technical point of view only in order to highlight further R&D needs, the “traditional” TRL scale is used in the technology evaluation. Non-technological aspects are covered in the economic evaluation, system analysis, and the business plans.

As a compliment to the TRL scale, specific questionnaires to end users and technology providers were developed and sent to partners within the consortium. With this approach, the knowledge, experiences and insights about each individual part of the process and how well they each work within the system was captured in more detail. The questions to the technology providers mainly focused on performance and level of integration and questions to end users mainly on level of satisfaction and level of integration. Questions regarding scale-up potential of the SaltGae system were included in all questionnaires.

5.1.3. Technology overview

The SaltGae-system is designed for saline wastewater with presence of organic content, which currently represents a challenge for many industrial sectors. The design of the SaltGae system is dependent on the incoming physio-chemical properties of the waste water, both in terms of which valorization routs that should be included, and in terms of process design within the "basic system" (including pre-treatment, algae cultivation, and algae harvesting) and each valorization route, see Figure 39. The description of TRL levels is presented in Appendix X. Within the SaltGae project, there are three demo sites: Koto, Arava, and Archimede (Table 1). At all three sites, the basic system is implemented (DAF at Arava and Archimede, and 2-AD at Koto). Effluent valorization is implemented at Arava (reverse osmosis), valorization of solids and sludge at neither of the sites, and regarding the valorization of biomass, only the drying step is implemented; at Arava in the form of a solar oven and at Archimede spray drying.

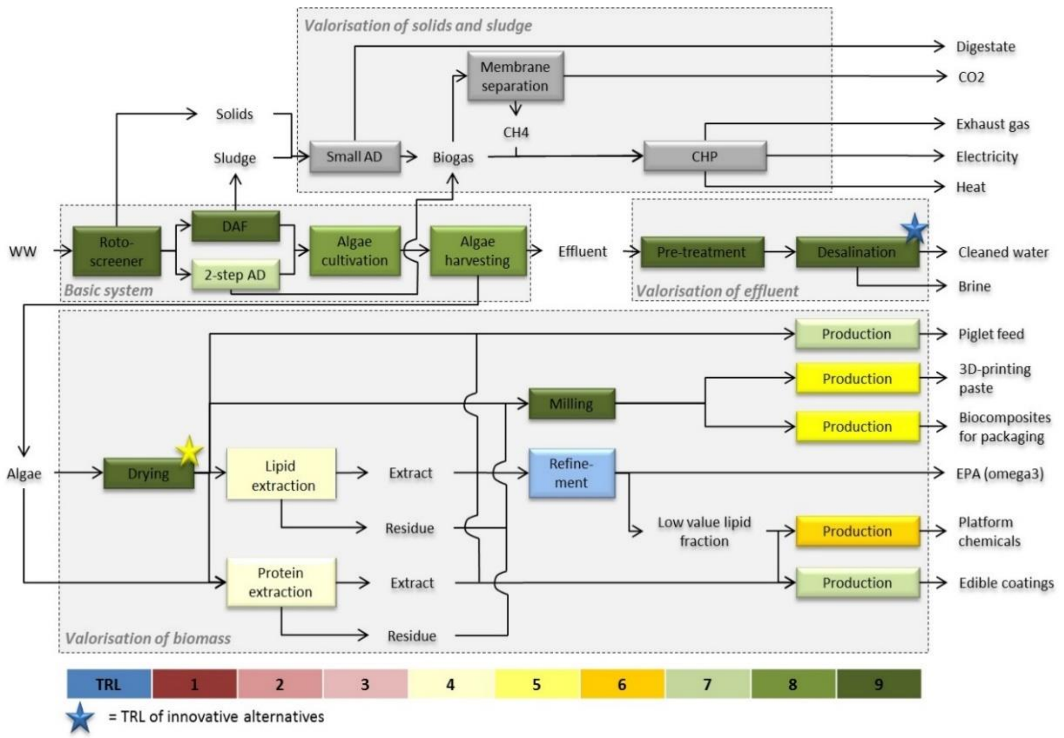


Figure 39. Overview of the SaltGae system and its TRL

Each demo sites and part of the system has been described in detail in deliverables made in WP2-6. Partners that has contributed to the technological assessment are Koto, Arava, Archimede, Algen, Biboaqua, Nova, iBET, Extractis, Funditech, INSTM/Polimi, Produmix, and DCU.

5.1.4. Basic system

The basic system starts with a roto-screener and in systems with high BOD configuration (≥500 mg O_2/L), it is followed by a 2-AD (e.g. Koto demo site). In systems with low BOD configuration (<500 mg O_2/L) a DAF unit is used instead (e.g. Arava and Archimede demo sites).

The 2-AD produces biogas that could be utilized to generate electricity and heat that could be used to cover some of the energy needs in the system, and CO_2 that may be possible to use in the algae cultivation and/or the buffer system prior the pond. There are two options for the utilization: combustion of the raw biogas in a CHP unit or, after separating the raw biogas into CH_4 and CO_2, combustion of CH_4 (Figure 1).

The second alternative includes an extra process step but result in a cleaner fraction of CO_2. At the Koto demo site, the first alternative with combustion of the raw biogas is applied. All biogas produced in the 2-AD system is sent via pipelines to an existing biogas plant at the site where it is combusted in a CHP unit. The exhaust gas from the CHP unit is used as a CO_2-source in the ponds and the heat generated in the CHP unit is used as main resource for the heating system for the 2-AD and the ponds.

An alternative to the Saltgae technology can be a reverse Saltgae technology. This would consist of an mixotrophic algal pond first and conventional AD second. Mixotrophic algal pond would be consuming both organic mass and nutrients and building it into the algal bacterial biomass. Growing algae in high salinity presents no issues, but relatively dense WW with dark colour would require a specialized algal ponds (shallow). Advances in mixotropic algal growth have shown species that can efficiently work at high BOD levels (e.g. syneccocystis) – depending on the nature of organic load. The resulting biomass could then be used for energy recovery in a conventional AD. It could be possible to design e.g. two stage algal systems where better quality algal biomass would be produced in the second stage. Ultrafiltration and reverse osmosis would come as the final step after harvesting for desalination. At present there is no experience with such systems, but they can be implemented with further development.

Shallow open pond systems, with paddlewheels for mixing, in moderate controlled environments (e.g. greenhouses covered for weather and infectants) are used for the algae cultivation. Different technologies for harvesting have been tested within the project, but the main focus has been on the combination of UF and centrifugation. However, all microalgae do not require centrifugation (with or without prior UF) for harvesting. Spirulina for e.g., forms something similar to clouds of hair and could be harvested with less expensive processes. This is the case at the Arava demo site, were a vibro-screen is used for harvesting instead of UF.

Market readiness from a technical point of view

The basic system with low BOD configuration for WW with low/medium salinity levels is ready for the market from a technical point of view; the system is completed and qualified (TRL 8-9) (Figure 39, Table 20).

Table 20. Issues in the basic system that need to be considered or which may occur depending on WW characteristics

Process	Issues	Effect	Possible solution
Roto-screener	None		
DAF	None		
2-AD	i) Outflow is dark black and contains solids ii) Condensate in gas pipeline iii) Troubles with pumps	i) The active volume of the pond is reduced. ii) Inaccurate measurements of produced gas. iii) Maintenance, lifespan, and efficiency.	i) Electrocoagulation ii) Use other measurement equipment iii) None suggested: general issue for AD
Algae cultivation	i) WW with high calcium and low phosphate: aggregation/ precipitation formation when phosphate is added. ii) Unstable source of WW with high salinity: self-selection of algae and algal (microbial) community structure changes. iii) Algal bloom	i) Inhibit algae growth and increases the need of cleaning. ii) May create troubles in the harvesting (depending on harvesting method) and limit possible end-uses of the biomass. iii) Limiting light availability for other algae and increased need of cleaning.	i) Calcium reduction/removal can be achieved through cation exchanger (e.g. sodium) – most simple, but also by ED, UF and RO. ii) Select a harvesting method that is flexible, target an end-product that is not sensitive to algae specie/composition, achieving a relatively stable source of WW may reduce the structure changes. iii) Greenhouse cover of ponds and higher pH limits the risks for airborne contamination.
Algae harvesting	None for harvesting with UF and centrifugation		

Depending on the WW characteristics and greenhouse cover, there may be some minor issues to consider (Table 20). Basic systems with high BOD configurations are almost ready for an initial market introduction

(TRL 7-9); some further trials at pilot scale are needed to validate the lab-scale results that the issue with the outflow of the 2-AD could be solved with electrocoagulation (Table 20). If land is available, no hindrances to scale-up are expected from a technical point of view (Table 20).

Table 21. Scale-up potential and hindrances from a technical point of view for the basic system

Process	Scale-up potential and hindrances from a technical point of view
Roto-screener	Easy to scale up.
DAF	No big issues connected to the scale-up of the DAF; the system will be more stable in larger scale.
2-step AD	Can easily be scaled-up.
Algae cultivation	If land is available, the scale-up potential is big.
Harvesting	A combination of sedimentation, DAF, electrocoagulation possibly augmented with centrifugation can be the most effective approach.

5.1.5. Valorization of solids and sludge

If there is enough solids and sludge separated in the first steps of the system, AD could be used to valorize the biomass into digestate intended for use as fertilizer Figure 1. As in the case with a 2-AD, the small AD generates biogas that could be utilized into electricity, heat, and a potential CO_2-source (exhaust gas and, depending on utilization route, a "clean" CO_2-stream). Since none of the three demo sites within the project generated enough amounts of solids and sludge in order to justify an investment in a small AD and a CHP-unit, this part of the system has not been demonstrated. However, for the AD, a yield of 0.35 LCH_4/gCOD and CO_2-content around 40 % could be assumed.

When an AD and/or CHP-plant are located nearby, an alternative to look into is the possibility to cooperate with these companies, and in cases where not enough solids and sludge are produced, it should be investigated if there is excess heat nearby and/or CO_2 that could be utilized in the SaltGae-system in order to reduce costs. This is what is being done at KOTO, where solids and sludge are fed into the existing biogas plant that is 10 m away.

<u>Market readiness from a technical point of view</u>

The equipment needed for the AD, membrane separation, and CHP are commercially available. If the solids/sludge has a high salinity, a gradual adaption to the high salinity conditions may be needed as in the case with the 2-AD.

5.1.6. Valorization of effluent

For the valorization of the effluent, ED could be relevant if the conductivity is equal to or higher than 1-2 mS/cm. The incoming effluent must be suspended matters free and if not, pre-treatment is needed prior the desalination. Of the pre-treatment alternatives tested within the project, NF performed best regarding TOC removal. For lower salinity levels, RO could be used for desalination. The desalinated water could be reused in the process, used for irrigation, or released to the environment depending on the expected (environmental) specifications.

ERD/new pump. The efficiencies of the reverse osmosis (RO) systems currently under development for the SaltGae project are influenced by several site-specific parameters and technical constraints. The key parameters are the influent flow rates and salinity concentrations. The technical challenges relate to selecting the most suitable high-pressure pump (HPP) and RO membrane configuration for a given set of site-specific conditions. It is difficult to assess how the high-pressure pump (HPP) will affect the valorization without supporting data. It was anticipated that the HPP could operate at high efficiency levels which would reduce energy costs. Now, both DCU and Arava are operating the RO with a commercial pump. For the ERD it is obvious that there is a trade-off between water recovery, energy recovery, and the cost of brine disposal. This is a site-specific issue i.e. the operating conditions will be dictated by the cost associated with each of these parameters. However, the consensus seems to be that that the RO system in the Arava will operate more economically without the ERD. See also Table 22 and Table 23.

Market readiness from a technical point of view

The effluent valorization part of the system is ready for the market from a technical point of view when considering using conventional equipment (Table 22) and the scale-up potential is good (Table 23).

Table 22. Issues in the effluent valorization that need to be considered

Process	Issues	Effect	Possible solution
Pre-treatment	None for NF	-	-
Desalination	None for ED	-	-
EDR pump	i) The first prototype received has been affected by air leakage (which has a strong impact on performance) and a lubricant leakage due to damaged seals. ii) The second prototype could not be delivered and tested due to the lack of remaining time of the project. iii) In relation to the ERD, it was found that energy recovery was greater with reduced water recovery (a greater swot flow carries more hydraulic power to the ERD).	-	i) The air leak should be repaired at DCU and test the device as part of a simulated system (substituting a valve for the RO membrane) so that lubricant leakage does not affect the RO unit. The aim is to devise a control strategy to test the pump and demonstrate feasibility but also obtain initial performance curves. DCU will repeat the test plan but will monitor carefully any possible failure. ii) OMS will ship the second prototype to DCU rather than RISE. It has tested the pump briefly at 70 bars and can confirm that it appears to be performing correctly. iii) Integrate the second prototype to the RO unit at DCU and perform a full series of test within the realistic environment.

Table 23. Scale-up potential and hindrances from a technical point of view for the effluent valorization

Process	Scale-up potential and hindrances from a technical point of view
Pre-treatment	Membrane processes are easy to scale up.
Desalination	ED is scalable and there are no hindrances for spreading and/or scaling-up the SaltGae-system related to the ED process. The scale-up potential for the RO is also judged to be good.
EDR pump	There are obvious economies of scale to be gained both in terms of energy consumption and the capital investment. It is difficult to assess without a functioning HPP.

5.1.7. Valorization of biomass

Several valorization routes for the microalgae biomass have been considered within the SaltGae-project. For most of the valorization routes, drying of the algae biomass is needed (Figure 39). However, for the protein extraction route it is possible to exclude the drying step if the extraction process is located nearby. It should be possible to connect the processes since the dry matter content of the inflow to the protein extraction is within the limits of what could be achieved for the harvesting outflow when UF and centrifugation is used for harvesting[9]. If another harvesting method is selected the compatibility with the protein extraction has to be considered if a direct connection between the harvesting and protein extraction is desired.

Drying of microalgae is necessary to produce further target products from microalgae in an efficient way. The selection of an appropriate drying method depends on the properties of the microalgae suspension such as content of target component, cell size, shape and surface charge, salt concentration and pH, but also on the subsequent downstream processes used for the isolation and production of final products, and the

[9] The dry matter content tested in the refinement has been 22 % (2.47: 8.93 for dry matter: water ratio) and It is possible to adjust the dry matter content of the harvested algae biomass between 15 and 25% when UF and centrifugation is used. One can expect the dry matter content of the harvested biomass to vary +/- 2% and too big fluctuations in dry matter content would probably create issues in the refinement process. However, variations in dry matter content of +/- 2% are expected to be neglectable.

acceptable production costs [67]. Common drying techniques for microalgae are freeze drying (lyophilization), spray drying, vacuum drying, solar drying and, conventional hot air drying. Within the SaltGae-project, solar drying (at Arava demo site) and spray drying has been applied (at Archimede site).

Refinement of the algae biomass (protein and/or lipid extraction) is needed for all routes except for use as piglet feed, 3D-printing paste and for biocomposites. The two latter could utilize either dried algae, or residues from a refinement process. However, for the biocomposite, the inclusion of algae residues does not enhance the mechanical properties as is the case when whole algae are used and is thus not as interesting from a technical point of view. For the piglet feed, dried algae could be used but refinement into nutritional fractions (protein and lipid extracts) would enable a better control over the composition of nutrients.

Market readiness from a technical point of view

Currently, none of the biomass valorizations routes considered, except the piglet feed, are ready for a market introduction seen from a technical perspective and further research and development is needed (Figure 39, Table 24, Table 25, Table 26, Table 27):

- The edible coating developed is, from a technical point of view, ready for an initial market introduction if the improvements are made regarding the microalgae smell and colour of the coating (should be transparent). However, the prior step needed in the form of protein extraction is not ready. For the edible coating, it is not critical that the lipid extraction is market ready since linseed oil could be used instead until the availability of algal oil improves.
- For the platform chemicals however, the lipid extraction is a prerequisite and further R&D is needed regarding the extraction as well as the production of platform chemicals and the production of the end-products including platform chemicals. It is thus judged to be the valorization route that, from a technical point of view, is furthest from the market.
- For the 3D-printing paste and the biocomposites there are needs for further R&D in the production. For the first, mainly in the form of trials at larger scale and for the latter, regarding the extrusion technology.

The protein and lipid extractions and most of the end-products considered require that the composition of microalgae species is maintained as equal as possible throughout the year (Table 25 and Table 27). Of the end-products, the 3D-printing paste is the one application that is least sensitive to changes of the algae composition which implies that this product could be targeted at sites where the algae selects themselves and/or the composition change every now and then, as the case at the Koto demo site.

Regarding the drying, there are options available that already is on the market. However, for sunny areas a need has been identified to develop a more advanced solar drying system to erase the limitations related to quality and health risks (if the biomass is intended for feed/food) that come with the “basic method” for solar drying commonly used.

Table 24. Issues in the first parts of the biomass valorization that need to be considered

Process	Issues	Effect	Possible solution
Drying	i) For solar drying; difficult to achieve consistent results	i) Inferior quality and potential health risks	i) R&D
Protein extraction	i) Seasonal variations in biomass production ii) Changes in microalgae characteristics iii) Dark colour of the resulting proteins iv) Difficulty to dry the resulting protein	i) Dimensioning of the equipment and need to store biomass ii) Yield, physical behaviour of the resulting protein fraction, and centrifugal separation iii) May limit the possible end-uses iv) -	i) In general, dimension the equipment based on yearly average inflow ii) Maintain, as much as technically feasible, the same composition of microalgae species iii) Target suitable end-uses since techno-economic justification for purification is currently lacking iv) Identify appropriate industrial large-scale technology
Lipid extraction	i) Low yield despite comparable to other products in development or already on the market	-	i) R&D

Table 25. Scale-up potential and hindrances from a technical point of view for the first parts of the biomass valorization

Process	Scale-up potential and hindrances from a technical point of view
Drying	Spray drying easy to scale up. Solar drying: easy to scale up after coming up with a satisfactory working model (provided that enough land is available in order to dry enough algae per unit of time).
Protein extraction	The potential to scale-up the protocol from the laboratory scale using usual industrial equipment seems difficult, especially for the centrifuging separations steps. Improved routes should be studied using combined technologies of centrifugation (with a hydrohermetic seal and flushing recycling) and filtration, while reducing foaming. Possible validation of the mass balances for this alternative approach, if it works properly, would require continuous runs with larger quantities needed for these technologies (to reduce dead volumes effects in particular).
Lipid extraction	The lab-scale process is validated, the purity of products is reached and nearly on the market in other developments. But the relevance of such a process, from an industrial point of view, is questionable as large volumes of organic solvents are needed, negatively impacting both the safety, environment and profitability of the process. Other processes, with lower impacts but not reaching exactly the target, were tested at the lab-scale during the project and would need further pilot developments if applied.

Table 26. Issues connected to the resulting end-products in the biomass valorization that need to be considered

Process	Issues	Effect	Possible solution
Piglet feed	i) Changes in microalgae characteristics	i) Instability among batches (protein, fibre, minerals, etc.)	i) Maintain, as much as technically feasible, the same composition of microalgae species
Platform chemicals	i) Changes of microalgae species ii) Production of end-products containing the platform chemicals are not ready for industrial scale	i) Performance ii) -	i) Maintain, as much as technically feasible, the same composition of microalgae species ii) R&D
Edible coatings	i) Microalgae smell ii) Green colour of the coating iii) Changes in protein concentration in the microalgae protein extract	i) Potential presence of ”off-flavour” ii) May limit the possible end-uses iii) Changes in performance of the coating	i) R&D (optimize the amount of algae included and/or add flavourings) ii) - iii) Maintain, as much as technically feasible, a composition of microalgae species with high protein content
3D-printing paste	i) Presence of big (>10 µm) aggregates in the biomass	i) Absence of big aggregates is a prerequisite	i) Usually ball milling
Bio-composites	i) Extrusion of the material ii) Microalgae smell iii) Wheat gluten is an allergen iv) Presence of big (>10µm) aggregates in the biomass v) Changes in microalgae characteristics	i) - ii) May be a concern in packaging for food iii) Could imply some limitations in the use iv) Absence of big aggregates is a prerequisite v) Performance (e.g. mechanical properties)	i) R&D is ongoing to find proper technology ii) Need to study user perception and eventual change in taste iii) - iv) Usually ball milling v) Maintain, as much as technically feasible, the same composition of microalgae species

Table 27. Scale-up potential and hindrances from a technical point of view connected to the resulting end-products

Process	Scale-up potential and hindrances from a technical point of view
Piglet feed	The hindrances to spread and/or scaling up the production of piglet feed do not lie within the production of the feed itself but rather in the production of dried algae biomass (algae growth rates, dry matter content after harvesting) and the refinement into nutritional fractions (protein and lipid fractions that would enable a better control over the composition of nutrients) and are both of technical and economic nature.
Platform chemicals	Scale-up of the production of platform chemicals is judged to be feasible since the main parameters are under control. Getting large amounts of algae oil extract that meet the requirements is the main hindrance for scaling-up the production.
Edible coatings	The scale-up potential is judged to be good. One limiting factor for scaling up the production is the availability of algal oil but until the availability of the algal oil improves, linseed oil could be used instead.
3D-printing paste	Scale-up is judged possible. However, the technology related to printing large scale objects with ceramic pastes is relatively new and therefore many tests will be required.
Biocomposites	Scale-up will be possible when the proper method for extrusion is found.

5.1.8. Positive and innovative aspects

The main positive aspect with the system, highlighted by the operators of the demo sites, is the production of valuable algae (instead of sludge, as in biologic systems) while cleaning the water. Positive and innovative aspects connected to individual parts of the system are summarized in Table 28.

Table 28. Positive and/or innovative aspects of each part of the system

Process	Positive and/or innovative aspects
Roto-screener	- nothing in particular
DAF	- it has been proved that the use of DAF with salty water works satisfactory
2-AD	- the adaption strategy to salinity - that the process can work up to 50 g Na/l in the first phase and 20 g Na/l in the second phase
Algae cultivation	- for a detailed description of the developments of pond and paddlewheel designs made within the project, see D 5.1 and 5.2
Harvesting	- nothing in particular
Pre-treatment	- when testing NF against activated carbon and light, it performed better for organic removal - membrane processes are usually use less chemicals compared with activated carbon processes that require regeneration
Desalination	- nothing in particular
Drying	-none reported
Protein extraction	- at this stage the process seems quite simple (two main separation steps and relatively usual equipment) - its transposition into a continuous process seems at this stage feasible
Lipid extraction	
Refinement	
Piglet feed	- the potential of including dried algae biomass in piglet feed is considered to be huge, if the price of the algal biomass is reduced
Platform chemicals	- if the current issues with the foaming agent/effect are solved, the use of H-NIPUS for polyurethane foam is judged to be promising, if the price of the algal biomass is reduced
Edible coatings	- a trial made indicate that the edible coating developed within the SaltGae-project has better performance than at least one of the competing products on the market, if the price of the algal biomass is reduced
3D-printing paste	- the mechanical properties are only slightly affected by the type of algae biomass (e.g. whole algae, algal residue, and algae specie), if the price of the algal biomass is reduced
Biocomposites	- the resulting biocomposite is renewable, biodegradable and has a limited carbon footprint, if the price of the algal biomass is reduced

5.1.9. Prerequisites for the WW to be treated

To specify which characteristics that make a WW suitable to treat with a SaltGae-system solution (and identify potential hindrances/limitations regarding process integration and system design), all partners were asked to specify process parameters of importance. Below follows a list of identified prerequisites for the WW to be treated:

- High BOD (≥500 mg O_2/L) configurations:
- WW needs to be diluted if too high salinity (max 50 g Na^+/L in the first phase in the 2-AD and 20 g Na^+/L in the second phase)
- 2-AD is disturbed if there are too big fluctuations in salinity.
- The efficiency of the 2-AD is limited if the content of organic matter is too low (what is too low depends on the type of organic matter, however, during the start-up the feed should contain at least 3-4 g COD/L)
- Independent of BOD configuration
- Absence of pollutants if the biomass is to be used in feed/food industry

5.1.10. Seasonal variations of biomass output

There is one aspect regarding the system design that not yet has been highlighted; the seasonal variations of the biomass output which mainly depends on algal genus and location (latitude), but as a rule of thumb the output during winter is 1/4 to 1/3 of the output in the summer. Depending on system design and WW characteristics, these variations could imply some challenges when scaling-up the system:

1. Keep the organic matter and nutrients in outgoing water within certain limits throughout the year
2. Processes after harvesting needs to be able to handle big variations in inflow

At the Koto demo site, the system operation is set according to output water which means that the quality of the output water should be quite constant. When conditions for algae growth aren't optimal (e.g. low light and/or problems with quality of input WW), smaller amounts of WW are treated. In large scale with constant flow of WW, however, such an approach would require lots of storage capacity and there is a need to investigate other solutions. The bacteria and algae work in synergy; the algae need sunlight and CO_2 (the latter provided by the bacteria) for growth incorporating nutrients (N, P) and release O_2 that the bacteria, in combination with organic matter, needs for growth. One alternative is thus to apply artificial lighting in combination with heating of the water in order to balance the system. However, this option is not judged feasible due to cost[10]. Another alternative is to supply oxygen with aeration[11] when there is lack of light. This approach should solve the issue with adjusting the organic matter content (the bacteria are provided with enough oxygen to decompose the organic matter). Since it is mainly the algae that reduce the nutrients levels there may still be an issue with nutrient load, especially the P since the aeration also removes ammonia[12]. If there is not enough biomass to take up the P it must be removed through precipitation with a chemical, e.g. ferric chloride. An alternative to consider is to size the ponds after the minimum biomass production and in high season add nutrients to boost the algae production. This last approach, with pond sizing and nutrient addition during summer, is like the one used at Archimede demo site.

Regarding the drying of the harvested biomass, no difficulties connected to seasonal fluctuations have been reported. For the extraction process the variations of the biomass output is a minor issue - if the biomass is dried prior the extraction, which is a prerequisite for the lipid extraction and optional for the protein extraction – since the dried biomass could be stored for long periods of time without losing quality[13] and thus, the equipment could be dimensioned after yearly average biomass output. In cases where the protein extraction is connected directly to the harvesting (no prior drying), the variation in biomass output puts demand on the refinement process and means that the equipment would either be over dimensioned some parts of the year[14] or that there is a need to level out the inflow to the process. The inflow could be adjusted

[10] The energy loss and increased production cost associated with artificial lightning for micro algae cultivation may be acceptable in the production of high value products, but in general they should be avoided.
[11] Aeration is used in traditional WWT and usually accounts for 30-70% of a WWTP total energy costs.
[12] Aeration reduces the ammonia to nitrate and then an anoxic process converts the nitrate to nitrogen gas which discharges into the atmosphere.
[13] If dried below 5% MC.
[14] If those demands could be met is dependent on the scale of the variations in biomass output and on how flexible the equipment is. The flexibility of the equipment should be confirmed with the manufacturers, especially for centrifugal equipment.

by drying the part of the biomass that is above the yearly average and, when the output is below yearly average, the dried biomass could (together with fresh water or cleaned water resulting from the effluent valorization; dependent on its characteristics and the specifications needed in the extraction) be used as an additional input[15]. In general, if the microalgae are dried and can be stored, the best economical solution is to design an average inflow equipment line[16].

To sum up, how to design the system to handle the seasonal variations is dependent on the WW characteristics, limits/demands of the cleaned water, and on intended use of the biomass.

5.1.11. Concluding remarks

From a technical point of view, the "basic system" and valorization of the effluent are ready for a market introduction as a WWT system intended for WW with low/medium salinity and BOD content, preferably with "constant" quality of the WW meaning not too big variation in important system parameters. Treatment of WW with high BOD and/or high salinity and the valorization of biomass are, however, not yet fully ready and further R&D is needed. The valorization of solids and sludge is judged to be ready for WW with low/medium salinity, even though not tested within the project. If introducing the SaltGae system on the market in the near future, facilities with suitable WW characteristics and available land in beneficial geographical locations (considering climatic conditions and closeness to WW source) should be targeted, and if not the piglet feed is a feasible option from perspectives other than solely technological, other uses of the biomass produced than those included in the SaltGae project must be found until these valorization routes are fully developed. Effort should be made to maintain the composition of microalgae species as equal as possible throughout the year in order to enable to target a wider range of end-products.

5.2. Production cost assessment

For this part, a business "suit" with overall costs and investment cost is added to the previous operational costs mentioned in Chapter 3. Additionally, biomass production is integrated in the result, with a market price of 15-30 €/kg (Annex XI). In order to assess the production costs, the results from a comparison between each of the demo sites and the benchmark described in Section 4.5, are shown in this section. Finally, a supplementary assessment of the transportation scenario mentioned in Section 4.7.2 is described to connect logistics with capital investments.

5.2.1. Koto

Koto which has the main focus of WWT coming from tannery, has a potential to develop CHP plant by using 2-AD in the WWT pre-treatment. The CHP plant can produce biogas converted to electricity, which in return could be used for the WWT process. However, the current flows of WW do not allow the production of biogas necessary to support the system. This could probably be solved by using biomass from adjacent plants.

The results presented in Figure 40. Koto investment costs (€/m3)Figure 40 shows that the greenhouse system account for more than 50 % of all investment cost of the sub-systems. Except for the greenhouse it also includes the costs for the pond, the mechanical equipment and electrical equipment for controlling the system, which makes it the largest cost contributor in the construction phase. The second largest, the distribution 2-step AD sub-system account for around 30 % of the construction phase. It mainly includes costs for pumps and the anaerobic reactor.

Comparing the cost for Koto and the cost for the benchmark, it is important to take into account the business as a whole. Figure 41 shows two sets. The one to the left is the cost for Koto, including both operational (Figure 5) and investment cost (Figure 44) but also additional cost categories like owner expenses and insurance. The one to the right represents the overall cost for the benchmark (see section 4.5.2). Since different equipment have different life lengths and needs therefore different amount of investments, the costs are averaged over a time period of 30 years.

[15] The fast deterioration rate of wet biomass calls for fast processing and storage of wet biomass is thus not an option.
[16] Concerning energy consumptions, well-adapted scale equipment will provide a better efficiency.

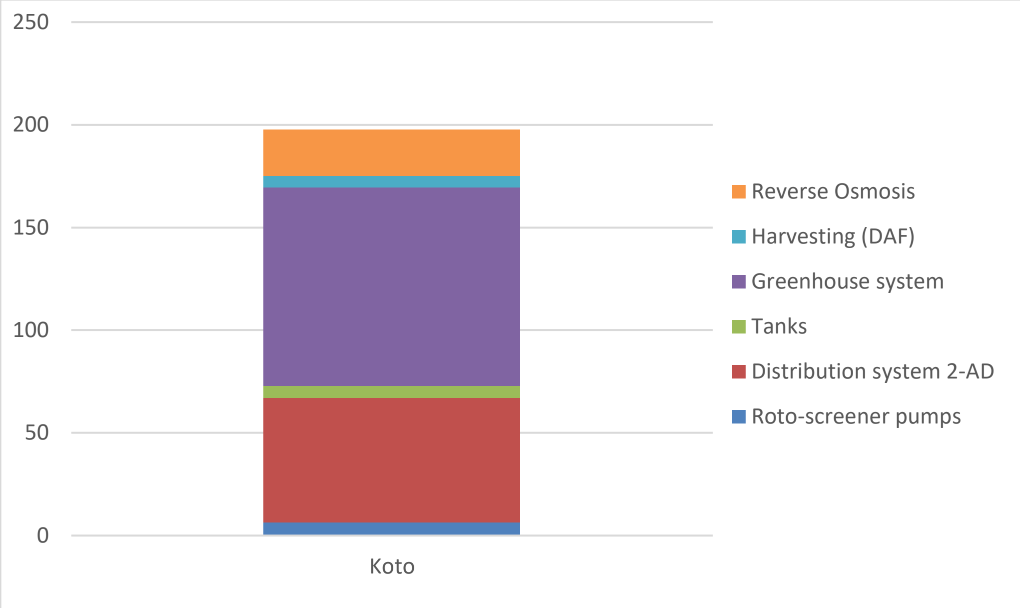


Figure 40. Koto investment costs (€/m^3)

Most of the costs of the Koto system are associated with the costs originating from investment cost and financial/ business categories. Owner expenses, which can be seen in Figure 41 includes costs for procurement, supervisory and administration for the demo site. This is assumed to be 10 % of the investment costs (Annex X). If comparing with the benchmark, the higher cost for Koto is mainly due to the demo site which is designed for a flow of 5 m3/day but are operating only at 0.45 m3/day. Since treatment cost strongly depends on the scale of the production capacity this means that especially the investment cost per m^3 wastewater is significantly higher than it needs to be [55]. If the daily flow would increase to 5 m^3/day, both the investment costs and operational costs would still be slightly higher for Koto than for the Benchmark. This is mainly because the investment cost for an algae pond is slightly more expensive than for a conventional aerated sludge system. Checking the NPV, the positive revenue that comes from producing and selling algae biomass is too low to make an impact for the overall result[17]. The amount of wastewater for producing algae is basically too low.

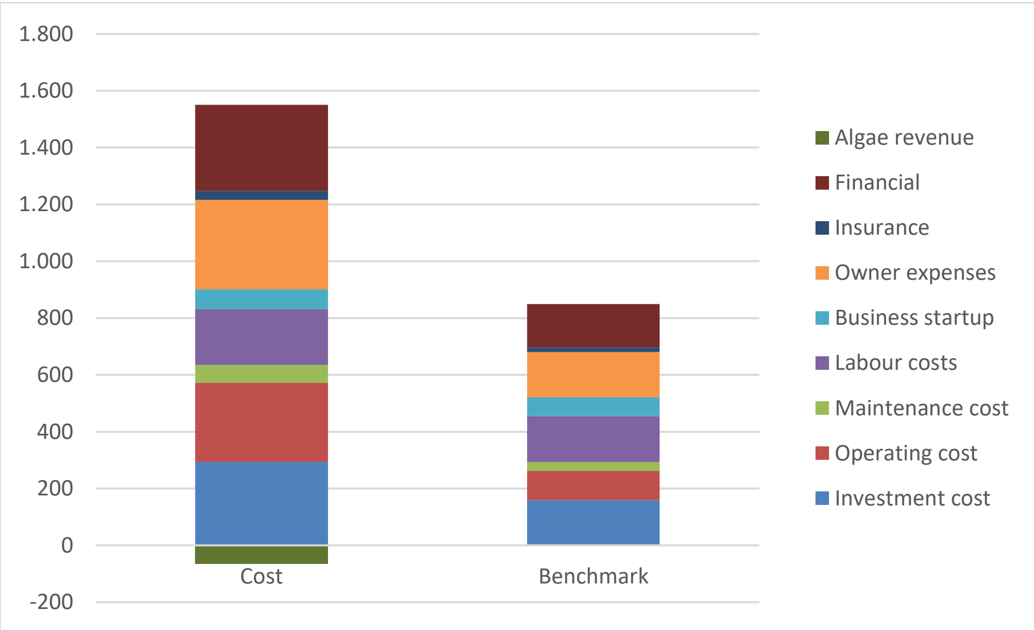


Figure 41. Koto economical assessment (€/m^3)

[17] The selling price for food grade algae was estimated 15-30 €/kg for the calculations, though in case of KOTO this price of algae would be lower, because this demo-site does not produce food grade algae. So the revenue from selling algae would be even lower than in Figure 41.

5.2.2. Archimede

The Archimede demo site is a high-tech facility that has a potential for upscaling not only for WWT and performing chemical analysis of the quality of water and biomass. Archimede is intended for WW coming primarily from dairies. The challenge is to ensure food grade quality of the WW, which is a requirement for most of the valorization routes, but also to use food grade CO_2 which is more expensive. It is possible to design industries so they have separate flows, so that a part of the WW could be classified as food grade and the rest as WW treated by e.g. municipality. Archimede could focus not only on WWT treatment but on the algal biomass production for the food applications.

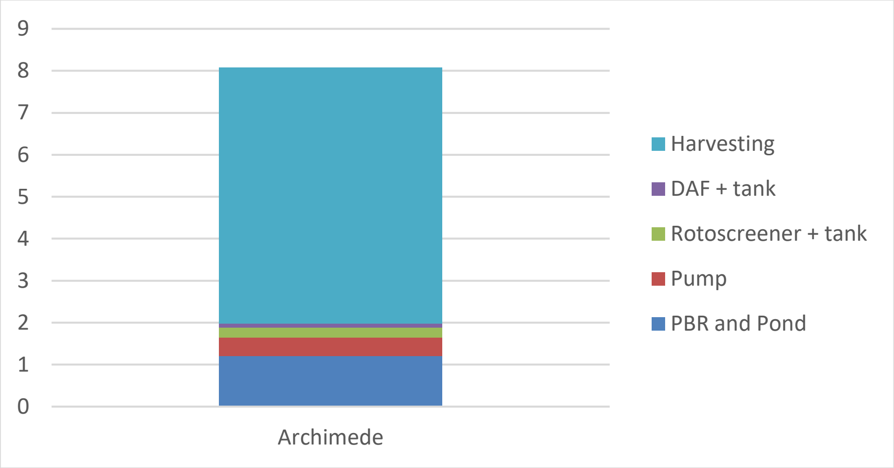


Figure 42. Archimede investment costs (€/m^3)

The results are presented in Figure 42 and Figure 43. Figure 42 show that the harvesting system account for more than 70 %, which makes it the largest investment cost contributor. The second largest, the PBR and pond sub-system account for around 20 % of the construction phase. The investment costs for the pumps are in comparison with the other sub-systems presented in Figure 42, rather small.

Comparing the cost for Archimede and the cost for the benchmark, it is important to consider the business as a whole. Figure 43 shows two sets. The one to the left represents the cost for Archimede, including both operational (Figure 9) and investment cost (Figure 42) but also additional cost categories like owner expenses and insurance. The one to the right represents the overall cost for the benchmark (see section 4.5.2). Since different equipment have different life lengths and needs therefore different amount of investments, the costs are averaged over a time period of 30 years.

Figure 43 shows that most of the costs are originating from labour costs. Salaries was calculated with average labour costs in Italy [68]. The total annual labour time was based on hiring three persons and the total cost of labour amounts to 147,000 €/yr. Except for labour cost, most of the cost comes from the harvesting part and cultivation which stands for the major impact on the operating cost of the algae systems.

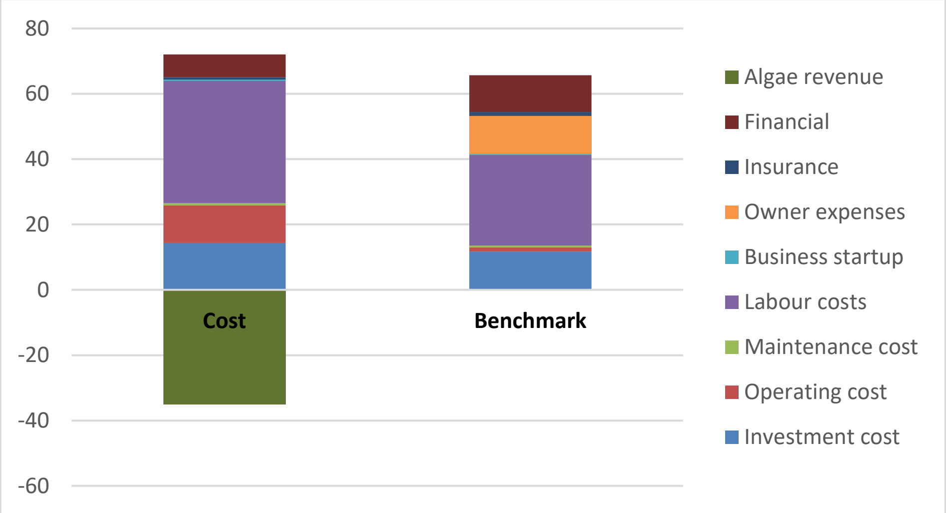


Figure 43. Archimede economical assessment (€/m^3)

Comparing with the benchmark, the investment cost for Archimede are slightly higher since special equipment is needed for operating the ponds, for instance paddlewheels, pumps and sensors. The operating cost is higher since nutrients are added and a higher level of labour is needed to operate the algae production. But taking into account the revenue from the algae production, the business looks better. For instance, calculating with a period of 30 years the net present value (NPV) for Archimede are roughly 50% better than for the benchmark. With the value received from the additional income of selling algae (Annex XI) the plant will therefore be cheaper than the benchmark.

5.2.3. Arava

Arava is a facility that can be used from the local producers of WW, such as aquacultures. The focus of the demo site is WWT, whereas the treated water can be used for the local farmers. However, the biomass production could be also performed using solar oven. The improvements of the solar drying should be performed, but the technology has a potential to be used for more sustainable drying where the solar energy is only required.

Comparing with the benchmark as seen in Figure 45, the investment cost for Arava are also slightly higher since special equipment is needed for operating the ponds, like for instance paddlewheels, pumps and sensors. Furthermore, the operating cost is higher since more nutrients are added and more energy and labour are needed to operate the algae production. But with the value received from the additional income of selling algae for 20 €/kg the demo site will have a slightly better NPV (less than 1 % in difference) after 10 years. Irrigation water prices in Europe vary a lot both within and between countries, e.g. 0.054–0.645 €/m^3 in Greece and 0.23–1.50 €/m^3 in France [72].

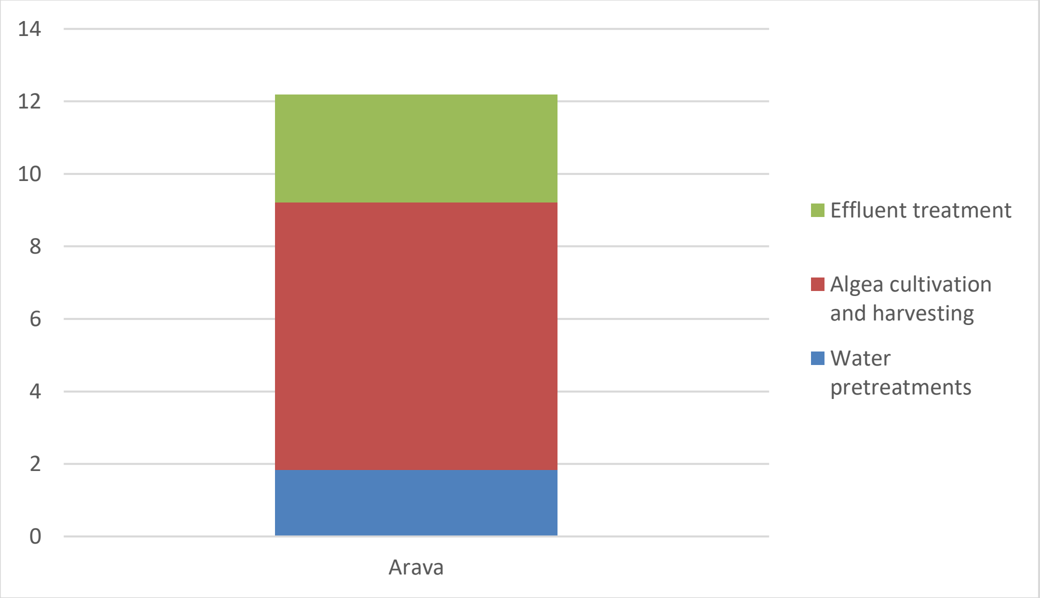


Figure 44. Arava investment costs (€/m^3)

The results presented in Figure 44 show that the algae cultivation and harvesting system account for more than 50 % of all investment cost of the sub-systems. It mainly includes costs for paddle wheels and circulation pumps. The second largest, the effluent treatment represents for around 30 % of the construction phase.

Comparing the cost for Arava and the cost for the benchmark, it is important to take into account the business as a whole. Figure 45 shows two sets. The one to the left represents the cost for Arava, including both operational and investment cost but also additional cost categories like owner expenses and insurance. The one to the right represents the overall cost for the benchmark (see section 4.5.2). The operational costs are also presented in Figure 13 and investment costs in Figure 44. Since different equipment have different life lengths and needs therefore different amount of investments, the costs are averaged over a time period of 30 years.

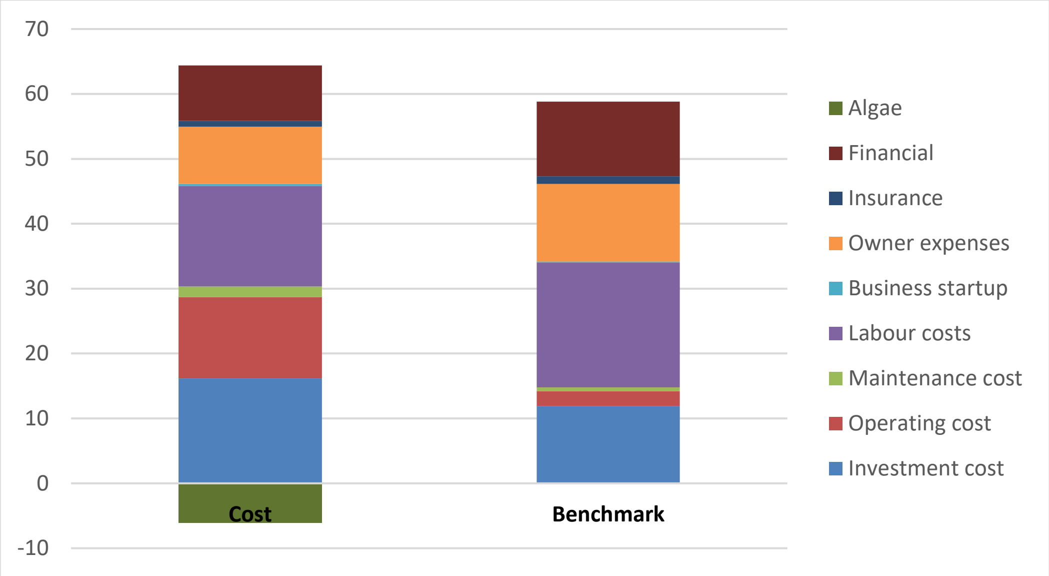


Figure 45. Arava economical assessment (€/m^3)

Most of the costs concerning the Arava system are associated with the costs originating from investment cost and financial/ business categories. Owner expenses, which can be seen in Figure 45 includes costs for procurement, supervisory and administration for the demo site. This is assumed to be 10 % of the investment costs (Annex XII and Annex X).

Comparing with the benchmark, the investment cost is slightly higher for Arava since an algae pond is slightly more expensive than for a conventional aerated sludge system. For instance, it needs paddle wheels and additional pumps which the sludge system does not. Also, the operating cost is higher since nutrients are added and a higher level of labour is needed to operate the algae production. But when considering the revenue from the algae production, the business looks better. With the value received from the additional income of selling algae (Annex XII) the plant will therefore be slightly cheaper than the benchmark. Calculating with a period of 30 years the net present value (NPV) for Arava are roughly 10% better than for the benchmark.

5.2.4. Terminals

As mentioned in section 4.7.2, algae production is a rather new production route. Therefore, there is a need for the business models to also consider economical calculations for building up a new kind of industry which can connect algae production with current factories. For instance, the potential wastewater treatment facilities aren't necessarily located close to an algae valorization facility, therefor it is important to consider transportation cost as a factor in the cost assessments.

Since the technologies for algae valorization are still a little bit vague, the terminal for this stage is assumed to consist of the drying stage. Algal biomass from preceding cultivation system typically carries a high-water content and, as mentioned in Section 5.1, in most of the valorization routes, drying of the algae biomass is needed. Within the SaltGae project, pre-treatment of algae has been performed in batches. However, for biomass pre-treatment at industrial scale continuous processes are usually employed [73]. It could be argued that the terminal also would include cost assessment for instance for protein extraction, but since the availability of reliable data is limited; further research and analysis are needed to further investigate the true impact of terminal, fully equipped for biomass recovery.

The drying stage is an important step, where the selection of drying equipment and an operator's know-how could be crucial for both which valorizations routes the biomass could go, but also for the quality of the end product [32]. Drying of the microalgae enables storage, handling and logistics of the raw material. The drying conditions affect the functional properties and the nutritional value of the microalgae [32]. For instance, it has been showed that wet Spirulina biomass has higher content of pigments and antioxidant activity compared to dried samples.

From the assumptions made in Annex VIII, the CAPEX and OPEX for treating the algae biomass on a terminal, on the demo site or on the end product factory are presented in Figure 46. The figure also integrates pretreating costs with the different transportation scenarios as discussed earlier in Section 4.7.2.

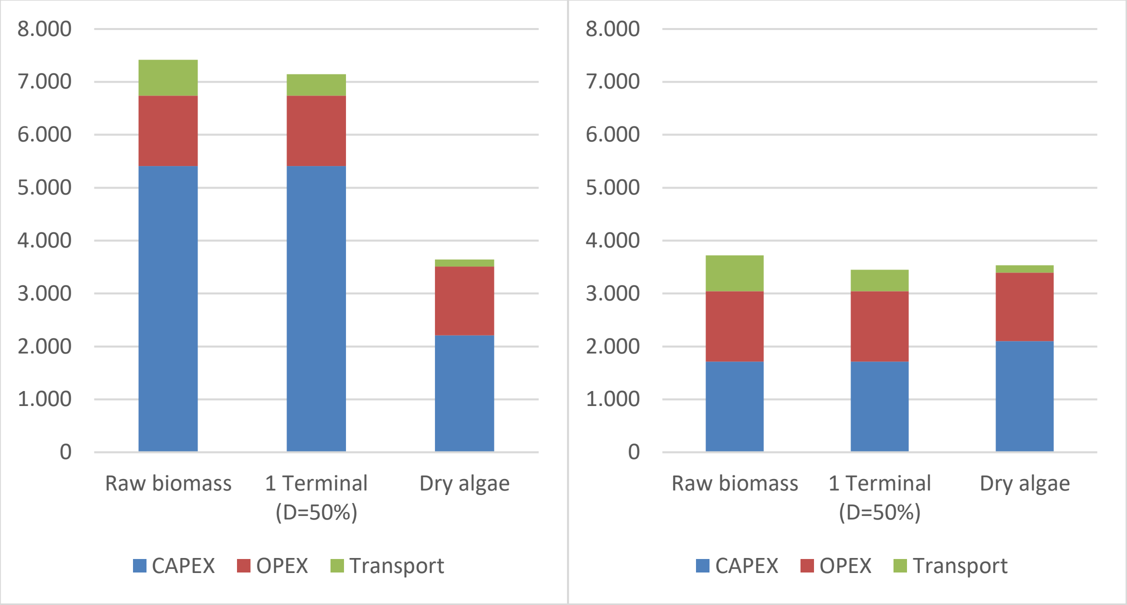


Figure 46. a) Terminal cost at distance = 500 km (€/ton) and b) Terminal cost at distance = 500 km and for a three times larger capacity (€/ton).

In Figure 46 a) three sets are presented. *Raw biomass* is when the demo site doesn't use pretreatment technology on site and raw biomass in transported to the facility. *Dry algae* is when pretreatment is installed at the demo site and only dried algae is transported. The cheapest case is having the pretreatment on site. But when increasing the capacity as in Figure 46 b) to three times larger (like for instance considering three other algae producers with the same capacity as for the demo site) it starts to become more feasible to invest in one shared terminal instead of having three separated, because of economy of scale. Therefore, if there is a need for three times larger biomass production; investing in a three times larger terminal is more feasible than investing in three different dryers on site.

5.3. Techno-economic system analysis

5.3.1. General conclusions/recommendations

The use of algae for treatment of wastewater, seems to be a practical and economic alternative for the treatment. From an economic point of view, the results indicate that for the wastewater treatment and algae production, the highest cost comes from algae cultivation and harvesting, but especially cost of labour. The work made by Fasaei et al. [1] concluded that the production costs is strongly dependent on plant scale. They showed that by increasing the cultivation size from 1 ha up to 10 ha, the cost impact from labour decreased from 8 €/kg harvested biomass to only approximately 1 €/kg. Since labour stands for 80 % of the costs, reducing labour costs is the main challenge for cost reduction.

Today, one third of EU suffers from water stress, and water scarcity is a concern for many European countries [74]. According to EU, water saving must be prioritized since the problem all across the continent will increase [75]. This means that the SaltGae technology could be applied in other countries. Since labour is a quite large cost post, it could be more beneficial to have algae production in EU countries with low average salaries to reduce the production costs. Still, from a social point of view, avoiding negative impacts in the economical dimension of sustainability often comes at the expense of positive social gains and vice versa. This balance should therefore be taken into consideration when developing the business model of future SaltGae technology. This does not mean that wastewater algae treatment always has negative impacts on society, only that costs for labour and energy vary from country to country.

More investment / development on algae biomass valorization, could increase the market demand. As mentioned earlier, the valorization of the algae biomass needs more investigations and research in order to increase the TRL. If the TRL could become higher, it means that more pathways for algae are possible, which would increase the market demand for algae. The goal is to increase the market price for the algae biomass, because if it goes up then the overall wastewater treatment/algae production could draw economic benefits from it and perceive an increase in demand and possibilities which can open new markets and investments.

Competitive advantages and disadvantages

During the SaltGae project, it has been proven that the algae-based WW treatment process allows the release of an effluent which can be discharged in surface water, complying with country specific standards for water quality. With that in mind, and that EU declares that reusing wastewater has a large priority for its member countries, the SaltGae technology has a good opportunity to make an impact on the market.

The water can also be an important competitive advantage compared to an algae production site. In a couple of algae research projects [76]–[78] it has been concluded that water is a limiting factor for future algae production. But since the SaltGae technology is located close to a WW plant this is an advantage for producing algae, and can become a valuable resource for the business

The classification of industrial effluents as wastewater is to a disadvantage for the further use of the algae biomass. Both from a social acceptance and from a potential market perspective, the classification increases the number of obstacles for finding new valorization routes. For some of the valorization routes, there are no limits for using algae. For instance, the limiting factors for producing animal feed from algae produced in wastewater are that the raw material needs to have no potential risk of pathogens and be below limit values for metals, pesticides, etc. But in general, it is recommended for future entrepreneurs to classify the wastewater as *water for production*, until legislation is changed to a fit-for-purpose perspective. The important acceptance barrier lies in national legislation, not EU legislation, because national legislation has too much of local variability. For example: northern Europe uses WW sludge-based fertilizers, while southern EU countries do not allow it.

Through the answers from our partners during the technology assessment, the technical performance of the different algae valorization routes in the SaltGae project was evaluated and connected with the economical assessment, as presented in Table 29.

Table 29. Summary techno-economic assessment valorization routes

Product	TRL	Technical performance	Production cost	Conclusion
Animal Feed	7	+	-	+
3D printing ceramics	5	+/-	0	+/-
Bio composites	5	+	0	+
Edible coatings	7	+	+	+

Animal feed

The production cost for animal feed is more expensive than the benchmark, since the market price for algae biomass is larger than the fish meal. But by substituting the fish meal by Spirulina meal it improves the gastrointestinal health (reduce the prevalence of diarrhea and need for antimicrobial against *E. coli* infection) and, consequently, reduces antibiotics use, improves the animal growth and feed efficiency.

3D printing

From an economical point of view, the cost for printing with algae isn't more expensive than printing without. But from a technical perspective is the process limited in speed, i.e. it is not possible to add too many layers on the fresh geopolymer paste because then the fluid will start moving causing a collapse. The key parameter is compressive strength. The presence of the biomass did not significantly change the compressive strength, and the mechanical properties are apparently only slightly affected by the type of algae biomass (e.g. whole algae, algal residue, and algae specie). But since 3D printing is a new technology, is it from a market perspective still too early to discard its potential

Bio composites

The resulting bio composite is renewable, biodegradable and with a limited carbon footprint, which imply that the user perception should be beneficial. The economic performance is almost the same as for the benchmark. The presence of the biomass in the material and the consequent smell can though be a concern in packaging for food. The proper method for extrusion has to be achieved.

Edible coatings

The edible coatings that was developed in the SaltGae project showed better performance than both the benchmark and control samples. It also can be producing with a lower production cost and has therefore a better economic performance. However, the smell is quite hard to avoid and could thus be an issue. One possible solution is to mask the sharp smell of microalgae by including better accepted flavours into the edible coating, but an efficient deodorization would be a preferred alternative.

5.3.2. Influence of existing standards and legislation

The specific standards and legislation procedures should be considered for different routes of the project. The basic system of wastewater treatment will depend mainly on the EU country where the SaltGae system will be proposed. The SaltGae technology is expected to be installed as integrated process within an existing wastewater treatment system. This could reduce authorization complexity and timestep. The SaltGae main components, excluding microalgae cultivation reactors, are common equipment adopted in wastewater treatment industry. Therefore, the only novelty will be represented by the algae product and harvesting system (D 8.2).

The main challenge regarding applying legislation and standardization lies in the area of biomass valorization, especially for the food applications such as dried algae, food supplements and edible coatings. No specific standards are still available for microalgae obtained from wastewater treatment plants as there are very few quality standards for any algal biomass. However some standardization activity is being performed. Being the algae biomass a product to be commercialized, a REACH certificate will be required per each wastewater treatment unit adopting SaltGae system - REACH will define the safety of the obtained bioproduct. Algae biomass recovered from wastewater will have to respect limits established for other feedstocks depending on the final industrial end use. In this case, algae will represent an intermediate product to be refined and processed for further products extraction. Theoretically, the lack of specific standards does not represent a strong barrier to the SaltGae system development, as the project considers the algae biomass as an intermediate material for additional processes (D 8.2).

The general directives for water treatment and algae products are presented in Deliverable 8.2. In addition, edible coatings are included in EC 1331/2008 and EU 234/2011 for food additives, enzymes and flavorings in Europe [79]. However, a product such as edible coating may be defined in various ways, for example, Flo Chemical Corporation is claiming that their product (FloZein™) can be ranked as a food ingredient, not an additive [80]. Therefore, other types of regulation can be applied to the product.

The fact that there are no specific regulations for the SaltGae routes, besides existing standards, new derivatives should be promoted on the EU level, especially on the use of algae as the wastewater treatment and the use of algal biomass grown in wastewater.

5.3.3. SWOT

A SWOT analysis was performed for the four SaltGae routes: basic system, valorization of solids and sludge, valorization of effluent and valorization of biomass (Figure 47 - Figure 50). The basic system is the most developed from the technological point of view, but more work on the legislative procedures must be done, because there are no direct policies for the WWT with algae. The solids and sludge produced in the system could be converted to green electricity, but the process must be optimized to the necessary number of solids and sludge is produced. For the effluent valorization it is still unclear the route of brine disposal.

The biomass valorization is the realistic route for the system, however more research must be performed on the lab scale in order to be able to produce the high-quality algal products.

Figure 47. SWOT for basic system

Figure 48. SWOT for valorization of solids and sludge.

Figure 49. SWOT for valorization of effluent

Figure 50. SWOT for biomass valorization

5.4. Business plans

In D8.2 there is a canvas which summarizes the SaltGae project, as a business model. The difference between a business plan, which is described in this section, and a business model, is that while the business model maps where the organization currently is, the business plan describes where the organization needs to go to make the business more sustainable and more profitable. The business plans presented in this section, starts with a description of the TRL for the technologies, market demand and competition. Then it continues with describing the strategy for the business plan; what resources, operations, financial and risks that is needed to take the business model into the future, the vision.

5.4.1. Positioning of the technologies

The business plan was made for SaltGae-system as an alternative to conventional WWT. TRL levels of the technologies have been studied in order to estimate the readiness of the system to be commercialized on the market. The basic system of WWT has high levels of TRL (7-9), though valorization routes have lower TRL and more research work has to be done before they can be commercialized (see more in 5.1).

5.4.2. Market volumes and demand

Wastewater treatment technologies

In 2018, the global water and wastewater treatment equipment market size was valued at 25.01 billion € and is estimated to expand at a CAGR of 3.68 % by 2025. The surge in investments in these equipment and facilities coupled with growth of the oil and gas industries is projected to drive the market. Increasing demand for clean water owing to rising population, industrialization, and rapid urbanization from emerging markets is resulting in a marked rise in the adoption of the equipment. Water treatment consists of chemical and physical separation processes to remove unstable elements and contaminants from water. Increasing requirements for minimized global water footprint and optimum quality yields in emerging economies such as Asia Pacific, are anticipated to drive the market (D 8.2).

Algae biomass

According to JRC report on microalgae market edited in 2014, although the global production volumes and market size of micro-algae in general are still relatively small, they have been characterized by high and increasing growth rates, from a thousand ton dry weight in 1999 to 9,000 ton dry weight in 2011. Over 75 % of this production was for the dietary supplements market, including algae-based high-value food additives and ingredients, such as DHA. EABA (European Algae Biomass Association) presented in 2016 its report on algae market in Europe. According to the association, “with more than 400 companies operating in the sector, and a total turnover estimated in 2015 to be overcoming 750 M€ per year, the total microalgae biomass production (on dry weight) is evaluated as 500 dry tons per year” (D 8.2).

Garcia et al 2017 [81] studies different algae biomass types and concluded that dried Spirulina has the largest global market, with more than 12,000 tons produced every year, of which about 70 % is produced in China, India and Taiwan. Worldwide, *Chlorella* producers cultivate an estimated 5,000 tons per year. The market volume of other microalgae can be shown by the following examples: *D. salina* (about 3,000 tn for carotene), *A. flosaquae* (about 1,500 tn for food), *H. pluvialis* (about 700 tn for astaxanthin), *C. cohnii* (500 tn DHA), *Shizochytrium* (20 tn of DHA). According to the European Commission's Annual Economic Report on EU Blue Economy, the EU algae biomass sector in 2018 jumped to a value of EUR 1.69 billion, including research and development, equipment production and jobs in the larger supply chain that depend on output from the algae sector. Specific market volume per country are reported by the above table, provided by EABA in 2016. Market development for algae-based products can be stated as an emerging market, where a modest production is now available in EU. The limit is given by lack of regulation, and high production costs. Different estimates have been provided by JRC and EABA concerning microalgae biomass available on the market. However, even considering the most optimistic vision of 9,000 dry tons/year, it comes out that most of the microalgae turnover is represented by research and demonstration activities. In fact, with a production of 9,000 tons of microalgae on dry basis per year, and an estimated selling price of 30 €/kg (Spirulina for food sector), the turnover generated by algae products in EU should not exceed 270 M€ (D 8.2).

5.4.2.1. Market volumes, trends and competition for SaltGae products

Proteins (food)

The current use of algae in food is predominantly the use as capsules sold as health food. Most of the algae is sold in dust (spray dried) form, but some sold incapsulated as well. The capsules containing algal powder are sold as remedy to a wide variety of illnesses [82]. Algae are also used as ingredients in pasta, drinks, snacks, candy and gum [83]. The species of micro algae that are currently used as food or food ingredient are restricted: only Spirulina (Arthrospira), *Chlorella* and *Tetraselmis* are used. Despite the positive nutritional composition, dried micro-algae use as direct food has not gained significance as food or food ingredient. The reason for this minimal use in food is several obstacles. The first is related to the "taste properties" of dried algae biomass. The powder-like consistency, the green colour and the fishy smell of the algae biomass are the most significant obstacles. The high production cost is the final obstacle [82]. Protein is one of the main nutrients that will be in short supply in the future. Alternative protein sources and production methods are required to fulfil the demand of consumers and to meet predicted global protein requirements. Algae are generally regarded as a viable protein source, with EAA composition meeting FAO requirements and they are often on par with other protein sources, such as soybean and egg. Several businesses have been set up for the sale of algal products, such as AlgaVia® (www.algavia.com), which produces protein- and lipid-rich algal flour from *Chlorella* protothecoides. According to Mordorintelligence [84], the global algae protein market is expected to register a CAGR of 6.5 % during the forecast period (2018-2023), owing to the growing demand for plant-based protein alternatives, the positive effects of the algae proteins on the immune system, and their attributes that improve the nutrient content of the food. Europe leads the market for algae proteins, owing to high research in the growth of algae and cheaper methods of preparation of the protein from algae. In the APAC region, India and China have been dominating the market, owing to increasing consumer awareness regarding the health benefits of algae protein. Ethical and traditional beliefs of consumers against using animal-based products also open an opportunity for the growth of the algae protein market in the APAC region (D 8.2).

Animal feed

The high protein content of algae can also be beneficial for use as animal feed, including aquaculture, farm animals, and pets. An estimated 30 % of global algal production is estimated to be used for animal feed, with 50 % of Spirulina biomass used as feed supplement due to its excellent nutritional profile. Several species of microalgae including Spirulina, *Chlorella*, and *Schizochytrium sp*, and seaweed can be incorporated as protein sources into the diets of poultry, pigs, cattle, sheep, and rabbits. Most of the research on the incorporation of algae as animal feed has been carried out with poultry, likely due to their promising prospects for improved commerciality. Tasco® is an example of a proprietary seaweed meal derived from A. nodosum, produced by Acadian Seaplants in Nova Scotia, Canada, which has demonstrated beneficial properties when included in animal feed (D 8.2).

Edible coatings

Interest in edible and biodegradable packaging including edible coatings has growing together with growing customers' demand of higher quality and safer food in the recent years. Edible coating market demand growth can be evident from the number of registered innovations within edible coatings [79]. The global edible films and coating market is expected at a CAGR of 7.1% during 2018-2023 [85]. The global edible films and coatings market is expected to reach USD 1355.2 Million by 2025, from USD 745.1 Million in 2017 growing at a CAGR of 7.3% during the forecast period of 2018 to 2025 [86]. The global edible films and coating market is segmented on the basic of ingredient type, application, end user and geography [85], [86].

- Ingredient type. Edible films and coatings vary depending on their ingredients, but mainly represented by proteins, lipids, polysaccharides, composites, palm stearin and chitosan.
- Application. Edible films and coatings are used for dairy products, nutritional products, bakery & confectionary, meat, poultry & fish, fruits & vegetables and others.
- End user. Global edible films and coatings market are used in food and beverages, pharmaceuticals.
- Geography. The global edible films and coatings market is segmented into North America & South America, Europe, Asia-Pacific and, Middle East & Africa.

The targeted clients are producers of fruits and vegetables in EU interested in applying protein-based coatings to their products. The edible coatings should satisfy the following needs:

- The coating should have the same performance as already existing products or even better performance.
- The price of the product should be competitive compare to existing products.
- The coating should be of vegetarian origin of the coating/vegan friendly.
- The coating should be a safe and allergen-free product.
- The protein coating should add extra nutrition to food.
- The coating should have possibility to be applied in various ways, allowing flexibility in handling the product for the producers of fruits and vegetables.
- The cost of application methods should not exceed the cost of application methods of the existing coatings.
- The coating is supposed to be tasteless and free of any smell.

The main competitor in the edible coating sector are presented in Table 30.

Table 30. Competition within edible coating sector

Brand	Product	Description
Apeel Sciences	Edipeel	Plant-derived lipids and glycerolipids. Sources: unused parts of plants-peels, rinds, the leftovers of the system (e.g. waste from farms)
Decco	Naturcover	Sucrose of fatty acid esters E-473 and ethanol.
	DeccoNatur 505	Carnauba wax and potassium hydroxide.
Fomesa Fruitech	Applewax	Shellac based coating
Pace International	PrimaFresh® 606 EU	Amine-free carnauba coating. Apple & pears coating
	PrimaFresh® Golden	Carnauba coating for Golden Delicious apples
	PrimaFresh® Pear Coat	Carnauba coating for pears
	SemperfreshTM	Sucrose ester-based coating for cherry fruit
	Shield-Brite® AP-34EU	Shellac apple coating for global markets
	Shield-Brite® AP-40	Premier shellac coating for apples
	Shield-Brite® AP-450	Shellac coating for apples
	Natural Shine® 320-OR	Ethanol, glycerol, shellac. Coating for organically grown fruit
JBT	Endura-FreshTM 214	Shellac coating for apples
	Sta-FreshTM	Series based on shellac, carnauba and resins
Flo Chemical Corporation	FloZeinTM	Prolamine (protein) derived from corn.
Nipro Fresh Waxes	Nipro-Fresh	Wax coating for fruits and vegetables
De Leye Agro	Bio-FreshTM	Sucrose ester (E473) and CMC (E466). Coating for fruits.

5.4.3. Strategy

The strategy is to present the opportunities for a possible start up, which can be a WWT company with SaltGae WWT technology with algae cultivation. WWT facility should be built close to wastewater plant. The first step will be to understand the needs of the WW producer, amount and parameters of WW in order to optimize WWT according to the needs of the specific WW producer. Besides cleaned water the company will produce an aditional product: algae, which could be sold further. Therefore, the company needs to establish business relationship with buyers of algal biomass and become a reliable supplier of algae. Since Spirulina grows 25-30 % faster than *Nannochloropsis* and needs less CO_2, the Spirulina biomass production shall be chosen primarily. The industries which could be interested in purchase of the algae are the ones who produce animal feed, suppliers of algal-based protein rich food, and producers of edible coating.

This company will represent a technical solution which is an intermediate step between wastewater plants and buyers of biomass. The wastewater suppliers can treat their water and produce valuable algal biomass. The new company will guarantee the purchase biomass from the WWT which might decrease the cost of WWT process. A potential risk is the need for a very broad know-how, and this underlines the importance of establishing a network which can provide key partners like design engineers, algae experts or wastewater treatment experts, who can help the new established business delivering / installing the equipment. It is necessary to have transport companies and labs for quality controls of the water and the algae.

Legislative issues are problematic because there is a lack of standards for the WWT using algae and algal biomass grown in WW and its possible allowed uses. Gaps in the current legislation and suites of standards regulating all relevant aspects of the combined processes wastewater treatment-algae production-biomass valorization should be addressed by initiating and promoting the development of new such agreements.

Figure 51 shows an example of a timetable on how the business can be implemented to an early adopter/entrepreneur. Identified early adopters in the SaltGae project are dairy, fish industries, machine contractors, agriculture associations or even food industries which could find usage of the technology.

Another illustration for early adopters is presented in Figure 52. This includes a more detailed description of technical and R&D activities necessary for the system.

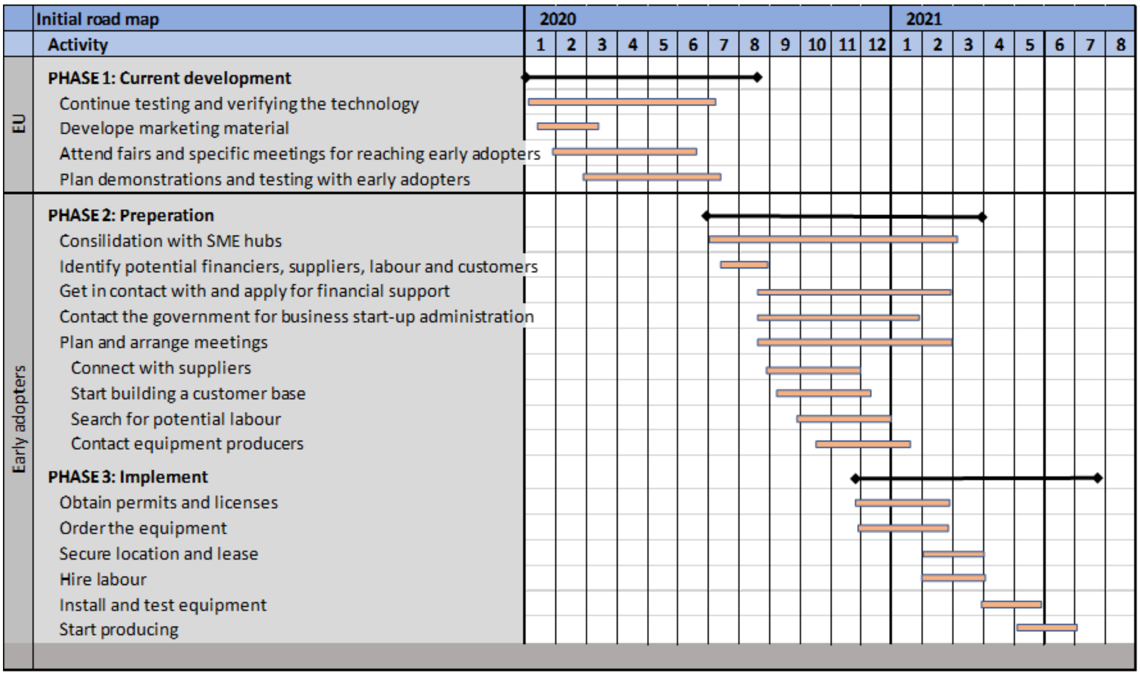


Figure 51. The strategy for the SaltGae technology for the near future

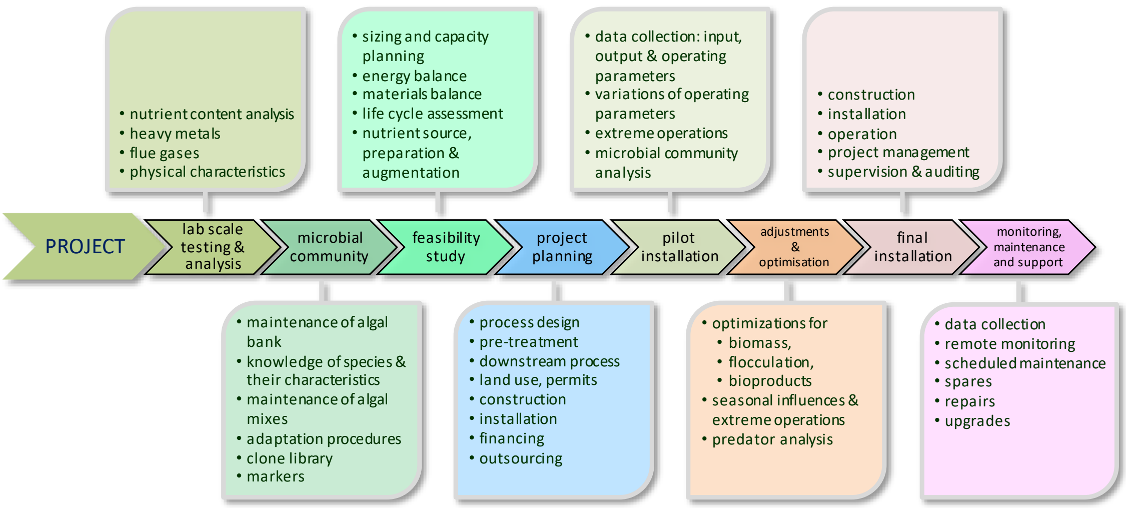


Figure 52. Stages of the project for early adopters

5.4.4. Resources

Human Resources

The company is aiming to get the professional help from specialists within WWT sector, algae valorization. They can be hired on a permanent basis or as consultants. The members of the Saltgae consortium can be part of the team or they can refer the individuals, since the consortium members have expertise in the area. Staffing agencies can be used as a source of finding human resources as well.

The help of lawyers is essential for this start-up, due to the lack of legislation for this technology in particular. This resource will presumably not be incorporated in the company's staff but acquired through cooperation with law firms.

Educational Resources

The company shall rely on the expertise of consortium but also on the existing trends and competition in the area of business in order to develop the best service, process and products.

The first step of knowledge building has been performed within SaltGae project and this knowledge is a great base for the startup and development of education. The development of up-to-date knowledge can be supported by being member and active participations in professional and trade organizations, establishing strong network and attending various seminars, workshops in order to understand the needs of the industry.

Universities and research partners from SaltGae are the main source of information and research update.

Physical Resources

The main physical resources needed are land due to algae cultivation and equipment for all stages of the process. The investment in workspace, working telephone and marketing tools shall be done. The example of the land required for Arava demo site is 3000 m^2. If a bigger facility shall be built, more land will be required.

5.4.5. Financial and risks

SMEs (*Small and medium-sized businesses*) are important actors in economic growth and transformation, creating positive value for the economy and contributing towards sustainable and balanced economic growth, employment and social stability. Although SMEs play an important role in economies, their access to finance is limited and has been a challenge for policy makers globally.

In any start-up using new technology will need funding for several reasons such as technology development and transfer, introducing new products on the market, develop technologies, buying technology. The financial needs and the financing options open to SMEs vary depending on the stage in a business's lifecycle. The access an SME has for funding's depends on several factors, such as their level of development, which region they work in, the nature of their business and their marketing capabilities, and for the professional connections of the entrepreneur behind the business. To solve this financial gap it is important to recognize the crucial role of capital investors. This deliverable aims to bridge this gap between keeping a business idea as just an idea and developing the idea to a real and prospering business, with the help of finance.

5.4.5.1. Different company phases

A lifecycle of an SME starting from scratch passes through several stages with different capital needs over time. Figure 53 demonstrates how the equity changes during the development of an SME. The management of finance, from acquisition until the time of its use, will require a pro-active decision-making. Through the graph, it can be predicted when investments are needed for maintaining a stable cash flow. The absence of economic capital is one of the most important obstacles to conquer in order to growth.

During the two first phases (R&D and Pre-Seed/Seed), the focus is on providing funding for the actual product. There is still no income and hence capital need is building. During the following phase, Start-up there is still no large income and a severe need of capital to step up production as well as penetrating the market. Following phase where market share grows, and sales go up it is still crucial to have enough capital to cover development and market costs. Next phase during expansion there will still be a need of capital to expand production and market. In this phase capital can be found in investors seeing the growth as a possibility of equity in relatively short term. The last phase of a maturing company that have grown into a stable company with stable economy is when equity founded back to its shareholders [87].

Any startup using new technology will need funding for several reasons such as technology development and transfer, introducing new products on the market, develop technologies or buying technology. If the idea is moving from an early stage of development to market, as in the SaltGae cases, the funding will mainly bridge the valley of death as shown Figure 53.

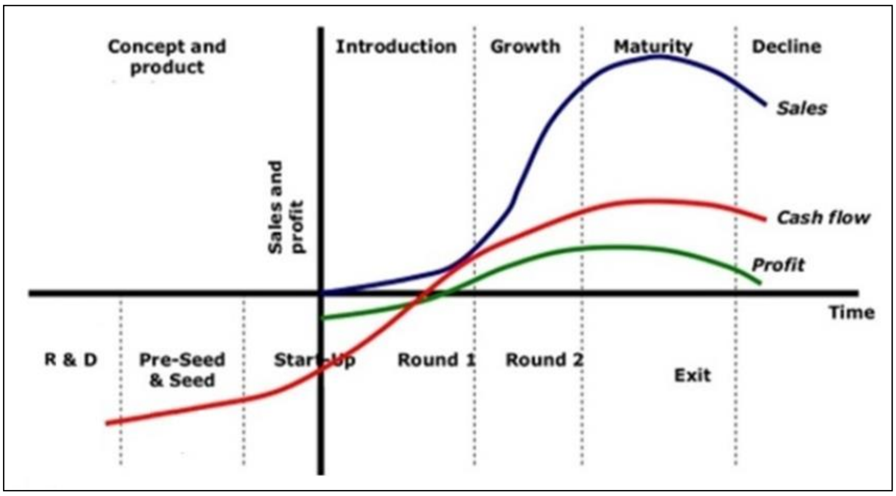


Figure 53. The SME lifecycle [88]

A traditional startup going from idea to a market ready product is usually founded by a private owner, using own capital or getting funding from friends and family or others, where others include private investigators as well as public funding. The second step to introduce a market ready product usually requires a lot more funding to really penetrate a market. The second step is a crucial step where an entrepreneur gets to the point where cost is the largest and no income from the product is coming in yet. This is where most projects fail and that is why this phase is called *Valley of Death*. In this project this development will occur but on different stages in time when the readiness of the different technologies is at different TRL levels. To get further it is very important to analyze the needs and demands of financing and to find ways to introduce capital in the different tracks at the right level in order to bridge the Valley of Death.

The different processes and tracks studied in SaltGae have during the project moved to different TRLs (Section Technological assessment 5.1) and except perhaps Archimede, all still are on the wrong side of the Valley of death. Also, the different tracks need different level of funding depending on level of complexity and the availability of efficient technology. With the aim of describing where in Figure 53 the SaltGae process currently can be found; the following classification has been conducted in Table 31:

Table 31. Phases of tracks

Phase 1 (TRL 4-6)	**Phase 2** (TRL 7-8)	**Phase 3** (TRL 9)
Protein extraction	Piglet feed	Archimede
Platform chemicals	Edible coatings	
3D printing paste	Arava	
Biocomposites		
Koto		

Most of the biomass valorization technologies is in phase 1, which is located somewhere between R&D and Preseed/Seed in Figure 53. The track still needs to verify the technology, as well as economic viability of the idea. Most of them are micro companies, with a high risk of failure. By comparing with the framework provided from EU [89] this means that for most of the algae biomass valorization needs about 50,000 € and about 6 months to evolve to the next phase. The funding could be useful for investing in activities like for instance more R&D, market analysis, technology improvement and partner search.

Piglet feed and edible coatings are located both in phase 2, somewhere in the stage Pre-seed/Seed - Start up. They still need testing, prototyping and piloting. But compared to for instance protein extraction they have developed much further in their trials and their business process. The growth potential is good, but the investments would still be defined as high risk because of the SME size. According to EU the needs for the next step to be taken is between 0,5-1 million € and a timespan between 12-24 months to reach the next phase [89]. The activities of this phase are focused on assessment between the product and the quality, but also innovation and demonstration actions.

The business stage of Arava is in phase 2. Manufacturing of the product is operational at low rate and they are producing algae which actual can work as a commercial product for early adopter markets. More financial is needed since the interaction between the product and the manufacturing technologies needs more fine-tuning. Further activities could also include innovation and demonstration actions. Archimede is in phase 3, Start up. The production is sustained, manufacturing and overall production is optimized. Hence, there is more of a need to start looking for possible private founding, networks etc. to find more pathways for the business.

5.4.6. Operations

5.4.6.1. Stage of Development Section

Workflow

The main focus shall be done on the improvement of workflow of WWT, but the WWT plant cannot function without cooperation with WW producing industries, industries producing algae and the companies purchasing the cleaned water (Figure 54).

Though the technology has high TRL levels the main risk is to become a WWT facility for the industry which needs to clean the water. Another risk is to be able to find the industries interested to purchase algal biomass grown in WW.

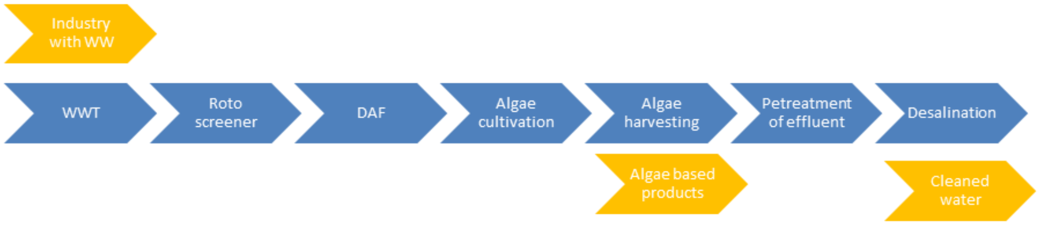


Figure 54. Workflow of WWT plant

Industry Association Memberships

In order to establish possibilities to affect the legislation and policies for making technology be allowed on the market, it is necessary to be a part of organizations which might help to influence the authorities and establishment of new standards. The associations presented below can be a good start point for the support for the new business within WWT.

The European Algae Biomass Association (EABA) has its objective to promote mutual interchange and cooperation in the field of biomass production and use, as well as creating, developing and maintaining solidarity and links between its members and at defending their interests at European and international level [90].

Founded in 2006, Global Water Challenge (GWC) is a coalition of leading organizations committed to achieving universal access to safe drinking water, sanitation and hygiene (WASH). With leading companies, civil society partners and governments, GWC accelerates the delivery of safe water and sanitation through partnerships that catalyze financial support and drive innovation for sustainable solutions [91].

The International Water Association is the network of water professionals striving for a world in which water is wisely, sustainably and equitably managed [92].

The World Water Council is an international multi-stakeholder platform organization whose mission is to mobilize action on critical water issues at all levels, including the highest decision-making level, by engaging people in debate and challenging conventional thinking. The Council focuses on the political dimensions of water security, adaptation and sustainability [93].

World Resources Institute is a global research organization working closely with leaders to turn big ideas into action to sustain the natural resources. Their work focuses on six critical issues at the intersection of environment and development: climate, energy, food, forests, water, and cities and transport [94].

UN-Water coordinates the efforts of UN entities and international organizations working on water and sanitation issues [95].

Stockholm International Water Institute (SIWI) is a water institute. They leverage knowledge to strengthen water governance for a just, prosperous, and sustainable future. SIWI's prime target audience is agents of change. These may be policy and decision makers on all levels – that is, those in charge of governance and management of resources and assets with an impact on availability, access and quality of water. It also includes those that may have an impact on change agents, such as advisors, researchers and media workers [96].

Quality Control

The quality control measures shall be done according to the following directives:

2000/60/EC Water framework directive;

96/676/EC Nitrates directive;

91/271/EC Urban wastewater treatment directive

86/278/EEC Directive on the protection of the environment.

5.4.6.2. Production Process Section

The business is supposed to run all year around, though the location will affect the algal growth in winter. In colder climates the algae could be grown mainly in summers. Therefore, the warmer climate is preferred for the location of the process.

The physical plant and equipment

Land availability plays an important role in installation of the SaltGae-plant due to the necessity of space for algae cultivation. The process of WWT consists of roto screener, DAF and algae cultivation. The technological process and equipment are described in detailed in Technology assessment (5.1). The process has been tested and have high TRL levels, however the process can be improved by addition of CHP plant for biogas production and supporting the plant with electricity source. In this case 2-AD shall be added after roto screener. The tested demo sites do not have enough biomass to produce gas, but this could be solved if a WWT facility is built nearby other plants generating biomass which could be used for biogas production.

The location suitable for the plant is preferably South Europe or Middle East, because it would be easier to use the experience of the demo-sites tested in the projects. Additionally, a warmer climate makes the algae cultivation easier through the year. However, a lower algae growth shall be expected in winter periods and WWT plant shall be adjusted to the possible variation of the biomass inflow. The biomass produced in the plant shall be sold further.

Special requirements

The power and blue water supply are necessary for the supporting the production. The energy needs and its price depend on the location but also on the design of the plant. Extra power could be produced by a CHP plant within the process, but the technology is not ready due to the lack of biomass produced by one WWT plant. The plant shall be approved in accordance to the local standards and regulations.

Production, materials and inventory

It is necessary to decide how long it takes to treat WW and produce algal biomass. The materials and suppliers of the equipment and materials must be established. Inventory management shall be performed in order to reduce the unnecessary purchase and optimization of the process. A controller should be hired in order to keep track on the inventory.

5.5. Conclusions for business plan

The WWT process tested at demo-sites has a high TRL level from the technical point of view but in order to be commercialized the legislative procedures should be investigated and new standards applied to the technology should be included in the current legislation. The partnership with WW sources shall be established in order to optimize process on the industrial scale. Regarding valorization routes of algae-based products, more research should be performed on the lab scale in order to guarantee the quality of the products. However, the raw biomass produced in the WWT can be sold further to the companies, producing algae-based products. In this way, the legislative procedures must be improved, because it is not clear if the algae grown in WW, could be allowed for further valorization in the food sector or not. At this stage more realistic route for algal biomass is non-food applications.

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Annexes

Annex I. Absolute LCA results

	Functional unit	**Water consumption** [kg]	**AP** [kg SO_2 eq.]	**EP** [kg P eq.]	**GWP** [kg CO_2 eq.]	**POCP** [kg Ethene eq.]	**Primary energy** [MJ]
Koto wastewater treatment (no drying)	m^3 treated water	1040	0.047	0.019	27.6	0.015	46
Archimede wastewater treatment with Spirulina (no drying)	m^3 treated water	211	$3x10^{-4}$	4.10^{-2}	5.7	$2.5x10^{-3}$	126
Arava wastewater treatment (with drying)	m^3 treated water	177	1.10^{-3}	1.10^{-2}	17.4	5.10^{-4}	283
Archimede *Nannochloropsis* production	kg *Nannochloropsis*	251	$3.4x10^{-4}$	$6x10^{-3}$	15.3	$4.2x10^{-4}$	187
Archimede Spirulina **production**	kg Spirulina	237	$3.6x10^{-4}$	1.10^{-2}	6.94	$2.9x10^{-4}$	130
Animal feed (2,5% Spirulina 2,5% Fishmeal)	kg animal feed		$7x10^{-6}$	$4x10^{-4}$	0.19		
Gluten thermoplastic (23% Spirulina debris)	kg thermoplastic		$1.6x10^{-4}$	$4x10^{-4}$	4.07		
3D-printed ceramic paste with 4% algae debris	kg paste		$1x10^{-5}$	$8x10^{-5}$	0.28		
High value Spirulina **protein cream**	kg cream		$3.5x10^{-4}$	$6x10^{-3}$	6.3		

Annex II. Pumps at Koto demonstration site

Unit name	Electricity use per day [kWh / d]	Type of data
Pump station 1	0.55	Estimations based on pump capacity installed on demo site and hours operated.
Pump station 2	0.55	
Dosing PH adjust Raw water	0.09	
Feed pump to AD1	0.78	
Feed pump to AD2	1.73	
Recirculation pump AD1	2.40	
Recirculation pump AD2	2.40	
Diluting pump to AD1	0.49	
Diluting pump to AD2	0.46	
Dosing alkaline pump 1	0.09	
Dosing alkaline pump 2	0.09	
Electricity circulation pump	3.00	
Heating water circulation	2.16	
Effluent flowmeter	0.06	

Annex III. LCI Koto demonstration site

Raw Material & Energy	Description	Data source and LCI data
Roto screener energy	Electricity from adjacent biogas combined heat and power to remove solids bigger than 0.15 mm.	LCI from Eco-invent V3.3. Process name "Heat and power co-generation, biogas, gas engine" in Slovenia. The dataset is representative of a 160 kWel biogas (from biowaste) cogeneration unit.
Buffer tank mixing energy	Electricity from adjacent biogas combined heat and power to mix the water in buffer tank.	LCI from Eco-invent V3.3. Process name "Heat and power co-generation, biogas, gas engine" in Slovenia. The dataset is representative of a 160 kWel biogas (from biowaste) cogeneration unit.
Two step AD system- KCl	Potassium chloride added to the two step AD system.	LCI from Eco-invent V3.3. Process name "Potassium chloride production" in Europe.
Two step AD system- Fresh water	Fresh water used in the two step AD system	Water for both KCl dilution and raw wastewater dilution. LCI from ThinkStep. Process name "Tap water". Environmental impact includes filtration, disinfection, ion. Surface water.
Two step AD system- Energy	Heat used in the two step AD system in winter time by heat exchanger.	LCI from Eco-invent V3.3. Process name "Heat and power co-generation, biogas, gas engine" in Slovenia. The dataset is representative of a 160 kWel biogas (from biowaste) cogeneration unit.
Two step AD system- Avoided heat and electricity	Avoided heat and electricity from biogas CHP plant due to the production of biogas in the Two step AD system.	LCI from Eco-invent V3.3. Process name "Heat and power co-generation, biogas, gas engine" in Slovenia. The dataset is representative of a 160 kWel biogas (from biowaste) cogeneration unit.
Conditioning tank mixing energy	Electricity from adjacent biogas combined heat and power to mix the water in conditioning tank.	LCI from Eco-invent V3.3. Process name "Heat and power co-generation, biogas, gas engine" in Slovenia. The dataset is representative of a 160 kWel biogas (from biowaste) cogeneration unit.
Pond - Fresh water	Freshwater used in the pond to compensate for evaporation.	LCI from ThinkStep. Process name "Tap water". Environmental impact includes filtration, disinfection, ion. Surface water.
Pond- Electricity	Electricity used in pond mainly for pumps and fan. Electricity sourced from adjacent CHP biogas plant.	LCI from Eco-invent V3.3. Process name "Heat and power co-generation, biogas, gas engine" in Slovenia. The dataset is representative of a 160 kWel biogas (from biowaste) cogeneration unit
Pond- Heat	Heat used in the pond.	LCI from Eco-invent V3.3. Process name "Heat and power co-generation, biogas, gas engine" in Slovenia. The dataset is representative of a 160 kWel biogas (from biowaste) cogeneration unit.
Pond- CO_2	The carbon dioxide used in the pond for algae growth. Sourced from the adjacent biogas plant.	Since the CO_2 is sourced from the adjacent biogas plant it carries no environmental burden. Ideally some environmental burden regarding the separation of the CO_2 from CH_4 should be calculated, but this is expected to be small.
Harvesting DAF - Flocculant	Flocculant used for DAF harvesting. Commercial name Superflocc C-62091 from Kemira Oyj	LCI estimated based on MSDS with 40 % polyacrylamide production LCI from Eco-invent V3.3. Then, 60 % is water. LCI from ThinkStep. Process name "Tap water".
Harvesting DAF - Electricity	Electricity used for DAF harvesting. Electricity source adjacent CHP plant.	LCI from Eco-invent V3.3. Process name "Heat and power co-generation, biogas, gas engine" in Slovenia. The dataset is representative of a 160 kWel biogas (from biowaste) cogeneration unit.
Pumps- Electricity	Electricity used for all pumps in the whole system (except for pond pumps). Disaggregated electricity per pump available in Annex II. Electricity source is adjacent CHP plant.	LCI from Eco-invent V3.3. Process name "Heat and power co-generation, biogas, gas engine" in Slovenia. The dataset is representative of a 160 kWel biogas (from biowaste) cogeneration unit.

Annex IV. Pumps in Archimede demonstration site

Unit name	Electricity use per day [kWh / d]	Type of data
Pump from truck to tank 1	0.35	Estimations based on pump capacity installed on demo site and hours operated, as well as power and flow factor.
Pump to Roto-screener	1.45	
Pump to DAF	1.79	
DAF main pump	3.28	
Dosing pump pH adj	0.18	
Coagulant pump	0.07	
Flocculant preparation and dosing pump	2.72	
DAF sludge discharge (fat) pump	0.17	
Pump to Buffer Tank	1.87	
2*PBR circulation pump	12.9	
RWP-A circulation pump	7.06	
RWP-B circulation pump	7.10	
RWP cooling tower pump (1/2)	13.8	
PBR heating pump (1/2)	4.80	
RWP heating pump (1/2)	4.13	

Annex V. LCI Archimede demonstration site

Raw Material & Energy	Description	Data source and LCI data
Roto screener energy	Electricity from Italian grid mix. Electricity used in drum.	LCI from ThinkStep, process name "Electricity grid mix" from Italy. About 33.54 % from natural gas and 15.23 % from hard coal.
Transfer tank-Phosphoric Acid	Phosphoric Acid used added in transfer tank.	LCI from Ecoinvent V3.5. Process name "phosphoric acid, industrial grade, without water, in 85 % solution state" average of European production.
DAF pre-treatment-Electricity	Electricity used for DAF belt and DAF sludge.	LCI from ThinkStep, process name "Electricity grid mix" from Italy.
DAF pre-treatment-Sludge	Sludge produced was assumed to be treated by anaerobic digestion.	LCI from Eco-invent V3.3. Process name "treatment of sewage sludge by anaerobic digestion" in Switzerland.
Buffer tank - Electricity	Electricity used in the buffer tank	LCI from ThinkStep, process name "Electricity grid mix" from Italy.
Pond-Electricity	Electricity use in for two PBRs and RWP paddle wheel and cooling tower.	LCI from ThinkStep, process name "Electricity grid mix" from Italy.
Pond-Heat	Heat used in the ponds. Source is adjacent vegetable oil CHP plant.	This heat is waste heat from the adjacent vegetable oil CHP plant, the heat has low temperate. This heat carries no upstream environmental burden.
Pond-Micro-nutrients	Micro-nutrients used for algae growth.	Micro-nutrients used are based confidential recipe, thereby LCI selection specification are excluded from this public deliverable.
Pond-Carbon dioxide	Carbon dioxide used in the PBR (and pond) for algae growth assumed in gaseous state.	LCI from ThinkStep for carbon dioxide produced in gaseous state through the Haber- Bosch process, from natural gas in Germany.
Pond- Sodium nitrate	Sodium nitrate used in PBR and starvation pond	LCI from Eco-invent V3.5. Process name "sodium nitrate production" in Europe.
Pond-Fresh water	Fresh water added to the pond to compensate evaporation.	LCI from ThinkStep for Tap water production including ion removal. Sourced from surface water.
Harvesting UF & CF-electricity	Electricity used for harvesting through centrifugation and ultrafiltration. Electricity source Italian grid mix.	LCI from ThinkStep, process name "Electricity grid mix" from Italy.
Spray drying-electricity	Electricity used for Spray drier. Electricity source Italian grid mix.	LCI from ThinkStep, process name "Electricity grid mix from Italy."
Spray drying-Heat	Heat used for spray drier. Heat from natural gas.	Calorific value natural gas of 41 MJ/kg and standard volume 1.19 Nm^3/kg = 34.45 MJ $/Nm^3$. LCI from ThinkStep, process name "Thermal energy from natural gas" production in Italy.
Pumps-Electricity	Electricity used for all pumps in the whole system (except for pond pumps). Disaggregated electricity per pump available in Annex IV. Electricity source is adjacent CHP plant.	LCI from ThinkStep, process name "Electricity grid mix" from Italy.
Sodium bicarbonate	Sodium bicarbonate used for pH regulation	LCI from Ecoinvent 3.5, process name "Market for sodium bicarbonate"

Annex VI. Arava sub-processes electrical consumption

Process name	Unit name	Electricity use per day [kWh / d]	Type of data
PBR	Lights for PBR	40.8	Estimations based on pump capacity installed on demo site and hours operated, as well as power and flow factor.
	Air bubbling blower	3.6	
	Air conditioning	49	
Drum filter	Motor and gear box	2.5	
	Membrane rotator	3,3	
	Water spray pump	6.7	
Biofilter	Fish wastewater pump	15.3	
Buffer tank	Pump to DAF	1.2	
	Heating system	1.3	
DAF	DAF total	7.7	
Reservoir tank	Pump	5.5	
	Mixer	2.0	
ORP	Small ORP paddle wheel x3	17.5	
	Medium ORP paddle wheel x2	10.4	
	Large ORP 1 paddle wheel x2	6.4	
	Large ORP 2 paddle wheel x2	3.5	
	Large ORP 3 paddle wheel x2	1.7	
	Pump small to medium ORP	0.1	
Vibrating screen	Pump ORP to vibrating screen	0.74	
	Vibrating screens	8.0	
RO	Pump to collection tank	3.53	
	Pump to RO	1.0	
	RO	13.3	

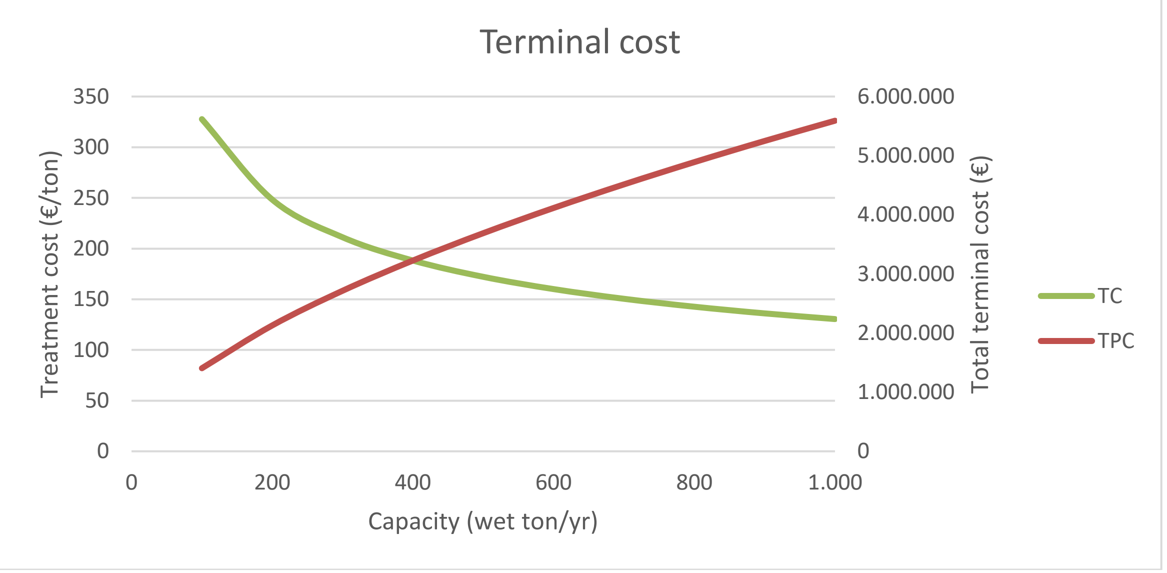
Annex VII. LCI Arava demonstration site

Raw Material & Energy	Description	Data source and LCI data
Drum filter and biofilter energy	Electricity from Israeli mix used for this sub-process	LCI from Eco-Invent v3.5. Process name "market for electricity, medium voltage". The dataset is representative for the Israeli electricity mix in 2014, following the IEA world energy statistics
Buffer tank energy	Electricity from Israeli mix used for this sub-process	LCI from Eco-Invent v3.5. Process name "market for electricity, medium voltage". The dataset is representative for the Israeli electricity mix in 2014, following the IEA world energy statistics
DAF energy	Electricity from Israeli mix used for this sub-process	LCI from Eco-Invent v3.5. Process name "market for electricity, medium voltage". The dataset is representative for the Israeli electricity mix in 2014, following the IEA world energy statistics
Reservoir energy	Electricity from Israeli mix used for this sub-process	LCI from Eco-Invent v3.5. Process name "market for electricity, medium voltage". The dataset is representative for the Israeli electricity mix in 2014, following the IEA world energy statistics
ORP energy	Electricity from Israeli mix used for this sub-process	LCI from Eco-Invent v3.5. Process name "market for electricity, medium voltage". The dataset is representative for the Israeli electricity mix in 2014, following the IEA world energy statistics
PBR energy	Electricity from Israeli mix used for this sub-process	LCI from Eco-Invent v3.5. Process name "market for electricity, medium voltage". The dataset is representative for the Israeli electricity mix in 2014, following the IEA world energy statistics
Vibrating screen energy	Electricity from Israeli mix used for this sub-process	LCI from Eco-Invent v3.5. Process name "market for electricity, medium voltage". The dataset is representative for the Israeli electricity mix in 2014, following the IEA world energy statistics
RO energy	Electricity from Israeli mix used for this sub-process	LCI from Eco-Invent v3.5. Process name "market for electricity, medium voltage". The dataset is representative for the Israeli electricity mix in 2014, following the IEA world energy statistics
Sodium bicarbonate	Used in the ORP for pH regulation	LCI from Eco-Invent v3.5. Process name "market for sodium bicarbonate". The data set is representative for the global market and based on 2011 data.
Polyacrylamide	Flocculant used in the DAF	LCI from Eco-Invent v3.3. Process name "Polyacrylamide production". The data set is representative for the global market and based on 2012 data.
Polyaluminium	Coagulant used in the DAF	LCI from Eco-Invent v3.5. Process name "Polyaluminium production". The data set is representative for the global market and based on 2015 data.
Water	Groundwater used in the PBRs and ORPs	LCI from ThinkStep. Process name "Tap water from groundwater". The data set is an average for the EU-28 from 2018.
Magnesium sulphate	Nutrient used in the ORPs	LCI from ThinkStep. Process name "Magnesium sulphate (agrarian)". The data set is for Germany from 2016.
Iron sulphate	Nutrient used in the ORPs	LCI from ThinkStep. Process name "Iron(II) sulphate". The data set is for EU-28 from 2018.

Annex VIII. Terminal assessment

A techno-economic study made in the Netherlands by Faseaei et al. (2018) about harvesting and dewatering processes, with microalgae as biomass input, concluded that the treatment cost strongly depends on the scale of the production capacity. In their analysis the equipment cost was derived from information by industrial equipment suppliers, literature and engineering databases and scaled-up to an industrial scale plant by using Lang factors. Other direct fixed costs were calculated as percentage of the purchasing value and indirect costs were calculated as percentage of the total plant direct costs.

Operational parameters of importance for drying are moisture content of the biomass feedstock, the applied temperature and the treatment time. According to Faseaei et al. (2018) the consumption of electricity is related to the process and is thus proportional to the treated biomass. In order to evaluate the total terminal cost (TTC), the result from Faseaei et al. (2018) were adjusted to the Italian scenario by for instance changing salaries and scaling the capacities with a Lang factor of 0.6 suiting the capacities for Archimede, and this method typically gives rise to an accuracy of +/- 40 % (Cheali et al. 2015). The results are presented in the figure below, which illustrates the terminal cost at different capacities



For capacities between 10 and 100 wet ton algae biomass per year, an investment with order of magnitude of 200,000 € to 500,000 € is needed and treatment cost is roughly 0.1 to 0.4 € per kg. The curve for the treatment cost indicates that when investing in a future terminal scenario, it would be most profitable to invest for a capacity above 200 ton/yr.

Annex IX. Valorization phase LCCA data assumptions

Parameter	Input	Unit	Type of data
Algae biomass cost	4900	euro / ton	Literature data.
Fish meal	1279	euro / ton	Literature data
Carbon black	900	euro / ton	Literature data
Rubber (latex)	1400	euro / ton	Literature data

Annex X. Koto operations data and assumptions

Parameter	Input	Unit	Type of data
Algae pond operational	330	days / year	Demo site data
Mechanical systems	220	days / year	Demo site data
Pond size	85	m²	Demo site data
Insurance	1 %	% of investment	Theoretical primary data
Bank loan duration	15	years	Theoretical primary data
Interest rate (loan)	5 %	% of investment costs	Theoretical primary data
Taxation of profit	22 %	% of investment costs	Theoretical primary data
Business startup cost	25 %	% of operational costs	Theoretical primary data
Algae market price	Partner data	€/kg	Theoretical primary data
Owner expenses	10 %	% of investment costs	Theoretical primary data
Energy price	0.06	euro /kWh	Literature data [97]
Labour cost	16.2	euro /hour	Literature data [98]

Annex XI. Archimede operations data and assumptions

Parameter	**Input**	**Unit**	**Type of data**
Cultivation production	330	days/year	Demo site data
Harvest production	220	days/year	Demo site data
Pond size	1810	m²	Demo site data
Insurance	1%	% of investment	Theoretical primary data
Bank loan duration	15	years	Theoretical primary data
Interest rate (loan)	5%	% of investment costs	Theoretical primary data
Taxation of profit	22%	% of investment costs	Theoretical primary data
Business startup cost	25%	% of operational costs	Theoretical primary data
Algae market price	15-30	€/kg	Partner data
Owner expenses	10%	% of investment costs	Theoretical primary data
Energy price	0.14	euro/kWh	Partner data
Labor cost	27.8	euro/hour	Literature data[98]

Annex XII. Arava operations data and assumptions

Parameter	Input	Unit	Type of data
Insurance	1%	% of investment	Theoretical primary data
Bank loan duration	15	years	Theoretical primary data
Interest rate (loan)	5%	% of investment costs	Theoretical primary data
Taxation of profit	22%	% of investment costs	Theoretical primary data
Business startup cost	25%	% of operational costs	Theoretical primary data
Algae market price	Partner data	€/kg	Theoretical primary data
Owner expenses	10%	% of investment costs	Theoretical primary data
Energy price	0.15	euro/kWh	Literature data[99]
Labor cost	27.8	euro/hour	Literature data [100]

Annex XIII. TRL for the components of the SaltGae-system. Assessment made in April 2019 by the partners

Process	TRL	Comment
Roto-screener	9	
DAF	9	
2-AD	7	In Koto demo.
Algal ponds	8	Judged 8/9 by one expert and 8 by another.
Harvesting	8	Combination of UF and centrifugation. Membrane filtration (UF or MF) is already used for microalgae harvesting (commercially), although it is still in expansion.
Pre-treatment before desalination	9	Nanofiltration for removal of organic compounds; is a well-established technology that is widely used.
Desalination with ED	9	ED is already used at a large industrial scale.
Desalination with RO	9	
Drying	5/9	Solar drying at Arava: TRL 5 Spray drying at Archimede: TRL 9
Protein extraction	3/4	Valid when only taking the technical development into account. With the broader EARTO reading: TRL2 because of the market section (advanced discussions with potential users which is probably less advanced).
Piglet feed	7/8	Valid if you take into account only technical development. With broader EARTO reading: TRL 2 since it is out of market price.
Platform chemicals	6	Valid for the prototypes developed within the project.
Edible coatings	7	A semi-industrial test has been carried on fruits (1.2 ton of pears).
3D-printing paste	4/5	3D-printing geopolymer paste with algae biomass as filler. A scale-up test has been made in a small company that works with 3D printing.
Biocomposites	4/5	Ongoing work to achieve a proper scale-up in an industrial environment.

Annex XIV. Archimede and Arava processes with attributed PSILCA datasets and their country of origin

Process	**Country**	**PSILCA Dataset name**
Electricity generation [Archimede]	Italy	Electricity, gas, heat generation IT
Phosphoric acid [Archimede]	Italy	Chemicals and chemical products, man-made fibres IT
Sludge and solids disposal [Archimede]	Italy	Sewage and refuse disposal IT
Freshwater [Archimede]	Italy	Collection, purification, and distribution of water IT
Dairy water [Archimede]	Italy	Secondary raw materials IT
Liquid CO_2 production [Archimede]	Denmark	Manufacture of industrial gases and other inorganic chemicals DK
Sodium nitrate production [Archimede]	U.K.	Manufacture of fertilisers and nitrogen compounds GB
Sodium bicarbonate production [Archimede]	Italy	Chemicals and chemical products, man-made fibres IT
Micro-nutrients [Archimede]	Spain	Manufacture of pesticides and other agro-chemicals ES
Electricity generation [Arava]	Israel	Electricity, gas, heat generation IL
Flocculant [Arava]	Israel	Manufacture of chemical products IL
Soda [Arava]	Israel	Extraction of salts, mining, and quarrying IL
Groundwater [Arava]	Israel	Water IL
Coagulant [Arava]	Israel	Manufacture of chemical products IL
Aquaculture water [Arava]	Israel	Pond culture fisheries IL
Nutrients [Arava]	Israel	Manufacture of basic industrial chemicals and fertilisers IL

Annex XV. Absolute S-LCA results

	Functional unit	DALYs [med risk hr]	Fatal accidents [med risk hr]	Non-fatal accidents [med risk hr]	Safety measures [med risk hr]	Industrial water depletion [med risk hr]
Electricity generation [Arava]	m^3 treated water	0.4842	0.0205	5.6307	1.4411	0.1615
Aquaculture water [Arava]	m^3 treated water	0.0050	0.0045	0.4228	0.0825	0.0417
Flocculant [Arava]	m^3 treated water	0.0297	0.0053	0.3622	0.2304	0.0539
Coagulant [Arava]	m^3 treated water	0.0017	0.0003	0.0209	0.0133	0.0031
Soda production [Arava]	m^3 treated water	0.0699	0.0007	0.0326	0.0289	0.0050
Groundwater [Arava]	m^3 treated water	0.0125	0.0052	0.6361	0.0954	0.0205
Dipotassium phosphate [Arava]	m^3 treated water	0.3084	0.0162	0.0533	0.6226	0.0827
Iron II sulphate [Arava]	m^3 treated water	0.0294	0.0006	0.0021	0.0249	0.0033
Sodium bicarbonate [Arava]	m^3 treated water	0.5012	0.0272	1.1941	1.0575	0.1832
Magnesium sulphate [Arava]	m^3 treated water	0.3304	0.0041	0.0133	0.1557	0.0207
Potassium nitrate [Arava]	m^3 treated water	0.0000	0.0203	0.0666	0.7783	0.1034
Sea salt [Arava]	m^3 treated water	0.4080	0.0114	0.4976	0.4406	0.0763
Phosphoric acid production [Archimede]	m^3 treated water	$2x10^{-5}$	$2x10^{-7}$	$1x10^{-4}$	$1x10^{-4}$	$2.4x10^{-4}$
Freshwater [Archimede]	m^3 treated water	$2.5x10^{-3}$	$7x10^{-5}$	0.033	0.013	0.046
Liquid CO_2 production [Archimede]	m^3 treated water	0.219	$2.1x10^{-3}$	0.043	0.244	0.179
Sodium nitrate production [Archimede]	m^3 treated water	0.155	$3.5x10^{-3}$	$4.6x10^{-3}$	0.043	0.016
Micro-nutrients [Archimede]	m^3 treated water	$2.3x10^{-3}$	$2x10^{-5}$	0.023	0.023	$2.5x10^{-3}$
Electricity generation [Archimede]	m^3 treated water	0.032	$5.8x10^{-4}$	0.271	0.414	0.644
Sodium bicarbonate production [Archimede]	m^3 treated water	0.0042	$3.8x10^{-5}$	0.023	0.029	0.054

