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Lakeweed Neuchatel

Study of the energy potential of algal biomass in Lake Neuchatel

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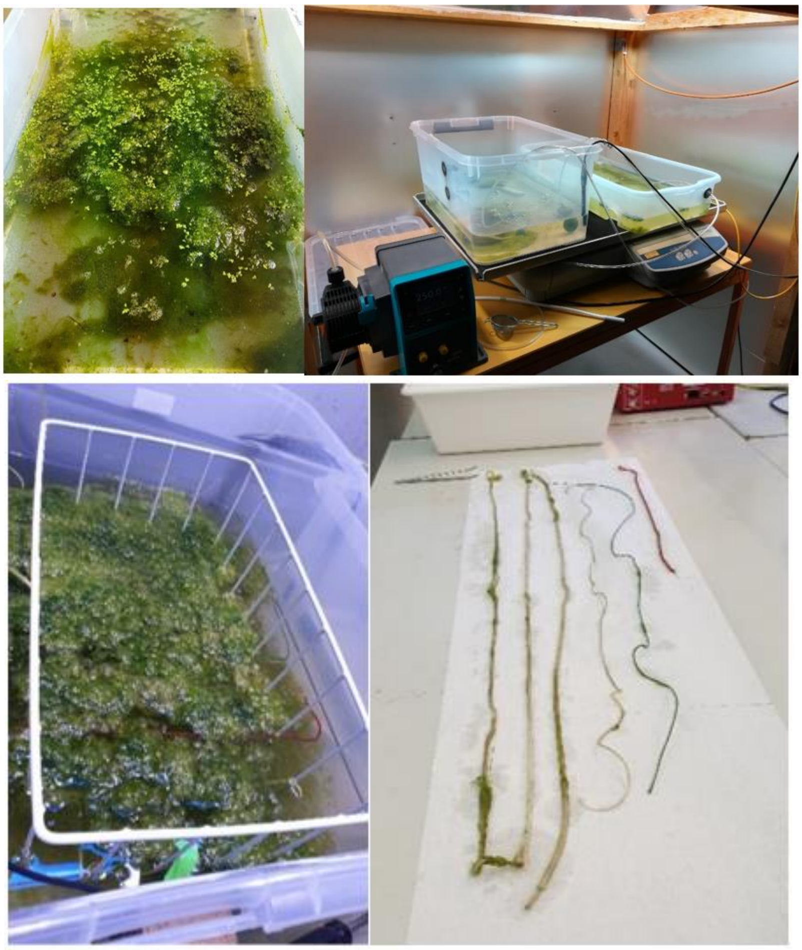

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Zusammenfassung

Das Projekt *Lakeweed Neuchatel* zielt darauf ab, das Potenzial der Kultivierung von Algen im Neuenburgersee für Biogasproduktion zu bewerten. In dieser ersten Projektphase wurden experimentelle Studien durchgeführt, um einheimische Algen zu identifizieren, ihre Wachstumsrate unter See imitierenden Laborbedingungen zu bewerten, und durch BMP-Tests herauszufinden, wie viel Biogas aus ihnen erzeugt werden kann. Anhand von Proben aus dem See wurden drei verschiedene Spezies identifiziert, aber nur eine davon, eine *Cladophora*- Spezies (die noch zu bestimmen ist), wurde für weitere Untersuchungen ausgewählt. Laut Messungen, beträgt die durchschnittlich Wachstumsrate der Algen dieser *Cladophora*- Spezies 1,4 g DW m^{-2} d^{-1} (d.h. etwa 5 Tonnen pro ha und Jahr). Die BMP-Tests zeigten, dass die Biomethan-Produktionsrate von *Cladophora* 313 NL CH4 kg-1 VS beträgt. Bei einem angenommenen Anteil an organische Masse von 75 %, wenn man große Kulturen auf dem See betrachtet, liegt die resultierende Biomethan-Trockengewichtsproduktivität bei 235 NL CH_4 kg^{-1} DW. Es wurden auch BMP-Versuche zur gemischten Schlammfaulung durchgeführt, bei denen *Cladophora* zusammen mit verschiedenen Substraten (Klärschlamm, landwirtschaftliches Substrat, industrielles Substrat) kombiniert wurde, und es zeigte sich, dass mit einem kleinen Anteil von *Cladophora* (5-10 %) ein zusätzlicher Gewinn bei der Biomethanproduktion erzielt werden konnte. Auf der Grundlage der in der experimentellen Studie erzielten Ergebnisse wurde eine techno-ökonomische Analyse durchgeführt. Die Analyse zeigte, dass die Umsetzung von Algenkulturen für den alleinigen Zweck der Biogasproduktion bei der derzeitigen Marktlage wirtschaftlich nicht machbar ist. Tatsächlich wurde geschätzt, dass die jährlichen Gesamtkosten (einschliesslich der Erntekosten und der jährlichen Investitionskosten) einer Algenfarm von 25 ha knapp 130 000 CHF betragen würden, was den Kosten für die Algenproduktion von rund 3 CHF/kg entspricht. Andererseits wird der Erlös aus dem Verkauf des produzierten Biogases auf rund 15 000 CHF geschätzt. Alternative Verwertungswege wie Lebensmittelproduktion, Pharmazeutika oder Tierfutter könnten zusätzliche Einnahmen bringen, die jedoch nicht weiter untersucht wurden, da sie den Rahmen der Studie sprengen würden. Schliesslich ermöglichte eine Stakeholder-Analyse die Identifizierung der kritischsten Stakeholder des Projekts, die eng eingebunden werden müssen, nämlich die Fischer und der Kanton. Es wurden auch die rechtlichen Verfahren für die Einrichtung eines Pilotprojekts auf dem See ermittelt. Wir sind der Meinung, dass ein Pilotprojekt notwendig ist, um Unsicherheiten zu beseitigen, die es derzeit schwierig machen, Schlussfolgerungen zu ziehen, wie z.B. die Wachstumsrate unter natürlichen Bedingungen, den Wert dieser Algen für verschiedene Anwendungen und die tatsächlichen Kosten einer Anlage.

Résumé

Le projet *Lakeweed Neuchatel* vise à évaluer le potentiel de la culture d'algues dans le lac de Neuchâtel pour la production de biogaz. Dans cette première phase du projet, des études expérimentales ont été menées pour identifier les espèces d'algues indigènes, évaluer leur taux de croissance dans des conditions de laboratoire imitant le lac, et découvrir quelle quantité de biogaz peut être produite à partir de ces algues grâce à des tests BMP. En utilisant des échantillons du lac, trois espèces différentes ont été identifiées, mais une seule d'entre elles, une espèce de *Cladophora* (qui doit encore être déterminée), a été sélectionnée pour la suite de l'étude. La productivité moyenne mesurée des algues de cette espèce de *Cladophora* était de 1,4 g MS m^{-2} d^{-1} (soit environ 5 tonnes par ha et par an). Les tests BMP ont montré que le taux de production de biométhane de *Cladophora* est de 313 NL CH_4 kg^{-1} MO. En supposant une teneur en matière organique de 75 % dans le cas de grandes cultures dans le lac, la productivité de biométhane de la matière sèche qui en résulte est de 235 NL CH_4 kg^{-1} MS. Des tests BMP de co-digestion combinant la *Cladophora* avec différents substrats (boues de stations d'épuration, substrat agricole, substrat industriel) ont également été réalisés et ont montré qu'un gain supplémentaire de production de biométhane pouvait être obtenu avec une petite fraction de *Cladophora* (5 à 10 %). Une analyse technico-économique a été réalisée, basée sur les résultats de l'étude expérimentale. L'analyse a montré que la culture de macroalgues dans le seul but de produire du biogaz n'est pas économiquement viable étant donné l'état actuel du marché. En effet, il a été estimé que le coût annuel total (comprenant le coût de la récolte et le coût d'investissement annualisé) d'une exploitation d'algues de 25 ha serait légèrement inférieur à 130 000 CHF, ce qui correspond à un coût de production d'algues d'environ 3 CHF/kg. D'autre part, les recettes tirées de la vente du biogaz produit sont estimées à environ 15 000 CHF. D'autres voies de valorisation, telles que l'alimentation, la pharmaceutique ou encore l'alimentation animale, pourraient fournir des revenus supplémentaires, mais elles n'ont pas été étudiées car cela sort du cadre de cette étude. Enfin, une analyse des parties prenantes a permis d'identifier les acteurs les plus critiques du projet et avec lesquels nous devront collaborer étroitement, à savoir les pêcheurs et le canton. Les procédures légales pour la mise en œuvre d'un projet pilote sur le lac ont également été identifiées. Nous pensons qu'un projet pilote est nécessaire pour lever les incertitudes qui ne permettent pas de conclure définitivement, telles que le taux de croissance en conditions naturelles, la valeur de cette algue pour différentes applications et les coûts réels d'une ferme de culture d'algues.

Summary

The project *Lakeweed Neuchatel* aims at evaluating the potential of seaweed cultivation in Lake Neuchatel for biogas production. In this first project phase, experimental studies were carried out to identify native algae species, evaluate their growth rate in laboratory conditions mimicking the lake, and find out how much biogas can be produced from them through BMP tests. Using samples from the lake, three different species were identified, but only one of them, a *Cladophora* specie (which still needs to be determined), was selected for further research. The average measured algae productivity of this *Cladophora* specie was 1.4 g DW m^{-2} d^{-1} (i.e. around 5 tons per ha and per year). The BMP tests showed that it has a biomethane production rate of *Cladophora* is 313 NL CH_4 kg^{-1} VS. With an assumption on the volatile solid content of 75 % when considering large cultures on the lake, the resulting dry weight biomethane productivity lies at 235 NL CH4 kg^{-1} DW. Co-digestion BMP tests combining *Cladophora* with different substrates (WWTP sludge, agricultural substrate, industrial substrate) were also carried out and showed that additional gain in biomethane production could be obtained with a small fraction of *Cladophora* (5-10%). A techno-economic analysis was carried out, based on the results obtained in the experimental study. The analysis showed that the cultivation of macroalgae for the sole purpose of biogas production is not economically feasible given the current state of the market. Indeed, it was estimated that the total annual cost (including harvest cost and annualised investment cost) of an algae farm of 25 ha would be just under 130 000 CHF, which corresponds to an algae production cost of around 3 CHF/kg. On the other hand, the revenue obtained from selling the produced biogas is estimated to be around 15 000 CHF. Alternative valorisation pathways, such as food production, pharmaceuticals, or animal feed, could provide additional revenues, but these were not further investigated as they it beyond the scope of the study. Finally, a stakeholder analysis allowed identifying the most critical stakeholders of the project which will have to be closely involved, namely the fishermen and canton. Legal procedures for setting up a pilot project on the lake were also identified. We believe that a pilot project is necessary to remove uncertainties which currently make it difficult to conclude, such as the growth rate in natural conditions, the value of this seaweed for different applications and the real costs of an algae cultivation farm.

Main findings

- The average measured algae productivity of the *Cladophora* algae specie found in lake Neuchâtel is 1.4 g DW m-2 d-1 (i.e. around 5 tons per ha and per year).
- The measured biomethane production rate of *Cladophora* is 313 NL CH4 kg-1 VS, and can reach 235 NL CH4 kg-1 DW when expressed in terms of dry weight.
- With total annual cost of 130 000 CHF, and an expected revenue from the sale of biogas of 15 000 CHF, the cultivation of macroalgae for the sole purpose of biogas production is not economically feasible given the current state of the market.
- A pilot project would be necessary to remove uncertainties which currently make it difficult to conclude: growth rate in natural conditions, value of this seaweed for different applications and real costs of an algae cultivation farm.

Contents

Abbreviations

BMP	Biochemical Methane Potential
CAPEX	Capital expenditures
DW	Dry weight
FW	Fresh weight
ISR	Inoculum-to-substrate
OPEX	Operating expenditures
TS	Total solid
VS	Volatile solid
WWTP	Waste-water treatment plant

1 Introduction

Macroalgae (seaweed) cultivation is a promising activity in the context of sustainable development, as it presents multiple economic, social and environmental benefits. Certain species of seaweed have been cultivated by humans as a source of food for centuries. More recently, active compounds with medicinal or dietary properties have been found in abundance in macroalgae which has raised the interest of the pharmaceutical, nutraceutical and cosmetics sectors. Macroalgae is also being considered for the production of animal feed, fertiliser and bioplastics. Last but not least, seaweed can also be a source of renewable energy, through the production of biofuels or biogas.

The development of renewable energy sources is one of the three pillars of the Energy Strategy 2050 of the Swiss Confederation. To reach its ambitious goal in terms of renewable energy production, the renewable sources should be diversified and novel technologies considered, including the use of renewable gas where it makes sense (e.g. high temperature industrial processes, consumers with high heating demand and limited accessible renewable sources, …). The use of macroalgae as feedstock to an anaerobic digester to produce biogas is one such opportunity.

The project *Lakeweed Neuchatel* aims at evaluating the potential of seaweed cultivation in Lake Neuchatel, and more generally in Swiss lakes, for the purpose of energy production, and more specifically for producing biogas. This report presents the results of the feasibility study, which is the first phase of the project. It aims to answer the following key questions:

- Which indigenous macroalgae species are present in lake Neuchatel?
- Which growth rate is observed in laboratory conditions for the most promising species?
- What is this species' biomethane potential, when tested by itself and in combination with other relevant substrates (co-digestion)?
- What kind of system should be used to cultivate the macroalgae?
- What is the economic benefit of cultivating macroalgae for biogas production?
- Who are the main stakeholders associated to this project, what are their interests and how can they influence the project?
- Which legal procedures need to be taken into account to set up a cultivation platform on lake Neuchatel?
- What are the next steps to set up a pilot project (second phase) on the lake?

To answer these questions, this report is divided into two parts:

- Part 1 presents the results of the experimental study carried out in the laboratory of the HEIG-VD.
- Part 2 presents the results of the feasibility study based on the results of the experimental study.

The conclusion will summarise the main findings and provide the rationale for the pursuit of the project with a pilot platform (second phase), which will be discussed at the end of the feasibility study (Go – No Go milestone).

Part I Experimental Study

2 Identification and Characterisation of Seaweed and Water Samples

2.1 Seaweed locations

To collect macroalgae samples, specific locations on Lake Neuchatel have been identified where seaweed naturally grow. This analysis, together with lake water characterisation, was performed to identify the most promising locations for macro-algae cultivation and for setting up the pilot platform planned in Phase II.

The activities of bio-prospecting, environmental sampling and identification of native algae species in Lake Neuchatel took place in summer 2019 and summer 2020, during the fertile period due to high solar radiation and temperature.

Algae samples were collected in 6 different sites where they were abundant and easy to collect, on public space and with no risk for personnel during the sampling.

Sampling points are shown in Figure 1 and related algae species are listed in Table 1, while an example of sampling point is given in Figure 2.

Figure 1. Algae sample locations

Table 1. List of algae samples

Location	Sampling date	Algae/plant family	Remarks
Morges	26.08.2019	Waterweeds	Noticed ubiquously in Lake Neuchatel but harvested in Morges (Lake Leman) due to ease of harvesting abundantly by boat.
Grandson port	11.09.2019 /23.09.2019	Characeae	
Tennis Grandson	10.10.2019	Cladophoraceae	
West canal Yverdon	13.09.2019	Cladophoraceae	
Yverdon beach	13.09.2019	Cladophoraceae	
Yvonand pond	11.09.2019	Vascular plant N.N.	Identified *in-situ* as a characean algae but latter (in lab) classified as vascular plant.

Figure 2. Picture of one of the sampling locations (West canal, Yverdon-les-Bains)

2.2 Laboratory tests for seaweed characterization

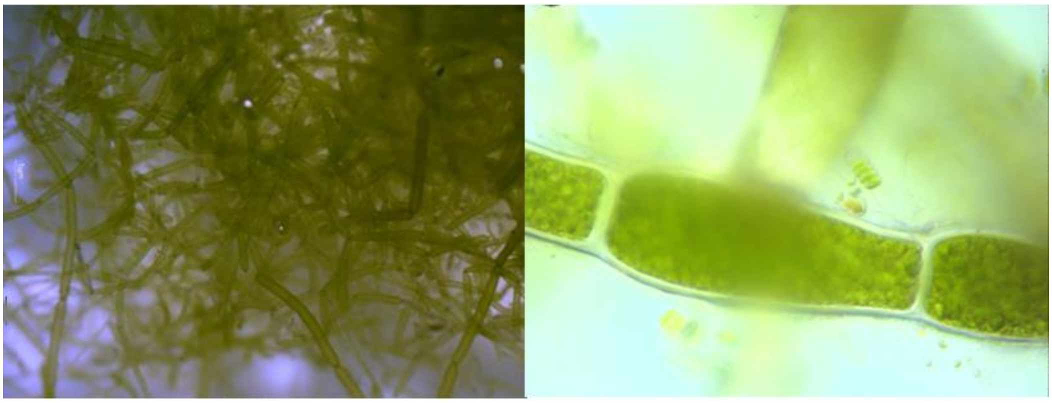
Algae species were identified based on taxonomic keys [1], [2]. Identification is generally possible to the genus level using a microscope. Although algae samples were collected in 6 different sites, we focused on three sites where they were abundant.

Two genera of algae were identified (*Cladophora* and *Nitellopsis*). In addition, we have noticed ubiquitously an invasive vascular plant known as *Elodea* (non-native) that should be continuously harvested/cut.

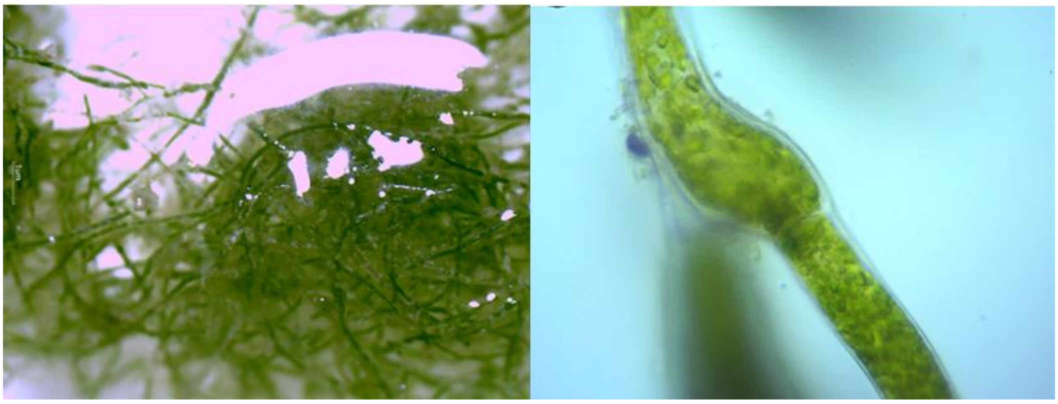
The algae that have been identified are as follows:

- SP1: *Cladophora* from Grandson, Tennis beach

As shown in the figures below, the genus *Cladophora* was confirmed mainly by branching of filaments, bifurcations roughly equal and divisions usually displayed in a tree-like manner with cross walls present. In addition, branch tips are rounded, no mucilage presence, nor macroscopic growths.



- SP2: *Cladophora* from Yverdon-les-Bains, West canal (same characteristics as for SP1)



- SP3: *Nitellopsis obtusa* (*Characée*) from Grandson port

Contain verticils (arrangement of branches that radiate from a single point and surround or wrap around the stem). Non-corticated plant having stellated bulbils and being larger than Tolypella.

2.3 Location and characterization of water samples

Water sampling points are shown in the map in Figure 3 and listed here:

- Tennis beach (Grandson)
- Reject canal WWTP (Grandson)
- Iris port (Yverdon)
- West canal (Yverdon)
- Cure d'air canal (Yverdon)
- Menthue canal (Yvonand)
- Viking beach (Yvonand)

Figure 3. Location of water samples

Water quality from the different sampling sites has been tested in autumn 2019 and summer 2020 and analysed to assess variability in time and space. Table 2 shows the average values obtained for each sampling site. The detailed results of each individual sample for each site are available in Appendix 1. The average nutrient concentration is represented on a bar chart in Figure 4.

Table 2. Water quality assessment at different sampling points (average values of in sampling period)

Sampling points	pH	Conductivity (µs/cm)	NH4-N (mg/l)	NO3-N (mg/l)	PO4-P (mg/l)	COD (mg/l)	Alcalinity (mg/lCaCO3)	dh°	Ca2+ (mg/l)	Mg2+ (mg/l)
Menthue canal	8.12	510.25	1.48	4.80	0.10	25.65	205.00	15.30	77.55	19.18
Viking beach	7.90	270.00	0.05	0.55	0.02	12.57	120.00	8.13	36.40	13.18
Reject canal WWTP	7.38	793.50	3.78	17.44	0.38	30.55	150.00	13.93	74.83	14.88
Tennis beach	7.88	295.50	0.14	0.91	0.02	16.30	120.00	8.03	42.15	9.06
West canal	7.66	704.00	0.33	3.81	0.16	24.90	240.00	18.29	99.03	18.97
Iris port	7.85	337.00	0.37	0.89	0.07	20.56	120.00	8.88	44.83	11.24
Cure d'air canal	8.02	290.67	0.07	0.94	0.02	12.20	110.00	8.21	34.67	14.48

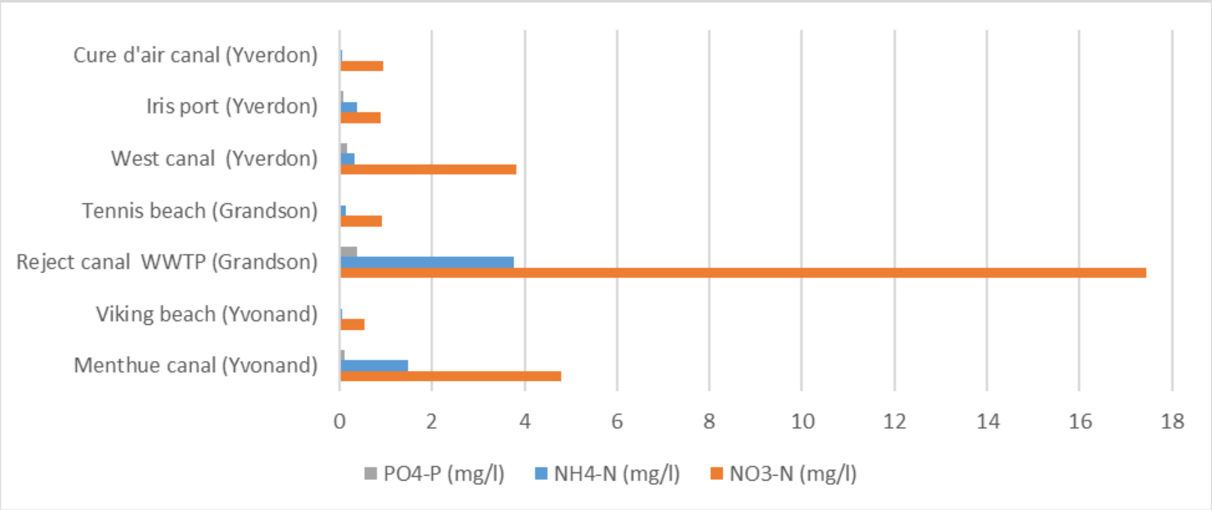


Figure 4. Average nutrients concentrations

The analyses show some spatial and temporal variability, with concentration peaks near the WWTP, as expected, where variability is stronger. These sampling data provide us with a knowledge base on nutrient distribution in different areas of the lake, but the experience gained during this project with laboratory algae cultivation has shown that these nutrient variations have a less significant impact on algae growth (as described in the following section) than other parameters such as temperature and sunlight, as visually observed in natural habitat.

3 Macroalgae Batch Cultivation Tests

Algae batch cultures have started using the laboratory facilities at HEIG-VD (IGT) as shown in Figure 5, using about 300 g fresh weight (FW) of the environmental sampling. The algae chosen for the cultivation tests were *Cladophora* species due to its abundance and its easy sampling.

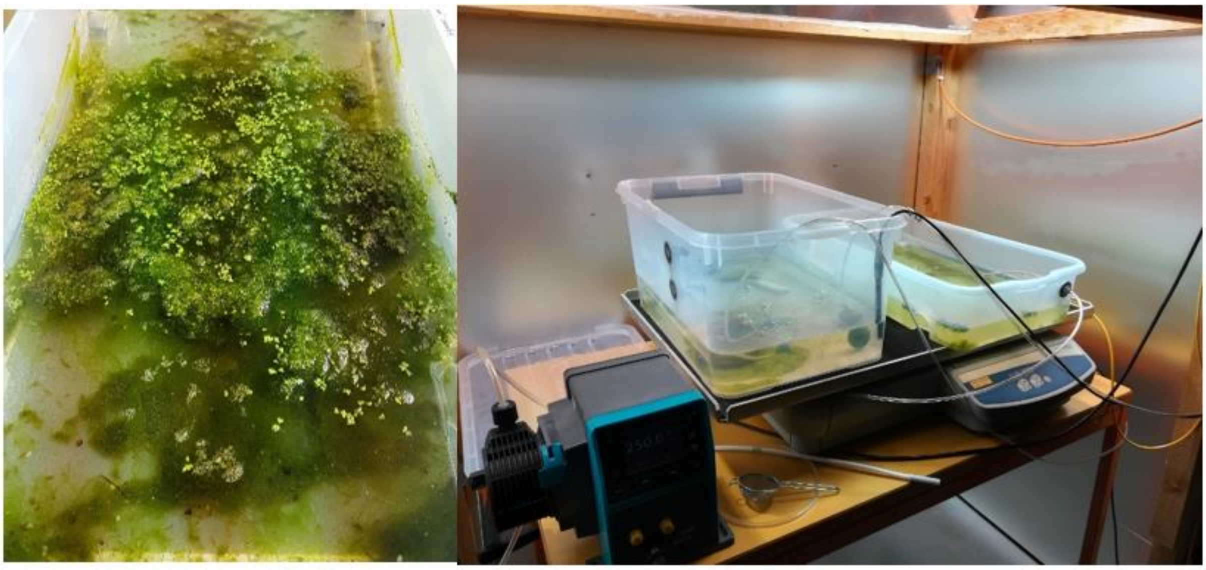


Figure 5. Batch algae cultures

Cladophora was grown in the laboratory set-up from the biomass collected at the end of summer in the lake from two locations: from the Iris canal and the from Grandson tennis.

They were washed with tap water and cleaned by hand from associated macrofauna and plants in the laboratory. Stock cultures started at a rate of 2 g FW L^{-1} and took place in lake water. The acclimation of species was preceded by a careful selection of culture parameters. CO_2 and light as major criteria for photosynthesis were applied: HQI lamps (metal halide with quartz technology) have been preferred because they have a spectrum close to that of solar radiation. The intensity chosen was set around 200 µmol photons m^{-2} s^{-1} confirmed by a PAR Quantum sensor (Kipp & Zonen). The lamps are placed so that the PAR available for algae is however between min-PAR and max-PAR. Photoperiod was set to 12h light / 12h dark. On the other hand, the CO_2 was dosed in order to replenish CO_2 that was used by photosynthesis, by mixing pure CO_2 with air and monitoring using a specific sensor (Dynament). CO_2 injection was automatized and controlled via pH: every time the pH rises above 7.7, CO2 is injected until pH drops below 7.5 (7.6 is the average pH of Lake Neuchâtel). Temperature was on average 25.5°C. Lake water was slightly enriched with KNO_3 at a concentration of 129 mg L-1 (corresponding to 18 mg N-NO_3 L^{-1}) to mimic chemical conditions founds in canals and renewed every 7 days.

The cultivation system consists of two plastic containers placed in a bigger plastic container that is filled with water and contains a heat-exchanger connected to a chiller in order to control the temperature. All the containers are placed on an orbital shaker that moves to mimic the water movement in the lake. One container where algae grew was only filled with water, the other with water amended with nutrients.

Only water from the lake was used in the two first months of tests and it was autoclaved and then for canal simulation amended with 18 mg N-NO_3 / L and 0,8 mg P-PO_4 / L. Every week the water was replaced. To 15 L of medium, 30 g of wet algae (after draining for 15 minutes) were added. Then, for 1 month, the medium recipe was switched from Lake water to tap water without any sterilization in autoclave. *Cladophora* stopped growing. This can be due to the lack of some micronutrients and/or the presence of chlorine in the tap water (in comparison to lake water). On top of this, a contamination of micro-algae occurred at the same time. The macro-algae culture was washed with a chlorine solution to remove this contamination, which caused its death.

In May 2020, new *Cladophora* samples could be retrieved from the West canal in Yverdon, as they were starting to grow and to expend for summertime. Since then, they were grown successfully in the laboratory, without any contamination issues. 3 batch-growing tests were performed with this set up to estimate algae growth, based on 2-weeks tests where water is changed weekly.

As can be observed in Table 3, no significant differences between water with/without amendment were found and the measured average algae productivity is 1.4 g DW m^{-2} d^{-1}.

Table 3. Laboratory growth tests

No amendment		**With amendment**	
Test #	**Productivity (g DW m^{-2} d^{-1})**	**Test #**	**Productivity (g DW m^{-2} d^{-1})**
1	1.19	4	1.72
2	1.65	5	1.16
3	1.38	6	1.17
Average	**1.41**		**1.35**

This shows that algae already grow in areas with adequate quantities of nutrients and that a higher concentration of these does not necessarily mean higher productivity, while other parameters such as sunshine level and temperature can strongly affect their productivity, and can even stop it (during winter).

4 Macroalgae Lab-scale Cultivation Platform

Tests of algae cultivation on different types of ropes in lab conditions were performed in order to assess different materials and diameters on algae anchorage. The ropes were purchased in DIY shops and in some cases the product material was not indicated: the choice was dictated by models that visually were different and that were known to be used in some sectors.

The 6 types of ropes tested are here listed:

- Polypropylene, ∅ 3mm,
- Polyester, ∅ 3mm,
- White similar-rope, ∅ 0.4mm
- Nylon, ∅ 1.5mm
- Red rope, ∅ 2mm
- Green rope for bricklayers, ∅ 1.75mm

The ropes were cut into 20 cm-pieces and left 1 hour in contact with an algae concentrate in lake water. Subsequently the ropes were placed in a test tank with 15 litres of sterilised lake water and 15 g FW of algae, under the same growing conditions as the productivity tests in terms of temperature, lamps operation and CO_2 injection.

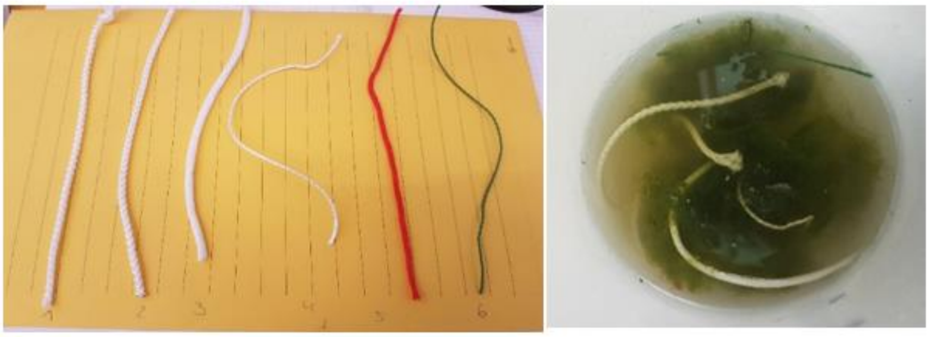


Figure 6. Ropes test – preparation

Laboratory experiments have shown that for the prototype of algae production in Lake Neuchâtel, a linear rope system alone would not be sufficient. *Cladophora* algae have a very weak mechanical grip compared to other types of cultivated algae, such as brown algae for instance. The results shown in Figure 7 prove that none of the different ropes tested seems to be suitable for algae anchoring and suggest that a possible solution for this type of algae cultivation could be a closed mesh system to enclose the algae rather than a single, linear support, like the fishing farms with their circular structures.

Figure 7. Ropes test - performance

5 BMP Tests

BMP tests were performed with Nautilus systems from Anaero Technology (UK), using recommendations issued by the international panel lead by Prof. Cristof Holliger (EPFL) that aims at standardizing BMP tests [3], [4]. For each test, anaerobic sludge from the WWTP of Yverdon-les-Bains was used as inoculum and was tested for alkalinity (> 3 $gCaCO_3$ L-1), volatile fatty acids (< 1.0 gCH_3COOH L-1), ammonium (< 2.5 $gN\text{-}NH_4$ L-1), total solids (TS) and volatile solids (VS). The sludge was kept up to 5 days at room temperature. Substrates were kept up to 3 days in the fridge or frozen (at -18 °C) for longer periods. They were tested for TS and VS. Microcrystalline cellulose was used as positive control only for the first test, in order to spare bottles in the subsequent tests for other samples. Inoculum-to-substrate (ISR) ratio were either 4 or 6. Incubation temperature was set to 37 °C, as it is the digester temperature where the inoculum was collected.

The list of the BMP tests conducted for this project is as follows:

- Test 1: Algae recovered at the end of summer 2019:
    - *Characaea* (from Grandson port, 23/09/2019)
    - *Cladophora* (from Iris port, 03/10/2019)
    - *Elodea* (from Morges port, 29/09/2019).
- Test 2: Co-digestion experiments for stranded algae recovered from the beach of Yverdon-les-Bains (03/10/2019) with WWTP sludge.
- Test 3: Co-digestion experiments for *Cladophora* grown in the laboratory with WWTP sludge.
- Test 4: Same co-digestion experiments with an industrial AD substrate (from Axpo-Kompogas, Chavornay).
- Test 5: Same co-digestion experiments with an agricultural AD substrate (from Agrogaz, Lignerolle).

For all the co-digestion experiments, the mix between both substrates was calculated on a VS-basis. For the tests 3 to 5, the same algae sample was used for the co-digestion experiments. In order to save biomass, this sample was measured without co-substrate only once (during test 3) and the ISR was set to 6 (instead of 4) for all the co-digestion experiments involving this algae.

Data were analysed with an in-house R script, which is based on the R package "biogas" [5]. Here are the main steps of the script:

- The event log files of the Nautilus systems are annotated with relevant information for each bottle (e.g. sample name, sample type, inoculum mass, substrate VS mass).
- Possible tumbling bursts events are identified using plots displaying the time difference between two tumbling events. In case, event log files are manually curated to remove them.
- For each channel, the cumulative production is calculated on a daily-basis based on standardized gas volume (i.e. at 0 °C and 101,13 kPa).
- BMP values of the inoculum-only reactors are calculated and checked for outliers using Dixon test. Outliers are removed from the dataset.
- Daily methane production rates (compared to total methane production) are calculated for each bottle and are averaged over 3 days.
- For each sample group, the termination date is determined using the following criteria:

- Each test should last of at least 25 days,
- The 3-days average methane production rate should be lower than 1% for all replicates.

- Dixon test are performed on substrates replicates to detect possible outliers and discard them from the dataset.
- BMP values for each substrate is calculated on a VS and WW basis.

Among the 75 tested bottles, 4 bottles had a lot of tumbling bursts events. Three of them could be manually parsed, but one bottle (an inoculum-only bottle from test 3) had to be discarded, as it was still strongly different than the two other replicates after trying to remove manually the tumbling bursts. Another bottle was lost in the second test, because a gas sampling line was disconnected from it for a few hours (a bottle with 5% algae in the co-digestion mix). Not a single outlier was detected with Dixon tests. The BMP value of the cellulose control was 371 NL CH_4 / g VS, with a relative standard deviation below 6%, which allows to validate the BMP tests. Figure 8 shows, as bar plots, the BMP values of each tested sample on a VS-, DW- and WW-basis. In this graph, the dark blue bars represent the average values, the error bar represent the standard deviation, the open circles represent the individual measurements, and the light blue bars represent the expected CH_4 production of co-digestion tests from individual substrates measurements. The cumulative CH_4 production for each of the 5 tests is given in Appendix 2.

Table 4 summarises all the results from the BMP tests. Volatile solid content of macroalgae collected at the end of summer 2019 can be quite low, between 21.1 and 24.2 % (test 1). Consequently, their BMP values on a DW-basis is low, less than 100 NL CH_4 / g DW. Fresh algae grown in the laboratory have a higher VS content (50.14 %, test 3), which means that its BMP value on DW-basis is better, about 180 NL CH4 / g DW. But as these samples have a higher water content, their BMP values based on WW are not necessarily higher than those from late-summer samples.

The lake average temperature decreased from August to September around 3°C and it is probable that the decrease in water temperature and the end of the algae maturation period caused a decrease in volatile solids in the algae biomass and therefore a probable decrease in BMP values.

It is reasonable to assume that earlier sampling of the algae would have resulted in a higher VS content with possible increased BMP values.

Further analyses on the organic fraction of algae cultivated in the laboratory have shown results of up to 75% of VS, as in laboratory conditions all those inert materials that can be found in a natural habitat such as the lake are not present.

C:N ratios of algae are usually rather low, between 10 to 12, except from some late-summer samples. This means that macro-algae are expected to provide better co-digestion yields with co-substrates with higher C:N. This is what was observed in this set of BMP assay. In co-digestion with WWTP sludge (primary and secondary sludge), which also have a low C:N ratio (9), the mix with 5% algae does not help the digestion, while with 20% algae, there are inhibitory effects. When co-digested with an industrial substrate (green waste mixed with kitchen waste) which have an intermediate C:N ratio (18), the gain in CH_4 production is only observed when the proportion of algae is 5% in the mix. Finally, with agricultural substrate (manure with straw) for which C:N ratio is higher (22), the co-digestion of algae seems to provide substantially more methane when their concentration is 10%.

Even though the trend of these co-digestion experiments is clear, one must be careful when looking at this dataset. Indeed, for some experiments, the relative standard deviation of BMP test can be important (up to 40%). This can be explained by the fact that algae are quite a heterogeneous substrate, and so further BMP tests should be performed in order to obtain BMP more accurate values. For example, for test 4, the co-digestion experiment with 10% algae give 40% more methane than what would be expected. But when removing one replicate which gives a higher BMP value (316 NL CH_4 kg VS) than the two other replicates (220 and 233 NL CH_4 kg VS), the average BMP is then 237 NL CH_4 kg VS, which would represent a CH_4 gain of 24% (instead of 40%). Similarly, when manually removing an outlier from the 20% algae sample in the same test, the gain in CH4 goes from -8% to 0%.

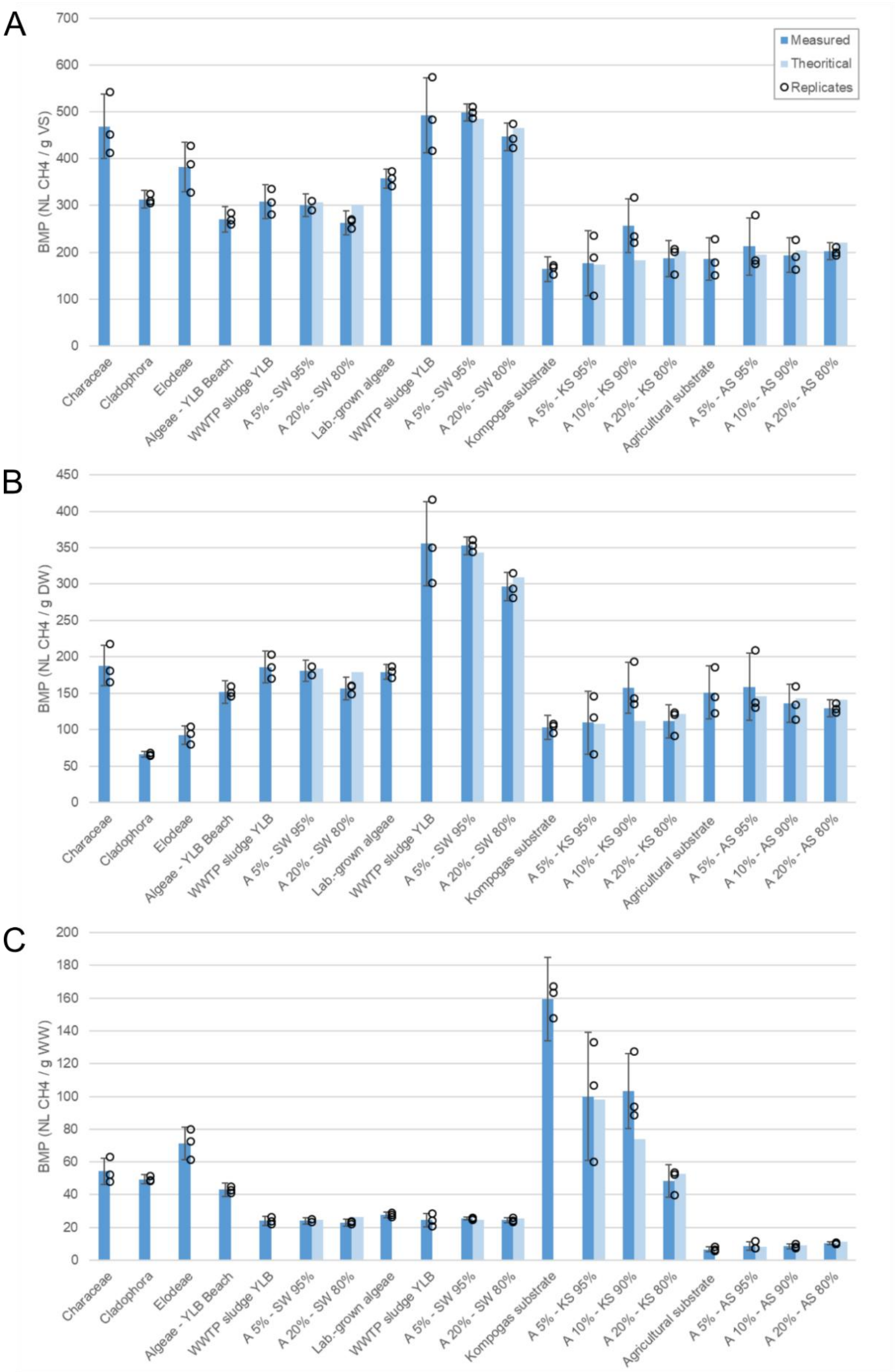


Figure 8. BMP values of all tested samples, on a VS-basis (upper panel A), on a DW-basis (middle panel B) and on a WW-basis (lower panel C).

Table 4. Summary of the BMP tests performed during this project. The C:N ratio of co-digested substrate was calculated based on the relative proportion of the co-substrate and their C:N value. For co-digestions tests, the gain in methane was calculated, relative to the expected CH_4 production (which is calculated based on BMP of individual substrates). WW = wet weight, DW = dry weight, VS = volatile solid, C:N = carbon-to-nitrogen ratio.

Test	Substrate	DW% (g/g WW)	VS% (g/g DW)	C:N ratio	BMP (NL CH4/kg VS)	BMP (NL CH4/kg DW)	BMP (NL CH4/kg WW)	CH4 gain from co-digestion (%)
1	Elodees	11.6	40.1	11.0	381.7 ± 125.6	153.1 ± 50.4	17.8 ± 5.8	-
	Characees	15.8	21.1	21.7	468.8 ± 166.8	98.9 ± 35.2	15.6 ± 5.6	-
	Cladophores	18.7	24.2	17.8	313 ± 25.9	75.7 ± 6.3	14.2 ± 1.2	-
2	Stranded algae	15.91	56.2	12.2	270.2 ± 30.5	151.9 ± 17.1	17.6 ± 2	-
	WWTP sludge	7.79	60.45	11.0	308 ± 67.2	186.2 ± 40.6	14.5 ± 3.2	-
	Algae 5%	8.02	60.21	11.1*	300.2 ± 124.4	180.8 ± 74.9	14.5 ± 6	-1.9
	Algae 20%	8.74	59.55	11.3*	262.6 ± 26.1	156.4 ± 15.5	13.7 ± 1.4	-12.6
3	Algae grown in lab	7.74	50.14	9.8	357.4 ± 39.4	179.2 ± 19.8	13.3 ± 1.5	-
	WWTP sludge	4.97	72.3	9.0	492.1 ± 196.6	355.8 ± 142.1	17.7 ± 7.1	-
	Algae 5%	5.1	70.73	9.1*	498.5 ± 30.3	352.6 ± 21.4	18 ± 1.1	2.7
	Algae 20%	5.49	66.43	9.2*	446.7 ± 65.1	296.7 ± 43.2	16.3 ± 2.4	-4.0
4	Agricultural substrate	97.3	62.8	21.9	163.9 ± 26.1	102.9 ± 16.4	100.2 ± 15.9	-
	Algae 5%	56.52	62.01	21.2*	176.7 ± 161.9	109.6 ± 100.4	61.9 ± 56.8	1.8
	Algae 10%	40.25	61.25	20.4*	256.6 ± 129.8	157.2 ± 79.5	63.3 ± 32	40.0
	Algae 20%	25.96	59.79	19.0*	186.9 ± 74.5	111.7 ± 44.5	29 ± 11.6	-7.7
5	Industrial substrate	3.58	81.2	17.7	186 ± 96.7	151 ± 78.5	5.4 ± 2.8	-
	Algae 5%	4.11	74.81	17.1*	212.5 ± 145	159 ± 108.5	6.5 ± 4.5	9.2
	Algae 10%	4.4	70.32	16.5*	193.3 ± 79.8	135.9 ± 56.1	6 ± 2.5	-4.8
	Algae 20%	5.07	64.16	15.4*	201.6 ± 23.9	129.3 ± 15.3	6.6 ± 0.8	-8.5

* Not measured, but calculated

Part II Feasibility Study

6 Stakeholder Analysis

The main stakeholders connected to the project that have been identified are as follows:

- Federal Office of Energy (SFOE):
- Federal Office of Environment (FOEN)
- Cantons around lake Neuchâtel (Vaud, Neuchatel, Bern, Fribourg)
- Municipalities along the lake shore
- Fishermen
- Grande Cariçaie Association
- Biogas producers
- Swiss Gas Industry Association (ASIG)

The level of interest and power of each of the above stakeholder have been evaluated in order to construct the stakeholder matrix (see Figure 10), which will be used to define a stakeholder management plan in the next steps of the project (Phase II). This evaluation is based on meetings and phone discussions which we had with some of the representatives of the stakeholder groups. The minutes of the meetings held with the fishermen's association and the Grande Cariçaie Association are available in Appendix 4.

Federal Office of Energy (SFOE)	
Interest	As the funder of the project, SFOE have a natural interest in the project results and outcomes. In the context of the Swiss energy strategy, they would like to know the potential of energy production from macroalgae cultivation in Swiss lakes as a new source of renewable energy. They are therefore particularly interested in the replication of the project at the national level.
Power	The SFOE can contribute to the funding of pilot projects such as this one. They can also communicate on this type of solution, and if a significant potential is identified, could give a legal frame for its country-wide development.

Federal Office of Environment (FOEN)	
Interest	The FOEN are not directly involved in the project. However, they should definitely be involved or consulted at the very least during the next phase of the project. Indeed, the FOEN would like to know if and how the project (and seaweed cultivation in general) could affect local wildlife and water pollution. Moreover, they are responsible for the application of the law on CO_2, so they are also interested in knowing to which extent this technology could contribute to reducing CO_2 emissions.
Power	Just as for SFOE, the FOEN can potentially contribute to the funding of pilot projects such as this one. They can also communicate on this type of solution, and if a significant potential is identified, could give a legal frame for its country-wide development. Moreover, they could give CO_2 certifications to such projects.

Cantons around lake Neuchâtel (Vaud, Neuchatel, Bern, Fribourg)	
Interest	Cantons may show some interest in the project, both from the energy and environmental perspective. Indeed, they are responsible for the application of environmental laws on their territory and also have their own energy strategy that they need to implement. So far, the canton of Vaud has shown interest in the project and has funded a part of the project. However, we do not know if all cantons will show the same interest.
Power	In Switzerland, lake domains are under the jurisdiction of cantonal authorities. Therefore, any project – however small – taking place on the lake needs to be approved by the canton.

Municipalities along the lake shore	
Interest	Generally speaking, municipalities are not expected to show a lot of interest in the project.
Power	Lakes are not under the jurisdiction of municipalities, and have therefore limited lever on the outcome of the project.

Fishermen	
Interest	The fishermen of Lake Neuchatel have a strong interest in the project as they are directly affected by it. Indeed, the macroalgae cultivation platforms will take up space on the lake, and will therefore compete for water area with other activities, especially fishing. But seaweed cultivation may also have a positive impact for fishermen, as it could provide a safe habitat for fish (protecting them from their predator birds) and also a new source of revenue through the installation and harvest of the platform.
Power	The fishermen are organised in an association, and they need to be tightly involved in any project or decision related to the usage of the lake as the authorities will consult them and get their approval before any new project takes place. This is even more true in the context of an economic downfall of fishing activities in Lake Neuchatel, leaving fishermen vulnerable to any changes related to the lake. Besides, previous promising projects have already failed because they did not get the support or approval of the fishermen (e.g. floating solar farms).

Grande Cariçaie Association	
Interest	The Grande Cariçaie Association manages the natural reserves located on the south bank of Lake Neuchatel. They showed limited interest in the project itself and are dubious of this technology. However, they want to be informed of how the macroalgae cultivation will affect the local wildlife.
Power	Any facility which is on the domain of the nature reserves needs their approval. They are against any cultivation platform being installed on their domain (see areas concerned on map in Figure 9). In any case, they should also be informed if a plant is installed in any region near the South Bank and should be further involved in the project to profit from their expertise on the biodiversity impact aspects.

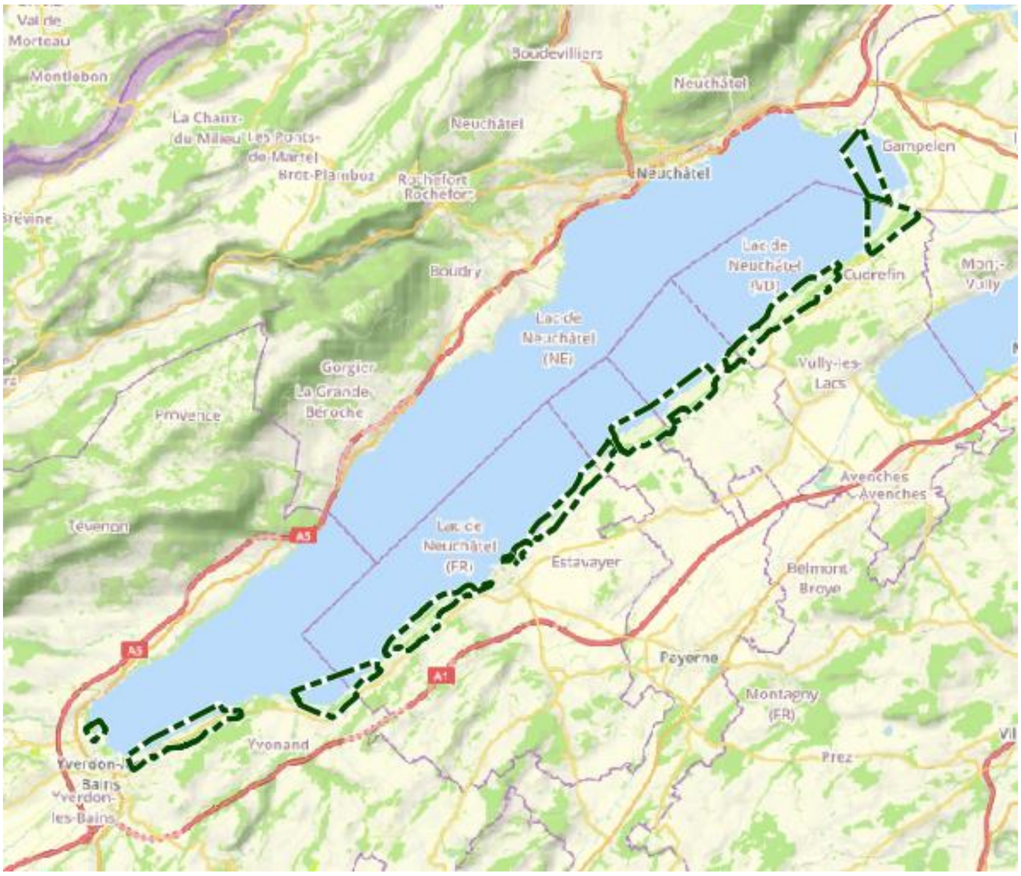


Figure 9. Areas managed by Grande Cariçaie Association (areas inside dotted green line boundaries)

Biogas producers	
Interest	For biogas plant operators, the seaweed produced by the cultivation platform could be an additional resource to be used a co-substrate for their anaerobic digesters. Lab results have shown that using a small amount of macro-algae (typically 5-10%) as a co-substrate to biowaste in anaerobic digesters boosts the overall biogas production. A biogas producer in canton Vaud has already shown their interest in the project and would consider a partnership in the next project steps.
Power	The biogas producers have no leverage on the cultivation platforms themselves, which is the heart of the project. However, they are an indispensable partner to the project for the energy valorisation aspect.

Swiss Gas Industry Association (ASIG)	
Interest	ASIG has shown their interest in the project. Indeed, they have a strong will to greatly increase the share of renewables in their gas mix. One way to achieve this is by diversifying the sources of biogas, which is exactly what this project could offer through the production of biogas from macro-algae.
Power	ASIG has no leverage on the cultivation platforms themselves, which is the heart of the project. They could however be a valuable partner for the deployment of the solution at a larger scale. Moreover, they are willing to co-finance a pilot project if a sufficient potential for biogas production is identified during the project.

Based on the previous analysis, the stakeholders have been arranged in a stakeholder matrix in Figure 10.

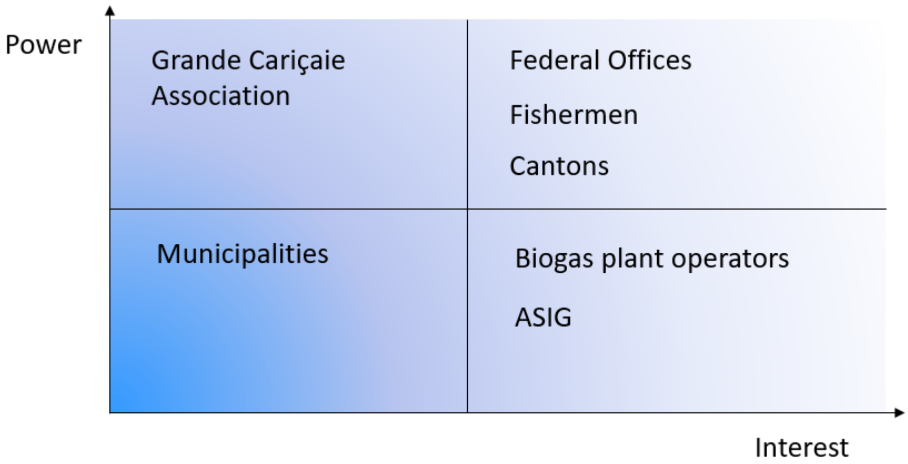


Figure 10. Stakeholader matrix for the *Lakeweed Neuchatel* project

The stakeholder matrix identifies different categories of stakeholders that should be dealt with differently within the project. The categories are as follows:

- **High power, highly interested stakeholders**: we need to fully engage with these groups and make the greatest efforts to satisfy them.
- **High power, less interested people**: we need to keep these groups satisfied and avoid making them an opponent of the project.
- **Low power, highly interested people**: we need to adequately inform these groups. They can also be helpful in the project in a supportive role.
- **Low power, less interested people**: these groups should be monitored and informed, but not so much as to bore them with excessive communication.

The stakeholder analysis carried out in this study will help us define the stakeholder management plan. The stakeholder management plan will be produced at the beginning of the next project phase to clarify the role, level of involvement, and communication strategy for each stakeholder, according to project management best practices.

7 Legal Constraints

The legal constraints related to the project have been investigated. To this end, several offices of the cantonal authority (from canton Vaud) and the Grande Cariçaie Association were contacted. From the meetings, phone interviews and e-mail exchanges which we had with these stakeholders, we were able to identify the following legal constraints on the project, which apply with varying degree to a pilot project and commercial exploitation.

Firstly, there are two authorisations which need to be obtained at the cantonal level.

- An authorisation for the construction of a platform on the lake. Indeed, any work or intervention in watercourses, on their banks and in the watercourse area is subject to authorisation by the Department of Environment and Security (DES) according to article 12 of the LPDP. In principle, and where applicable, the issuance of the authorisation is the result of a public enquiry and consultation with the cantonal authorities concerned by the project. Restrictions may of course apply in concession areas (e.g. ports) or nature protection zones (e.g. navigation ban in bird reserves).
- An authorisation for special works in the natural environment. This can be obtained from the Biodiversity division (DGE-BIODIV) of the canton.

In addition to these authorisations, the federal Order on internal navigation (ONI) should be taken into account when installing an algae cultivation platform on the lake. The appropriate signalisation needs to be applied so that boats can know the presence of the cultivation platforms and avoid navigating in the designated area. The navigation police also need to be informed.

8 Techno-economic Analysis

8.1 System design

The system that is considered for the techno-economic analysis consists of multiple macro-algae cultivation lines of 50 m long and attached to a buoy at each end. Each buoy is attached to a chain, which is attached to an anchor (or “dead body”) at the other end in order to tether the buoy to the sea bottom. Multiple lines are installed in parallel and separated by around 5 m, and physically connected to each other at each end by a rope. This way, the seaweed is “trapped” between two cultivation lines. This system is illustrated in Figure 11 and Figure 12. It should be noted however, that there is some uncertainty on the effectiveness of the system to contain the macroalgae inside the rope perimeter. This would have to be tested with a pilot installation on the lake.

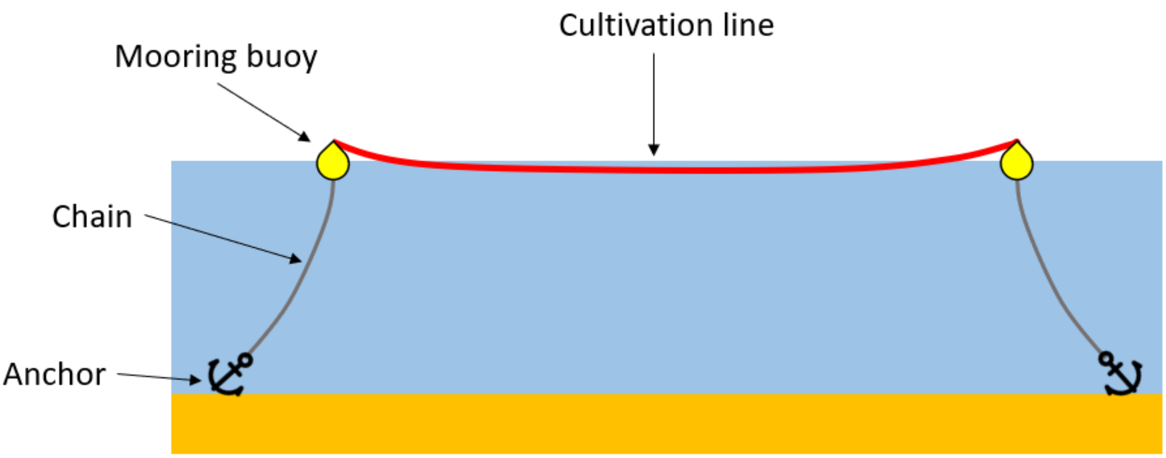


Figure 11. Cross-section schematic representation of a cultivation line

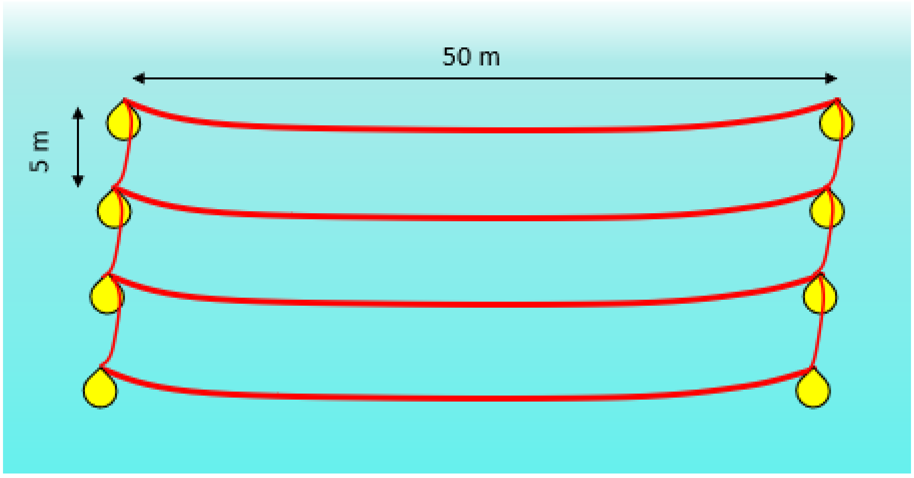


Figure 12. Schematic birds-eye view of system with multiple cultivation lines

8.2 Estimation of algal growth rate

In Part I of this report, cultivation tests were carried out in the lab to estimate the growth rate that can be obtained from *Cladophora* macro-algae. According to the tests, the growth rate is on average 1.4 g DW/m^2/day. We will use this value in the calculations.

8.3 Estimation of biogas and energy production

In Part I of this report, BMP tests were carried out in the lab to estimate the biogas production that can be obtained from *Cladophora* macro-algae. The biomethane potential is 313 NL CH_4/kg VS. The share of organic matter is estimated to be 75%. Therefore, the BMP of the dry matter is estimated to be around 235 NL CH_4/kg DW.

Moreover, we make the assumption that the biomethane is sold to the gas network (after treatment).

8.4 Estimation of investment and operating costs

8.4.1 Investment cost

The investment cost (also known as capital expenditures or CAPEX) is the sum of:

- the equipment cost ($CAPEX_{equip}$)
- the installation cost ($CAPEX_{install}$)

The equipment cost is calculated with the following formula:

$$CAPEX_{equip} = N_u^{SF1} \times CAPEX_{equip,unit}$$

where

N_u is the number of cultivation units;

SF1 is the scaling factor of the equipment cost (equal to 0.9);

$CAPEX_{equip,unit}$ is the cost of one cultivation unit (equal to 1 590 CHF).

The scaling factor is a factor that reduces the per unit cost of an installation with increasing size (number of units) of the installation. In our case, a scaling factor can be applied on the equipment cost as we can expect that the more equipment we buy (e.g. number of buoys, length of rope…) the better we will be able to negotiate prices and obtain a bigger discount. Therefore, we have applied a scaling factor of 0.9 which is probably quite conservative[1].

The cost of one cultivation unit can be determined accurately by summing the cost of all individual pieces of equipment (see Table 5). The cost of the equipment is taken from www.bucher-walt.ch (a nautical sports and fishing equipment provider). The cost of one cultivation unit (equipment only) is 1 590 CHF.

[1] The scaling factor is typically equal to 0.67 for more complex industrial plants

Table 5. Calculation of investment cost of one cultivation unit

Item	Unit	Unit Price CHF/unit	Quantity	Price CHF
Mooring Buoy		100	2	200
Chain	m	10	60	600
Anchor		360	2	720
Rope 50 m		20	1	20
Swivel		15	2	30
Shackle		10	2	20
Total Cost				**1590**

The installation cost is the cost billed by the fishing crew to install the equipment on the lake. We make the assumption that this cost is proportional to the number of hours spent by the fishing crew to install the cultivation units, and we apply an hourly rate which includes the cost of fuel, the salary of the fishermen and the cost related to the usage of the fishing boat (maintenance, amortisation).

The installation cost is calculated with the following formula:

$$CAPEX_{install} = N_u^{SF2} \times n_h \times c_h$$

where

N_u is the number of cultivation units;

SF2 is the scaling factor of the installation cost (equal to 0.7);

n_h is the number of hours required to install one cultivation unit (equal to 1 hour);

c_h is the combined hourly rate of the fishing boat and crew (equal to 180 CHF).

The scaling factor of the installation cost is mainly due to the fact that the fishing boat has some fixed costs related to getting to and from the location of where the cultivation units will be installed. We assume this to be equal to 0.7. The values used for the number of hours required and the hourly rate come from discussions with a fisherman. The installation cost of one cultivation unit is estimated to be 180 CHF.

The total investment cost of one cultivation unit, including both the equipment and installation, is 1 770 CHF. However, the cost per unit decreases as the number of units increase, due to the scaling factors. The total investment cost as a function of the number of units is shown in Figure 13. As there is a lot of uncertainty on the investment cost, especially when it comes to the scaling of the technology, a +/- 50% error on the investment is also represented in Figure 13 in dotted lines. From this graph, it can be seen that, according to the assumptions described above:

- 200 cultivation units (corresponding to 2.5 ha) would cost around 195 000 CHF;
- 1000 cultivation units (corresponding to 25 ha) would cost around 820 000 CHF.

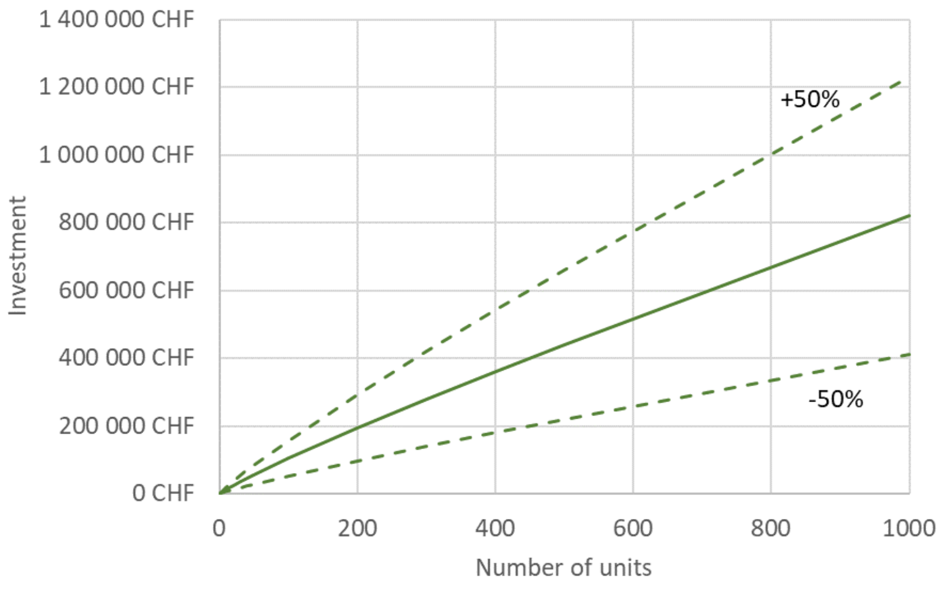


Figure 13. Total investment cost as a function of number of cultivation units installed (solid line: investment cost according to current assumptions; dotted lines: +/- 50% error on investment cost)

For the economic analysis, the investment cost is annualised using the following formula:

$$CAPEX_{annual} = CAPEX \times \frac{r \times (1+r)^n}{(1+r)^n - 1}$$

where

CAPEX is the total investment cost (equipment + installation);

r is the interest rate (equal to 3%);

n is the lifetime of the installation (equal to 10 years).

We made the assumption that the lifetime of the installation will be around 10 years, with the exception of the rope, which will be replaced every year. To account for the replacement of the rope (20 CHF per year), we include it in the equipment cost which now becomes 1 770 CHF per unit (1 950 CHF for the total investment cost).

8.4.2 Operating cost

Once the cultivation units are in place, they do not require any maintenance. The operating cost (also known as operating expenditures or OPEX) is therefore only associated to the harvest of the macroalgae, and its transport to the biogas plant. The operating cost is calculated using the following formula:

$$OPEX = N_u^{SF3} \times n_{harv} \times t_{harv} \times c_h$$

where

N_u is the number of cultivation units;

SF3 is the scaling factor of the operating cost (equal to 0.7);

n_{harv} is the number of harvests per year (equal to 2);

t_{harv} is the time required to harvest one cultivation unit (equal to 0.5 hours);

c_h is the combined hourly rate of the fishing boat and crew (equal to 180 CHF).

We assume that there will be 2 harvests per year and that it takes around 30 minutes to harvest the seaweed of one unit. These assumptions will have to be verified during the pilot project (Phase II).

8.5 Results and discussion

To benefit from the scaling of the installation, we considered that 1 000 cultivation lines are installed, which corresponds to a water area of 25 ha with a 5 m spacing between each line. The results of the techno-economic analysis are given in Table 6. It takes into account all the technical and cost assumptions described above. All input parameters and detailed results are presented in Appendix 3.

It should be noted that the revenues calculated in the table below come from the sale of biomethane that could be produced from the macroalgae. In reality, the revenue would most likely come from the sale of macroalgae to a biogas plant operator and would be much less than the actual biomethane sale price because the operating cost and amortization of the biogas plant would be deduced. However, we were not able to get a sale price for the macroalgae and therefore we used the sale of biomethane, which should be considered as an upper bound for the revenues.

Moreover, the cost of land transportation from the harbour to the biogas plant is not accounted for since no specific location is defined.

Table 6. Results of techno-economic analysis

Parameter	Value	Unit
Number of cultivation units	1000	
CAPEX	909 762	CHF
OPEX	22 661	CHF
Total annual cost	129 313	CHF
Macroalgae production	42	tonnes/year
Specific macroalgae production cost	3.1	CHF/kg
Biomethane production	9 860	Nm^3/year
Primary energy production	98 595	kWh/year
Biomethane sale price	0.15	CHF/kWh
Revenue	14 789	CHF/year

The techno-economic analysis shows that the revenues that could be expected from the cultivation of macroalgae for energy production in the form of biogas is one order of magnitude less than the expected total costs, and would not even cover the operating costs. There are however multiple uncertainties that need to be accounted for:

- Uncertainty on growth rate: tests were carried out in the lab with conditions as close as possible to those in the lake, but we can only be sure by testing it in the lake.

- Uncertainty on investment and operating costs of cultivation platform: some parameters were estimated grossly (e.g. time required to install the equipment, harvest time, scaling factors, etc.). A pilot project would enable us to get a more precise estimation of these parameters.
- Uncertainty on revenues: as mentioned above, the revenues estimated here are based on the sale of biomethane, but the real revenues would come from the sale of the seaweed. The value of the seaweed for biogas plant operators is uncertain at this stage.

9 Alternative Valorisation Pathways

The techno-economic analysis presented in chapter 8 shows clearly shows that, with such a high resource cost (3.1 CHF/kg) the cultivation of macroalgae for the sole purpose of energy production is not economically viable. However, macroalgae has a number of potential other uses, including:

- Food products
- Animal feed
- Pharmaceuticals
- Cosmetics
- Fertilisers
- Bioplastics

Munir et al. [6] conducted a comprehensive review of the potential uses of *Cladophora*. The paper shows that *Cladophora* is regarded by the scientific community as a potential source of food and animal feed, and as a reservoir of medicinally and industrially valuable chemical compounds. The main classes of phytochemicals present in Cladophora species include lipids, fatty acids, volatiles, terpense, sterols, hydrocabons, alcohol, phenols, aldehyde and glycoside. These compounds are of pharmacological significance and have the following bioactivities: anti-bacterial, anti-fungal, anti-oxydant, anti-diabetic, anti-coagulant, anti-inflammatory, immune-modulatory, anti-ulcer, hypotensive, analsegic, anti-parasitic, anti-cancer, anti-mycobacterial and cytotoxicity. The review conducted by Munir et al. concludes that although significant bench scale research has been conducted to isolate chemical constituents, commercial scale application and mass culture techniques still need to be developed.

Here it is important to mention that *Cladophora* is a genus comprising 183 species taxonomically accepted and that types of phytochemicals present in the plant – and therefore potential uses and value in the different sectors – varies from species to species [6]. The exact species of *Cladophora* has not been clearly identified. Further investigation is therefore required to determine the species present in Lake Neuchatel, which can be done by a specialised laboratory. If the species has not already been studied in the literature, tests will also be needed to evaluate the type and concentration of active compounds, and their value on the market.

The possibility of using *Cladophora* as a food product is a complex topic. In their study, Munir et al. mentioned that Cladophora is widely used as food throughout the world. According to [7], *Cladophora glomerata* Kützing (a species of *Cladophora*, locally known as "Kai") is known as a source of nutritious food in the northern part of Thailand, especially in Nan province. However, the species present in Lake Neuchatel is very likely a different one. Therefore, to the best of our knowledge, the species of

Cladophora in lake Neuchatel falls under the “novel food”[2] category and would need to undergo the authorisation procedure for novel foods before it can be marketed in Switzerland and the EU[3].

In any case, the idea of using the algae as a food product has received support from the fishermen with whom we discussed. Indeed, they see potential in adding it to the fish that they sell to give it an added value.

Another alternative to human food for the use of macroalgae is animal feed. Seaweed can be used as as a binder, as a source of essential minerals, as a pigment or for their immuno-stimulant properties. Algal flour and their extracts are relatively new on the market and require more research to establish their true potential.

[2] Novel Food is defined as food that had not been consumed to a significant degree by humans in the EU or Switzerland before 15 May 1997, when the first Regulation on novel food came into force.
[3] More information on the authorisation procedure for novel foods here.

10 Conclusion

The project *Lakeweed Neuchatel* aims at evaluating the potential of seaweed cultivation in Lake Neuchatel, and more generally in Swiss lakes, for the purpose of energy production, and more specifically for producing biogas. This report presents the results of the experimental and feasibility studies, which is a preliminary step (phase I) before deciding to launch a pilot project on lake Neuchatel (phase II).

To begin with, macroalgae species present in lake Neuchâtel were identified, based on several samples taken on the south shore of the lake and adjacent canals. Three species were identified: *Cladophora*, *Nitellopsis obtusa* (*Characée*) and *Elodea*. The latter is not an algae as such, but an invasive vascular plant, and was therefore put aside. Due to its composition, its abundance and its easy sampling, *Cladophora* was selected for the algae culture tests. However, it was not possible to identify the specific species of *Cladophora*, as it would require a DNA analysis.

Water samples were also taken in different areas and at different periods, and analysed to determine water quality, including nutrient concentration, and assess its variability in time and space. The goal was to identify the areas which are the most promising for the location of a future pilot platform. Although variations do exist (e.g. nutrient concentration is significantly higher near WWTP rejection zones), these do not seem to affect algal growth substantially compared to other parameters such as water temperature and solar radiation, according to laboratory tests. The selection of the location for a pilot platform should therefore not necessarily be limited to the zones with high nutrient concentrations.

Algae batch cultures were conducted on *Cladophora* under a variety of conditions in the HEIG-VD laboratory. Different water sources (tap, lake) and pre-treatments (filtered or non-filtered, nutrient addition) were used, which led to different nutrient concentrations. The average measured algae productivity is 1.4 g DW m^{-2} d^{-1}. This is equivalent to around 5 tons per ha and per year.

In order to identify the most suitable equipment for a pilot platform, tests of algae cultivation on different types of ropes in lab conditions were performed. The results of these tests show that *Cladophora* algae have a very weak mechanical grip compared to other types of cultivated algae. Therefore, none of the different ropes tested seem to be suitable for algae anchoring and suggest that a possible solution for this type of algae cultivation could be a closed mesh system to enclose the algae rather than a single, linear support.

BMP tests were performed on the three species of algae identified in lake Neuchâtel. These tests showed that *Characae* have the highest biomethane production rate when considering the volatile solid fraction (469 NL CH_4 kg^{-1} VS). In comparison, the biomethane production rate of *Cladophora* is 313 NL CH_4 kg^{-1} VS. However, the volatile solid content of *Cladophora* is higher than that of *Characae* (24% against 21%), and this difference is expected to be much higher under controlled growing conditions (up to 75%), resulting in a higher biomethane production rate on dry weight, which is expected to be around 235 NL CH4 kg^{-1} DW for *Cladophora* (as opposed to 99 NL CH4 kg^{-1} DW for *Characae*).

Distinct co-digestion BMP tests combining different substrates (WWTP sludge, agricultural substrate, industrial substrate) with different fractions of *Cladophora* (5 to 20%) were also carried out. Indeed, it is likely that the macroalgae will be supplied to existing biogas plants and mixed with other substrates, rather than used alone in a dedicated plant. The results showed that, for the different co-substrates, additional gain in biomethane production could be obtained with a small fraction of *Cladophora* (5-10%), which proves that these algae could have a value for biogas plant operators.

A techno-economic analysis was carried out, based on the algae cultivation and BMP test results obtained in the experimental study. The investment and operating cost of a cultivation platform system was estimated, and this allowed calculating the profit. A business case consisting of 1000 cultivation units – corresponding to 25 ha – would require an initial investment of around 820'000 CHF. The harvest of the algae would cost almost 23'000 CHF per year. In total, the annual cost of such a platform would be just under 130'000 CHF (including operating cost and annualised investment cost). On the other hand, the revenue that could be obtained from selling the biogas produced is estimated to be around 15'000 CHF. However, this value does not include the operating cost or amortization of the biogas plant itself. It therefore results from the economic analysis that the cultivation of macroalgae for the sole purpose of biogas production is not economically feasible given the current state of the market. It should be mentioned however, that there is a high uncertainty on the investment and operating costs of the system, as well as on the value of the macroalgae, and the results of this analysis could therefore be revisited if more precise data are made available, for instance thanks to a pilot project.

Alternative valorisation pathways, such as food production or additives, pharmaceuticals, or animal feed, could provide additional revenues. However, more research would have to be carried on this species of *Cladophora* in order to define the compounds of interest for medicinal or dietary uses, and specify its value to these different markets.

A stakeholder analysis allowed identifying the main stakeholders of the project. Thanks to this analysis, we now know which stakeholders should be actively involved in the next project phase, what their expectations are, and their attitude to the project (ally or opponent). The stakeholder analysis will help us define the stakeholder management plan in the next project phase. The fishermen and cantons will be the two most important partners of a future project. We will also have to work closely with the Grande Cariçaie Association, and with biogas plant operators.

Finally, the legal constraints for the establishment of a cultivation platform were analysed, and will be taken into account if there is a project follow-up. In particular, several authorisations will have to be obtained from the canton.

11 Outlook and next steps

Based on the results of the study, a decision will be made (Go-No Go milestone) on whether or not to follow-up with a pilot project on Lake Neuchatel (phase II). We believe that a pilot project is necessary to remove uncertainties which currently make it difficult to conclude. This pilot project would enable us to:

- Measure the growth rate in natural conditions (are they very different to what was observed in the lab?)
- Evaluate the effectiveness of the system to contain the macroalgae inside the rope perimeter
- Refine the investment and operating costs of a cultivation platform: some parameters were estimated grossly (e.g. time required to install the equipment, harvest time, scaling factors, etc.). A pilot project would enable us to get a more precise estimation of these parameters.
- Estimate more precisely the value of the macroalgae for energy production (by working together with biogas plant operators) and for other uses. To achieve this, a more specific characterisation of the *Cladophora* samples would have to be performed.
- Assess the environmental impact of the macroalgae cultivation platform on local aquatic wildlife, and also its synergy with fishing activities (does it provide a habitat for fish, and does it bring added value to the fishermen?)

12 References

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13 Appendices

Appendix 1: Water quality assessment

Menthue canal

Sampling date	pH	Conductivity (µs/cm)	NH4-N (mg/l)	NO3-N (mg/l)	PO4-P (mg/l)	COD (mg/l)	Alcalinity (mg/lCaCO3)	dh°	Ca2+ (mg/l)	Mg2+ (mg/l)
10.10.2019	8.09	419	0.041	3.83	0.116	17.9	190	11.8	58.8	15.4
13.11.2019	8.34	584	0.392	6.17	0.048	5.9	250	18.4	96.2	21.4
23.07.2020	8.09	530	4.85	4.85	0.112	57.1	190	15.3	74	21.4
20.08.2020	7.95	508	0.621	4.33	0.142	21.7	190	15.7	81.2	18.5
min	7.95	419	0.041	3.83	0.048	5.9	190	11.8	58.8	15.4
max	8.34	584	4.85	6.17	0.142	57.1	250	18.4	96.2	21.4
average	8.12	510.25	1.48	4.80	0.10	25.65	205.00	15.30	77.55	19.18

Viking beach

Sampling date	pH	Conductivity (µs/cm)	NH4-N (mg/l)	NO3-N (mg/l)	PO4-P (mg/l)	COD (mg/l)	Alcalinity (mg/lCaCO3)	dh°	Ca2+ (mg/l)	Mg2+ (mg/l)
10.10.2019	8.09	281	0.036	0.0986	0.017	4.4	140	8.21	37.7	12.7
13.11.2019	7.88	322	0.071	0.858	0.007	7.37	150	10.6	49.2	16.2
23.07.2020	7.82	248	0.028	0.833	0.02	23.4	100	7.22	31	12.4
20.08.2020	7.81	229	0.075	0.418	0.026	15.1	90	6.5	27.7	11.4
min	7.81	229	0.028	0.0986	0.007	4.4	90	6.5	27.7	11.4
max	8.09	322	0.075	0.858	0.026	23.4	150	10.6	49.2	16.2
average	7.90	270.00	0.05	0.55	0.02	12.57	120.00	8.13	36.40	13.18

Reject canal WWTP

Sampling date	pH	Conductivity (µs/cm)	NH4-N (mg/l)	NO3-N (mg/l)	PO4-P (mg/l)	COD (mg/l)	Alcalinity (mg/lCaCO3)	dh°	Ca2+ (mg/l)	Mg2+ (mg/l)
10.10.2019	7.43	480	2.41	8.89	0.363	26.6	100	8.7	44.7	10.5
13.11.2019	7.51	1065	10.7	8.08	0.378	39.2	280	17.7	93.5	19.9
23.07.2020	7.33	746	0.49	22.5	0.32	37.9	100	12.9	71.7	12.5
20.08.2020	7.24	883	1.52	30.3	0.448	18.5	120	16.4	89.4	16.6
min	7.24	480	0.49	8.08	0.32	18.5	100	8.7	44.7	10.5
max	7.51	1065	10.7	30.3	0.448	39.2	280	17.7	93.5	19.9
average	7.38	793.50	3.78	17.44	0.38	30.55	150.00	13.93	74.83	14.88

Tennis beach

Sampling date	pH	Conductivity (µs/cm)	NH4-N (mg/l)	NO3-N (mg/l)	PO4-P (mg/l)	COD (mg/l)	Alcalinity (mg/lCaCO3)	dh°	Ca2+ (mg/l)	Mg2+ (mg/l)
10.10.2019	7.91	323	0.131	1.14	0.018	9.69	140	8.63	43.6	10.8
13.11.2019	7.67	347	0.308	1.46	0.01	25.3	150	10.1	53.7	10.9
23.07.2020	7.92	266	0.04	0.535	0.02	19.1	100	6.58	35.8	6.73
20.08.2020	8.02	246	0.088	0.495	0.025	11.1	90	6.79	35.5	7.82
min	7.67	246	0.04	0.495	0.01	9.69	90	6.58	35.5	6.73
max	8.02	347	0.308	1.46	0.025	25.3	150	10.1	53.7	10.9
average	7.88	295.50	0.14	0.91	0.02	16.30	120.00	8.03	42.15	9.06

West canal

Sampling date	pH	Conductivity (µs/cm)	NH4-N (mg/l)	NO3-N (mg/l)	PO4-P (mg/l)	COD (mg/l)	Alcalinity (mg/lCaCO3)	dh°	Ca2+ (mg/l)	Mg2+ (mg/l)
08.10.2019	7.88	859	0.19	1.39	0.082	27.4	290	20.2	112	19.7
13.11.2019	7.63	904	0.307	9.67	0.033	28.6	350	29.1	154	32.5
23.07.2020	7.57	550	0.447	1.84	0.293	31.5	190	11.54	58.6	13.7
20.08.2020	7.57	503	0.359	2.35	0.238	12.1	130	12.3	71.5	9.96
min	7.57	503	0.19	1.39	0.033	12.1	130	11.54	58.6	9.96
max	7.88	904	0.447	9.67	0.293	31.5	350	29.1	154	32.5
average	7.66	704.00	0.33	3.81	0.16	24.90	240.00	18.29	99.03	18.97

Iris port

Sampling date	pH	Conductivity (µs/cm)	NH4-N (mg/l)	NO3-N (mg/l)	PO4-P (mg/l)	COD (mg/l)	Alcalinity (mg/lCaCO3)	dh°	Ca2+ (mg/l)	Mg2+ (mg/l)
04.10.2019	8.09	332	0.956	1.04	0.176	37.2	110	9.46	42.1	15.4
13.11.2019	7.76	365	0.334	1.53	0.013	9.42	150	10.7	54.5	13.3
23.07.2020	7.73	340	0.136	0.774	0.074	25.1	120	8.19	43.5	9.07
20.08.2020	7.8	311	0.064	0.207	0.025	10.5	100	7.16	39.2	7.2
min	7.73	311	0.064	0.207	0.013	9.42	100	7.16	39.2	7.2
max	8.09	365	0.956	1.53	0.176	37.2	150	10.7	54.5	15.4
average	7.85	337.00	0.37	0.89	0.07	20.56	120.00	8.88	44.83	11.24

Cure d'air canal

Sampling date	pH	Conductivity (µs/cm)	NH4-N (mg/l)	NO3-N (mg/l)	PO4-P (mg/l)	COD (mg/l)	Alcalinity (mg/lCaCO3)	dh°	Ca2+ (mg/l)	Mg2+ (mg/l)
10.10.2019	8.09	297	0.066	1.15	0.014	12.8	120	8.49	28.3	19.6
23.07.2020	8.04	272	0.066	0.849	0.018	15	100	7.31	36.1	9.75
20.08.2020	7.92	303	0.07	0.818	0.033	8.8	110	8.82	39.6	14.1
min	7.92	272	0.066	0.818	0.014	8.8	100	7.31	28.3	9.75
max	8.09	303	0.07	1.15	0.033	15	120	8.82	39.6	19.6
average	8.02	290.67	0.07	0.94	0.02	12.20	110.00	8.21	34.67	14.48

Appendix 2: BMP Test Results

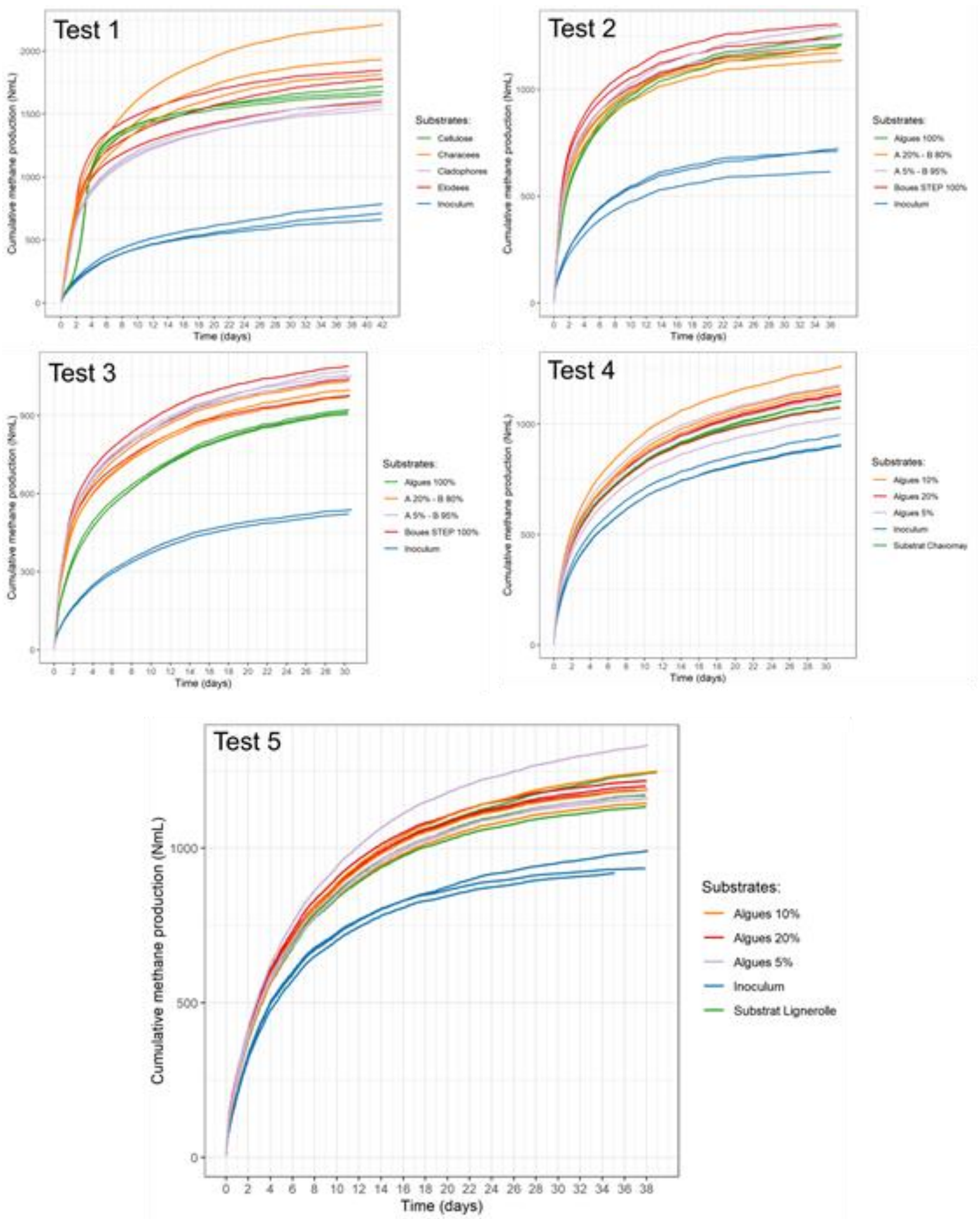

Figure 14. Cumulative production of CH4 (standardized) for all bottles from all 5 tests (each colour represents a substrate)

Appendix 3: Parameters and detailed results of techno-economic analysis

Table 7. Details of techno-economic analysis (Colour key: green: input parameters; orange: calculated intermediate variables; blue: calculated output variables)

Parameter	Value	Unit	Source	Comment
Cost calculation				
Number of cultivation units	1000	units		
Scaling factor equipment	0.9		Assumption Planair	
Unit equipment price	1770	CHF	www.bucher-walt.ch	Based on proposed system design
CAPEX equipment	887101	CHF		
Scaling factor installation	0.7		Assumption Planair	
Unit installation time	1	h	Assumption Planair	Based on discussion with fisherman
Hourly rate fishing boat	180	CHF/h	Assumption Planair	Based on discussion with fisherman
CAPEX installation	22661	CHF		
Total CAPEX	909762	CHF		
Interest rate	3%		Assumption Planair	
Lifetime	10	years	Assumption Planair	
Annual factor	12%			
Annualised CAPEX	106652	CHF		
Scaling factor harvesting	0.7			
Annual harvests	2		Assumption Planair	
Harvest time per unit	0.5	h	Assumption Planair	Based on discussion with fisherman
Total harvest time	126	h		
OPEX	22661	CHF		
Total annual cost	**129313**	**CHF**		
Algal biomass production calculation				
Spacing between lines	5	m	Assumption Planair	Based on proposed system design
Length line	50	m	Assumption Planair	Based on proposed system design
Area per cultivation unit	250	m2		
Total area	250000	m2		
Algal growth period	120	days/year		
Algal growth rate	1.4	g DW/m2/day	Lab tests HEIG-VD	
Total algal production	**42000**	**kg DW/year**		
Energy production calculation (biomethane)				
BMP VS	313	NL CH4/kg VS	Lab tests HEIG-VD	
Organic share	75%		Lab tests HEIG-VD	
BMP DW	235	NL CH4/kg DW		
Total biomethane productio	9860	m3 CH4/year		
LHV CH4	10	kWh/m3	https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html	Rounded to 0.1
Energy production	**98595**	**kWh**		
Gas sale price	0.15	CHF/kWh		
Revenue	**14789**	**CHF**		
Profit	**-114523**	**CHF**		
Specific production cost	**3.1**	**CHF/kg**		

Appendix 4: Minutes of meetings with Fishermen’s Association and Grande Cariçaie Association (CONFIDENTIAL)