DOI: 10.1111/jiec.13170

JOURNAL OF INDUSTRIAL ECOLOGY WILEY

RESEARCH ARTICLE

Assessing energy return on investment for harvest of wild *Nodularia spumigena* during blooms in the Baltic Sea

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Editor Managing Review: Ian Vázquez-Rowe

Abstract

Recurring summer cyanobacteria blooms in the Baltic Sea has gained academic interests for decades. The harvest of wild cyanobacteria, for example, *Nodularia spumigena*, during summer blooms in the Baltic Sea has been studied in the past but lacked evaluation for environmental and economic performances. This study provides a first-hand assessment of environmental and economic performance from an energy perspective, using energy return on investment (EROI) as evaluation method where harvest of biomass and the downstream conversion of biomass to biogas and biofertilizer are considered for Gotland, Sweden. Energy analysis results indicate fuel consumption during harvest and transport operations to be the major energy consumer. Traditional sailing boats have been suggested as an alternative. Overall, when considering only biogas yield and usage of sailing boats, a break-even EROI of 1 is achieved. When including biofertilizer as product, a breakeven EROI of 1 is also achieved. Depending upon the biomass concentration in the Baltic Sea at the time of harvest, an EROI > 6 is possible, surpassing the economic viability EROI benchmark of 3, indicating the importance of nutrient recovery as the driver for harvest of wild cyanobacteria biomass during blooms in the Baltic Sea. This article met the requirements for a gold-gold *JIE* data openness badge described at http://jie.click/badges.

KEYWORDS
Baltic Sea, biofertilizer, cyanobacteria harvesting, energy return on investment, industrial ecology, nutrient recovery

1 | INTRODUCTION

Blooms of cyanobacteria has gained academic interests for many years, especially in the Baltic Sea (Kahru & Elmgren, 2014; Kahru et al., 1994; Kahru et al., 2020; Lilover & Stips, 2008). Studies on the causes to cyanobacteria blooms (Paerl & Otten, 2013) and control for such blooms have been investigated at length in literature (Paerl et al., 2011a) and are currently ongoing in the foreseeable future with many investigating the effects of nutrient loads toward the formation of blooms (e.g., Kahru et al., 2020; Lilover & Stips, 2008; Paerl et al., 2011b). Despite efforts to manage nutrient loads to the Baltic Sea, issues of eutrophication (Murray et al., 2019) and frequency of cyanobacteria blooms (Kahru et al., 2020) remain an environmental challenge. The persistence of cyanobacteria bloom formation, despite ongoing efforts, has led to interests in the direct removal, or harvesting, of cyanobacteria from the water column.

Although interests for removal of cyanobacteria biomass from large open-bodied water column during blooms exist, literature on their approaches remain few, for example, laboratory attempts at removing blooms through electroflocculation at reservoirs and coasts (Valero et al., 2015), construction of screening canals at lakes (Carmichael et al., 2000), and filtering Baltic Sea surface water with modified oil booms (Gröndahl, 2009). These interests are motivated by, especially in the Baltic Sea region, human and livestock health risks (Sellner, 1997; Sivonen et al., 1989a; Sivonen et al., 1989b) and economic risks that result from cyanobacteria blooms (Hasselström, 2008). Benefits for harvest of blooms are not limited to management of blooms and their associated impacts, but also as a potential recovery of pollutants through their assimilation by biomass, for example, copper (Wang et al., 2010) and nutrients (Buchmann, 2016).

In the past, Gröndahl (2009) pilot tested a method to remove surface accumulation of cyanobacteria biomass during the summer and achieved *Nodularia spumigena* harvests in the Baltic Sea. The removal of the biomass not only avoided the exposure to nodularin toxins prominent in *N. spumigena* (Lehtimaki et al., 1997) but was also found to have additional environmental benefits. Potentials for recovery of nitrogen and phosphorus as fertilizer through the conversion of cyanobacteria biomass into biogas were also found to be substantial in the literature (Pechsiri et al., 2014; Buchmann, 2016). However, as pointed out by Pechsiri et al. (2014), additional environmental and economic assessments for methods of wild cyanobacteria harvests during summer blooms are needed, which remain to be a main research gap in the literature and therefore motivates this study.

In order to provide first-hand preliminary assessment of environmental and economic performances for harvesting wild cyanobacteria biomass during blooms, an energy analysis of such operations was assessed using energy return on investment (EROI) as an evaluative indicator. Energy analysis can provide an overview of environmental performance as it considers the overall inputs and outputs of a given system (Brown & Ulgiati, 2004; Brown, 2004; Odum, 1973; Hall & Day Jr, 1977; White, 1943) while EROI is a well-established indicator for assessing environmental performance from an energy perspective (Murphy & Hall, 2010) for a given system where the production of either one or multiple energy products are achieved. EROI also provides a first-hand perspective on the economic potential of a system from an energy perspective by comparing the relativity of systems' inputs and outputs with either a break-even quantity, a set of EROI benchmarks (Hall et al., 2009; Lambert et al., 2014; Hall et al., 2014; Pechsiri et al., 2016), or by reflecting on the potential economies of scale (e.g., Pechsiri et al., 2016).

Therefore, this study performed a quantified approximation for wild cyanobacteria harvesting potentials during cyanobacteria blooms using the summer blooming episodes of *N. spumigena*, in the Gotland basin of the Baltic Sea during 2013–2020 as a case study. The environmental and economic performance for harvesting the biomass and the downstream processing of biomass into biogas was evaluated from an energy perspective using energy return on investment (EROI) as an evaluative indicator. Potential added benefits and potentials for methodological improvements to the harvesting of cyanobacteria biomass during blooms are discussed.

2 | METHODOLOGY

2.1 | Case study and estimations for wild *N. spumigena* harvest

In this work, the Baltic Sea has been used as the focus of study due to the persistent recurring summer surface accumulation of cyanobacteria in the region (Kahru et al., 1994; Kahru et al., 2020; Pechsiri et al., 2014) while acting as a steady recipient of anthropogenic sourced nutrients (Murray et al., 2019; Wasmund et al., 2001). The changes in dissolved inorganic nitrogen and phosphorus are considered one of the crucial factors influencing the formation of summer cyanobacteria blooms in the Baltic Sea (Walve & Larsson, 2010). The nature of specific cyanobacteria species also contribute to the persistence of blooms. During the pilot study (Gröndahl, 2009), microscopic observations of *N. spumigena* cells harvested were found to be chained together by their filaments and possess the characteristics of a maturing and potentially senescent biomass similar to that found in Hoppe (1981). Bimodal buoyancy is a characteristic that allow vertical distribution (buoyant surfacing) of *N. spumigena* (Walsby et al., 1995), where if left intact and unregulated would keep the biomass buoyant during the senescent and decomposition phases of the cyanobacteria biomass in blooms (Sellner, 1997; Hoppe, 1981), hence contributing to the persistence of blooms. Other various factors known in the literature that contribute toward the surface accumulation and persistence of blooms, especially for *N. spumigena*, include nitrogen fixation (e.g., Bergman et al., 1997; Ferber et al., 2004), phosphorus pools (e.g., Kahru et al., 2020), and weather conditions of the Baltic Sea (e.g., Kanoshina et al., 2003), among others.

Literature observations for summer blooms of cyanobacteria in the Baltic Sea suggest a very sporadic blooming behavior in terms of frequency of cyanobacteria surface accumulation (Kahru et al., 2020), location (Pechsiri et al., 2014), and spatiotemporal aspects of summer cyanobacteria blooms (Kahru et al., 1994; Pechsiri et al., 2014). Regardless of the sporadic nature of the summer cyanobacteria blooms in the Baltic Sea, in the past, the Gotland basin section of the Baltic Sea has retained regular blooms in the summer (Pechsiri et al., 2014) and was therefore chosen to be the specific location of study.

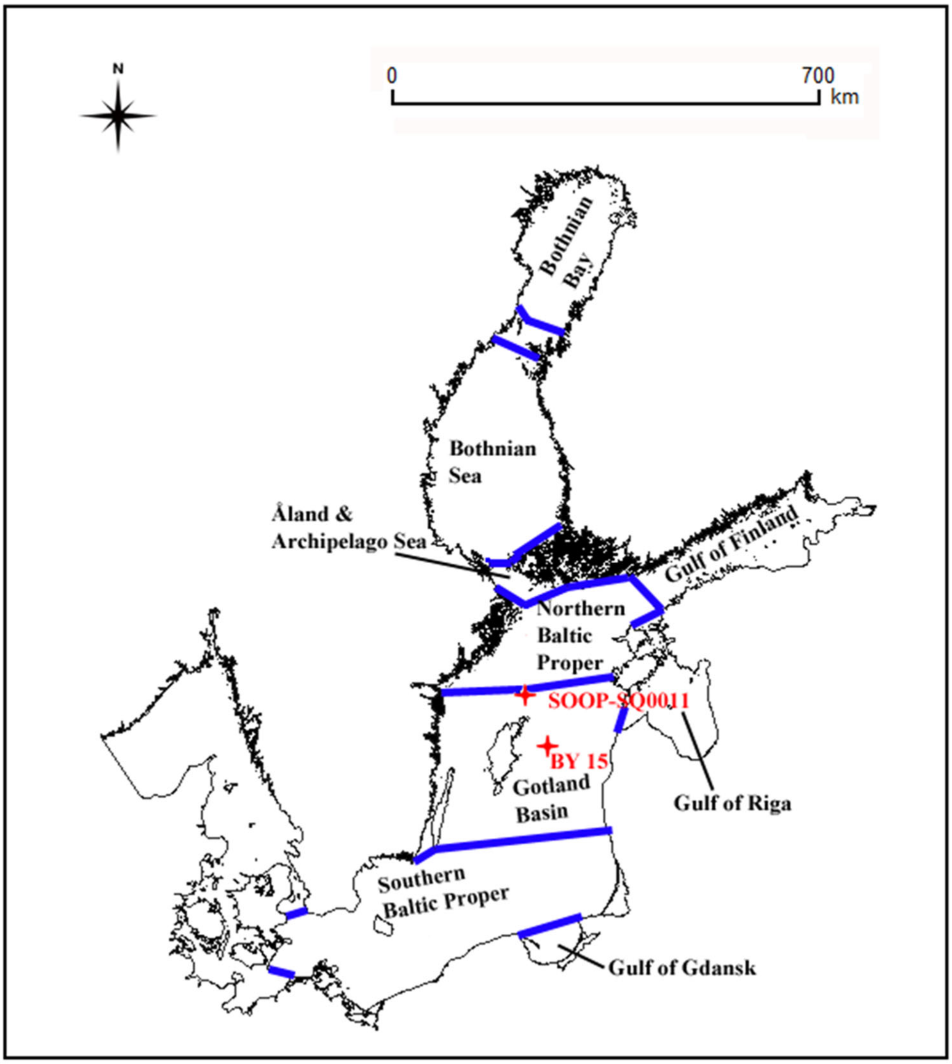

FIGURE 1 The study area of concern is Gotland Basin in the Baltic Sea using SOOP-SQ0011 and BY 15 monitoring station as data source for determining biomass concentration during summer cyanobacteria blooms for years 2013–2020

Biological and hydrological data for the Gotland basin was therefore obtained from monitoring stations “SOOP-SQ0011” and “BY15” (SMHIa, 2020; also see Figure 1), which was accessible through the Swedish Meteorological and Hydrological Institute (SMHI) and The Baltic Marine Environment Protection Commission (Helsinki Commission–HELCOM). Estimation for the biomass concentration in the water column during a cyanobacteria blooming event follows the approach conducted in Pechsiri et al. (2014) as follows:

$$M_{\text{wild harvest}} = C^{\text{dwt}}_{\text{Cyanobacteria}} \times W_{\text{processed}} \times t, \tag{1}$$

where $M_{\text{wild harvest}}$ is the estimated yield for biomass dry weight in μg dwt during operations of harvest. A substantial amount of surface water, $W_{\text{processed}}$, in L is harvested over a period of time in hours, t, containing biomass concentrate, $C^{\text{dwt}}_{\text{Cyanobacteria}}$, in μg/L. Satellite data and imagery have been used to identify and monitor blooming events in the Baltic Sea by SMHI (SMHIb, 2020), who provided the information on occurrences of cyanobacteria blooms for July and August in the Gotland Basin. Potential biomass concentration during blooms, $C^{dwt}_{Cyanobacteria}$, are estimated by coupling monitored biomass data from “SOOP-SQ0011” and “BY15” with specific dates of satellite detected and selected blooming events during summer months of 2013–2020.

The harvesting method chosen for the removal of the cyanobacteria biomass during blooms follows Gröndahl (2009) and is assumed to conduct the harvesting operation for 1 h. The method involves applying a polyester filter net to a 50 m oil boom and tolled by either 1 or 2 boats. The harvesting method has an effective depth of 1 m and can be operated at a maximum speed of 2 knots (≈3.7 km per hour). Operations exceeding this speed will result in less effective harvest. Concerns exist in the effectiveness of oilbooms when wave heights are > 1 m (USEPA, 1999), but

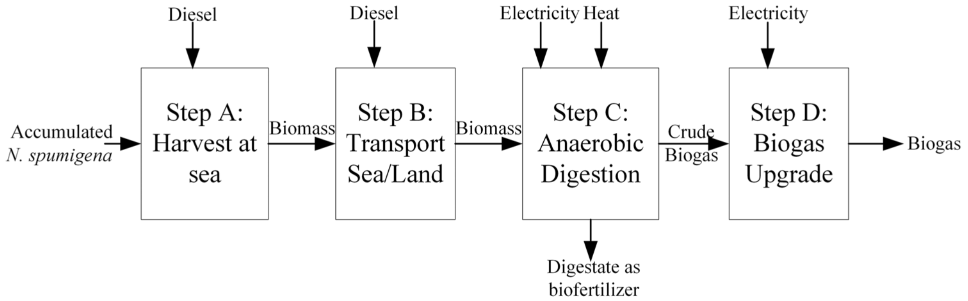

FIGURE 2 Systems overview for the harvest of cyanobacteria biomass during summer bloom episodes in the Baltic Sea, and the downstream conversion of biomass into biogas and biofertilizer

during blooms, wave heights were < 1 m (Pechsiri et al., 2014). The boat considered in this study follows a commercial sea-worthy tugboat with attached barge and crane (personal communication with Jenkins Marine). In light of achievable against-wind 2-knot speeds of traditional sailing boats (Casson, 1951) coupled with the relatively low speed of the harvest method, this study explores the use of sailing ship as an alternative. In any case, it was assumed that the location of harvest is approximately 30 km from harbor.

The cyanobacteria species that surface accumulate and dominate the summer blooms in the Baltic Sea are *Aphanizomenon sp.* and *Nodularia sp.* (Hajdu et al., 2007; Håkanson et al., 2007; Larsson et al., 2001; Lignell et al., 2003; Walve & Larsson, 2007; Wasmund & Uhlig, 2003; Carmichael et al., 2000; Gröndahl, 2009). During the pilot field experiments conducted in Gröndahl (2009), the method was found to be consistently effective for *N. spumigena* but less for *Anabaena sp.* and *Aphanizomenon sp.* Moreover, *N. spumigena* was found to consistently dominate and accumulate either at depths between 0–1 or 0–5 m from the surface (Hajdu et al., 2007), which is within the maximum operational limit in Gröndahl (2009). Due to the need for further study in the efficacy of filter fabrics and the harvesting method for *Anabaena sp.* and *Aphanizomenon sp.*, coupled with the known potential benefits of harvesting *N. spumigena* (Pechsiri et al., 2014), only biomass concentrations for *N. spumigena* are considered. Chl-a data were not used in this study as this was found not to correlate with the presence of *N. spumigena* in the literature (Carlsson & Rita, 2019). Instead, concentrations, in μg C/L, for *N. spumigena*, are obtained.

Biomass dry weight concentrations, $C^{dwt}_{Cyanobacteria}$, and the intracellular N and P were determined following C:N:P of 208:58:1, where on average C, N, and P constitute 43%, 8%, and 0.6% of *N. spumigena* dry weight, respectively (Walve & Larsson, 2010). Due to the sporadic nature of blooms, as observed in Pechsiri et al. (2014), a minimum and maximum biomass concentration potential was considered.

The monitoring protocol for cyanobacteria biomass involves submerging a 10-m tube from the surface, from which a sample is taken to determine species-specific biomass concentration (Helcom, 2020). According to Hajdu et al. (2007), *N. spumigena* was found to accumulate either between 0–1 or 0–5 m from the surface. Therefore, the biomass concentration obtained from the monitoring stations on a blooming-event-identified day was multiplied by factors of 2 and 10 to reflect the low and high estimates of accumulation of biomass at 1 and 5 m depth from the surface, respectively.

The harvested cyanobacteria biomass is assumed to undergo anaerobic digestion at a major Biogas plant on Gotland, situated northeast from the city of Visby, to which biogas and digestate were considered as systems output. Since most main harbors around Gotland are approximately 100 km on road from the Biogas plant, it was assumed that the harvested biomass is transported via transport freight lorry (200 km total return trip). The biogas production conditions for the harvested cyanobacteria biomass is assumed to follow the biomethane potential experiments (BMP) in Rui et al. (2008), where 70% volatile solids (VS) and a crude biogas production of 366 mL per gVS (with 60% methane) were achieved using a 2:2:1 mixture of blue-green algae, pig manure, and water at approximately 20°C. Resulted digestate is assumed to be used for fertilizing soil. This study considers the recovery of nitrogen and phosphorus to be the equivalent of intracellular nitrogen and phosphorus contents of the biomass as estimated above. The recovered nutrients are assumed to replace the use of artificial fertilizer on arable land. Therefore, the system for producing biogas and biofertilizer from the harvested cyanobacteria biomass is shown below (Figure 2).

The biogas obtained from the anaerobic digestion was assumed to be further upgraded. Local demands for biogas exist on the island of Gotland, for example, vehicle fuels and industrial heating (Plötz, 2019) and form the basis of this assumption.

2.2 | Energy analysis

This study employs the standards for energy analysis provided by the International Federation of Institutes for Advanced Study (IFIAS), where direct energy (immediate energy delivered to the studied processes) and indirect energy (energy requirements of the background supply chain) required "to make the good or service available" must be included (IFIAS, 1974). In order to fulfill this obligation, the study employs a cradle-to-gate perspective of the system using Ecoinvent v3.6 (Wernet et al., 2016) as data source for considering indirect energy input in the form of cumulative energy demand. Data for direct energy requirements of the system are obtained from literature and industrial contact. Infrastructure is excluded from the study due to a lack of information regarding construction materials of various subprocesses in the system. All data along with associated calculations thereof are available upon request from the authors. The data that support the findings of this study are available in SMHI at https://www.smhi.se/data, Helcomm at https://helcom.fi/, and Ecoinvent at https://www.ecoinvent.org/.

One of the major concerns for this study is electricity production for Gotland. Due to the remoteness of Gotland island, onshore wind electricity was considered as an alternative scenario replacing Swedish electricity mix to demonstrate a shift in electricity generation (e.g., Parks & Wallsten, 2020; Nilsson, 2019) and is motivated further by the fact that wind power constitutes approximately 45% of Gotlands power consumption in 2016 (Nilsson, 2019). Meanwhile, Sweden aims for 100% renewable electricity by 2040 (SEA, 2019) and has policy instruments to promote wind power expansion as an attempt to reach net zero greenhouse gas emissions by 2045 (Government offices of Sweden Ministry of the Environment, 2020).

The energy output of the system is considered to be biogas and biofertilizer. In order to estimate the biogas yield, a quantified estimate for the biomass obtainable during one harvesting operation needs to be achieved. This study adapts the approach from Pechsiri et al. (2014) where the potential harvesting yield of cyanobacteria during blooms can be quantified using the monitored *N. spumigena* concentrations during cyanobacteria blooms visible on satellite images. The current study, however, only considers recent data (2013–2020) from BY 15 and SOOP-SQ0011 situated in the Gotland basin rather than accounting for the Baltic Sea whole as achieved in Pechsiri et al. (2014). Furthermore, as explained in section 2.1, the monitored biomass concentration was multiplied by factors of 2 and 10 to reflect a minimum and maximum potential biomass yield during one harvest and to account for uncertainties resulting from the sampling method employed at the monitoring stations (Helcom, 2020). The quantified estimates for biomass yield during one operational harvest obtained from Equation (1) coupled with results from BMP experiments in Rui et al. (2008) provide a first-hand estimate for biogas yield. Direct energy demands (primary energy) for the production of biogas in Sweden are taken from literature (Lindkvist et al., 2017; Liljestam Cerruto, 2011; Risén et al., 2013; Risén et al., 2014; Pechsiri et al., 2016).

In addition to biogas, biofertilizer is also produced. Although biofertilizer is not an energy product, the use of biofertilizer to provide nutrients to arable land avoids the use of artificial fertilizer. Therefore, the avoided energy production of artificial fertilizer is considered as a part of energy output in this study. Evaluation of the energy performance is achieved by using the EROI method (Murphy & Hall, 2010) as follows:

$$\text{EROI} = \text{Total energy output}/\text{Total primary energy input} \tag{2}$$

This formulation is a standardized simplification of Mulder and Hagens (2008), which details how direct and indirect energy demands are considered when performing EROI calculations as well as how to handle non-energy coproducts, which form the basis for the energy analysis approach for biofertilizer in this study. The economic viability of the system can be measured by comparing the EROI benchmarks (Hall et al., 2009; Hall et al., 2014; Lambert et al., 2014), where the production of fuels are considered to be useful by the society when an EROI of 3 is achieved. However, since the main goal for harvesting cyanobacteria in the Baltic Sea is for the improvement of local and regional environment, an EROI of 1, which reflects a break-even between the system's outputs and the overall environmental resource demands of the system, is also considered acceptable from an environment and energy perspective.

2.3 | Sensitivity and uncertainty

In order to account for and reflect upon the effect of biomass yield uncertainties on EROI results, which has been found to be the greatest uncertainty in the system (Pechsiri et al., 2014), a simple Monte Carlo simulation (Sheel, 1995; Johnson et al., 2011) is applied to the adjusted observed biomass concentrations during summer cyanobacteria blooms at SOOP-SQ0011 and BY15 monitoring stations for 2000 trials (1000 for tugboat and 1000 for sailboat scenarios). The minimum and maximum adjustments applied to the observed biomass concentration (see Section 2.1) follow the established approach in Pechsiri et al. (2014). Due to the limited amount of compatible data points during cyanobacteria blooms, a visual method for normality test, P-P plot (Ghasemi & Zahediasl, 2012), was applied to the adjusted observed biomass concentration dataset. Although the P-P plot is a visual method for normality test, due to limited data points and data availability, this study estimated the R^2 value of the linear trend (Motulsky, 1995) between the observed and expected cumulative probability where an $R^2 > 0.75$ is considered acceptable in this study.

3 | RESULTS AND DISCUSSION

3.1 | Energy analysis results

The resulted energy analysis is presented in Table 1 (Swedish electricity mix) and Table 2 (100% wind electricity) with all inputs and outputs inclusive, and provides a first-hand EROI for harvesting cyanobacteria during blooms, currently lacking in the literature. The basis for the quantified estimation for the potential biomass yield during harvest follows the reported concentration of monitoring stations in Gotland during summer

TABLE 1 Systems inputs and outputs for using 1 h of Gröndahl (2009)'s harvesting method during summer Nodularia *spumigena* blooms and the production of biogas and biofertilizer (Swedish Electricity Mix)

Processes and parameters	Values	Unit	Ecoinvent v. 3.6	Unit	Estimated Energy Equivalents (GJ) Min conc. + Tugboat	Max conc. + Tugboat	Min conc. + Sailboat	Max conc. + Sailboat
Harvest yields								
Min yield biomass[a]	1.2	tons dwt						
Max yield biomass[a]	209	tons dwt						
Energy output								
Volatile solids (VS) [b]	70	% of substrate						
VS—Min yield	0.8	tons VS						
VS—Max yield	146	tons VS						
Biogas potential [b]	366	mL per g VS						
CH_4 in biogas[b]	60	% of crude biogas						
Energy from CH_4[c]	0.022	MJ per liter						
Biogas—Min yield	305	m^3 crude biogas			3.9	n/a	3.9	n/a
Biogas—Max yield	53479	m^3 crude biogas			n/a	690	n/a	690
Avoided N fertilizer[a]	8	%	91.6	MJ/kg N[g]	8.7	1530	8.7	1530
Avoided P fertilizer[a]	0.6	%	17.97	MJ/kg P[h]	0.1	22.5	0.1	22.5
Total energy output					12.8	2242	12.8	2242
Energy demands								
Harvest and transport								
Harvest by tugboat[d]	153	kg diesel	53.5	MJ/kg[i]	8.2	8.2	0	0
Transport at sea[d]	510	kg diesel	53.5	MJ/kg[i]	27.3	27.3	0	0
Land lorry-min yield	238.35	tkm	1.09	MJ/tkm[j]	0.26	n/a	0.26	n/a
Land lorry-max yield	41748	tkm	1.09	MJ/tkm[j]	n/a	45.5	n/a	45.5
Anaerobic digestion								
Heat—Hygenization[e]	454	MJ/ton biomass dwt	0.989	MJ/MJ[k]	0.5	94	0.5	94
Electricity—Stirring[e]	54	MJ/ton biomass dwt	2.37	MJ/MJ[l]	0.15	27	0.15	27
Biogas upgrading								
Electricity—Upgrade[f]	1.3	MJ/m^3 crude biogas	2.37	MJ/MJ[l]	0.9	165	0.9	165
Total energy input					37	366	1.9	331
Energy return on investment (EROI)								
EROI (– biofertilizer)					0.11	1.88	2.09	2.09
EROI (+ biofertilizer)					0.3	6.12	6.78	6.78

[a]Following Pechsiri et al. (2014) factors of 2 and 10 are applied to the biomass concentrations during 2013–2020 summers. Min and max *N. spumigena* concentrations monitored are 1385 and 97036 ug C/L, respectively. Biomass dwt and intracellular N and P are determined following C:N:P from Walve and Larsson (2010).
[b]Following the biomethane potential experiment in Rui et al. (2008).
[c]Calorific value of biogas (Bansal et al., 2013) can increase to 35.8 MJ/m^3 depending on purity.
[d]Personal communication with Jenkins Marine for sea-worthy coastal tugboat and barge with crane.
[e]Following Swedish biogas production figures (Liljestam Cerruto, 2011).
[f]Biogas upgrading energy demand (Singhal et al., 2017; Pechsiri et al., 2016).
[g]Nitrogen fertilizer, as N (GLO)| market for | APOS, U.
[h]41.4 MJ/kg phosphate fertilizer, as P_2O_5 (GLO)| market for | APOS, U, then fractioned based on P part in P_2O_5.
[i]Diesel (RER)| market group for | APOS, U.
[j]Transport, freight, lorry > 32 metric ton, euro6 (RER)| APOS, U, only diesel consumption portion considered.
[k]Heat, district or industrial, other than natural gas (RER)| market group for | APOS, U.
[l]Electricity, high voltage (SE)| market for | APOS, U.

TABLE 2 Systems inputs and outputs for using 1 h of Gröndahl (2009)'s harvesting method during summer Nodularia *spumigena* blooms and the production of biogas and biofertilizer (100% Wind Electricity)

Processes and parameters	Values	Unit	Ecoinvent v. 3.6	Unit	Estimated energy equivalents (GJ) Min conc. + Tugboat	Max conc. + Tugboat	Min conc. + Sailboat	Max conc. + Sailboat
Harvest yields								
Min yield biomass[a]	1.2	tons dwt						
Max yield biomass[a]	209	tons dwt						
Energy output								
Volatile solids (VS)[b]	70	% of substrate						
VS—Min yield	0.8	tons VS						
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Biogas potential[b]	366	mL per g VS						
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Energy from CH_4[c]	0.022	MJ per liter						
Biogas—min yield	305	m^3 crude biogas			3.9	n/a	3.9	n/a
Biogas—max yield	53479	m^3 crude biogas			n/a	690	n/a	690
Avoided N fertilizer[a]	8	%	91.6	MJ/kg N[g]	8.7	1530	8.7	1530
Avoided P fertilizer[a]	0.6	%	17.97	MJ/kg P[h]	0.1	22.5	0.1	22.5
Total energy output					12.8	2242	12.8	2242
Energy demands								
Harvest and transport								
Harvest by tugboat[d]	153	kg diesel	53.5	MJ/kg[i]	8.2	8.2	0	0
Transport at sea[d]	510	kg diesel	53.5	MJ/kg[i]	27.3	27.3	0	0
Land lorry—Min yield	238.35	tkm	1.09	MJ/tkm[j]	0.26	n/a	0.26	n/a
Land lorry—Max yield	41748	tkm	1.09	MJ/tkm[j]	n/a	45.5	n/a	45.5
Anaerobic digestion								
Heat—Hygenization[e]	454	MJ/ton biomass dwt	0.989	MJ/MJ[k]	0.5	94	0.5	94
Electricity—Stirring[e]	54	MJ/ton biomass dwt	1.14	MJ/MJ[l]	0.07	13	0.07	13
Biogas upgrading								
Electricity—Upgrade[f]	1.3	MJ/m^3 crude biogas	1.14	MJ/MJ[l]	0.5	79	0.5	79
Total energy input					37	267	1.3	231
Energy return on investment (EROI)								
EROI (− biofertilizer)					0.11	2.56	2.98	2.98
EROI (+ biofertilizer)					0.3	8.41	9.7	9.7

[a] Following Pechsiri et al. (2014) factors of 2 and 10 are applied to the biomass concentrations during 2013–2020 summers. Min and max *N. spumigena* concentrations monitored are 1385 and 97036 ug C/L, respectively. Biomass dwt and intracellular N and P are determined following C:N:P from Walve and Larsson (2010).
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[f] Biogas upgrading energy demand (Singhal et al., 2017; Pechsiri et al., 2016).
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[k] Heat, district or industrial, other than natural gas (RER)| market group for | APOS, U.
[l] Electricity, high voltage (SE)| electricity production, wind, 1–3 MW turbine, onshore | APOS, U.

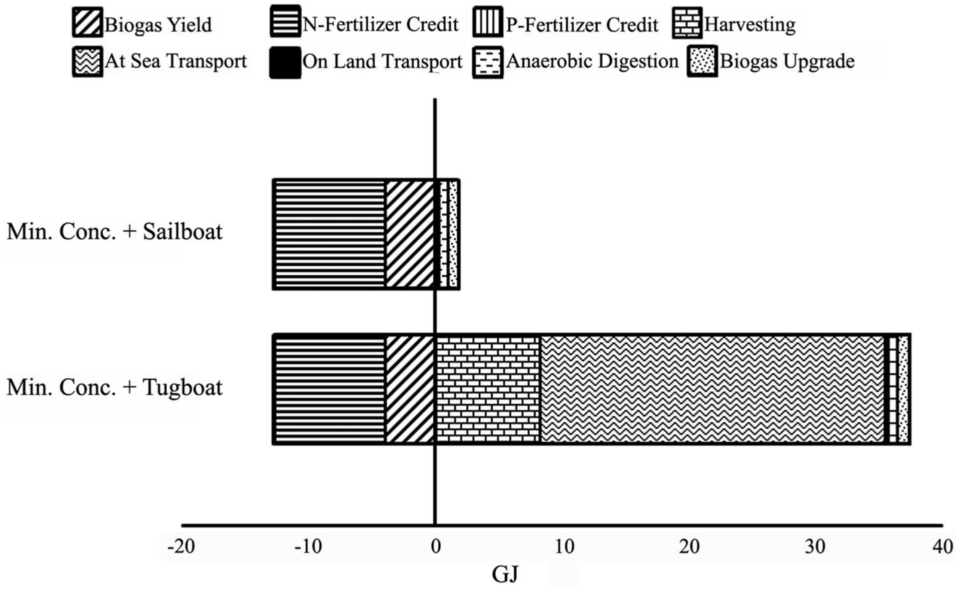

FIGURE 3 Representation of energy inputs and outputs from Table 1 for hourly harvest of wild *Nodularia spumigena* when considering minimum biomass concentration and Swedish electricity mix during summer cyanobacteria blooms in the Baltic Sea. Data underlying this figure is available in the Supporting Information

cyanobacteria blooms between 2013–2020. Similarly to the literature (e.g., Pechsiri et al., 2014), the nature of cyanobacteria blooms are highly sporadic, but occurs in all summers during 2013–2020.

Biomass concentrations remain to be the greatest uncertainty in this study with the lowest and highest *N. spumigena* concentrations prior to adjustments for (uncertain) depth distribution of biomass monitored are 1385 and 97036 ug C/L, respectively, or 3220 and 225665 ug dwt/L, respectively, using C:N:P ratios provided in Walve and Larsson (2010). After corrections for depth distribution, although the total potential biomass yield during harvests is magnitudes higher than observations in the literature (e.g., Pechsiri et al., 2014; Kanoshina et al., 2003), the degree of difference between the minimum and maximum yield remains similar to the literature. The cyanobacteria blooms found during the study were also substantially more extensive in number of days and size compared to (Pechsiri et al., 2014).

Due to the highly uncertain nature of biomass yield estimated during each harvest, the energy analysis for the harvest of biomass and the downstream processing of the biomass were conducted on the minimum and maximum biomass yield basis rather than averages (Tables 1 and 2). The second highest uncertainty in this study is the consideration of wind electricity. Following Gotland's policy to move toward wind power electric generation (Nilsson, 2019), this study has included onshore wind electricity from Ecoinvent v 3.6. If primary energy for wind electricity (Table 2) is applied instead of Swedish electricity mix (Table 1), the energy demand for the electrical energy consuming processes would decrease by approximately twofold, resulting in a decrease in the overall cumulative energy demand by approximately 30%.

The conducted energy analysis identified key hotspots to energy consumption within the system. As suggested in Figure 3, the main contributor toward energy demand is diesel consumption in at-sea processes during harvest and transport operations, constituting 90% of the total energy demand when considering Swedish electricity mix, tugboats for harvesting, and the observed minimum *N. spumigena* concentrations during summer blooms.

The removal of fuel consumption at sea, which is the main energy demand of the overall system (Figure 3), through using sailboats as alternative achieved a substantial improvement of EROI from 0.11 to 2 (Table 1), considering minimum biomass yields, Swedish electricity mix, and excluding biofertilizer as product.

In the sailboat scenarios, and excluding biofertilizer as product, there is a negligible difference in EROI when considering minimum and maximum concentrations of *N. spumigena* during blooms. Although the difference in the minimum and maximum biomass concentrations is several degrees of magnitude, the amount of biogas yield and the energy demand in the biogas production processes are relatively proportional as reflected by the EROI results. This finding suggests although, when attainable biomass concentrations are less in literature (e.g., Pechsiri et al., 2014; Kanoshina et al., 2003), similar EROI results may be achievable when sailboats are considered. Nonetheless, a breakeven EROI of 1 was achieved for all sailboat scenarios. However, when excluding biofertilizer as product, none of the considered scenarios surpassed the EROI benchmark of 3 for economic viability.

It is important to note that the EROI in this study only considers the dominating *N. spumigena* portion of the cyanobacteria bloom. The realistic potential yield of biomass during harvest would be higher as the harvesting method may also recover other surface accumulating biomass during

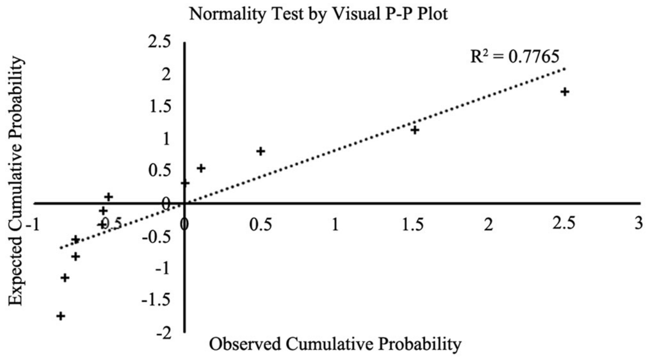

FIGURE 4 Normality test by Probability-Probability plot for the adjusted observed biomass concentration obtained from BY15 and SOOP-SQ0011 monitoring stations in the Gotland basin. Data underlying this figure is available in the Supporting Information

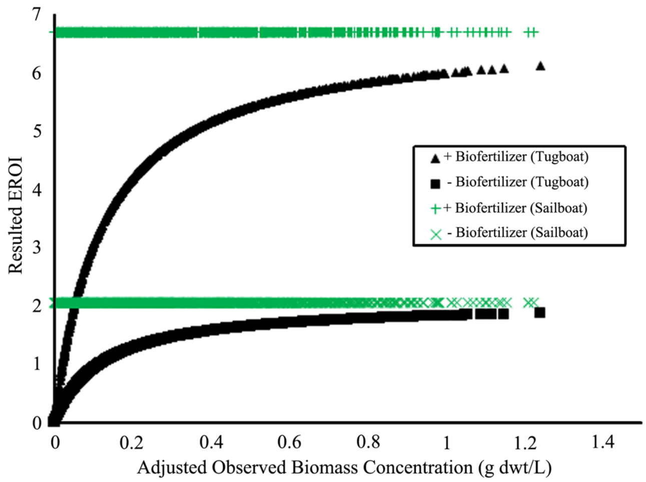

FIGURE 5 Monte Carlo simulation for the adjusted observed biomass concentration obtained from BY15 and SOOP-SQ0011 monitoring stations and the calculated EROI results thereof. Data underlying this figure is available in the Supporting Information

summer cyanobacteria bloom in the Baltic Sea, for example, *Anabaena sp.* and *Aphanizomenon sp.* (Hajdu et al., 2007). Although Gröndahl (2009) reported recovery of *Anabaena sp.*, only *N. spumigena* biomass was found to be consistently recoverable by the chosen fabric filters in the harvesting method. Efficacy of fabric filters on the recovery of *Aphanizomenon sp.* and *Anabaena sp.* needs to be further investigated. Therefore, other species that surface accumulate during summer blooms were not considered in this study; hence, the EROI represented in Tables 1 and 2 where biofertilizer is excluded only reflects a conservative estimate for potential biomass harvest yield.

Monte Carlo simulation for the biomass concentration has been conducted for 2000 trials (1000 for tugboat and 1000 for sailboat) to reflect upon their uncertainties and effects on EROI. The P-P plot (Figure 4) suggests the adjusted observed biomass concentration dataset used in this study retains to an acceptable degree of normality with an R^2 of 0.77.

Monte Carlo simulation results are demonstrated in Figure 5 (standard deviation and mean of simulated biomass concentration to be 0.25 and 0.35, respectively). After 2000 simulations, Figure 5 further exemplifies that regardless of biomass concentration, the calculated EROI result does not achieve an EROI minimum of 3 for economic viability, but a break-even EROI of 1 can be achieved when biomass concentrations are greater than 0.1 g dwt/L and excluding biofertilizer as product. However, when biofertilizer is included, the potential to achieve the economic viability EROI benchmark of 3 is substantial for nearly all scenarios.

When compared to the calculated EROI result from the simulated adjusted observed biomass concentration in the sailboat scenario, the tugboat scenario requires a substantially larger biomass concentration to achieve a similar EROI result due to high fuel consumption at sea, which constitutes a major share of the total energy demand for the tugboat scenario (Table 1 and Figure 3).

The EROI results shifted threefold when considering biofertilizer as product for nearly all scenarios. (Figures 5 and 6). When tugboat is considered for use in harvesting method, although large energy demands are accounted for from the fuel consumption during harvest and transport, increased biomass concentration from the minimum to the maximum biomass concentration extremes improves the resulted EROI from 0.3 to 6 with biofertilizer output inclusive (Table 1 and Figure 5). When fuel consumption at sea is removed (sailboat scenarios) with inclusive biofertilizer

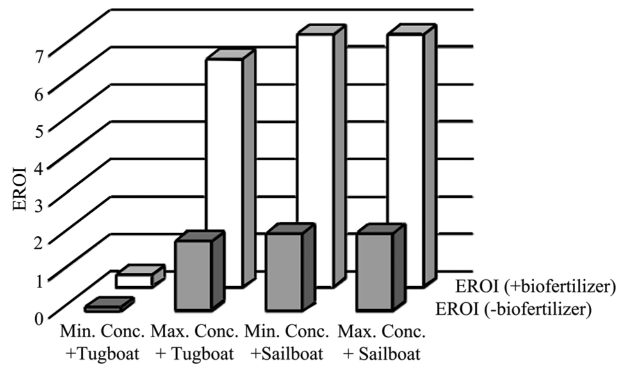

FIGURE 6 Representation of EROI results from Table 1, with and without biofertilizer as product. Data underlying this figure is available in the Supporting Information

as product and Swedish electricity mix as electrical energy source, a maximum EROI of 6.8 is achieved (Figure 6), surpassing the economic viability EROI benchmark of 3. When considering wind electricity instead of Swedish electricity mix, the maximum EROI of 9.7 is achieved, still surpassing the EROI benchmark of 3. This finding demonstrates the importance for considering biofertilizer as an additional product to biogas if economic viability is to be achieved for wild cyanobacteria harvesting from an energy perspective.

3.2 | Implications within an industrial ecology and circular economy context

From an industrial ecology and circular economy perspective, there has been steady interest in performing anaerobic digestion on waste streams (e.g., Chojnacka et al., 2019; Monlau et al., 2015) since it leads to the production of energy and biofertilizer as products. Energy analysis was conducted to harvesting of cyanobacteria blooms in order to reflect the potential environmental performance of such venture. EROI was used here not as a direct determinant of whether harvesting of cyanobacteria during blooms should be conducted but more so as a preliminary guide to the potential benefits and concerns that need to be addressed if such practices are to be considered. The main goal for harvesting cyanobacteria biomass was to improve the environmental conditions of the Baltic Sea (Gröndahl, 2009), at least locally for the island of Gotland. The removal of cyanobacteria blooms would reduce health and economic risks as a result of cyanobacteria blooms (Hasselström, 2008) for Gotland. The performed energy analysis identified hotspots for potential environmental burdens that need to be addressed, for example, fuel consumption at sea as identified in Figure 3, and demonstrating, as shown in Figures 5 and 6, how biofertilizer will be a major factor for a more extensive environmental performance evaluation, for example, life cycle analysis, in the future. The effect of shifting national energy policies toward renewable and less greenhouse gas emitting electricity sources was also reflected by the energy analysis conducted (Tables 1 and 2).

The potentially achievable EROI > 3 from including biofertilizer as a byproduct of the system from an energy perspective shows the possible incentive to harvesting cyanobacteria bloom in the Baltic Sea as an attempt to improve environmental conditions of the Baltic Sea. From the legislative and policy standpoint, harvesting cyanobacteria could be a potential approach to be considered under the Circular Economy Action Plan (EC, 2020) produced as part of the European Union's Green Deal where the European Commission plans to assess means of nutrient removal by algae as part of their integrated Nutrient Management Plan. The recovery of nutrients by harvest of the cyanobacteria blooms could also be considered as an effort to improve Baltic Sea eutrophication challenges while fulfilling the spirit of the European Union's Water Framework Directive (EC, 2000) and the global Sustainable Development Goals (United Nations General Assembly, 2015).

From an economic and market perspective, according to official governmental figures provided by Statistics Sweden (publicly available at www.scb.se, latest access was March 24, 2021), sales in mineral fertilizer in Sweden amount to approximately 180 and 10 tons of nitrogen and phosphorus, respectively, in 2017–2018. A combination of manure and mineral fertilizer sales in Sweden for 2019 amount to approximately 200 and 30 tons nitrogen and phosphorous, respectively. These mineral fertilizer market figures for Sweden indicate a potential market where biofertilizer can expand their market share. From the biofertilizer market perspective, literature projections show a potential increase of global biofertilizer market size from USD 1.49 billion in 2019 to USD 3.28 billion in 2027 and a compound annual growth rate of 10.9% with North America and Europe remaining to be the two major consumers (FBI, 2020).

From an academic perspective, anaerobic digestion of wild photosynthetic marine biomass where digestate is to be used as biofertilizer is of high interest especially to reuse nutrients from nonpoint sourced waste streams. The efficacy of using harvest of wild photosynthetic microorganism such as microalgae and cyanobacteria is still in its infancy and is still a subject of many ongoing studies both directly either as biofertilizer (e.g., Garcia-Gonzalez, 2014) or biostimulant (e.g., Supraja et al., 2020), and indirectly through biogas production (e.g., Rui et al., 2008; Collet et al., 2011) providing digestate as biofertilizer. Literature on biogas production from both photosynthetic marine macro- (e.g., Gregeby & Welander, 2012;

Risén et al., 2013) and micro- (e.g., Rui et al., 2008) biomass harvested from the wild have shown good biogas yield when used as co-substrate to other input waste streams, for example, manure. Previous studies on the efficacy of digestate as biofertilizer from anaerobic digestion of manure have shown improved qualities for soil (e.g., Hammad et al., 2019) and the resulted crops (e.g., Hammad et al., 2018). Ongoing studies exist where wild cyanobacteria and macroalgae are incorporated but are not yet finalized or disclosed. These findings demonstrate the importance to further investigate the efficacy and efficiency for different pathways to produce biofertilizer for harvest of wild photosynthetic marine biomass, which can be a major incentive to environmental ventures such as the harvest of cyanobacteria blooms in the Baltic Sea.

4 | CONCLUSION

This study has provided a quantified estimate for potential yields of biomass, biogas, and biofertilizer for hourly harvest of wild *N. spumigena* under tugboat and sailboat scenarios, resulting in an EROI ranging from 0.1–9.7. The study finds fuel consumption at sea to be the main contributor to the energy demand. When biofertilizer is not accounted for, none of the scenarios achieved the economic viability EROI of 3. However, EROI results improved when biofertilizer is included as an added product to biogas production. Electricity source also affects EROI substantially. The results emphasize the importance of addressing the recovery of nutrients and use as biofertilizer when considering operations for wild cyanobacteria harvest.

The study however has only considered *N. spumigena* fraction of the surface accumulation of the biomass. Further study is needed to include other species of cyanobacteria that surface accumulate during bloom with improved data acquisition techniques and a wider range of environmental impacts to be considered. Future study on the feasibility of using the digestate as biofertilizers can help validate the EROI in this study.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Pechsiri JS, Gröndahl F. Assessing energy return on investment for harvest of wild *Nodularia spumigena* during blooms in the Baltic Sea. *J Ind Ecol*. 2022;*26*:1979–1991. https://doi.org/10.1111/jiec.13170