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THE INTRODUCTION OF MICROALGAE IN WASTEWATER TREATMENT PLANTS – EMISSION CONTROL AND POLICY GUIDELINES

Användning av mikroalger i avlopps- och reningsverk – Utsläppskontroll och riktlinjer

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Abstract

This article considers cost-effective environmental policy instruments supporting the adoption of microalgae cultivation by wastewater treatment plants WWTPs coupled to biogas. One problem in reaching the nutrient reduction targets suggested by the Baltic Sea Action Plan has been differences among countries on their economic ability and on their willingness to pay for abatement. Another is the policy instrument design of specific countries and sectors having ambiguous effects on reaching the environmental target. Considering that in a very local market WWTPs act as in a mixed oligopoly situation, the privatisation of public WWTPs will increase social welfare depending upon how well competitive market conditions are encouraged. Moreover, an international cross-sector market-based instrument as nutrient trading, is considered to incentivise the rate of abatement and productivity of the industry as well as the economic growth in the Baltic Sea region. The potential value-added of the microalgae in the abatement efficiency as well as in the production of biogas make WWTPs competitive in renewable energy and fertilisers in coherence with the agricultural sector. Microalgae cultivation offer environmental and social benefits simultaneously promoting the privatisation of the wastewater into a potentially competitive abatement market.

Key words – wastewater treatment plants, native microalgal species, nutrient trading, mixed oligopoly situation, eutrophication, green-house gases, abatement efficiency, Baltic Sea

Sammanfattning

Denna studie redogör för kostnadseffektiva policyåtgärder för att uppnå miljömålen föreslagna i Baltic Sea Action Plan och analyserar odlingen av mikroalger som en potentiell reningsteknik inom reningsverken kopplade till biogas. Ett problem för att nå miljömålen har varit skillnaderna mellan länderna i deras betalningsförmåga och vilja att åtgärda näringsminskningen i Östersjön. Ett annat problem är utformningen av de nuvarande policyåtgärderna som riktas specifik till länder och sektorer vilket medför ineffektiva och orättvisa lösningar för näringsminskningen till havet. En lokal marknad med offentliga och privata reningsverk kan karakteriseras som en blandad oligopolmarknad. Det innebär att privatisering av offentliga reningsverk medför en välfärdsökning givet konkurrenskraftiga marknadsförhållanden. Näringshandeln är en policyåtgärd som möjliggör agerande både på en internationell marknad och mellan olika sektorer i en ekonomi. Det stimulerar nya innovationer samt den lokala ekonomiska tillväxten. Exempelvis, det potentiella ökat mervärde av mikroalger som ökar reningseffektiviteten i reningsverken och produktion av biogas och biogödsel. Mikroalger som en reningsteknik möjliggör samarbetet mellan reningsverken och jordbrukssektorn och mynnar ut i miljömässiga samt sociala fördelar samtidigt som privatiseringen skapar en konkurrenskraftig marknad för reningen.

Introduction

The stability of aquatic ecosystems depends on the recovery of the basins in cohesion to anthropogenic pollution loads into the Baltic Sea. Almost 50 % of the nutrients entering to the Baltic Sea ends up into the Baltic Proper. Poland, Lithuania and Sweden constitute 91 % of the sub-catchment area for the Baltic Proper (HELCOM, 2015).

Main sources of anthropogenic pollution are intensive agricultural systems and WWTPs with outdated and insufficient technology. Between 60 and 70 % of the total catchment area is devoted to agricultural production (HELCOM, 2015). Diffuse emissions from agriculture mainly stems from the use of artificial fertilisers and pesticides as well as poor quality manure handling and spreading (HELCOM, 2008).

To control emissions, environmental policy instruments have been implemented resulting in increased abatement efficiency in WWTPs and changes into agro-environmental practices in agriculture. Under the last decades, considerable investments have been made towards WWTPs in urban areas (Eurostat, 2017). Wastewater treatment involves relatively low abatement costs in relation to other sectors in the economy (Hautakangas et al., 2014).

Still, there is a wide variation in the abatement efficiency in WWTPs among countries in the catchment area. To eliminate pollution sources, the change of agricultural practices, from intensive to more ecological ones, requires efficient use of inputs and appropriate technology. However, these changes have not been distributed proportionally to the damages of the Baltic Sea. Hence, further measures are needed. The required economic incentive on the appropriate measure implementation not only brings environmental benefits in terms of higher levels of abatement but also it brings capital formation (Campos, 2015) on new investments towards a sustainable regional economic growth.

A cost-effective solution will be where the abatement costs are relative low and the impact of the abatement is high. In a mixed oligopoly situation, the privatisation of public WWTPs will increase social welfare depending upon how well competitive market conditions are encouraged. The privatisation of WWTPs requires economic incentives leading to technological advance bringing private economic profits to the industry. One such alternative is the adoption of microalgae cultivations by WWTPs coupled to biogas. The microalgae will increase the abatement efficiency and the value-added of sewage sludge, supporting a closed recycling system. The surrounding of the Baltic Proper is a perfect scenario for the industrialisation of native microalgal species requiring nutrients to grow in WWTPs in need of upgrading. This article considers cost-effective environmental policy instruments as emission control, providing incentives to adopt microalgae cultivation by wastewater treatment plants WWTPs coupled to biogas. The conclusions offer guidelines and recommendations ensuring a cost-effective solution for a sustainable economic growth in the Baltic Sea region.

Environmental policy instruments in the Baltic Sea region

Policy instruments are to control emissions and to change the behaviour of polluters by creating incentives to reduce environmental damages. Among countries in the catchment area, there are a wide variety of policy instruments in practice. Policy instruments are classified as (BalticStern, 2013a):

- Command and control: legislation, standards, best available technology
- Market-based: taxes, fees, subsidies, cap and trade system
- Informational: education, information campaigns.

The main differences between command and control instruments and market-based are the administration and control costs as well as the possibility to generate economic growth. For instance, the reduction on fertilisers in agriculture could be very costly to monitor. A tax generates a more efficient use of fertilisers. However, the effect of the tax would vary with the market prices on crops.

The consequences of agricultural policy regulations towards environmental protection strike against small parcels creating gaps in social welfare. This is due to a lack of flexibility in the implementation. Major environmental regulations are in directly discrepancy with national production targets affecting the competitive economic growth in the region (EEA, 2012). However, the embedded economic incentives in market-based instruments have also given rise to the development of ecological production (BalticStern, 2013) as an efficient market competitive solution.

Market-based instruments are fair and cost-effective measures to protect the environment simultaneously achieving economic growth. The implementation of market-based instruments in Europe has been in effect since the mid-1990s (EEA, 2005). The specific implementation in the Baltic Sea region aims to reduce emission loads into the Sea from land-based sources and from the atmosphere. Land-based sources include agriculture, WWTPs and industries in the catchment area of the Baltic Sea, while emissions from the atmosphere include air transportation from the catchment area and long-distance sources (HELCOM, 2015).

Social costs arising from the implementation is a main determinant in achieving cost-efficient nutrient reduction at a fair price-setting. Another important factor is how to handle socioeconomic distribution effects of the implementation (BalticStern, 2013). However, the estimation on social costs is very difficult to establish involving political decisions and uncertainties (EEA, 2005).

Calculations on cost-efficient nutrient reduction state that the cost of achieving the reduction quotas by countries stated by the Baltic Sea Action Plan are overestimated disregarding fairness. Fairness considers a cost-effective distribution of nutrient loads related to population and GDP based on the distribution of efforts per capita (Gren, 2008). One of the criticisms to a cost-efficient distribution however, is that countries attaining the target at low marginal abatement costs experience higher cost-burden.

Under market-based instruments, the cap and trade principle is a cost-effective and fair environmental policy instrument. The mechanism is as follows, a total maximum level of emissions is allowed to be emitted by polluters in the market. In the market, polluters trade emission permits. The polluters monitor and report their emissions and if emissions are reduced the polluter can save the permits to be used in the future or else to sell them.

The cap and trade scheme is built on the first-moving advantage, promoting cost efficiency and innovation. In theory, emissions are mitigated achieving the reduction at the lowest cost to society. Cap and trade provides a flexible market stimulating technological advance and economic growth. Emissions trading requires a large and diverse number of sources, demanding less stringent technological restrictions on individual sources.

The economic benefits of cap and trade involve cost-saving solutions to polluters, taking advantage of economies of scale and economies of scope and simultaneously reduce total expenditures on emission control in local regions.

Nutrient trading – The target on eutrophication

In the particular case of reaching the target of eutrophication in the Baltic Sea, there is a lack of effectiveness among policy instruments in practice. One underlying reason is the design of country and sector specific instruments affecting the magnitude of the environmental effects. The effects in turn depends on the relation between the health status of the basins and the quantities discharged (BalticStern, 2013). Hence, instruments applied across economic sectors and local measures will be more efficiently to reach the target. Nutrient trading is a feasible way to create appropriate incentives (Gren, 2008).

Nutrient trading is efficiently used by the US Environmental Protection Agency to control nutrient loads in waterways emerging from agriculture and wastewater treatment however under certain assumptions (Ashida et al., 2003). The trade becomes efficiently in the situation of free market competition where there are many buyers and sellers, with none or very little government intervention avoiding transaction costs. The caps need to be set at regional levels allowing balanced trading ratios including local stakeholders. Unnecessary transaction costs arise in the presence of too much regulations.

The trade allows an international interaction across economic sectors, point-pollution sources and diffuse-pollution sources in a region of the catchment area. For instance, the interaction between the WWTPs and the agricultural sector.

Nutrient trading also allows the trading on pollution rights between point to point, diffuse to diffuse or point to diffuse sources. Hence, a specific sub-catchment area will be able to reduce pollution in a cost-effective manner. For instance, a WWTP may upgrade the technology in the plant and improve abatement performance. In the same area, there is a farm in need of nutrient reduction. The farmer can pay the WWTP to reduce the excess of nutrient leading to a net local reduction in the subcatchment area. Or vice versa, by the fact that the polluter facing lower opportunity cost in the reduction of nutrient loads will abate.

Nutrient trading operates mutually efficiently between point-pollution and diffuse-pollution sources assuming the less expensive abatement alternative to apply. The interaction across economic sectors makes trade less difficult and costly, with limited transaction costs allowing self-regulation in the market (Hoag et al., 1997). The market equilibrium would be where the marginal benefit of abatement equals the marginal abatement cost.

The situation of mixed oligopoly

WWTPs perform on a very regional abatement platform (BalticStern, 2013). The situation can be described as a mixed oligopoly (Campos, 2016b). That is a market structure characterised by a few public and private treatment plants dominating the local market depending on the size of agglomerations. The optimal objective for public and private-owned WWTPs may differ depending on whether to maximise the social welfare or to maximise the economic expected return of the investment.

In a mixed oligopoly market, the privatisation of public WWTPs will increase abatement and thereby social welfare as long as there are sufficient private WWTPs to encourage competitive market conditions. That is assuming competition on the amount of abatement they produce, with no governmental intervention apart from the operation of the public WWTPs. However, if public and private WWTPs compete on new abatement technology and operational costs, the best strategy in a mixed market is that the public WWTP adopts a new abatement technology in where the market price of abatement equals the marginal operational cost of the private WWTP which is lower, increasing overall social welfare.

The financial structure of wastewater treatment differs among countries (Eurostat, 2017). The diversification of investment sectors may have ambiguous impacts on reduction targets due to varying perceivedness of the incentives arising from market-based instruments and regulations. In Sweden or Denmark there are no direct investments from the general government. In Lithuania and Poland, the investments by the government are 72 % and 58 % respectively indicating very low involvement from the private sector while in Finland, the investments are more evenly distributed. The private and public specialized producers of environmental protection services finance 78 % and 59 % of the investments in Estonia and Germany respectively.

Technology advances in wastewater treatment plants

Compared to other alternatives, WWTPs are considered to be cost-effective solutions to reduce nutrients in the Baltic Sea (BalticStern, 2013). However, the ability to abate among WWTPs widely varies between an efficiency of less than 30 % and almost 100 % (EEA, Waterbase Urban Waste Water Treatment Directive). The upgrading of the WWTPs has been in action since the 1990s.

The treatment in general is conducted in three different phases. The primary treatment is a mechanical removal of *coarse debris* and part of the suspended solids, while the secondary treatment uses biological aerobic or anaerobic decomposition, microorganisms organic matter can be decomposed up to 90 % retaining nutrients up to 20–30 %. The advanced tertiary treatment removes the organic matter more efficiently where more than 80 % of phosphorus and 50–90 % of nitrogen can be removed (Luft et al., 2012).

The cost of improving abatement efficiency by upgrading WWTPs is estimated by Hautakangas et al., (2014). Estimations are based on investments and operational costs in selected WWTPs in the catchment area where WWTPs are classified by sizes. The plants are assumed to abate a high share of nutrients 95–98 % as a first step reducing total nutrient contents in wastewaters by 30 %. A next step is to reduce phosphorus applying a mostly chemical abatement process, and then nitrogen with more challenging technology processes. The potential reduction of nitrogen by 90 % in WWTPs would account on 70 % of the nitrogen target in the Baltic Sea Action Plan. For phosphorus, a 95 % abatement level from WWTPs achieves 80 % of the target. The nitrogen reduction, 83 000 tonnes will cost 670 million Euros per year while the phosphorus, 9 400 tonnes will cost 150 million Euros per year.

The cultivation of native microalgal species

Due to the unique properties of the microalgae its cultivation has been in research focus since the 1950's and the industrialisation today is applied in many countries around the world. The biological growth of the microalgae and the adverse climate conditions in the Baltic Sea region requires however two main determinants in the adoption by WWTPs:

- Continuous and balanced nutrient inflows in the wastewaters to secure algal biomass in the long-run.
- Native microalgae species resistant to Nordic climate conditions to reduce uncertainty in the process at low investment and operational costs.

The Baltic Proper – the most damaged basin of the Baltic Sea – receives steadily nutrient discharges increasing eutrophication and greenhouse gases. However, rural areas with point-pollution and diffuse-pollution sources are perfect nutrient sources for the microalgae cultivations.

Simulations of microalgal cultivation (Campos, 2016) in WWTPs by using information from 2012 on WWTPs encountered in the Waterbase Urban Waste Water Treatment Directive (EEA), based on lab-scale results consist of native species containing the consortia *Chlorella Scenedesmus* from Lithuanian lakes (Koreiviene et al., 2014). The algal production indicates good cultivation performance at an optimal harvesting of 15 days with five days of residence time. Similar results are reported for Swedish conditions on native species including native algal species from the lake of Mälaren (see for instance Odlare et al., 2011; Krustok et al., 2013; Olsson, 2015).

The geographic advantages of the Baltic Proper offer plenty of sunlight and temperatures in a range of 10°C to 22°C, during at least six month of the year between late spring, summer and early autumn for the microalgae to grow (Larsdotter et al., 2004). Moreover, the excessive supply of atmospheric carbon dioxide in the region is also an essential input in the microalgae cultivation. The environmental conditions imply input-savings in term of energy and carbon, resulting in considerable lowering on operational costs in addition to rich-nutrient contents in wastewaters.

When it comes to a situation where economies of scale and economies of scope applies – the investment decision on whether to reduce operational costs by increasing the capacity of the plant or to increase efficiency by technological advance. Microalgae offers the possibility of increasing abatement capacity and abatement efficiency (Campos, 2016).

The industrial cultivation of native microalgal species is feasible in relative simple environments (Olsson, 2015) acquired at low costs. Cost-effective raceway cultivation ponds are already in use for industrialisation purposes (Pittman et al., 2011). However, depending on the size of the operation, open raceway ponds requires relative large areas of land, suggesting the use of land with low value.

Anaerobic digestion in the second treatment biological process is becoming a more common technology in WWTPs among countries in the catchment area (Luft et al., 2012). The main objective with anaerobic digestion has been to reduce the amount of sewage sludge. However, the use of chemical precipitation – the addition of sulphide ions, aluminium or lime – to help in the coagulation and sedimentation of the sewage sludge make the recycling of the nutrients hard to recover (Frederiksen et al., 2013) limiting its value-added.

An alternative is to use the microalgae in activated sludge which can reduce chemical precipitation and treatment time, improving the recovery of nitrogen and phosphorus (Anbalangan, 2016). The microalgae also allow a self-hygienisation process of the biomass where the anaerobic digestion of a mixture containing microalgae enhances the methane potential in the biogas production (Olsson, 2015).

In the absence of an industrial microalgae cultivation with no market prices or managerial decisions, productivity measures – as changes of inputs into outputs – can be used to simulate an industrial process. The productivity of the consortia *Chlorella and Scenedesmus* was estimated for each of the countries in the catchment area excluding Russia. The estimation indicates positive effects on abatement and the algal biomass is likely to increase the production of biogas through anaerobic digestion however depending on the physical conditions of the plants (Campos, 2016a). The increased demand on renewable energy promotes the development of the production of methane. Poland, Sweden, Finland and Denmark indicate highest potential on the production of methane from sewage sludge gas (Eurobserver, 2014), implying further reductions on emissions by increasing the supply of biogas as an alternative to reduce the use of fossil fuels.

The abatement efficiency gains of adopting microalgae arise from their ability to assimilate nutrients and other compounds in wastewaters. The consortia *Chlorella and Scenedesmus* is able to assimilate total nitrogen on 91 % and total phosphorus on 94.7 % and 95.7 % (Makareviciene et al., 2011). A high absorption of total nitrogen may also reduce airborne emissions such as ammonia and nitrogen oxides as well as carbon dioxide. The needed reduction on the Baltic Proper – 98 921 tonnes nitrogen and 10 960 tonnes phosphorus – can in part be reached by the introduction of microalgae cultivation in WWTPs. Poland, Lithuania and Sweden jointly can reduce 32 456 tonnes of nitrogen and 1336 tonnes of phosphorus. That is a reduction of 33 % nitrogen and 12 % phosphorus respectively to the Baltic Proper by only including 37 % of the WWTPs in Poland (Campos, 2017). Based on the results of Koreiviene et al., (2014) the reduction of atmospheric carbon dioxide is calculated to a total of 20 193 tonnes CO_2 where Poland only contributes by 54 % of the total reduction.

One of the limitations to achieve a closed recycling system in the treatment of wastewaters is the disposal of sewage sludge. That is since the content of hazardous substances and heavy metals in wastewaters. The geographical concentration of sewage sludge disposal is also an environmental threat. The use of sewage sludge in agriculture requires stabilization and hygienisation before use. Microalgae facilitates the process but at a higher assimilation amount of heavy metals jeopardising its final disposal on agriculture.

The final disposal of sewage sludge is carefully legislated by EU-framework directives as well as national legislation and policies including limit values on heavy metals, pathogens and organic compounds. Luft et al., (2012) gives a good exposition on the EU and national regulations in the countries of the catchment area. The quantities allowed to dispose in Finland depends on the soil quality and nutrient need of cultivated crops while in Sweden it depends on the phosphorus class of soil and of total ammonium 150 kg per ha and year. In Denmark and Germany, the disposal is on 7 tonnes of dry matters per ha and year as well as 5 tonnes of dry matter per ha every three years.

In Estonia, the agricultural disposal of sewage sludge is not used. In Latvia and Lithuania, the disposal of sewage sludge in agriculture is limited to 40 kg phosphorus per ha and year while in Latvia the total ammonium 30 kg per ha and year and in Lithuania the total nitrogen 170 kg per ha and year are valid. Poland allows 3 tonnes of sewage sludge per ha and year. The use of willow plantations has been an alternative as a vegetation filter to catch heavy metals, especially cadmium and nitrogen. Fast-growing trees are alternative complements in the treatment of wastewaters and landfill leaching (Arosson and Perttu, 2001).

Hence, the adoption of microalgae by WWTPs is a potential technology to further reduce nutrients in the Baltic Sea. The improvements in the abatement efficiency as well as in the production of biogas make WWTPs competitive in renewable energy and fertilisers in coherence with the agricultural sector. An international cross-sector market-based instrument as nutrient trading, is considered to incentivise the rate of abatement and productivity of the industry as well as the economic growth in the Baltic Sea region.

Concluding remarks and recommendations

One of the problems to reach the nutrient reduction quotas specified by the Baltic Sea Action Plan, has been the ability and willingness to pay among countries. There is a need on cost-effectiveness and fairness measures on abatement. Another problem has been the design of country and sector specific instruments regardless the magnitude of the environmental effects. That is taking into account the relation between the biological status of the basins in the Baltic Sea and pollution discharges. In the particular case of WWTPs acting in a very regional abatement platform, as in a mixed oligopoly situation, the privatisation of public WWTPs will increase social welfare depending upon how well competitive market conditions are encouraged. The privatisation of WWTPs requires economic incentives, leading to technological advance bringing private economic profits to the industry.

Even if the reduction of nutrients into the Baltic Sea has improved significantly during the last decades, intensive agricultural practices and outdated WWTPs still remain major pollution sources. According to cost efficiency, an international market on nutrient trading across the agricultural sector and WWTPs in the most eutrophic areas of the Baltic Sea is considered to create incentives on technological advances, reinforcing regional economic growth. Unlike the experience on carbon dioxide trading, a regional market consisting of agricultural farmers and WWTP managers, fulfils the required assumptions on nutrient trading.

The marginal abatement costs faced by agriculture and WWTPs are closed enough to secure balanced trade-ratios without governmental intervention. Moreover, nutrient trading will incentivise on technological advances and the change into agro-environmental practices in the agricultural sector as well, due to the mechanism of opportunity cost arising from the implemented reductions. This proves that nutrient trading is a cost-effective and fair policy instrument regardless of a well-defined distribution of income among countries while also creating appropriate incentives on technological advances to reach local targets on nutrient reduction.

The question on which technological advances to apply to WWTPs remains. The costs on upgrading the WWTPs in the Baltic Sea region are estimated to 670 million Euros on nitrogen per year and 150 million Euros on phosphorus per year. However, the distribution of the cost burden remains unfair. Nutrient trading allows proportional distribution effects. Furthermore, there are no observable costs on the microalgae cultivations, since there is still no industrial process. The analysis is based on the available technology on WWTPs among the countries in the catchment area collected from the database Waterbase Urban Waste Water Treatment Directive, literature review and simulations, hence the results should be used as guidelines and be carefully interpreted.

However, the choice of adopting native microalgal species by WWTPs coupled to biogas in the Baltic Sea region offers additional improvements in the abatement efficiency of the plants. The stabilisation of the sewage sludge including the microalgae reduce the use of chemical precipitation usually used in the biological treatment's secondary phase of abatement in WWTPs. The microalgae in activated sludge is regarded to be a cost-saving technology while avoiding the addition of heavy metals to the sewage sludge. In WWTPs coupled to biogas, the digestate including microalgae enhances the production of methane increasing the potential use of the digestate into agriculture together with vegetation filters as willow. This also improves the production of biogas, making WWTPs market competitive in renewable energy and fertilisers in coherence with the agricultural sector.

The surroundings of the Baltic Proper – the most damaged basin in the Baltic Sea – take advantage of economies of scale while fulfilling the assumptions of nutrient trading and cost efficiency, as well as the biological conditions that the microalgae need. Furthermore, the ability of microalgae to assimilate carbon dioxide is another reason to regard their cultivations as a sustainable ecological abatement technology, promoting economic growth at overall reduced costs given that the ecological determinants for the microalgae to grow are met.

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