Economic and emissions impact of producing bioenergy from seaweed

Kristinn Hermannsson & Kim Swales
University of Strathclyde[i]

Biomass is already widely used as a low-carbon source of energy with a range of bioenergy options in use across Europe. This includes everything from traditional sources such as heat from wood-burning stoves to crop-based biofuels and biogas plants using household and farm waste. One of the main drawbacks of many bioenergy sources is that the energy crops displace alternative land use, such as for food production. Seaweed has been suggested as a source of next generation bioenergy to address these concerns. It is harvested and cultivated on a commercial scale in several countries across the world but in most coastal areas it is relatively underexploited and therefore offers significant potential.

The Western Isles, or Eileen Siar in Gaelic, is a council area in the Hebrides of the west coast of Scotland. In 2011 the community counted just over 26 thousand inhabitants residing on 14 islands. Due to a convergence of technical, natural and knowledge capabilities the community in the isles is uniquely situated to pioneer the use of seaweed for production of bioenergy. The islands are situated in waters that produce large quantities of seaweed (macroalgae) that is suitable as marine biomass for energy production. There is already an anaerobic digestion facility in operation in the islands that is used to dispose of household waste and produces both heat and bioenergy as its outputs. Furthermore, there is a wide range of know-how in existing marine-focussed sectors, such as fisheries and aquaculture, that can be drawn on in the development of an algae harvesting sector.

Of the seaweed habitats around the coast of Scotland approximately 1,000km^2 provide sufficient densities to be commercially harvestable. Approximately a fifth of these are around the Western Isles. Based on sustainable harvesting, seaweed could power more than 2,000 homes in the islands or just over a fifth of the homes in the community. The economic, social and environmental benefits of this are potentially significant.

As we shall see this development would probably not be viable as a standalone commercial venture. However, given existing facilities and availability of subsidies for green energy the prospect could be commercially viable. This is in addition to potential further impetus from social benefits such as the green credentials of the community. Therefore, we set out to estimate ex ante the potential impacts upon the economy of the Western Isles and the potential contribution of this development to reduction of greenhouse gas emissions. It is important to understand the sector's potential economic and environmental contribution as it is futile committing resources to develop this approach unless it can provide a positive impact. This is not complicated in principle, given that detailed information on how to conduct environmentally extended economic impact analyses is widely available in textbooks. However, in practice, this raises some challenges. In particular, as the production sector does not exist any analysis is bound to be somewhat speculative as a result. Seaweed is harvested and cultivated for various uses around the World and various technologies are used to extract energy from biomass. However, these functions have (to the best of the authors' knowledge) yet to be combined.

We start by analysing the potential and feasibility of the new bioenergy sector. Then we use an Input-Output model for the year 2008, based on the Western Isles Economic Accounts, to estimate multiplier impacts. Input-Output is a well-established technique in impact analysis. A particular strength is that it is an accounting framework that allows a detailed identification of the interplay between the different sectors (and sometimes households) of the regional economy. In addition to economic impacts, this can be extended to take account of greenhouse gas emissions. This is important as one of the primary drivers behind developing bioenergy is its contribution towards the reduction of greenhouse gas emissions. However, there are likely to be emissions embedded in the production process and the stronger the economic impact, other things being equal, the more greenhouse gas emissions. Therefore, these two impacts are likely to counteract each other, when it comes to adding up the potential benefits of producing bioenergy from macroalgae.

In the next section we shall briefly outline the feasibility and potential for producing bioenergy from marine biomass in the Western Isles. In the third section we outline the conventional Input-Output framework and use it to estimate the Output, GDP and Employment impacts of new marine bioenergy activities in the islands. In the fourth section we extend this to look at greenhouse gas emissions embedded in the electricity production. Fifth section concludes.

Energy from marine biomass in the Western Isles

Macroalgae, or seaweed as it is more commonly known, is harvested wild or cultivated for various uses around the World. Around the British Isles seaweed has been put to various uses at different times, depending on availability and price of substitutes. Following the Second World War, resource scarcities stimulated comprehensive survey work of the extent and nature of seaweed off the coasts of Great Britain (Walker 1947ab, 1954ab). Recently, this interest has been revived as seaweed is seen as a potential source of biomass for energy production, that does not suffer the drawbacks of some terrestrial energy crops, such as displacing food production. This has sparked research activity, which is summarised in several recent publications. Kelly & Dworanjin (2008) review evidence on the extent of harvestable macroalgae off the UK coasts and explore the potential for using it as a feedstock for producing bioagas via anaerobic digestion. Bruton et al (2009) examine the potential of marine algae as a source of biofuel in Ireland and Lewis et al (2011) review and compare options for the commercial utilisation of macroalgae in the UK. Hermannsson and Swales (2012) draw on available evidence to estimate the energy potential from sustainable harvesting of wild seaweed in UK waters and examine the feasibility of harvesting seaweed off the Western Isles for local bioenergy production.

An anaerobic digester is a facility where organic matter (e.g. household waste, farm waste, and bio crops) is decomposed to form biogas (a mixture of methane, CO_2 and other gases) that can be used for electricity generation, heating or input into further processing. The Western Isles council has already invested in an AD facility for refuse disposal as landfill options are severely limited by the isles' geography. With this investment already in place the Western Isles are ideally placed to pilot the anaerobic digestion of seaweed on a commercial scale.

Surveying available evidence, Kelly & Dworjanyn (2008) conclude that in UK waters there are approximately 1,000km^2 of habitat where seaweed can be found in sufficient densities to be harvestable. If we focus exclusively on the Western Isles, the macro algae estimated to be harvestable there is approximately 18% of the total in UK waters (Kelly & Dworjanyn, 2008, Table 4.1, p. 48) or 180km^2.

Given available information we can estimate the potential sustainable harvest of seaweed around the Western Isles. We have 180 km^2 of seaweed forests in harvestable densities. Each plot can be harvested on average every 5th year[ii] so that every year we can expect to harvest from 36km^2 of water. As every m^2 will yield 3.7 kg, each km^2 will yield 3,700 tonnes (3,7kg x 1,000m^2 /1000). Hence for 36km^2 we can expect an annual harvest of about 133,200 tonnes[iii].

Hermannsson & Swales (2012) draw on information from Kelly & Dworjanyn (2008, Table 5.3, p. 73) to deduce the energy yield per tonne of seaweed. If the seaweed is anaerobically digested to produce biogas, which in turn is used to generate electricity each wet tonne of seaweed can be used to produce 64.26 kWh of electricity

Based on our previous estimates of potential wild harvest our annual energy yield could therefore equal 133, 200t × 64.26 kWh/t = 8,559,432 kWh/yr. To put this into context OFGEM reports that an average home consumes 3,300kWh of electricity per year and therefore the Western Isles seaweed harvest could potentially support the electricity consumption of 2,594 homes. According to the General Registrar for Scotland there were 12,208 households in the Western Isles in 2011. Therefore, seaweed could potentially provide electricity for 21.3% of households in the isles. This locally produced energy could be used to substitute imports of energy to the islands or exported to the UK grid. In either case, it is a significant boost to the local economy.

1.1 Direct impacts of the marine bioenergy production

Lewis et al (2011) provide a comprehensive overview of the commercial feasibility of AD plants using macroalgae as inputs. They provide a range of scenarios and conclude that given the availability of other (cheaper) inputs such as household waste to complement the seaweed input (for which harvesting costs have to be covered) the AD facility is viable as a standalone commercial entity. However, based on scenarios where seaweed is the sole input the plant is no longer able to cover the full market price of harvesting the seaweed. A cross subsidisation from waste disposal is therefore necessary. In the case of the Western Isles there already is an AD facility in place[iv], which is used for refuse disposal and is running under capacity. Therefore we expect the use of seaweed inputs to be viable and concentrate on estimating the economic impact of that production. To further simplify the analysis we assume the AD facility can accommodate the extra input/production at existing staff levels and therefore the direct employment impact occurs through the harvesting sector.

Based on the available information it is simple to derive the direct impact at market prices. Given the maximum sustainable harvest of 133,200 tonnes the AD facility can produce 8,559,432 kWh of electricity per annum (in addition to existing production based on other inputs). We abstract from detailed analysis of the viability of the AD plant and simply assume that this is sufficiently lucrative (with cross-subsidisation from other AD inputs and the fact that investment in facilities has already been covered) to pay a sufficient price for the outputs of the harvesting sector[v]. Following Lewis et al (2009) the AD facility has to pay £20 per wet tonne of harvested seaweed or £200 per dry tonne[vi].

Input-Output analysis of the economic impact of marine bioenergy

Based on the potential for harvesting macroalgae for energy production as introduced in the preceding section it is possible to determine the direct impact of these additional activities for the economy of the Western Isles. Then the Western Isles Input-Output model is used to derive the economy-wide impacts of the anaerobic digestion of seaweed. Before turning to this analysis it is useful to provide a general introduction to Input-Output models and their use in economic impact studies.

1.2 Input-Output impact analysis

Regional IO impact analyses are frequently used to capture the total spending effects of institutions, projects or events. These analyses incorporate the multiplier, or “knock-on”, impacts of any expenditure injection, obtained by summing the subsequent internal demand feedbacks within the economy. This section briefly outlines the methods adopted by impact studies[vii].

Regional demand-driven models, including IO, distinguish between two types of expenditures: exogenous and endogenous. Exogenous expenditures are independent of the level of economic activity within the host economy. In IO studies exports, government expenditure and investment are typically taken to be exogenous. On the other hand, endogenous expenditures are driven by the overall level of economic activity within the host economy. Specifically, demand for intermediate inputs and often household consumption demands are taken to be endogenous. Input Output analysis thus identifies a clear causal pathway from exogenous expenditure to endogenous economic activity.

The derivation of the demand-driven multipliers draws on the notion that exogenous expenditure determines endogenous economic activity. In the standard Leontief Input-Output approach the endogenous vector of final outputs, $\boldsymbol{q}$, is determined by the exogenous vector of final demands, $\boldsymbol{f}$, through the operation of the Leontief inverse multiplier matrix. This can be summarised as:

(1)

$$\boldsymbol{q} = (\boldsymbol{1} - \boldsymbol{A})^{-1}\boldsymbol{f}$$

where $\mathbf{(1-A)^{-1}}$ is the Leontief inverse (Miller & Blair, 2009, Ch. 2). The Leontief inverse identifies the indirect and induced effects of any exogenous demand stimulus. Indirect effects arise through increased demands for intermediate goods and, with Type-II multipliers, induced effects are also generated through the impact of increased household income on consumption demand.

These demand-driven models assume that the supply side of the regional economy is entirely passive. This can be motivated in two alternative ways. In the short and medium run such a model applies where there is general excess productive capacity and significant regional unemployment. In the long run, supply-side passivity holds where the supply of the primary inputs of labour and capital eventually becomes infinitely elastic, as migration and capital accumulation ultimately eliminate any short-run capacity constraints (McGregor *et al.,* 1996). The legitimacy of either set of conditions is ultimately an empirical issue. For example, Learmonth et al., (2007) models the island economy of Jersey. Here the labour market is tight and the institutional framework restricts migration so that the supply side cannot be treated as passive over any time interval. Therefore, in the context of a small peripheral economy like the Western Isles, the Input-Output multipliers should be regarded as representing the upper limit of potential impacts.

1.3 Applying Input-Output to estimate the impact of new bioenergy generation

It is evident from equation (1) above that in order to determine the change in output across all sectors($\boldsymbol{q}$) produced by bioenergy generation upon the Western Isles, we need to determine the exogenous component of this impact, the change in final demand ($\boldsymbol{f}$) attributable to these additional activities. The supply chain is simple. Seaweed is harvested and sold to the AD facility, which uses it to produce biogas, which in turn is used to produce electricity. The electricity is then exported to the national grid. These export earnings (price + subsidy) are obtained by the AD facility, which in turn uses the income to pay seaweed harvesters, which use their income to purchase intermediate inputs and labour – hence the multiplier process is set in train. Since we expect the AD facility to be able to meet this additional production with existing capacity we abstract from their role in the supply chain and simplify the analysis by modelling the sales of the harvesting sector as an exogenous shock. Determining the exogenous income shock to the harvesting sector is straightforward. It harvests 133,200 tonnes of seaweed, for which the AD sector pays £20 a tonne. The total income is therefore £ 2,664,000.

From the Input-Output table we can derive multipliers for how this final demand shock feeds through the economy and impacts different activity metrics, in this case gross output, gross regional product (GRP) and Full Time Equivalent (FTE) employment. We use the multipliers to estimate the knock-on impacts of the additional activity in algae harvesting. These results are reported in Table 1.

Table 1 Final demand and knock-on impacts of algae harvesting the Western Isles, Type-I and Type-II impacts.

	Final demand	Type-I			Type-II		
		Output	GRP	FTE Emp.	Output	GRP	FTE Emp.
Impact (£000's, FTEs)	2,664	4,154	1,407	95.86	4,633	1,848	100.13
% of ES total	0.47%	0.63%	0.39%	1.04%	0.70%	0.52%	1.08%
Multiplier		1.56	0.53	0.036	1.74	0.69	0.038

If we move through the table from left to right we can see that the final demand injection from the additional harvesting activities represents a 0.47% increase in the final demand for outputs of all sectors' in the Western Isles. Based on Type-I assumptions (i.e. accounting for direct and indirect effects) we can see that under these assumptions the increase in output, GRP and FTE employment in the isles amounts to 0.63%, 0.39% and 1.04%, respectively. As expected, the Type-II impacts (direct, indirect and induced effects) are slightly stronger with the change in Western Isles output, GRP and employment amounting to 0.70%, 0.52% and 1.08%, respectively. The direct indirect and induced employment generation could amount to 100 full time equivalent jobs – a significant stimulus for a community of that size. Moreover, the employment intensity ensures that the positive economic impacts are dissipated in the local community. This is in contrast to new developments in many energy production sectors, such as wind or hydro, where there is little continuing additional employment and local impacts are only generated if the host community has access to residual income through ownership or revenue sharing agreement (Allan et al, 2011). However, the strong economic impact raises a further issue that requires careful attention, namely how much greenhouse gas emission will be saved once everything has been added up.

Greenhouse gas emissions

The primary motivation for developing bioenergy sources is to access energy while saving greenhouse gas (GHG) emissions. However, if something has a large economic impact, it quite likely follows that it drives significant GHG emissions as well. The question is how big are these embedded emissions relative to the GHG emissions saved by substituting bioenergy for conventional electricity sources. To determine the GHG emissions involved in harvesting macroalgae for energy production we use Scottish sectoral emissions, thereby assuming that production sectors in the Western Isles have equal emissions intensities as equivalent sectors in Scotland on average. To attribute the emissions to economic activity we use a standard extended IO-model, following Leontief (1970), (see Wiedman et al. (2007), Miller & Blair (2009, ch. 10)). Total greenhouse gas generation in production is determined as:

(2)

$$\boldsymbol{g^x = \Omega^x x}$$

where $\boldsymbol{g^x}$ is a K x 1 vector, with elements g^x_k, where k = 1,…,K. Element g^x_k represents the total greenhouse gas of type k generated by the production activities in the economy. Ω^x is a K x N matrix where element $\omega_{k,I}$ is the average generation of emissions k per unit of gross output in sector i.

Then the standard Leontief model can be employed so that it is extended to

(3)

$$\boldsymbol{g^f = \Omega^x (1 - A)^{-1} f}$$

where $\mathbf{g^f}$ is the vector of total generation of emissions directly or indirectly required to satisfy total final demand, f, in the economy

Final demanders (households) also directly generate emissions (for instance by combusting fuels and driving cars) and hence Eq. (3) is extended for final demand as

(4) $$g^f = \Omega^x(1 - A)^{-1}f + \Omega^f f$$

where we distinguish the K x N matrix of emission coefficients for the N production sectors Ω^x from a K x Z matrix, Ω^y, where each K x 1 column within has elements $\omega_{k,z}$ as the average direct use of resource k per unit of expenditure by final demand group z.

The greenhouse gas emissions are obtained from the Scottish National Accounts Project, which publishes data for 93 sectors up to the year 2006[viii]. These are then aggregated to 25 production sectors (+households) to conform with the Western Isles economic accounts. Gross sectoral outputs (and household final demand) from an equivalently aggregated Scottish IO-table for 2006 are used to determine average emission intensities per £1 of output. This vector of emission intensities is then used to extend previous economic impact results. The results are reported in Table 2 below. This suggests that the emissions embodied in harvesting of macroalgae for electricity production, both directly and indirectly (type-I assumption), amounts to the equivalent of 1,464 tonnes of CO^2. Given the estimated electrical capacity of this amount of macroalgae, this would result in direct and indirect emissions equivalent to 0.17 kg of CO_2 per kWh.

Table 2 Energy capacity and greenhouse gas emissions driven by harvesting of macroalgae for electricity production.

Algae harvest	133,200
Price	20
Exogenous increase in sales of macroalgae	2,664,000
kWh electricity	8,559,432
cost per kWh	0.31
Emission in CO2 equivalent tonnes (Type-I)	1,464
% of ES total	0.18%
Emissions per kWh (CO2 equivalent kg)	0.17

This raises the question how effective this method of electricity production is at saving GHG emissions, which is of course contingent upon the emissions intensity of the displaced energy source. A benchmark is available from the Department for Environment Food and Rural Affairs (DEFRA), which publishes estimates for the average emissions intensities of electricity production in the UK, allowing for imports and exports of electricity[ix]. Annex 3 reports the average emission intensity per kWh of generated energy in the UK. This reveals that in 2006 the average direct and indirect emissions required to produce a kWh of electricity in the UK amounted to 0.60kg, CO^2 equivalent (Table 3c, p. 13). Against this benchmark, per kWh of electricity produced via anaerobic digestion of macroalgae could save 0.43 kg of CO^2 equivalent greenhouse gas emissions.

There is some room to argue that this is a conservative estimate. In this calculation we are assuming marine bioelectricity displaces average electricity, whereas if it displacing fossil fuel generated electricity at the margin, this GHG saving could be significantly higher. Furthermore, if it is the case that locally produced electricity would displace imports from the grid, we could further factor in efficiency savings from avoiding losses in the grid. Moreover, anaerobic digestion can provide a combined electricity and heat source. We have not factored the latter energy output into our calculation. Its economic impact is likely to be less than from electricity, but still significant (for details see Lewis et al, 2011). However, given the simplifying assumptions that had to be adopted the margin of error in our analysis could be significant and therefore detailed interpretation of these findings is premature. First of all the harvesting sector does not exist and therefore we had to proxy its structure based on seafishing. Secondly, emission intensities are based on broad averages, rather than specific observations.

Conclusions

In this paper we analyse the potential economic and environmental impact of harvesting macroalgae and using this as input into anaerobic digestion to produce electricity. Although current estimates suggest this would be a relatively expensive energy source, it has potential supplementary benefits, such as greenhouse gas emissions saving and local economic impacts. We use the Western Isles as case study due to the availability of detailed economic accounts and the suitability of the isles for generating marine based bioenergy. We briefly summarise the energy potential of this approach and find that although it would be minor in the context of the UK as a whole it could be significant in terms of a small community like the Western Isles, providing electricity sufficient to power about 20% of the homes there.

Given that electricity from macroalgae is unlikely to be viable as a stand-alone commercial venture, it is critical that other benefits compensate for the relatively high price required. Our results show that at the very least this approach can overcome two of the necessary hurdles, i.e. it contributes to local economic development as well as greenhouse gas reduction. The local employment impacts are significant, which ensures that the positive economic impacts are dissipated in the local community. Furthermore, despite initial worries that strong economic impacts could undermine GHG reduction (Hermannsson & Swales, 2013), our analysis shows that the emissions intensity per kWh of electricity produced from macroalgae is just over a quarter of the UK average.

As this analysis is based on a hypothetical sector and given inevitable lack of data various simplifying assumptions had to be adopted, we caution against an overly detailed interpretation of our findings. Our aim was to provide ball park figures given available information in order to aid decision making about devoting further resources to understanding the approach. The initial findings are positive. However, given the current state of knowledge, it is premature to conclude as further work is needed. In particular, a comprehensive and detailed social cost-benefit analysis, based on a thorough investigation of ecological, economic and social factors.

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[ii] For harvesting procedures Kelly & Dworjanyn (2008. p. 49) refer to Norway where algae are harvested for industrial use. As a rule of thumb a given patch can be harvested every 5th year, although this varies given the bio productivity of the waters.

[iii] See Kelly & Dworjanyn (2008, p. 45).

[iv] For additional activities this investment represents a sunk cost and therefore investment costs do not have to be covered until current capacity is exhausted and further investment needed.

[v] For a further discussion of the viability of seaweed as an AD input we refer to Lewis et al (2011). In particular, Scenario 6 (p. 34) demonstrates commercial viability.

[vi]This is the middle range of available estimates. Bruton et al (2009) reports an input cost of £240 per dry tonne of macroalage. Horn (2000) reports based on Norwegian experience that seaweed harvesting costs are NOK 120 per wet tonne and then following Bird (1986) processing and cleaning costs are estimated at 50% of raw material costs. Based on historical exchange rates and UK inflation since 2000 this would imply an input cost tonne of wet seaweed of £18.7 per wet tonne or £187 per dry tonne.

[vii] For a more detailed account see Armstrong & Taylor (2000), Loveridge (2004) and Miller & Blair (2009).

[viii] For details see: http://www.scotland.gov.uk/Topics/Statistics/Browse/Economy/SNAP/expstats/EnvironmentalAccounts

[ix] http://www.defra.gov.uk/publications/files/pb13625-emission-factor-methodology-paper-110905.pdf