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Eco-efficiency of a wind farm. A case study.

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Implications

Eco-efficiency is an indicator used for management of sustainable development. One of its attractive features is allowing a fair allocation of responsibilities. It can be claimed reasonable that emissions are allowed or decreased in relation to the economic value created in a business activity. Another feature is its ability to create benchmarks. Any decision for a business activity can be compared in terms of its environmental impact per monetary value produced.

This study shows how different actors involved will see different eco-efficiency when evaluating their involvement in building a wind park.

If this study was used for the decisions it investigates, it would have given them a clear support from all actors involved. It would also have given recommendations for improvements.

Summary

Decision	Choice		Actor	NPValue created, €		Environmental cost, €		Eco-efficiency		Conclusion
	A	B		A	B	A	B	A	B	
Offshore investment, 30yrs new electricity added to grid	Invest	7% interest	Investor	1.79E+09	0	1.78E+07	0	0.99	n.a.	Chose A, Low financial risk from environmental issues
Offshore investment, 30 yrs substitue lignite based electricity	Invest	7% interest	Investor	1.79E+09	0	-8.4E+08	0	1.47	n.a.	Chose A, Low financial risk from environmental issues
Location, new electricity	Offshore	Shore	Investor	1.79E+09	1.73E+09	1.78E+07	1.44E+09	0.99	0.17	Chose A, Low financial risk from environmental issues
Location, lignite substitute	Offshore	Shore	Investor	1.79E+09	1.73E+09	-8.4E+08	5.82E+08	1.47	0.66	Chose A, Low financial risk from environmental issues
Location, new electricity	Offshore	Shore	Government	3.4E+08	-5.9E+08	1.78E+07	1.44E+09	0.947	n.a.	Chose A, Low financial risk from environmental issues
Location, lignite substitute	Offshore	Shore	Government	1.2E+09	2.73E+08	-8.4E+08	5.82E+08	1.70	-1.13	Chose A , Low financial risk from environmental issues
Building of offshore windpark, 30 yrs new electricity added to grid	Permit	Forbid	Government	3.4E+08	0	1.78E+07	0	0.947	n.a.	Chose A, Improved eco-efficiency compared to average economic activity
Building of offshore windpark, 30yrs substitued lignite based electricity	Permit	Forbid	Government	1.2E+09	0	-8.4E+08	0	1.704	n.a.	Chose A, Improved eco-efficiency compared to average economic activity
End user choice of 1000 kWh electricity	Borkum2	Lignite based	End user	110	110	0.493	23.9	0.996	0.783	Chose A, but B is close to average economic activity

Overview of data and values obtained when studying eco-efficiency of different decisions

Introduction

Eco-efficiency is an established concept since 1992, when it was made publicly known by the World Business Council of Sustainable Development (WBCSD). The core idea of business is to create as much value as possible with as little resource input as possible, often expressed as "to create more from less". Eco-efficiency relates the value of a business activity to the environmental impact it causes. A common way of quantifying eco-efficiency is to divide the value created by an environmental impact measure, but there are many other ways.

During the past five years, the interest for the eco-efficiency concept has increased in the scientific community, and two international conferences have been held (1). An interesting feature of eco-efficiency is that you may link macro-level sustainability management with micro-level management. Any budget, be it on national level, department level or consumer level, can be given eco-efficiency targets. Eco-efficiency is a way of allocating environmental resources and related responsibilities to organisations and single actors. On a budget level, targets may be set up for and monitoring made of single transactions. In that way it may be an efficient sustainability management tool.

The aim of this study is to investigate how eco-efficiency could have been used in the decisions made in relation to building a wind farm.

Method

The eco-efficiency measure used in this case study is based on the common notion that efficiency is useful output divided by useful input. The monetary value created by the business, γ, is the useful input. The monetary value created, justified for environmental external costs, ψ is the useful output. The eco-efficiency is equal to

$$(\gamma - \psi)/ \gamma \text{ , for } \gamma > 0$$

The external costs may be determined in different ways, but here we use the EPS 2000 default method (2). The ExternE method (3) is often used in this contexts but it lacks value assessments for environmental resources, which is a central aspect in sustainability management.

If there is no external environmental costs and just monetary value created from the business, its eco-efficiency will be 1, i.e. 100%. If the external costs are equal to the value created, the eco-efficiency will be 0. Using the total external costs of global emissions and the global GNP (2), the average eco-efficiency for all economic activities may be estimated to 87%. Any activity with an eco-efficiency above 87% is thus likely to contribute to increased sustainability. To compensate for economic growth of x%, the benchmark for a new product may be increased to 87 + x% if the environmental impact is kept constant.

The case

45 km northwest of the Borkum Island on the German west coast, a 400 MW offshore wind park is built. It consists of 80 5MW plants and will deliver 1.2 billion kWh per year. The consortium building the wind park, Prokon Nord, estimates the production to be somewhat higher: 1.76 billion kWh. The total cost of the wind park is about one billion €. The average wind speed at the turbines is estimated to be 10 m/s at 80 m height and the wind park is

expected to work at full capacity 4400 hours per year. The wind park is planned to be in operation in 2010.

ABB is delivering a platform for a converter station offshore, a submarine HVDC Light® cable, a land cable and a converter station on land and a connection to the grid.
The total length of the submarine cable is 256 km and the total length of the land cable is150 km. The submarine cable has a 1200 mm^2 copper conductor, steel armouring and extruded polymer isolation. Its weight is 29 kg/m and diameter 98 mm. The land cable has a 2300 mm^2 aluminium conductor and extruded polymer isolation. Its weight is 11 kg/m and diameter 96mm. All the materials in the cables are assumed to be recycled after use and the organic parts used as fuel in the recycling processes. The recovery of copper is assumed to be 98%.

The price for electricity in Germany is at present 11 eurocents per kWh for consumers and around 10 cents for industry. The government subsidiaries are 9 eurocent per kWh, but may be as high as 14 cents in the future (6).

There are several business decisions taken in connection with the wind park. Below some are mentioned:

1. The investors decide to build the wind park instead of saving their money at 7% interest rate
2. The investors/authorities respectively chose to locate the wind farm offshore instead of at land
3. The authorities gives permission to the building of the wind park offshore
4. The end user chose to buy electricity from the wind park and not from the average grid.

Decision type 1, the investment decision

In this decision EE and its data components serves as an indicator of the efficiency in use of capital. The first question to be answered is whether external costs are high compared to the return on investment. If so, there is a danger of future costs that may jeopardise the success of the investment, and there is a need to further investigate the risk. A second question to be answered is whether the eco-efficiency meets the target for the activity. Such a target could be the average or best of the competitors.

Assume that the required return on investment is x % per year and the eco-efficiency is η % (η is calculated as described under the chapter named Method), then the environmental adjusted return on investment is x – (100- η) %. If this is a significant and unacceptable decrease of the return on investment, it is of interest for the investors to estimate the risk for internalisation of these external environmental costs. This risk depend on several factors, among them: 1) what is already internalised (like taxes, fees and abatement measures), 2) the types and values of environmental impacts and 3) the likely internalisation scenario of each impact type.

In the case of Borkum 2 the investment is about 1 billion €. The return on investment is the market price for electricity (0.11 €/kWh for households and 0.099 for industries) + subsidiaries (9 cents/kWh now, and maybe 3.5 cents after 12 years) times 1.2 billion kWh, which is 240 million €/year minus operating and maintenance costs. The operating and maintenance cost is unknown at this stage, but assumed to be 30 million €. If prices are assumed to follow the inflation rate and the interest rate is set to 7%, the profit expressed as

Net Present Value is 1.79 billion € for a 30 years period. External environmental costs for wind energy is rather low, 0.0005 €/kWh (see calculation in table 1) or with 1.2 billion kWh/year 600 000 € per year or 0.018 billion € for the 30 year period. This means that the eco-efficiency for the wind park is (1.79-0.018)/1.79 = 99.0 % if the system boundaries are narrow and include just the wind park and its grid connections. The financial risk in terms of increasing costs due to future internalised environmental cost is therefore very low and the return on investment "safe" in that aspect.

If the system boundaries are expanded to include impacts on the German energy system, and the building of the wind park will substitute lignite based electricity, the external environmental costs would decrease. The external environmental cost from lignite based electricity is 86108€/TJ or 0.024 €/kWh (table 2). For 1.2 billion kWh/year this means 28.7 million € per year and the corresponding eco-efficiency would be (1.79 – 0.018 + 0.0287*30)/1.79 = 148 %.

It is worth noting that the 3.5 cents subsidiary after 12 years is of similar magnitude as the 2.4 cents external cost for the competing lignite based electricity.

Direction	FlowType	Substance	Quantity	Unit	Environment	EPS Value, EUR/kwh
Input	Natural resource	Area	0,0151	m2	Ground	
Input	Natural resource	Bio fuel	0,000001	kWh	Other	
Input	Natural resource	Coal	0,00146	kWh	Other	
Input	Natural resource	Copper ore	0,59	mg	Ground	0,00012272
Input	Natural resource	Iron ore	0,0412	g	Ground	0,000039552
Input	Natural resource	Natural gas	0,000005	kWh	Other	
Input	Refined resource	Electricity	0,000002	kWh	Technosphere	
Input	Refined resource	Electricity	0,000007	kWh	Technosphere	
Input	Refined resource	Heavy oil	0,000032	kWh	Technosphere	
Output	Emission	CO	32,5	ug	Air	
Output	Emission	CO2	0,0607	g	Air	6,5556E-06
Output	Emission	HC	16,4	ug	Air	
Output	Emission	NOx	0,139	mg	Air	2,9607E-07
Output	Emission	N-tot	0,432	ug	Water	
Output	Emission	Particles	33	ug	Air	
Output	Emission	SO2	0,152	mg	Air	4,9704E-07
Output	Product	Electricity	1	kWh	Technosphere	
Output	Residue	Building waste	0,367	g	Technosphere	
Output	Residue	Other rest products	0,0131	g	Technosphere	
					SUM	0,000169621

Table 1 Calculation of external environmental cost from wind power generation. LCI data are from SPINE@CPM database (4). If the cable is used for 30 years and recycled with 98% efficiency (5) there will be an extra consumption of Cu resource of 54.8 tons corresponding to an external cost of 0.000317 €/kWh. The total external cost is therefore 0.000487 €/kWh.

Directio	FlowType	Substance	Quantity	Unit	Environment	EUR/kg	EUR/TJ
Input	Resource	Bauxite	7.99	kg	Ground	0.2	1.598
Input	Resource	Chromium in ore	0.731	kg	Ground	84.9	62.0619
Input	Resource	Copper in ore	5.46	kg	Ground	208	1135.68
Input	Resource	Crude oil	478	kg	Ground	0.506	241.868
Input	Resource	Hard coal	1400	kg	Ground	0.0498	69.72
Input	Resource	Iron in ore	319	kg	Ground	0.961	306.559
Input	Resource	Lead in ore	0.0394	kg	Ground	175	6.895
Input	Resource	Lignite	414000	kg	Ground	0.0498	20617.2
Input	Resource	Manganese in ore	0.455	kg	Ground	5.64	2.5662
Input	Resource	Natural gas	392.3	Nm3	Ground	0.785	308.235
Input	Resource	Nickel in ore	0.299	kg	Ground	160	47.84
Input	Resource	Palladium in ore	0.0000000953	kg	Ground	7430000	0.708079
Input	Resource	Platinum in ore	0.000000108	kg	Ground	7430000	0.80244
Input	Resource	Rhodium in ore	0.000000101	kg	Ground	49500000	4.9995
Input	Resource	Uranium in ore	0.0947	kg	Ground	1190	112.693
Output	Emission	BOD	0.0371	kg	Water	0.002	0.0000742
Output	Emission	Cd	0.000000775	kg	Ground	10.2	0.0000079
Output	Emission	Cd	0.00928	kg	Air	10.2	0.094656
Output	Emission	CFC-11	0.00003	kg	Air	541	0.01623
Output	Emission	CFC-114	0.000793	kg	Air	1110	0.88023
Output	Emission	CFC-12	0.00000645	kg	Air	1040	0.006708
Output	Emission	CFC-13	0.00000405	kg	Air	1390	0.0056295
Output	Emission	CO	45.177	kg	Air	0.331	14.953587
Output	Emission	CO2	370979	kg	Air	0.108	40065.732
Output	Emission	COD	0.098	kg	Water	0.001	0.000098
Output	Emission	Cr	0.0237	kg	Water	20	0.474
Output	Emission	H-1301	0.000186	kg	Air	2200	0.4092
Output	Emission	H2S	0.0224	kg	Air	4.96	0.111104
Output	Emission	HCl	136.019	kg	Air	2.13	289.72047
Output	Emission	HF	13.80369	kg	Air	2.07	28.57
Output	Emission	Hg	0.0194	kg	Air	61.4	1.19116
Output	Emission	Hg	0.000000196	kg	Ground	61.4	0.0000120
Output	Emission	Hg	0.0000388	kg	Water	61.4	0.002382
Output	Emission	Methane	31.49704	kg	Air	2.72	85.6719
Output	Emission	N total	0.09817	kg	Water	-0.38	-0.03730
Output	Emission	N2O	1.84632	kg	Air	38.3	70.714
Output	Emission	NH3	1.800892	kg	Air	1.96	3.5297
Output	Emission	NMVOC	12.6	kg	Air	2.14	26.964
Output	Emission	NO3-	0.05258	kg	Water	-0.085806	-0.00451
Output	Emission	NOx	557.999	kg	Air	2.13	1188.5
Output	Emission	PAH	0.00358	kg	Air	64300	230.194
Output	Emission	Particles	257.6644	kg	Air	36	9275.9184
Output	Emission	Pb	0.0192	kg	Water	2910	55.872
Output	Emission	PO43-	0.138	kg	Water	0.0171875	0.00237
Output	Emission	SO2	3623.53	kg	Air	3.27	11848.9
						SUM	86107.90

Table 2 Calculation of external environmental costs from lignite burning. LCI data are from SPINE@CPM database (4)

Decision type 2, the alternative location decision

The choice is here between a location on shore or off-shore. Decisions are made both by authorities and investors, so there are two perspectives and two scenarios (new electricity and substitution of lignite based electricity). The society is apt to include full environmental costs in the economical aspect, while the investors focus on those environmental costs that may impose a financial risk. According to (6) “A megawatt (MW) of wind power capacity costs EUR 2.65 million to install in German seas, about a third more than British offshore projects, almost double German onshore wind power.” The investment on land would therefore be in the order of 500 million €.
Would the cost of environmental impacts justify such a choice?

For the investor, the eco-efficiency of the off-shore location was 99.0% when producing new electricity and 147% when substituting lignite based electricity. The eco-efficiency of a land based location will change due to lower investment cost lower electricy price (0.035€/kWh less subsidiaries) and higher environmental costs (Nuisance to people in the area).

The WTP for visual intrusion was determined by Ladenburg and Dubgaard (7) to about 122 Euros per household and year. Ladenburg and Dubgaard presented images of off shore located windparks to Danish citizens in a CVM study. They found however that young people value the visual intrusion to zero €. This raises the question of for how long the nuisance prevails. Besides there is a question of how many that are influenced. If we assume that young people stays tolerant with respect to wind power as they grow older, and that others keep their WTP values, it seems reasonable to use the figure 122 as an upper limit. If the wind park would be placed on the coast it could be viewed at most by people at 50 km distance. This is the distance where the curvature of the earth hides the wind park. Assuming 100 persons per km2 and a half circle with the radius of 50 km, there are 392500 people influenced. With 2 persons per household and 122€/household, the total WTP is 24 million €/year. Assuming a 30 years operating life time on the shore, this would give an environmental cost of 720 million €.
For new electricity this would give an eco-efficiency of (1.73-1.44)/1.73 = 17%.

This indicates that there are significant financial risks involved in the land based alternative and that the off-shore alternative is to prefer.

But if the new electricity replaces lignite based electricity, the eco-efficiency will increase to 66%, which still makes the off-shore alternative better (147%), but which is not too far from acceptable when comparing with the average eco-efficiency of economic activities (87%).

For the government, the added value in the offshore location may be seen as the production value of the electricity (0.11€/kWh) minus external environmental impact costs minus capital and operating costs. The value of introducing new technology is hardly possible to estimate with any meaningful accuracy. The only way of addressing this problem is to regard the subsidiaries as investments and estimates of how the government values future gains to the society. The economic value created for the government is 0.340 billion € for new electricity and 1.2 billion € for lignite substitute, giving eco-efficiencies of 95.7 and 170 % respectively for the off-shore location.

For the on-shore location the economic value created is negative for the new electricity scenario and 0.273 billion for the lignite substitution scenario, which would give an eco-efficiency of -113 %.

Thus the off-shore location is to prefer from the government perspective.

Decision type 3, the authorities permit/forbid of the offshore location

With an eco-efficiency of 94.7 % for new electricity and 170% for lignite substitution, the offshore location is acceptable as it creates economic value with very low loss of environmental value.

Decision type 4, the end user's choice of electricity

For the end user, the eco-efficiency of electricity from the off-shore wind farm is (20 – 0.05)/20 = 99.6 % compared to 78% for lignite based electricity. From an eco-efficiency point of view, the wind based electricity is to prefer.

Sensitivity analysis

The assessments above are based on best estimates of relevant quantities and on several choices of methods and system boundaries. A sensitivity analysis is needed to see if any of these uncertainties or choices was of importance for the conclusions.

The uncertainties in the figures used are estimated as follows:
Investment in the offshore location: 1.0 billion € up to 1.2 billion €.
Production: 1.2 billion kWh/year in the interval 1.0 – 1.76 billion kWh/year (the top figure are claims from Prokon Nord)
Income: A lower income with loss of the offshore specific subsidiary is tested corresponding to 0,165 €/kWh.
Recovery of copper: assumed 98 %, could be as low as 95%.
Lifetime: assumed to be 30 years. Would a lifetime of 40 years change the conclusions?
WTP for visual intrusion: As young people do not object to visual intrusion it is reasonable to test a scenario, where the WTP for visual intrusion gradually decreases during the lifetime of the windpark, and approaches 60 €/household as an average.

The quantitative results of the sensitivity analysis are shown in table 3.

The sensitivity analysis shows no change of priorities for any of input parameters, but the shore location may be acceptable to the investor and to the government if the production is as high as 1.76 billion kWh/yr or if the WTP for intrusion decreases to 60 €/household and year in those cases where the electricity produced substitutes lignite based electricity.

Input value\issue	Value	Invest		Location, investor		Location, investor		Location, gov.		Location, gov.		Permit		Consumer	
		new el	lignite	new electricity		lignite substitute		new electricity		lignite substitute		new el	lignite		
				Offshore	Shore	Offshore	Shore	Offshore	Shore	Offshore	Shore			Borkum	Lignite
Investment, billion €, best estimate	1	99.0	147.3	99.0	17	147.3	66	95.7	n.a	170.5	-113	94.7	170.4	99.6	78.3
Investment, billion €, high value	1.2	99.1	153.3	99.1	12	153.3	64	89.6	n.a	184.6	-237	89.6	184.6	99.6	78.3
Billion kWh/year, best estimate	1.2	99.0	147.3	99.0	17	147.3	66	95.7	n.a	170.5	-113	94.7	170.4	99.6	78.3
Billion kWh/year, low value	1	98.7	155.8	98.7	-12	155.8	44	64.2	n.a	191.9	547	64.2	191.9	99.6	78.3
Billion kWh/year, high value	1.76	99.6	138.2	99.6	51	138.2	94	99	-538	151.6	88	99	151.6	99.6	78.3
Income, €/kWh, best estimate	0.2	99.0	147.3	99.0	17	147.3	66	95.7	n.a	170.5	-113	94.7	170.4	99.6	78.3
Income, €/kWh, decreased subsid.	0.165	98.8	168.8	98.8	17	168.8	66	95.7	n.a.	170.5	-113	95.7	170.5	99.6	78.3
Consumer price, €/kWh, present	0.11	99.0	147.3	99.0	17	147.3	66	95.7	n.a	170.5	-113	94.7	170.4	99.6	78.3
Consumer price, €/kWh, high	0.13	99.2	147.3	99.2	17	147.3	66	97.8	n.a.	155.7	2	97.8	155.7	99.7	81.6
% recovery of copper, best estimate	0.98	99.0	147.3	99.0	17	147.3	66	95.7	n.a	170.5	-113	94.7	170.4	99.6	78.3
% recovery of copper, low value	0.95	98.4	146.6	98.4	17	146.6	66	95.7	n.a.	155.3	2	95.7	155.3	99.4	81.6
Lifetime, years, best estimate	30	99.0	147.3	99.0	17	147.3	66	95.7	n.a	170.5	-113	94.7	170.4	99.6	78.3
Lifetime, years, high estimate	40	99.2	156.7	99.2	-1	156.7	59	96.3	n.a.	171.3	-332	96.3	171.3	99.7	78.3
WTP for intrusion, €/houshold&yr, best estimate	122	99.0	147.3	99.0	17	147.3	66	95.7	n.a	170.5	-113	94.7	170.4	99.6	78.3
WTP for intrusion, €/houshold&yr, low estimate	60	99.2	147.3	99.2	59	147.3	109	95.7	-403	170.5	115	95.7	170.5	99.6	78.3

Table 3 Sensitivity analysis of Eco-efficiency results. The n.a. notes in the shore column is caused by negative economic results, for which the eco-efficiency algorithm is not valid.

Discussion of results

The results show clear indications of which alternative to choose. The difficult question to answer is what is acceptable. If other design aspects would favour the shore alternative, would for example 66% eco-efficiency be acceptable?

One benchmark to compare with is the global average eco-efficiency of 87%. If the decision resulting in 66% eco-efficiency would compete with average investments, like for a bank, 66% would not be acceptable if SD was a commitment.

Another is 100 – %GNP growth. As long as the growth value of economic activities is more than the values taken out of the environment, there is at least a weak sustainability. (The concept of weak sustainability allows trade-offs between different sustainability aspects, strong sustainability does not)

Still another benchmark is the average or leading product of a certain type. If a customer wants a refrigerator, the choice is between refrigerators and the eco-efficiency of refrigerators is a reasonable benchmark. In our case the customer's choice is between wind power electricity and lignite based electricity.

Conclusions

Not surprisingly, the eco-efficiency for wind power generated electricity is high, and the off-shore based alternative is to prefer.

Different values for the eco-efficiency indicator is obtained for different actors, but the recommended alternatives are the same.

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