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Evaluating the Economic Efficiency of the Technologies for Greenhouse Gas Footprint Reduction

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Several conflicting objectives, like economic benefits and environmental impacts, has to be taken into account when evaluating the footprint reduction technologies. These problems are often dealt with by multi-objective optimization yielding a set of the Pareto non-dominated solutions. Although the Pareto curves provide useful information, deeper insights are needed for investment decision-making in order to establish suitable relationships between lost economic efficiency and improved environmental performance. This contribution presents the methods for the economic evaluations of the technologies for greenhouse gas footprint reduction within the Pareto region. Based on the incremental analysis, a new combined economic/environmental measure, called a 'Marginal Footprint' is defined. As long as its value remains higher than one or lower than minus one for those economic criteria to be maximized or minimized, the savings originating from footprint reduction would be larger than the loss of the economic potential. This sub-interval of the Pareto region could be regarded 'as low footprint as reasonably practicable'. The incremental variation of the economic potential for reducing one footprint unit is determined, and compared to the reference values in order to determine a priority ranking of a particular technology to be applied for greenhouse gas footprint reduction.

1. Introduction

Industries are highly motivated to improve the economic and environmental efficiencies of their processes. The main aims are increasing the efficiency of energy and material usage, reducing the emissions and various footprints (Čuček et al., 2015), and maximizing the economic value (Yancy-Caballero et al., 2015). A variety of alternative technologies are available to achieve these usually conflicting goals leading to a multi-objective decision-making. While some of these technologies increase the cost, e.g. CO_2 capture and storage (Man et al., 2014), the others may earn profit by improving energy efficiency of processes as Process Integration, see Klemeš and Kravanja (2013). Industrial implementations have been published elsewhere - heat exchanger network, distillation columns and furnaces by Varga et al. (2009), producing bioenergy from waste (Drobež et al., 2012) and Waste-to-Energy (WTE) network synthesis for Municipal Solid Waste by Ng et al. (2014). Integrating renewables into Total Sites (Liew et al., 2014) and supply networks (Kiraly et al., 2013) are some other options. The alternatives for greenhouse gas (GHG) footprint reduction are often evaluated with regard to the operating cost and capital investment (Xiang et al., 2014a) as well as CO_2 removal and avoidance cost (Cormos, 2014). During the evaluation and decision-making, the capability of long-term economic value creation, and the life cycle footprint assessments of such alternatives should be also taken into account (Vujanović et al., 2014). The appropriate economic criteria have to be applied for achieving the economically and environmentally efficient processes (Novak Pintarič and Kravanja, 2015). Multi-objective optimization generates a set of Pareto solutions from which a single final solution should be selected suitable for the investors as well as for the environment and society. The objective of this contribution is to highlight the relationships between the loss of the economic efficiency and GHG footprint reduction when deviating from the economically optimal solution. The following important issues are addressed: i) how much GHG emissions can be saved at a reasonable decrease of

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the economic value, ii) what are the amounts of the increased cost or lost profit or net present value for footprint reduction, iii) what influence would the environmental taxes have on decision-making when striving for suitable trade-offs among the economic benefits, sustainability and social responsibility of the processes.

2. Economic evaluations of footprint reduction

Economic and environmental objectives are most commonly conflicting, and consequently, maximizing the economic benefits would not produce the same optimum solutions than minimizing the environmental impacts. The investors can be naturally interested to invest their money into the projects at the highest economic advantage even if the environmental impacts of these solutions are not at the minimum achievable values. Every deviation from the economic optimum would reduce their profit and increase the cost, but on the other hand, the environmental impacts would be lesser, yielding more sustainable and socially responsible processes. The question arises to what extent it would be reasonable to decrease the economic benefits in order to reduce the footprints.

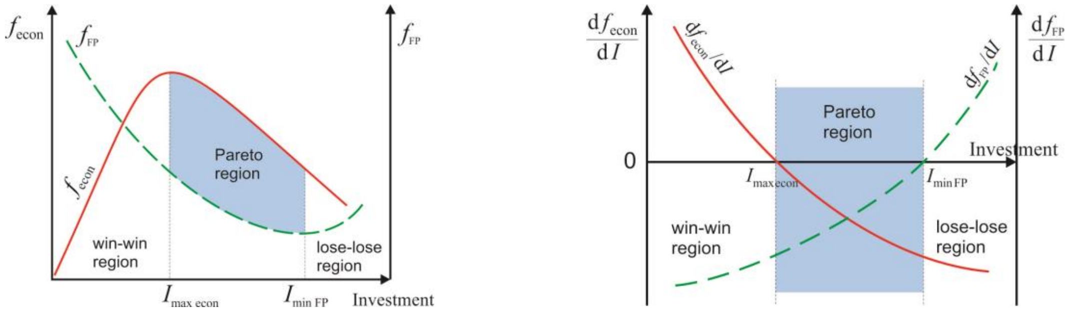
Footprints reductions are typically connected with investing money into suitable technologies. Figure 1a represents the variations of the economic measure, f_{econ}, and the footprint, f_{FP}, with regard to the investment. The maximized economic objectives, like a profit or net present value (NPV) would rise with increasing investment up to the maximum level $I_{\text{max econ}}$ (solid red line). Above this investment level the profit or NPV would decrease. The environmental footprint (dashed green line) decreases with investment, and achieves its minimum value at $I_{\text{min FP}}$. If the objectives are conflicting, both investment levels would be different, thus yielding the Pareto region between $I_{\text{max econ}}$ and $I_{\text{min FP}}$. In most cases, the optimum investment level for maximum economic benefit would be lower than for minimum footprint because more investment into footprint reduction technologies is required to achieve lower environmental impacts. At those investment levels below $I_{\text{max econ}}$ both objectives are improving yielding a win-win region. To the right of the $I_{\text{min FP}}$, both objectives get worse yielding lose-lose region.

The incremental analysis reveals the rate of changes, and stationary points for both objectives at the intersections of derivative curves with the investment axis (Figure 1b). The Pareto region is defined between the two stationary points. It can be seen in Figure 1 that the preferential selection for the investors would be the point of the maximum economic efficiency, assuming the legal environmental norms are fulfilled. From the sustainability point of view, further investing would be desired for reducing the footprint as low as possible. The question is how low would be reasonable to reduce a footprint in order to attain suitable compromise between the economic loss and environmental impact reduction. The following two indicators are defined for resolving this issue:

a) Let us define a novel parameter called the Marginal Footprint (MFP), η_{MFP}:

$$\eta_{\text{MFP}} = \frac{\Delta f_{\text{FP}} \cdot c_{\text{eco}}^{\text{int}}}{\Delta f_{\text{econ}}} \tag{1}$$

Δf_{FP} in the nominator represents the reduction of the footprint expressed either on an annual basis if an annualized economic objective is applied, e.g. profit, or as the total reduction during the life time if the NPV is used. $c_{\text{eco}}^{\text{int}}$ is the company's internal footprint cost determined, for example, by the pollution tax or virtual eco-cost coefficient (Vogtländer, 2010). The latter represents the money which should be spent for reducing the environmental pollution to a sustainable level.



a) b)

Figure 1: Economic and footprint objectives vs. investment (a), the derivatives vs. investment (b)

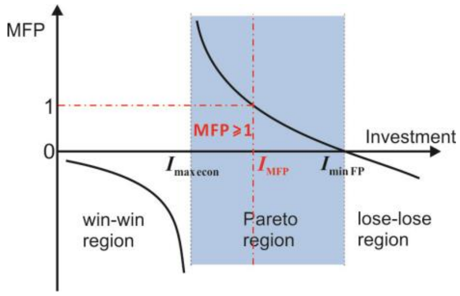


Figure 2: Marginal footprint for maximized economic objective

For example, the eco-cost of the CO_2 emission in 2012 was reported to be 135 €/t (TU Delft, 2012), which means that investment in CO_2 reduction technologies at that price or lower should be applied for reducing the pollution. MFP then represents a dimensionless ratio between those savings originating from the footprint reduction, and lost economic value which is the result of the deviation from the economic optimum because of decreased footprint. Theoretically, the values of MFP may vary from negative to positive infinity (Figure 2). Assuming that the economic objective is maximized, like the profit or NPV, then it follows:

- Negative values of MFP mean that each monetary unit of the increased profit would result in the savings originating from decreased footprint (win-win situation), or every unit of lost profit would lead to additional cost due to increased footprint (lose-lose situation).
- Positive values of MFP would be obtained within the Pareto region where the lost profit would lead to decreased footprint cost, i.e. savings. Moreover, MFP values larger than 1 imply that every EUR of lost profit would result in more than one EUR of footprint reduction savings.
- The threshold value of MFP=1 represents a margin where the reduced economic benefit equalizes with the savings from the footprint reduction. It could be argued that at the investment level I_{MFP} where MFP=1 the footprint would be ‘as low as reasonably practicable’, and the investors would lose as much units of profit as they will earn from environmental impact reduction. It is therefore a fair win-lose situation which leads to environmentally and socially more responsible process solutions, yet still economically attractive.

b) Another important indicator for the economic viability of the footprint reduction technologies is the incremental ‘cost’ of the saved emissions. This price is measured as the incremental change of the economic figures, like the cost, profit or NPV, subject to the change of the footprint:

$$\eta_{\mathrm{CFR}} = \frac{\Delta f_{\mathrm{econ}}}{\Delta f_{\mathrm{FP}}} \tag{2}$$

where η_{CFR} represents the incremental cost of footprint reduction (CFR), e.g. in €/t CO_2, which measures a company’s internal eco-cost of CO_2 emissions. It measures the economic losses or gains expressed as increased or decreased cost, profit or NPV per unit footprint reduction. The obtained CFR values can be compared with the reference values if they exist, for example the eco-cost (Vogtländer, 2010). Those technologies with the CFR lower than the reference could be regarded as cheaper, and should preferably be selected.

If the cost is minimized, the negative values of CFR would imply that the footprint reduction is connected with the increased cost (win-lose, Pareto), while positive values would indicate win-win or lose-lose situations. When maximizing the profit or NPV, the positive values correspond to the Pareto region where the reduced footprint would decrease the profit or NPV, while negative values represent lose-lose or win-win cases. The win-win situations could occur for those technologies that utilizes wastes and/or renewables for production of energy and useful products. High savings could be also derived by installing GHG footprint reduction technologies within the existing plants in the case of high emission taxes.

3. Examples

The above described analyses are applied to two case studies: optimal Heat Exchanger Network (HEN) design, and the analysis of the coal-to-olefin process with carbon capture and storage (CCS). The effects of carbon tax are studied in both examples.

3.1 Optimization of Heat Exchanger Network

Heat integration is one of the more efficient engineering measures for reducing the utility usage, and consequently the emissions, and footprints.

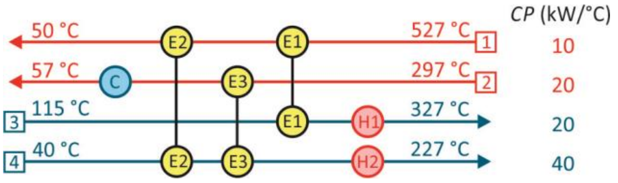


Figure 3: A Grid Diagram of a HEN case study

However, larger heat exchanger units produce more environmental impacts during the manufacturing and installation. There are several conflicts among the economics, decreased environmental impacts from operation of integrated HEN, and increased emissions from its manufacturing.

Figure 3 represents the case-studied HEN which is optimized by maximizing the net present value of the retrofitted network related to the non-integrated streams utilized by the external utilities. The GHG footprint is evaluated as proportional to the Global Warming Potential (GWP) expressed as the annual equivalent CO_2 emission originating from the utility usage, and HEN construction. The latter is determined by using the EIO-LCA on-line tool (Carnegie Mellon University Green Design Institute, 2008) which estimates the emissions produced during the construction of specific equipment or plant based on the invested funds.

The NPV curves at different carbon tax values (solid lines in Figure 4) show that the optimum investment level increases with the carbon tax. The GWP firstly decreases with the investment (green dashed line) because those reduced emissions resulting from the lower utility usage prevail over the increased emissions during the construction of larger HEN. Minimum GWP value of 3,327 t/y CO_2 is achieved at the investment level of 1.393 M€. Above this value the increasing emissions from HEN's construction becomes dominant. The largest Pareto region is obtained at zero carbon tax, while higher carbon tax values diminish the Pareto regions.

The incremental analyses at different carbon tax rates are shown in Figure 5. At 10 €/t CO_2, the marginal footprint (MFP) reaches a value of one at the investment level 1.130 M€, which corresponds to the GWP level of 3,434 t/y CO_2, and lies in-between the maximum and minimum values, 3,443 t/y and 3,327 t/y. The region between the investment level of maximum NPV at 10 €/t carbon tax (1.122 M€) and investment level with MFP = 1 (1.130 M€) can be considered as the region of reasonable decline in the economic benefit in return for higher savings from the reduction of the environmental impact. At higher carbon tax values, the MFP investment levels would increase resulting in lower CO_2 emissions.

Based on the incremental analysis, the incremental cost for reducing CO_2 emissions (CFR) is derived when deviating from the maximum NPV solutions (Figure 6). Taking the eco-cost of 135 €/t as the reference for CO_2 pollution prevention cost, the GWP values should be reduced by 41 t/y, 52 t/y, 58 t/y, and 64 t/y at (60, 30, 10, and 0) €/t carbon tax. These would correspond to 1.20 %, 1.52 %, 1.71 %, and 1.86 % reductions of GWP with regard to the optimum NPV solutions.

3.2 Analysis of coal-to-olefins process with CCS

This example is taken from (Xiang et al., 2014b) where detailed techno-economic analysis of coal-to-olefins process without and with CO_2 capture and storage (CCS) technology is presented. Based on the data provided in the paper, the incremental analysis of CCS installations is carried out at various CO_2 capture rates that require different incremental investment with regard to the process without CCS. The incremental NPVs are calculated at three values of carbon tax: 0 €/t, 25 €/t and 50 €/t CO_2 (solid lines in Figure 7).

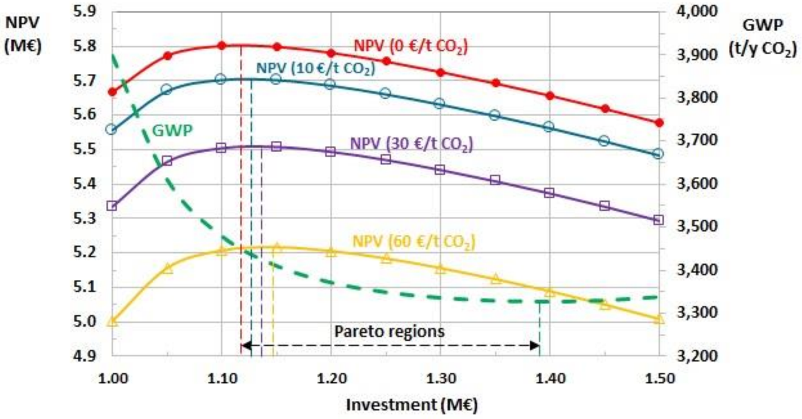


Figure 4: NPW and GWP vs. investment for HEN case study

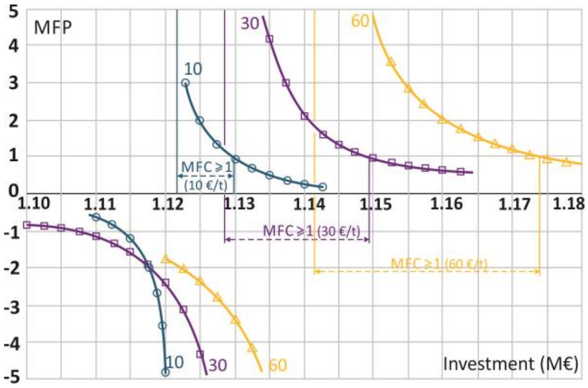


Figure 5: Marginal footprint analysis of HEN

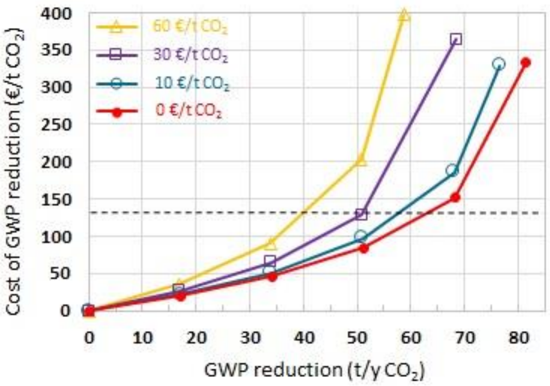


Figure 6: Cost of GWP reduction in HEN

Green dashed line represents the reduction of CO_2 emission. The marker points correspond to the CO_2 capture rates of 60 %, 70 %, 80 %, 90 %, and 95 %. At zero carbon tax the incremental NPVs of all CCS options are negative, and coal-to-olefin process with CCS is not an optimal choice. At 25 €/t carbon tax, however, the optimum is obtained at 70 % CO_2 capture rate which requires the additional investment of around 136 M€. At 50 €/t CO_2 tax, the optimum CCS would be at 90 % capture rate at the incremental investment of 153 M€. The marginal footprint (MFP) at carbon tax 50 €/t is above one only for 95 % CO_2 reduction rate (Figure 8). This implies that deviation from the optimal 90 % capture rate to 95 % would be acceptable because the savings from the reduced carbon tax would exceed the lost NPV. At 25 €/t CO_2 tax, the MFP values are highly above one for 80 % and 90 %, while it is close to one for 95 % capture rate. Deviations from the optimum (70 %) would be therefore reasonable. The incremental cost of CO_2 reduction is between 15 €/t and 22 €/t in the case without carbon tax (Figure 9), while at 25 €/t and 50 €/t CO_2 the incremental cost is negative meaning that the saving is earned from the saved CO_2 emissions.

4. Conclusion

This paper presents a novel approach to economic evaluations of projects where the trade-offs need to be established between the economic efficiency and environmental impacts. The Pareto regions are analysed with regard to the variations of the footprint subject to the deviations of the economic objective. A new indicator is proposed, called the Marginal Footprint, which indicates the sub-region of the Pareto region in which the reduction of footprint expressed in monetary unit is higher than the economic loss. This indicator expresses a sort of ′environmental return′ on the economic criteria by providing the amount of footprint which could be saved by each monetary unit of lost (invested) economic criterion. A threshold value of the Marginal Footprint equal to 1 determines a boundary investment level which could be considered as the solution with ‘as low footprint as reasonably practicable’. The economic impacts of deviating from the economically more efficient solution can be evaluated by the parameter ‘cost of footprint reduction’ which measures the incremental cost, profit or NPV per unit footprint reduction. By comparing these values with benchmarks if there exist, the footprint reduction technologies could be ranked with regard to the priority for the application.

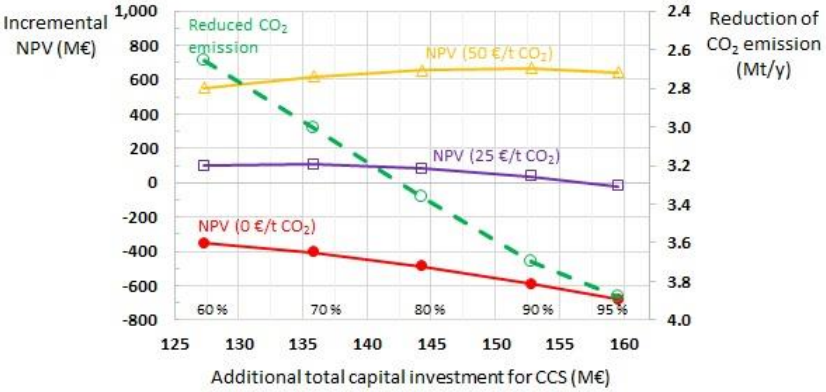


Figure 7: Incremental analysis of CCS technology

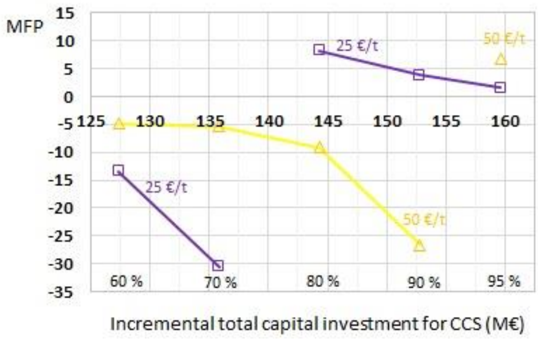


Figure 8: Marginal footprint analysis of CCS technology

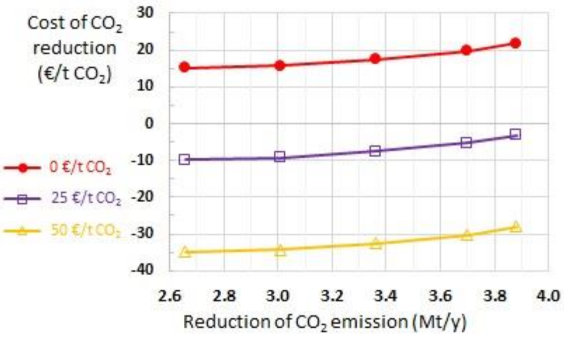


Figure 9: Cost of CO_2 emission reduction

The proposed novel indicators could be useful for investment decision-making when balancing the conflicting objectives for final selection of process design that would be acceptable to the investors, environment and society.

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