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DOCTORAL DISSERTATION

Economic and environmental benefits of technology fusion of solar photovoltaics with alternative technologies

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Samenvatting

"Technology fusion" of "het fusioneren van technologieën" verwijst naar het samenvoegen van bestaande technologieën om zo nieuwe markten en groeimogelijkheden te creëren. Bij "technology fusion" is één plus één gelijk aan drie. Dit is ook het geval wanneer de photovoltaic (PV) of fotovoltaïsche zonnecellen gefusioneerd worden met alternatieve technologieën; naast de reductie van broeikasgassen zijn er nog bijkomende voordelen zoals het verminderen van gebruikte landoppervlaktes, het verminderen van het effect van variabiliteit van hernieuwbare energiebronnen en het verbeteren van technologische prestaties. Deze sociale en technische voordelen gaan helaas vaak gepaard met hogere kosten, wat een hinderpaal kan vormen voor grootschalige implementatie. Elke rationele investeerder gaat immers enkel investeren in de combinatie van technologieën als dit hem meer winst zou opleveren. Beleidsmakers zijn vooral bezorgd om het potentieel van technologieën om op kostenefficiëntie manier vervuilende emissies te reduceren. Er is dus een sterke behoefte voor zowel private investeerders als voor beleidsmakers om de economische en ecologische prestaties van gecombineerde technologieën te evalueren. Hiertoe worden in dit doctoraat economische en ecologische beoordelingsmethodes voorgesteld en toegepast op verschillende gevalstudies van PV gefusioneerd met alternatieve technologieën, met als doel het ondersteunen van beslissingsnemers.

De economische en ecologische impact van gecombineerde technologieën kunnen geïntegreerd worden in een enkele monetaire maatstaf wanneer de externe milieu-impact gemonetariseerd wordt, bijvoorbeeld met behulp van een milieu kosten-batenanalyse. In Hoofdstuk 2 wordt deze methode gedemonstreerd met een case van een PV geluidsscherm. Deze werkwijze is geschikt om de winstgevendheid van gecombineerde technologieën te vergelijken, ze laat echter niet toe om de beperking van een gelimiteerd investeringskapitaal mee in rekening te brengen. Hoewel er wel "rationing capital" modellen met betrekking tot het verdelen van een gelimiteerd kapitaal bestaan in de literatuur, is er geen systematische methode voorhanden om de winstgevendheid van een willekeurige combinatie van

technologieën te berekenen. In Hoofdstuk 3 wordt een methode ontwikkeld om de winstgevendheid van individuele technologieën te vergelijken met deze van de geïntegreerde combinatie onder budgettaire beperkingen. Als de winstgevendheid van de gecombineerde technologie groter is dan die van de individuele technologieën, dan zijn er "benefits of combined technologies" (BOCT) of "voordelen van gecombineerde technologieën". De aanwezigheid van BOCT hangt af van het beleid, de eigenschappen van de technologie zelf en de marktomstandigheden die kunnen leiden tot non-lineariteiten wanneer technologieën gecombineerd worden. Het model wordt geïllustreerd met een case over zonnepanelen en elektrische wagens voor een Belgisch bedrijf.

Tegenstanders van milieu kosten-batenanalyses geven aan dat het monetariseren van externaliteiten een subjectieve materie is. Rekening houdend met dit argument, worden gecombineerde technologieën in dit werk ook beoordeeld op basis van de mitigatiekost. Beleidsmakers kunnen gebruik maken van de mitigatiekost om in te schatten hoeveel emissies verminderd kunnen worden aan welke prijs en waar beleidsinterventie nodig is om bepaalde emissiedoelstellingen te bereiken. Deze werkwijze laat toe om een beoordeling te maken over het potentieel van technologieën om op kostenefficiënte wijze emissies te reduceren, zonder het gebruik van monetarisatie. In Hoofdstuk 4 wordt een algemeen kader ontwikkeld dat toelaat om de mitigatiekost van individuele en gecombineerde technologieën te vergelijken onder een beperkt budget. Dit wordt toegepast op een case van zonne-energie, elektrische wagens opgeladen met elektriciteit van het net en opgeladen met zonne-energie voor een Belgisch bedrijf. In termen van kostenefficiënte emissiereductie is het voor het bedrijf voordeliger om te investeren in elektrische wagens dan om zonnepanelen te plaatsen.

Hoewel een beoordeling op basis van de mitigatiekost geschikt is om technologieën te evalueren in termen van kostenefficiënte emissiereductie, laat deze methode niet toe om de afweging tussen de economische en de ecologische impact te kwantificeren. Om hieraan tegemoet te komen, wordt in dit eindwerk gebruik gemaakt van multi-objectief optimalisatie. Naast het rangschikken van technologieën op basis van kostenefficiënte emissiereductie, laat deze methode toe om *(i)* een overzicht te geven van *alle* oplossingen die optimaal zijn vanuit economisch en ecologisch standpunt; *(ii)* de trade-off tussen economische en ecologische prestaties te kwantificeren en *(iii)* een optimale mix van technologieën samen te stellen. In Hoofdstuk 5 tonen we de meerwaarde aan van een multi-objectief aanpak naast de evaluatie op basis van de mitigatiekost, toegepast op twee cases van verlichting op basis van zonne-energie (draagbare LED verlichting en "solar home systemen") binnen het Clean Development Mechanism. De lineaire multi-objectief analyse toont aan dat "solar home systemen" zowel op economisch als op ecologisch vlak beter presteren dan de draagbare LED verlichting. In Hoofdstuk 6 breiden we de multi-objectief optimalisatie uit door schaalvoordelen mee in rekening te brengen. Schaalvoordelen zijn van nature uit discreet en impliceren het gebruik van gemengd integer programmeren. In de veronderstelling dat de relaties lineair zijn, leidt dit tot een multi-objectief gemengd integer lineair programmeringprobleem. In dit doctoraat wordt voor het eerst het uniek algoritme toegepast dat ontwikkeld werd om dit type problemen exact op te lossen (Vincent, Seipp et al. 2013). De methode wordt geïllustreerd met een Belgisch bedrijf dat tracht de optimale combinatie van technologieën te vinden die voldoet aan hun energie- en transportbehoeften en gelijktijdig de economische kosten en de broeikasgas emissies minimaliseert. Beschikbare technologieën voor elektriciteit zijn PV en het net, voor transport hebben ze de keuze uit benzinewagens, elektrische wagens aangedreven door netstroom en elektrische wagens aangedreven door zonne-energie. Het optimale Pareto front laat duidelijk de afweging zien tussen de economische en de ecologische prestaties. Elektrische wagens aangedreven door elektriciteit van het net zijn de minst dure optie om emissies te vermijden, gevolgd door zonnepanelen en elektrische wagens opgeladen met zonne-energie. Het nadeel van deze methode is dat complexe problemen vaak moeilijk te modelleren zijn, wat kan leiden tot dure oplossingsprocedures. Om te bepalen welke methode geschikt is voor de beslissingsnemer moet er een afweging gemaakt worden tussen kosten en tijd enerzijds, en volledigheid van de oplossingen anderzijds.

Summary

Technology fusion refers to the blending of several previously separate fields of existing technology, creating novel markets and growth opportunities. In technology fusion, one plus one equals three. This is indeed the case when fusing solar PV with alternative technologies: besides greenhouse gas emission reductions, additional advantages such as the savings of scarce land area, grid independency, diminishment of the effect of power variability of intermittent clean energy sources, and increased system performances can be established. These social and technical advantages however often come at increased economic costs, implying a barrier for wide-scale implementation. Moreover, any rational investor will only invest in a combination of technologies, if this is economically profitable. Furthermore, the policy makers' major concern is the technologies' cost-efficiency to decrease polluting emissions. Hence, there is a strong need for private investors and for policy makers to evaluate economic and environmental performances of combined technologies. This doctoral dissertation fills this gap by providing economic and environmental assessment methods applied to three different cases of solar PV combined with alternative technologies, aiming to support decision making.

Economic and environmental performances of combined technologies can be integrated into a single monetary measure only if external environmental aspects are quantified in monetary terms or hence monetized. Such a technology assessment can be conducted by using an environmental cost benefit analysis (CBA). This approach is demonstrated in Chapter 2, in which economic and environmental performances of a photovoltaic noise barrier are integrated into one monetary measure. This approach is straightforward to support the decision maker in comparing the profitability of combined technologies, yet it does not allow comparing projects under budgetary constraints. Nonetheless, any rational investor will only opt to implement the combined technology if the latter is more profitable. Despite the existence of rationing capital models, a systematic method to calculate the joint payoff of a random combination of technologies is missing in literature. In Chapter 3,

research is presented that is the first to provide a method to calculate and compare the economic payoff of individual complementary technologies with the payoff of their integrated combination, under budgetary limits. If the profitability of the combined technology exceeds that of the individual technologies, economic synergies or benefits of combined technologies (BOCT) are present. This methodology is applicable to perform an economic evaluation of any combination of complementary technologies. The existence of BOCT is not guaranteed; this depends on the policy measures provided for each technology, on the characteristics of the technology itself, and on the market conditions that may cause nonlinearities when combining technologies. The model is illustrated with a case of solar PV and battery electric vehicles (BEVs) for a Belgian company.

Opponents of environmental CBA argue that monetizing externalities is highly subjective. Recognizing this drawback, we propose in this doctoral thesis to assess combined technologies using a mitigation cost assessment. Policy makers can make use of the mitigation cost to determine how much abatement can be achieved at a certain economic cost and to assess where policy intervention is needed in order to achieve certain emission reductions. Such an assessment allows evaluating the technologies' cost-efficiency to decrease polluting emissions, while disregarding the aspect of monetization. In Chapter 4, we elaborate upon the traditional mitigation cost assessment by developing a framework that enables the comparison of the mitigation cost of individual and combined technologies, given the constraint of a limited capital for investment. The framework is illustrated with a case of PV solar power, grid powered battery electric vehicles (BEVs), and solar powered BEVs for a Belgian enterprise. In terms of cost-efficient emission reduction, the company gains more by replacing petrol fueled vehicles with grid powered BEVs than with installing solar panels.

While the mitigation cost analysis allows evaluating the cost-efficiency to decrease polluting emissions, it does not allow quantifying the trade-off between economic and environmental impacts of combined technologies. This dissertation encourages the use of a comprehensive multi-objective approach to overcome this drawback. Additional to ranking technologies in terms of cost-efficient emission reduction under budgetary constraints, this method *(i)* provides an overview of *all* the solutions that are optimal from economic and environmental viewpoint, *(ii)* allows the decision maker to quantify the trade-off amongst economic and environmental performances, and *(iii)* allows determining the optimal mixture of combined technologies under limited budgetary resources. In Chapter 5, we clearly demonstrate the added value of complementing the mitigation cost analysis with a multi-objective approach, applied to two types of rural solar lighting projects under the Clean Development Mechanism, *i.e.* portable solar LED lanterns and small-scale rural solar home systems (SHS). The relatively simple multi-objective linear programming analysis shows that solar LED lanterns are never part of the optimal solution frontier; in all cases they are outperformed by SHS. In Chapter 6, we extend the multi-objective approach by accounting for economies of scale. This inherently discrete phenomena implies the use of mixed integer programming. Assuming linear relations, this implies a multi-objective mixed integer linear programming (MOMILP) problem. This research is the first to apply the improved version of the only algorithm available to solve MOMILPs exactly (Vincent, Seipp et al. 2013). The approach is illustrated with a Belgian company that seeks to find the optimal combination of technologies to satisfy electricity and transportation demands under budgetary constraints, while minimizing environmental emissions and economic costs. Technologies at hand are solar PV and grid electricity to cover electricity needs, and internal combustion engine vehicles (ICEVs), grid powered battery electric vehicles (BEVs) and solar powered BEVs to cover transportation requirements. The Pareto frontiers clearly illustrate a tradeoff between economic and environmental performances. Grid BEVs are the least costly option to decrease environmental emissions, followed by solar PV panels and solar BEVs. The downside of this method is that complex problems are often hard to model, leading to expensive solution procedures. Hence, to determine the appropriate solution method to support the decision maker, trade-offs should be made in terms of cost and time on the one hand, and completeness of the solutions on the other.

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α	Annual system performance deterioration rate
#	Number
A	Amortization period
AHP	Average house price
ALP	Average lot price
AMS	Approved methodology for small-scale projects
AWV	Agentschap Wegen & Verkeer
β	Solar irradiation factor
B	Benefits
BEV	Battery electric vehicle
BOCT	Benefits of combined technologies
C	Cost
CBA	Cost benefit analysis
CDM	Clean Development Mechanism
CER	Certified emission reduction
CF	Cash flow
CO_2eq	Carbon dioxide equivalents
Cp	Crediting period
D	Distance travelled
dB	Decibel
DPBP	Discounted payback period
E_b	Baseline emissions
E_i	Project emissions
EID	Elevated investment deduction
Electr	Electricity
EOS	Economies of scale
ESUBS	Ecology subsidy
ET	Emissions Trading
Fuse	Fuel use
Gasol	Gasoline
TGC	Tradable green certificate
GHG	Greenhouse gas
GPRS	General Packet Radio Service
HFC	Hydrofluorocarbons

I_0	Initial capital
IC	Investment cost
ICEV	Internal combustion engine vehicle
IEA	International Energy Agency
INSC	Insurance cost
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal rate of return
JI	Joint Implementation
kWh	Kilowatt-hour
kWp	kilowatt-peak
L	Length
LCA	Life cycle analysis
LCC	Life cycle costing
LCE	Life cycle emissions
LED	Light emitting diode
lm	Lumens
m	Metre
MaC	Maintenance cost
MC	Mitigation cost
MOLP	Multi-objective linear programming
MOMILP	Multi-objective mixed integer linear programming
mon	Monitoring
MOO	Multi-objective optimization
n	Lifetime
N_2O	Nitrous oxide
NB	Noise barrier
NPV	Net present value
NSDI	Noise sensitivity depreciation index
η	PV system efficiency
O&M	Operation and maintenance
P	Price
$\dot{P}$	Annual price evolution
PBT	Payback time
P_{tot}	Total power
PV	Photovoltaics
PVNB	Photovoltaic noise barrier

Q	Costs
r	Discount rate
RNP	Reduced noise pollution
SHS	Solar home systems
SME	Small and medium sized enterprise
SUBS	Subsidies
t	Ton
T_0	One-off vehicle registration tax
T_d	Tax deduction
T_n	Annual traffic tax
T_r	Tax rate
UC	Unit cost
Val	Value
y	Year

1 Introduction

In this chapter, the need of decision makers to evaluate economic and environmental performances of combined technologies is demonstrated. We elaborate on the concept of technology fusion, and more specifically, we discuss the fusion of the solar PV technology with alternative technologies. Hence, a broad description of the solar PV technology, markets, environmental impacts and policies is given in section 1.1. The concept of technology fusion is described in section 1.2. Section 1.3 handles on the research questions that are tackled in this dissertation and section 1.4 concludes with a chapter overview.

1.1 Solar PV

1.1.1 Technology

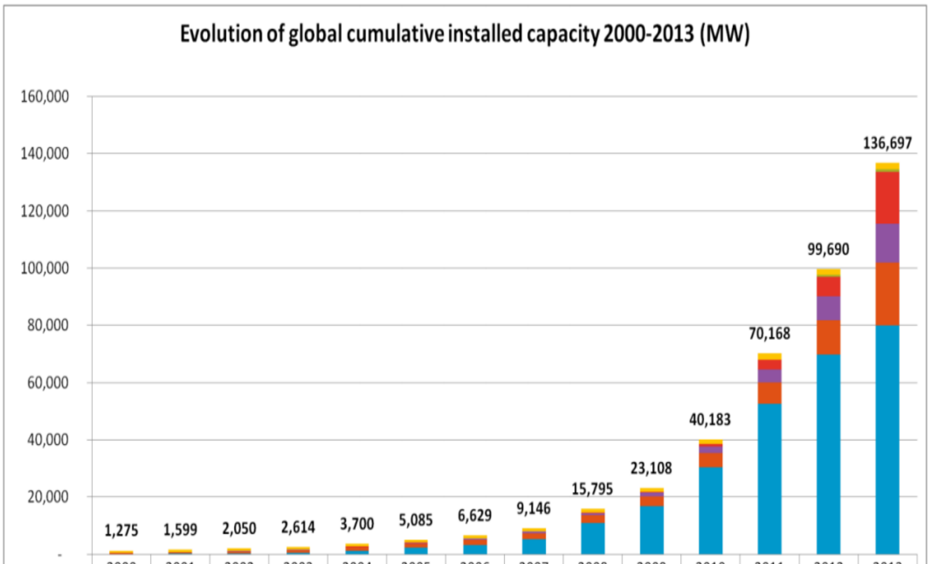
Solar energy is abundantly available; every hour the Earth receives more solar energy than is needed to meet the world's annual energy needs. Solar cells or photovoltaic (PV) cells can capture this solar energy and convert it directly into electricity by the photovoltaic effect. The photovoltaic effect, which was first observed by Becquerel in 1839 (Becquerel 1839), is the creation of voltage or electric current in a material upon exposure to light. To understand the photovoltaic effect, knowledge is required about the energetically lower lying valence band and the higher lying conduction band, which are energetically separated by a bandgap. Under thermal equilibrium, the valence band is fully occupied by immobile electrons and the conduction band is empty. When a photon (light) is absorbed, energy is transferred to a bound immobile electron in the valence band, which is then excited across the bandgap into the conduction band, eventually creating an electrical current (Bubenzer and Luther 2003).

1.1.2 Market

Silicon PV solar cells are on the market for more than 35 years (Nielsen, Cruickshank et al. 2010). Due to government support, falling costs, CO_2 pricing in some regions and rising fossil fuel prices, solar PV makes up an increasing share of primary energy use. From 2000 to 2010, electricity generation from solar photovoltaics has increased by 42% per year on average (International Energy Agency 2012). In 2013, the global cumulative installed capacity reached 136.7 GigaWatt, which represents a 35% increase compared to 2012 (Figure 1). This growth is largely due to an increase of new installations in the Asian market, led by China and Japan. European PV markets on the other hand have experienced a slowdown. While Europe concentrated more than 70% of the world's new PV installations in 2011, they accounted for only 28% of new installations in 2013, covering 3% of European electricity demand. This slowdown can be largely explained by retrospective measures that have negatively influenced investors' confidence and investment viability (European Photovoltaic Industry Association 2014).

1.1.3 Environmental impacts

Photovoltaic systems have a very low carbon footprint with no CO_2 emissions during operation. We note though that a relatively small amount of emissions is due to the energy required during the manufacturing process of the PV modules. The carbon footprint of PV systems -assuming a location in southern Europe- ranges from 16 to 32 gCO_2eq/kWh. This is negligible when compared to the carbon footprint of fossil fuels, which ranges from 300 to 1000 gCO_2eq/kWh. The carbon footprint of PV has decreased by approximately 50% in the last 10 years, owing to improved performances, raw material savings, and improved manufacturing processes. Moreover, the carbon footprint of PV electricity is expected to continue decreasing in the future. Hence, the use of solar PV provides significant environmental benefits compared to traditional fossil-fuel or nuclear technologies (European Photovoltaic Industry Association 2011).



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
ROW	751	807	887	964	993	1,003	1,108	1,150	1,226	1,306	1,590	2,098	2,098	2,183
MEA	-	-	-	-	1	1	1	2	3	25	80	205	570	953
China	19	24	42	52	62	70	80	100	140	300	800	3,300	6,800	18,100
AMERICA	21	24	54	102	163	246	355	522	828	1,328	2,410	4,590	8,365	13,518
APAC	368	496	686	916	1,198	1,502	1,827	2,098	2,628	3,373	4,951	7,513	12,159	21,992
Europe	116	249	381	580	1,283	2,264	3,258	5,274	10,970	16,777	30,352	52,462	69,699	79,952
TOTAL	1,275	1,599	2,050	2,614	3,700	5,085	6,629	9,146	15,795	23,108	40,183	70,168	99,690	136,697

Figure 1 Evolution of global cumulative installed capacity in MegaWatt from 2000-2013 (European Photovoltaic Industry Association 2014)

1.1.4 Policy

A wide range of government policies -including tradable green certificates, feed-in tariffs, and investment tax deductions- have been essential to recent growth in the photovoltaic sector. The key policy driver are environmental concerns, aiming to decrease emissions of carbon dioxide and local pollutants. Declining political support for PV has led to declining markets in several European countries, including Germany, Italy, France and Belgium. Conversely, new supporting measures in China and Japan have led to a growing, dynamic market in these countries (European Photovoltaic Industry Association 2014). The phasing out of policy measures in Europe goes hand in hand with the occurrence of grid parity. Grid parity refers to the moment at which the present value of the long-term earnings of the electricity supply from a PV installation equals the long-term cost of receiving traditionally produced and supplied power over the grid. This so-called grid parity has been reached in several European countries. Reaching grid parity is considered to be the point at which the energy source will be implemented without subsidies or government support. Indeed, as shown by the substantial regulatory policy changes in several countries in 2012, dedicated financial support as the main driver for PV development is progressively vanishing. In the coming years, deployment strategies will depend much more on the capacity of PV power to actively participate in the electricity system (European Photovoltaic Industry Association 2013).

1.2 Technology fusion: Combining solar PV with alternative technologies

1.2.1 Technology fusion

The concept of "technology fusion" is strongly related to the process of innovation. With an ever increasing pace of technological innovation, companies can no longer afford to miss out on a generation of technologies to remain competitive. A company can either replace an older generation of technologies –*i.e.* the "breakthrough" approach- or it can focus on combining existing technologies into hybrid technologies –*i.e.* the "technology fusion" approach. Technology fusion refers to the blending of several previously separate fields of existing technology. The fusion of technologies goes beyond the mere combination of technologies, creating novel markets and growth opportunities. It implies adding one technology to another to come up with a solution greater than the sum of its parts. In a world where the "one technology - one industry" is no longer applicable, a singular breakthrough strategy is inadequate; companies need to include both the breakthrough and fusion approaches in their technology strategies (Kodama 1991; Kodama 1992). Moreover, the more interdisciplinary cross-border research is required, the less a single company's existing capabilities are sufficient to provide successful innovations (Gassmann 2006). Recently, Protogerou et al. (2013) found that technology fusion is one of the major sources of contemporary innovations, and that EU collaborative networks have the potential to significantly contribute to forming technology fusion.

1.2.2 Advantages of fusing solar PV with alternative technologies

In technology fusion, one plus one equals three (Kodama 1992). This is indeed the case when fusing solar PV with alternative technologies. A first and straightforward social advantage is *(i) greenhouse gas emission reduction.* Amongst many other examples, this can be established when solar PV -rather than grid electricity- is used to power electric vehicles (Doucette and McCulloch 2011). A second social advantage is *(ii) savings of scarce land area*. The issue of competition for land has often been cited as an important concern for renewables. Amongst others, Nonhebel (2005) presented a review regarding the competition for land between renewable energy and food supply. This issue can be overcome by integrating solar PV on places that require no or a minimum of land use. Examples include building integrated photovoltaics (Petter Jelle, Breivik et al. 2012), agrivoltaic systems (Dupraz, Marrou et al. 2011), and photovoltaic noise barriers (Chapter 2). Thirdly, solar PV can be integrated into electricity consuming technologies to enable *(iii) grid independency*. This is of particular interest in rural areas -*e.g.* solar powered LED lighting (Durlinger, Reinders et al. 2012)- but it can also be interesting for developed countries -*e.g.* solar powered consumer electronics (Lizin, Van Passel et al. 2012). When combining solar PV with alternative technologies, technical synergies can be established as well. Moreover, one of the most crucial elements of future electricity systems is the capability for ”smart” controls to perform under real-time dynamics. Amongst other technologies, electric vehicles and heat pumps are very helpful for integrating more PV power by absorbing excess electricity in future smart electricity systems (Zhang, Tezuka et al. 2012). Hence, combining solar PV with alternative technologies can contribute to *(iv) diminishment of the effect of power variability of intermittent clean energy sources*. The implementation of hybrid photovoltaic thermal (PVT) collector systems on the other hand is one example in which the combination of photovoltaics with an alternative technology can lead to *(v) increased system performances* (Park, Pandey et al. 2014).

1.2.3 Barriers

The social and technical advantages of solar PV combined with alternative technologies may come at increased economic cost, implying a barrier for large-scale implementation. Moreover, any rational investor is bounded by a limited initial capital, and will only invest in the combination of technologies if this is advantageous from economic viewpoint. Hence, for private companies, evaluation of the economic profitability of combined technologies is a prerequisite for implementation. Moreover, investors face a problem of rationing capital among competing investment possibilities. The first pure rationing capital model was proposed by Lorie and Savage (1949). This model assumes the payoff of combined technologies to be given data. In literature, examples of the economic assessment of combined technologies can be found on a case-by-case basis: Amongst others, Mousazadeh et al. (2009) conducted an economic assessment of an agricultural vehicle using PV systems as a power source; Shaw and Peteves (2008) used a cost-benefit approach to evaluate the impact of linking wind and hydrogen energy sectors; and Wu et al. (2009) determined the economic feasibility of solar powered LED roadway lighting. Nonetheless, a systematic method to calculate the joint payoff of a random combination of technologies under budgetary constraints is missing in literature.

While the private investor's major concern for implementing combined technologies is profitability, policy makers are particularly interested in their potential to mitigate climate change. Moreover, they are concerned with the technologies' cost-efficiency to decrease polluting emissions. To this end, economic and environmental performances of combined technologies need to be quantified simultaneously. The economic costs and environmental impacts of individual clean technologies can be integrated into a mitigation assessment (Sathaye and Meyers 1995), and the technologies' costs for mitigation can be calculated accordingly. Moreover, policy makers can make use of the mitigation cost to determine how much abatement can be achieved at a certain economic cost and to assess where policy intervention is needed in order to achieve certain emission reductions. This mitigation cost assessment needs to be extended for combined technologies, considering the joint economic and environmental performances. Additionally, for policy makers as well as for private investors the trade-off between economic and environmental performances of combined technologies needs to be quantifiable in order to determine the optimal mixture of technologies. To this end, a multi-objective approach is required that minimizes economic costs and environmental emissions of the joint technologies.

1.3 Research questions

Given the advantages of combining solar PV with alternative technologies, we demonstrated the need of private investors and policy makers to evaluate economic and environmental performances of combined technologies. This dissertation fills this gap by answering the following main research question:

How can the economic and environmental performances of solar PV combined with alternative technologies be evaluated to support decision making?

In order to operationalize this research question, it has been subdivided in several subquestions which will be answered in the respective chapters of this dissertation as follows:

Subquestion 1: How can economic and environmental costs and benefits of combined technologies be integrated into one monetary measure?

A technology assessment including financial and environmental aspects can be conducted by means of an environmental CBA, which accounts for all costs and benefits -including externalities- of the related technologies (Hoogmartens, Van Passel et al. 2014). Accordingly, the external environmental aspects of the technologies need to be “monetized” or quantified in monetary terms. Results can then easily be summarized into one economic measure, *e.g.* the net present value. This approach is demonstrated in Chapter 2, in which we conduct an environmental CBA of a photovoltaic noise barrier, including monetization of the environmental benefits of emission and noise reduction. While applying the CBA approach as such allows integrating economic and environmental performances of combined technologies into one monetary measure, it fails to compare the profitability of different projects given a limited investment resource. This problem of rationing capital amongst competing investment opportunities is tackled in Subquestion 2. Further, we note that the monetization of environmental impacts is not straightforward. A possible manner to overcome this difficulty is addressed in Subquestion 3.

Subquestion 2: How can the profitability of combined technologies be assessed, given the constraint of a limited investment resource?

Notwithstanding plentiful social and technical advantages of combining solar PV with alternative technologies, any rational investor will only opt for the combined clean technology when the latter has a nonnegative economic payoff that exceeds the payoff of the single technologies, given budgetary restrictions. Moreover, investors face a problem of rationing capital among competing investment possibilities. The first pure rationing capital model was proposed by Lorie and Savage (1949). However, a systematic method to calculate the joint payoff of a random combination of technologies is missing. Moreover, no information is provided on the comparison of investing in the integrated combination of technologies with investing in their individual counterparts, given budgetary constraints. Chapter 3 fills this gap by developing a computational model -with a focus on the investor- that *(i)* calculates the economic payoff of individual complementary technologies and their integrated combination under budgetary constraints; *(ii)* quantifies economic synergies labeled “benefits of combined technologies” (BOCT) when combining complementary technologies; *(iii)* explains the rationalization behind BOCT.

Subquestion 3: How can economic and environmental performances of combined technologies be integrated into one measure without monetizing the environmental impacts?

Economic and environmental performances of combined technologies can be integrated by converting environmental impact figures to monetized measures, as is the case in environmental CBA (Subquestion 1). Applying a monetization approach as such however is not straightforward. Moreover, results of current monetization approaches can vary widely, due to subjective decisions based on subjective values and beliefs, as well as level of education, region, and monetary means (Krieg, Albrecht et al. 2013). Therefore, we propose in this dissertation to integrate economic and environmental performances by means of a mitigation cost assessment; an approach that does not require monetization. A mitigation cost assessment requires the assessment of both economic and environmental performances, for instance by means of life cycle costing and life cycle assessment. Based on this assessment, the mitigation cost of an individual technology can easily be calculated (Sathaye and Meyers 1995). In Chapter 4, we extend this traditional mitigation cost, allowing the calculation and the comparison of the mitigation cost of individual technologies and a combination of these technologies, given the constraint of a limited capital for investment. The approach is illustrated with a Belgian medium sized enterprise that seeks to evaluate the cost of emission reduction of solar PV, grid powered battery electric vehicles and solar powered battery electric vehicles under budgetary limits.

Subquestion 4: How can the integrated assessment of economic and environmental performances of combined technologies be used to evaluate the impact of policy and to develop policy recommendations accordingly?

In the light of climate change, establishing emission reductions in a cost-efficient manner is an important goal for society. Low (high) mitigation cost projects imply low (high) economic costs as well as high (low) avoided CO_2 emission reductions. A negative cost of mitigation means that the project provides net benefits to society, with the financial benefits outweighing the costs even before considering the value of reduced emissions. The mitigation cost analysis allows ranking technologies in order of decreasing cost of emission abatement or hence in order of increasing attractiveness for rational investors. Policy makers can make use of the mitigation cost to determine how much abatement can be achieved at a certain economic cost and to assess where policy intervention is needed in order to achieve certain emission reductions. In Chapter 4, we assess the impact of current Belgian policy measures on the cost-efficient emission reduction of solar PV, grid powered battery electric vehicles, and solar powered battery electric vehicles by comparing mitigation costs with and without subsidies, the latter accounting for all direct subsidies and taxes. In Chapter 5, the integrated assessment of economic and environmental performances is used to evaluate small-scale rural solar lighting projects under the Clean Development Mechanism. Based on the analyses, policy recommendations are provided.

Subquestion 5: How can the trade-off between economic and environmental performances of combined technologies be quantified in order to determine the optimal mixture of technologies?

Better environmental performances of combined technologies often imply a trade-off with increased economic costs. The decision makers (private investors as well as policy makers) necessitate quantification of this trade-off in order to determine the optimal mixture of technologies. Moreover, an overview of all possible solutions that simultaneously optimize economic and environmental performances is required, allowing the decision maker to opt for one of these solutions based on personal preferences. An appropriate method to calculate all optimal solutions considering conflicting objectives, is multi-objective optimization. This method has the additional advantage that the results are not dependent on a baseline or reference technology, the latter being the case in both the environmental CBA and the GHG mitigation cost methods. In Chapter 5, we demonstrate a straightforward multi-objective continuous linear programming approach to quantify the economic-environmental trade-off of small rural solar home systems and solar powered light emitting diode (LED) lighting. In Chapter 6, we apply a multi-objective mixed integer linear programming approach (considering economies of scale) to evaluate the economic-environmental trade-off of solar powered battery electric vehicles.

1.4 Chapter overview

In Chapter 1, we illustrated the need for decision makers to evaluate the economic and environmental benefits of combining solar PV with alternative technologies, while considering the impact of policy measures. In Chapter 2, we demonstrate how economic and environmental impacts of combined technologies can be integrated into a single monetary measure. Moreover, we conduct an environmental CBA of a photovoltaic noise barrier including monetization of two externalities; emission and noise reduction. In Chapter 3, we develop a computational model to calculate the profitability of a combination of technologies under budgetary constraints, allowing to determine the economic benefits of combining technologies (BOCT). The model is illustrated with a case of solar powered battery electric vehicles (BEVs). Chapter 4 shows how economic and environmental performances of combined technologies can be integrated into one measure without the need for monetization by calculating the mitigation cost of combined technologies (solar powered BEVs) under budgetary limits. Additionally, the technological and subsidized costs of mitigation are compared in order to evaluate the impact of policy. In Chapter 5, the integrated assessment of economic and environmental performances is used to evaluate small-scale rural solar lighting projects under the Clean Development Mechanism. Moreover, the added value of complementing the mitigation cost analysis with a multi-objective linear programming (MOLP) approach is demonstrated. Amongst other advantages, we point out that the results of multi-objective approaches are not dependent on a baseline or reference technology, as is the case in CBAs and mitigation cost analyses. Chapter 6 exemplifies how the trade-off between economic and environmental performances of combined technologies can be quantified in order to determine the optimal mixture of technologies while considering economies of scale by means of multi-objective mixed integer linear programming (MOMILP). An overview of

Chapters 2-6 is presented in Table 1. We end this dissertation with a conclusion of the findings in Chapter 7.

Note that this dissertation handles on three different case studies: solar PV combined with noise barriers (Chapter 2), with electric vehicles (Chapters 3, 4, and 6), and with lighting technologies (Chapter 5). On the one hand, the case of solar PV & electric vehicles is used three times to compare the impact of the different methods used. On the other hand, the cases of solar noise barriers and solar lighting have been studied as well to demonstrate that the proposed frameworks are valid for different cases.

Table 1 Economic and environmental assessment of combining solar PV with alternative technologies – Chapter overview

	Chapter 2	Chapter 3	Chapter 4	Chapter 5	Chapter 6
Method	Environmental CBA	Economic BOCT	Mitigation cost	Mitigation cost + MOLP	MOMILP
Case: solar PV combined with …	noise barrier	BEV	BEV	rural lighting	BEV
Economic impacts	☒	☒	☒	☒	☒
Environmental impacts	☒	☐	☒	☒	☒
Constraint of limited investment resource	☐	☒	☒	☐	☐
Evaluation of environmental performances without monetization	☐	☐	☒	☒	☒
Evaluation of policy impacts	☐	☐	☒	☒	☒
Results not dependent on reference technology	☐	☐	☐	☒	☒
Trade-off between economic and environmental performances in order to determine the optimal mixture of technologies	☐	☐	☐	☒	☒
Economies of scale	☐	☐	☐	☐	☒

2 Combining photovoltaics and sound barriers: An environmental CBA

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ABSTRACT

In the light of global warming, renewables such as solar photovoltaics (PV) are important to decrease greenhouse gas emissions. An issue regarding the implementation of solar panels on large scale, is the limited available area. Hence, it can be interesting to combine PV with alternative applications to reduce the requirements for land. One example is a photovoltaic noise barrier (PVNB), where a noise barrier located along a highway or railway is used as substructure for PV modules. Even though a PVNB is not a novel concept, the absence of economic assessments in literature can be a barrier to their wider implementation. In this chapter, a feasibility study of a hypothetical PVNB in Belgium is conducted, using a cost benefit analysis including a Monte Carlo sensitivity analysis. Besides purely economic aspects, also environmental benefits are monetized. The sensitivity analysis indicates that the environmental benefit of noise reduction, which is valuated using a noise sensitivity depreciation index applied to real estate prices, is of major importance in determining the net present value of the case study. On the contrary, the impact of reducing CO_2 emissions seems to be negligible when expressed in monetary terms. The results suggest that the PVNB is a profitable project when environmental benefits are included.

2.1 Introduction

To counter global warming, renewables are important to decrease greenhouse gas emissions. The sun provides the most abundant source of energy available. One way to capture this solar energy, is by the use of photovoltaic (PV) systems that convert the energy of the sun directly into electricity. In 2005, solar PV accounted for less than 0.1% of the worldwide energy supply, totaling less than 0.26% of all the renewables (IPCC 2007).

The International Energy Agency (2010) estimates its share of global generation to be only around 2% in 2035. One issue concerning the implementation of solar panels on a large scale, is limited available area. The issue of land use has often been cited as an important concern for renewable technologies. Several authors have estimated the total land use required to meet the electricity demand from PV (Turner 1999; Love, Pitt et al. 2003; Denholm and Margolis 2008; Fthenakis and Kim 2009). Further, numerous papers have been published about the competition for land between food and energy production (Nonhebel 2005; Dijkman and Benders 2010; Graebig, Bringezu et al. 2010; Rathmann, Szklo et al. 2010). All these papers stress the issue of limited space on a global scale, underlining the importance of minimizing the competition for available areas. Therefore, it can be interesting to look for alternative PV applications that reduce land requirements. Examples include PV on rooftops, building integrated PV (Jo and Otanicar 2011), agrivoltaic systems (Dupraz, Marrou et al. 2011), and PV sited in areas of low land quality such as brown fields (Denholm and Margolis 2008). Another example is a photovoltaic noise barrier (PVNB), where a noise barrier is used as substructure for the PV – modules (Nordmann and Clavadetscher 2004).

A PVNB is most appropriately located along a highway or railway nearby a densely populated area. This is an interesting theoretical concept for several reasons. Firstly, on these locations noise barriers are needed, since many local residents are affected by noise nuisance. Secondly, in a crowded area there is not much room available to install ground mounted PV, which makes a sound barrier an interesting alternative to mount PV on. Finally, when the energy supply system -in this case the PVNB- is located nearby the consumer, advantages of decentralized electricity generation are realized. Examples include reduced energy transportation costs, savings in primary energy consumption, and emission reduction of CO_2 and other pollutants (Karger and Hennings 2009). It should be noted that in a crowded residential area, a large surface is accessible to install roof mounted solar panels. Yet, there are many specific issues regarding the integration of PV panels in the roof structure. The roof tilt angle can significantly impact the efficiency of the panels (Yamawaki, Mizukami et al. 2001; Mondol, Yohanis et al. 2007; Ordóñez, Jadraque et al. 2010). Further, structural roof characteristics are not always ideally suited for the installation of solar panels. There can be a possible need for re-roofing within the lifetime of the PV array or the roof might be too unstable to support the transferred loads of solar panels (Barkaszi and Dunlop 2001). Also, the use of roof space for other applications such as heating, ventilation, and air conditioning installations or roof terraces should be taken into account (Izquierdo, Rodrigues et al. 2008). Additionally, it is possible that residents are not willing to accept the installation of solar panels on their roofs, due to concerns about economic and financial risks (whether the home insurance would increase, what would happen with the PV panels if the owner moved,…), health and safety concerns (roof damage, vandalism,…), and aesthetic concerns (Farhar and Buhrmann 1998). While we recognize that some of these drawbacks are also applicable for mounting PV on noise barriers, the need for an increased share of renewables in contrast to limited available ground space and the presence of noise barriers nearby residential areas can lead to a win-win situation where sound barriers -complementary to roofs- can be used as PV support structures.

PVNBs as an integrated concept were introduced in Switzerland in 1989 (Nordmann and Clavadetscher 2004). Studies about technical insights (van der Borg and Jansen 2001; Grottke, Suker et al. 2003; Nordmann and Clavadetscher 2004; Nordmann and Clavadetscher 2006) and the potential (Goetzberger 1999) of PVNBs in Europe are already published, but economic information is still missing. The aim of this study is to provide insights in the costs and benefits of PVNBs. More specifically, this research presents an environmental cost benefit analysis (CBA) including a Monte Carlo sensitivity analysis of a case study in Belgium, taking into account economic as well as environmental aspects. In section 2.2, the methodology is discussed. Section 2.3 presents a description of the case study and the results of the technology assessment. The chapter ends with a conclusion and a discussion of the findings in section 2.4.

2.2 Methodology

2.2.1 Environmental cost benefit analysis (CBA)

Environmental CBA contains financial and environmental aspects. Central to environmental CBA is the concept of external costs and benefits (Hoogmartens, Van Passel et al. 2014). Accordingly, in this research the relevant environmental aspects of each technology are quantified in monetary terms or monetized. For purposes of comparison, an assessment will be made of the separate technologies, as well as the combined technology. They will be evaluated based on four criteria: the net present value (NPV), the internal rate of return (IRR), the payback period (PBP) and the discounted payback period (DPBP). These measures can be calculated according to Eq. 1-4, with I_0 being the initial capital, CF_t the cash flow in year t, r the discount rate, and n the technology lifetime.

$$NPV = \sum_{t=1}^{n} \left[\frac{CF_t}{(1+r)^t}\right] - I_0 \quad (1)$$

$$\sum_{t=1}^{n} \left[\frac{CF_t}{(1+IRR)^t}\right] - I_0 = 0 \quad (2)$$

$$\sum_{t=1}^{PBP} CF_t - I_0 = 0 \quad (3)$$

$$\sum_{t=1}^{DPBP} \frac{CF_t}{(1+r)^t} - I_0 = 0 \quad (4)$$

2.2.2 Sensitivity analysis

To incorporate the uncertainty regarding the numerical value of the parameters in the CBA, a Monte Carlo sensitivity analysis is conducted. Accordingly, values for uncertain variables are generated randomly out of their predefined distribution. After a number of trials are executed, one obtains the entire range of results that are most likely to occur in the situation as defined in the model. Furthermore, sensitivity charts are generated to determine the extent to which the assumptions affect the obtained results.

2.3 Case Study

2.3.1 Description of the case study

Focusing on the issue of limited available area, the integrated PV application considered is a PV noise barrier. The hypothetical case study assessed is located in Belgium, along the highway E313 near Tuilt (Hasselt). Governmental plans have been made to install a noise barrier on this location in 2012, but inclusion of a PV array has not yet been foreseen. However, in this research, the assumption is made that the PV array will also be established. On this location, the highway -and also the PVNB- is oriented south-easterly. As we can see in Figure 2, the PV modules will be oriented towards the south under an azimuth angle of -45°. Consequently, the PV panels will be directed towards the residential area, in the opposite direction of the highway. This has a number of advantages. First, the PV panels will not experience an additional decrease of electricity production due to shading of passing trucks, nor will they suffer from road traffic dirt. Also, traffic sound reflection towards the residential area is avoided. Finally, there is a reduced possibility of suffering from damage due to stone chippings or traffic accidents. The design of the 429kWp PVNB can be found in Figure 3.

2.3.2 Data of the case study

The numerical values of the parameters concerning the PV array are summarized in Table 2. Values of the variables relating to the noise barrier can be found in Table 3. Table 4 lists the uncertain parameters in the model that are included in the sensitivity analysis. For each variable, a triangular distribution is specified. The minimum, most plausible, and maximum value -as well as a motivation- are listed.

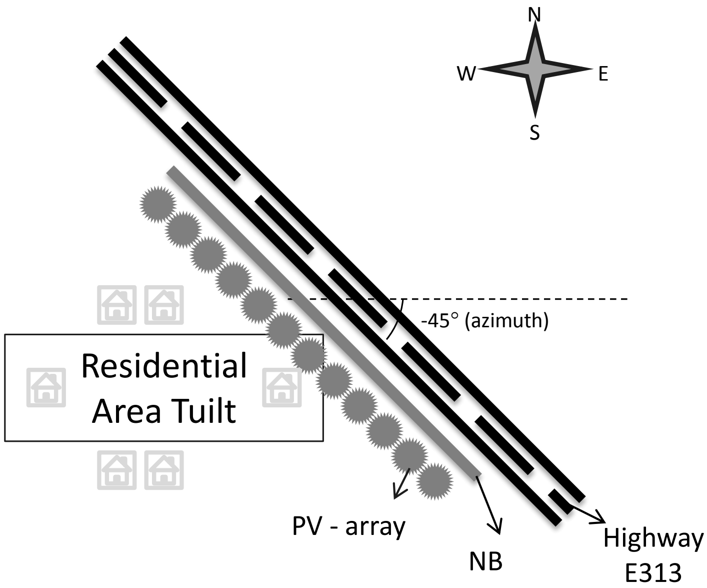

Figure 2 Orientation of the PVNB along the E313, Tuilt (Hasselt)

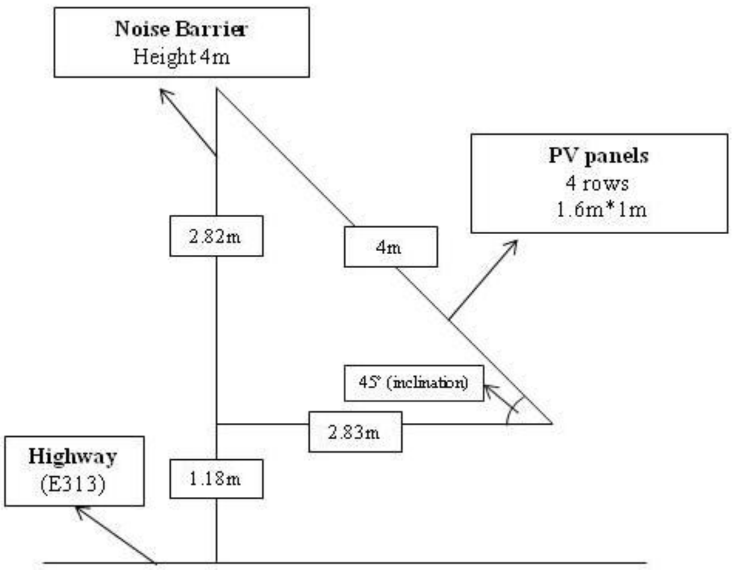

Figure 3 Design of the PVNB along the E313, Tuilt (Hasselt)

Table 2 Values of the parameters of the PV array in 2012 (as predicted in November 2010)

Parameter	Value	Motivation
P_{tot}	429kWp	Total PV power
UC_{PV}	2,800€/kWp	PV unit cost according to 4 different Belgian companies
n_{PV}	20 y	PV lifetime according to (Kato, Murata et al. 1998)
$INSC_{PV}$	5,000€/y	PV insurance cost according to PV company Verisol
MaC_{PV}	0.03€/Wp	PV maintenance cost.
β	850kWh/kWp	Solar radiation factor in Belgium (Súri, Huld et al. 2007)
η	94%	System efficiency, assuming an inclination angle of 45° and an azimuth angle of -45° (Mondol, Yohanis et al. 2007)
α	1%/y	System performance deterioration rate
P_{electr}	0.092€/kWh	Electricy price, assuming a company invests in the PV array and uses the produced electricity, data available from Statbel
$\dot{P}_{electr}$	3.1%/y	Average inflation of energy prices in Belgium over the last 12 years, data available from Eurostat
TGC_{val}	0.31€/kWh for 20 y	Value of tradable green certificates according to (Flemish Energy Agency 2010)
t_r	33.99%	Tax on profit (Wetboek der Inkomstenbelastingen 1992)
$EID_{\%}$	13.5% of I_0PV	Elevated investment deduction (Flemish Energy Agency 2010)
$ESUBS_{\%}$	0.5% of I_0PV	Ecology subsidy (Flemish Energy Agency)
$AvCO_2$	$0.254*10^{-3}$t/kWh	Average CO_2 emissions in Belgium between 2006-2008 generated by fossil fuels, nuclear, hydro, geothermal, solar and biomass (International Energy Agency 2010) Assuming this number already includes the CO_2 emission of PV installations over their life cycle, we therefore decided not to deduct the PV life cycle emission (Fthenakis and Kim 2007)
$ValCO_2$	20€/tCO_2	Value per ton CO_2 emission reductions according to Tol (2008)
r	4%	Discount rate according to (European Commission 2009)

Table 3 Values of the parameters of the noise barrier in 2012 (as predicted in November 2010)

Parameter	Value	Motivation
L_{NB}	747m	Length of the noise barrier according to AWV
UC_{NB}	1,200€/m	Unit cost of the noise barrier according to AWV
n_{NB}	20y	Lifetime of the noise barrier according to AWV
n_{house}	30y	Lifetime of the houses according to 3 notaries in Hasselt
AHP	200,000€	Average house price according to 3 notaries in Hasselt
$\#_{house}$ with RNP -11.5dB	2	Number of houses where the reduced noise pollution is -11.5dB according to the cadastre of Limburg and a local noise map made by specialists of AWV
$\#_{house}$ with RNP -10.5dB	3	Idem (RNP -10.5dB)
$\#_{house}$ with RNP -8dB	1	Idem (RNP -8dB)
$\#_{house}$ with RNP -6dB	11	Idem (RNP -6dB)
$\#_{house}$ with RNP -5.5dB	23	Idem (RNP -5.5dB)
$\#_{house}$ with RNP -3dB	348	Idem (RNP -3dB)
n_{lot}	35y	Lifetime of lots according to 3 notaries in Hasselt
ALP	75,000€	Average lot price according to 3 notaries in Hasselt
$\#_{lot}$ with RNP -6dB	3	Number of lots where the reduced noise pollution is -11.5dB according to the cadastre of Limburg and a local noise map made by specialists of AWV
$\#_{lot}$ with RNP -5,5dB	1	Idem (RNP -5.5dB)
$\#_{lot}$ with RNP -3dB	69	Idem (RNP -3dB)
NSDI	0.5%/dB	NSDI according to a comparison of articles, books and reports (Bateman, Day et al. 2001; Nijland, Van Kempen et al. 2003; Navrud 2004; Jabben, Potma et al. 2007; Julien and Lanoie 2007; Kim, Park et al. 2007; Victoria Transport Policy Instute 2009; Boardman, Greenberg et al. 2011)
$\dot{P}_{Real\ estate}$	2.26%/y	Annual increase of real estate prices according to 3 notaries in Hasselt

2.3.3 Assessment of the case study: calculations

To assess the importance of the environmental benefits of the technologies, a distinction is made between the different options excluding respectively including environmental benefits. Using the equations listed in Table 5, all the evaluation criteria mentioned above in Eq. 1-4 can be calculated. Note that the NPV is defined as the sum of the discounted cash flows *(CF)* minus the initial cost of investment (I_0) over the lifetime *(n)* of the technologies.

2.3.3.1 The solar panels

The net investment cost of the solar panels $(I_{PV,net})$, being the total cost of investment (I_{PV}) after having obtained the ecology subsidy *(ESUBS)* and the elevated investment deduction *(EID)*, can be calculated according to Eq. 5 a-c. Eq. 6 can be used to determine the cash flow of the PV installation (CF_{PV}). To this end, one should calculate the benefit of the produced electricity $(B_{electr\ prod})$ according to Eq. 6a, the obtained tradable green certificates *(TGC)* according to Eq. 6b, and the operation & maintenance cost of the array $(O\&M_{PV})$ according to Eq. 6c. To assess the cash flow of the PV investment including environmental aspects, the benefit of CO_2 reduction (B_{CO2}) should be included (Eq. 7, 7a). Note however that PV technologies are not totally carbon free, as CO_2 and other gasses are emitted during the extraction, processing, and disposal of associated materials (Fthenakis and Kim 2007). We focus on the carbon footprint, which quantifies the climate change impact of GHG emissions in a life cycle perspective. Using this approach, assessment of the environmental impact is limited to contributions to climate change (Laurent, Olsen et al. 2010). Further, the value of the avoided CO_2 emissions will be monetized as proposed by Tol (2008). One could argue that including both the benefit of CO_2 reduction and the obtained subsidies implies double counting. However, according to Boots (2003), green certificates and CO_2 credits are regarded as separate instruments each serving a specific target. Moreover, in a real life situation, a company trading CO_2 emission rights can obtain TGCs as well. Accordingly, we propose to include in the CBA both the CO_2 reduction benefits and the TGCs.

Table 4 Assumptions of the Monte Carlo sensitivity analysis

Parameter	Unit	Minimum	Most likely	Maximum	Motivation
L_{NB}	m	650	747	747	Assuming the possibility of shadow or other obstacles
$ESUBS_{\%}$	%	0	0.5	0.5	Assuming that possibly no ecology subsidy is obtained
UC_{PV}	€/kWp	2,600	2,800	3,400	According to 4 Belgian companies (3E, Verisol, Soltech, LRM)
P_{electr}	€/kWh	0.083	0.092	0.10	Assuming a maximum upwards or downwards evolution of 10% in energy prices
$\dot{P}_{electr}$	%/y	2.8	3.1	3.4	Assuming a maximum upwards or downwards evolution of 10% in the energy inflation rate
AHP	€	170,000	200,000	250,000	According to 3 notaries in Hasselt
ALP	€	50,000	75,000	110,000	According to 3 notaries in Hasselt
$\dot{P}_{eeal\ estate}$	%/y	0.49	2.26	3.42	Assuming an increase of real estate prices with 5%, 25% and 40% after 10 years, according to 3 notaries in Hasselt
NSDI	%/dB	0.3	0.5	1	Based on (Bateman, Day et al. 2001; Nijland, Van Kempen et al. 2003; Navrud 2004; Jabben, Potma et al. 2007; Julien and Lanoie 2007; Kim, Park et al. 2007; Victoria Transport Policy Instute 2009; Boardman, Greenberg et al. 2011)
TGC_{val}	€/kWh	0	0.31	0.31	Assuming no TGCs in the long run
$ValCO_2$	€/tCO_2	15	20	20	Upper limit according to (Tol 2008) and lower limit based on the future price today (November 2010) of EUAs in March 2012 (http://www.theice.com)
$AvCO_2$	t/kWh	0.240	0.254	0.770	According to (International Energy Agency 2010) and (Nawaz and Tiwari 2006)

Table 5 Investment cost *(I_0)*, cash flow *(CF)*, and lifetime *(n)* of the technologies

	$PV_{excl\ env\ benefits}$	$PV_{incl\ env\ benefits}$	$NB_{incl\ env\ benefits}$	$PVNB_{incl\ env\ benefits}$
I_0	$I_{0,PV,net} = I_{PV} - ESUBS - EID$ (5)		$I_{0,NB} = L_{NB} * UC_{NB}$ (8)	$I_{0,PVNB} = I_{0,PV,net} + I_{0,NB}$ (10)
	$I_{PV} = P_{tot} * UC_{PV}$ (5a) $ESUBS = I_{PV} * ESUBS_{\%}$ (5b) $EID = I_{PV} * t_r * EID_{\%}$ (5c)			
CF_t	$CF_{PVexcl,t} = B_{Electr\ prod,t} + TGC_t - O\&M_{PV,t}$ (6)	$CF_{PV\ incl,t} = CF_{PV,excl\ ecol\ ben,t} + B_{CO_{2},t}$ (7)	$CF_{NB,t} = B_{noise,t} = \left[\frac{B_{house}}{n_{house}} + \frac{B_{lot}}{n_{lot}}\right] * [1 + \dot{P}_{Real\ estate}]^t$ (9)	$CF_{PVNB,t} = CF_{PV\ incl,t} + CF_{NB,t}$ (11)
	$B_{Electr\ prod,t} = P_{tot} * \beta * ŋ * [1 - \alpha * t] * P_{electr} * [1 + \dot{P}_E]^t$ (6a) $TGC_t = P_{tot} * \beta * ŋ * [1 - \alpha * t] * TGC_{val}$ (6b) $O\&M_{PV,t} = INSC_{PV,t} + MaC_{PV,t}$ (6c) $B_{CO_{2},t} = P_{tot} * \beta * ŋ * [1 - \alpha * t] * AvCO_2 * ValCO_2$ (7a)		$B_{house} = \sum_{i=1}^{\#_{house}} [AHP * RNP_i * NSDI]$ (9a) $B_{lot} = \sum_{i=1}^{\#_{lot}} [ALP * RNP_i * NSDI]$ (9b)	
n	$n_{PV} = n_{NB} = n_{PVNB} = n$ (12)			

2.3.3.2 The noise barrier

As a noise barrier doesn't bring any private economic advantages with it, we will focus only on the assessment including environmental benefits. The total investment cost can be calculated as indicated in Eq. 8 by multiplying the length of the noise barrier *(L_{NB})* with the cost per unit *(UC_{NB})*. The social benefit of a noise barrier is quite obvious, surrounding neighbors suffer less from noise pollution. Noise exposure is associated with a number of health effects, such as socio-psychological responses (annoyance, sleep disturbance) and physical responses (high blood pressure, heart disease) (Nijland, Van Kempen et al. 2003). These health problems imply social costs, including costs of medical care and reduced performance during working hours. As there is no market for the effects on health caused by reduced noise nuisance, it is not possible to express them directly in monetary terms. Therefore, several environmental valuation techniques have been developed, including stated preference and revealed preference methods (Adamowicz, Louviere et al. 1994).

In stated preference methods, consumers are asked directly how much they are willing to pay for a change in an environmental amenity. The most commonly used example is that of contingent valuation, in which the willingness to pay for a change in the quantity/quality of an environmental good -such as noise- is estimated using survey techniques. Moreover, respondents are asked directly how much they are willing to pay for a house where the noise load is reduced (Navrud 2002; Nijland, Van Kempen et al. 2003; Navrud 2004). In revealed preference methods on the other hand, actual consumer behavior is observed using data on housing prices, noise loads,… One example is the hedonic pricing method, which is used in the majority of noise valuation studies (Navrud 2002). The idea underlying this methodology is that the housing price is a function of characteristics of the house itself, neighborhood characteristics, and environmental variables such as noise loads. Under the ceteris paribus assumption, it is assumed that a change in noise level will be reflected in a change in the house price. These changes in housing prices are then interpreted as the degree of how much people are willing to pay more. The results of hedonic pricing studies are described by means of the noise sensitivity depreciation index (NSDI), defined as the percentage depreciation in house prices per decibel (dB) increase in noise level (Nijland, Van Kempen et al. 2003; Boardman, Greenberg et al. 2011).

In this chapter, the environmental benefit of noise reduction is valuated using the NSDI applied to real estate -both housing and lot- prices. To apply this technique, it is necessary to obtain data about how many houses benefit from the noise barrier and which level of noise reduction is established at each house. It is important to note that when moving further away from the noise barrier, the noise reduction effect diminishes. Accordingly, Eq. 9 a-b can be used to calculate the benefit of noise reduction *(B_{noise})*, accounting for the increase in real estate prices ($\dot{P}_{eeal\ estate}$*),* the average housing and lot prices *(AHP, ALP)*, the reduced noise pollution *(RNP)*, and the noise sensitivity depreciation index *(NSDI)*. To include these numbers in the CBA, the benefit of noise reduction is expressed in annual terms (Eq. 9). Note that we only consider noise pollution, we assume that the GHG emissions during the production of the noise barrier are negligible.

2.3.3.3 *The PVNB*

Finally, the investment in the integrated entity –the PVNB as a whole- can be assessed. Assuming the absence of economies of scale or scope, the investment cost and the cash flow can be calculated by adding up the results obtained for both separate technologies (Eq. 10-11). The lifetime of the technologies is assumed to be equal for the separate and the integrated technology (Eq. 12). The results of the CBA are summarized in Table 6. Further, a probability distribution of the model output (NPV) is obtained by conducting a sensitivity analysis. A distinction is made between TGCs guaranteed at 0.31€/kWh on the one hand, and TGCs varying according to a triangular distribution between 0 en 0.31€/kWh on the other hand. This way, the influence of the variability of the green certificates on the probability of a positive NPV is assessed (Table 7). Finally, sensitivity charts are generated to assess the importance of the variability regarding the input variables. To make sure that only the parameters with an important influence on the economic performance (NPV) are investigated, a preliminary exploration of the elasticities was conducted. Results are presented in Table 8.

2.3.4 *Results*

2.3.4.1 *The solar panels*

The CBA (Table 6) indicates that the solar panels are profitable, with a NPV of €423,052 and an IRR of 8.06%. According to the PBP (DPBP) it would take respectively 9.7 (12.6) years to break even from undertaking the initial expenditure. The benefit of reduced CO_2 emissions was included in the analysis, but in monetary terms this environmental benefit is only of minor importance. The sensitivity analysis (Table 7) confirms the profitability of the solar panels, *i.e.* the investment in PV has a 100% chance of obtaining a positive NPV, even without including the environmental benefits of CO_2 reduction. However, this only holds under the assumption of guaranteed TGCs. If TGCs are allowed to vary, chances of being profitable decrease to 49.35%. The major impact of TGCs is confirmed in Table 8; they determine the variability in the NPV for 95.9%. However, assuming fixed TGCs, it is the PV system cost that declares the major part of the NPV variability (88.2%). Note that the ranges in variation of the input parameters are determined based on realistic expectations. This implies that some parameters are extremely uncertain (*e.g.* the value of the TGCs can decrease with 100%), while other parameters only vary under a limited range (*e.g.* the price of electricity can vary maximally with plus or minus 10%). As a consequence, the results of the sensitivity analysis do not represent dependence on the model only. Instead, they represent uncertainty due to the combination of *(i)* the range of uncertainty for each parameter and *(ii)* the dependence on uncertainty within the model itself. To overcome this issue, we have repeated the sensitivity analysis with an equal range of uncertainty for each parameter, *i.e.* with a minimum (maximum) deviation of -10% (+10%) of the assumed value of each input parameter. We find that the influence of the same parameters (TGC and PV unit cost) remain the most important to determine the profitability of the PV installation within this model. The influence of the TGCs however becomes less predominant while the unit cost of PV however now becomes a larger influencer (% share in explanation of variation in NPV of 49.6% for the TGCs and 36% (-) for the PV unit cost).

2.3.4.2 The noise barrier

Assuming a lifetime of 20 years –the lifetime of the solar panels- the noise barrier has a negative NPV of €-137,516. Although this indicates that the investment is not profitable in social terms, still a significant amount of the initial investment cost (84.6%) can be recovered via the environmental benefit of reduced noise nuisance. Moreover, when the lifetime is expected to be 25 years -which is realistic for a noise barrier- the NPV becomes positive with a value of €8,499. The PBP and DPBP of this noise barrier amounts to 16.4 and 22 years respectively (Table 6). Table 7 indicates that over 20 (25) years, the sound barrier has a chance of 55% (100%) to be "profitable". This shows that the sound barrier located in Tuilt can be profitable in social terms. Based on the results presented in Table 8, we point out that the spread in the value of the NSDI is crucial in determining the profitability of the sound barrier. The other parameters are negligible.

Again, we point to the fact that the sensitivity analysis assumes realistic deviations for each input parameter, assuming a large spread for the NSDI. The second sensitivity analysis, which assumes equal deviations of +-10% for each input parameter, relativizes the impact of the NSDI (% share in explanation of variation of NPV of 29.6%), while the impact of the housing prices (26.5%) and the length of the noise barrier (-42.9%) are found to be larger influencers of the profitability of the noise barrier.

2.3.4.3 The PVNB

Being the combination of two profitable components, the PVNB as a whole is also profitable, with a NPV of €306,447 and an IRR of 5.67%. The investment can be earned back after 12 respectively 16 years, depending on whether we include the time value of money (Table 6). The profitability of the PVNB is again heavily dependent on the TGCs. When taking their value for granted, there is a probability of 98% to be profitable. Yet, assuming that TGCs can vary, this percentage reduces to 54% (Table 7). Finally, we note that the profitability of the PVNB as a whole is largely determined by the value of the TGCs and the NSDI (Table 8). Figure 4 illustrates this impact in more detail. In this graph, TGC values are set at 0.31, 0.21 and 0.09€/kWh, the assumed compensation for TGCs in 2012, 2015 and 2018 respectively (Flemish Energy Agency 2010). The second sensitivity analysis, which assumes equal deviations of +-10% for each input parameter, relativizes the impact of the NSDI (12% share in explanation of NPV variation) and the TGCs (39.2%) and points to the importance of the impact of the housing prices (10.9%) and the PV unit costs (-28.7%).

Table 6 Results of the CBA

	NPV (€)	IRR (%)	PBP (y)	DPBP (y)
$PV_{excl\ env\ benefits}$	423,052	8.06	9.7	12.6
$PV_{incl\ env\ benefits}$	443,964	8.25	9.6	12.3
NB (over 20 years)$_{incl\ env\ benefits}$	-137,516	2.25	16.4	22.0
NB (over 25 years)$_{incl\ env\ benefits}$	8,499	4.0	16.4	22.0
$PVNB_{incl\ env\ benefits}$	306,447	5.67	12.0	16.4

Table 7 Sensitivity analysis: probability of a positive NPV

	PV		NB incl env benefits		PVNB incl env benefits
	Excl env benefits	Incl env benefits	20 y	25 y	
Probability % of positive NPV with TGC guaranteed(0.31€/kWh)	100	100	55.04	100	98.51
Probability % of positive NPV with TGCs vary (0 - 0.31€/kWh)	49.35	51.71	55.04	100	54.28

Table 8 Sensitivity analysis: share in explanation of variation in NPV

	PV excl env benefits		NB_{20} incl env benefits		PVNB including env benefits		
TGC:	guaranteed	uncertain	n.a.			guaranteed	uncertain
TGC_{val}	/	95.9 (+)	NSDI	89.4 (+)	TGC_{val}	/	61.3 (+)
UC_{PV}	88.2 (-)	4.1 (-)	AHP	7.5 (+)	NSDI	82.4 (+)	33.2 (+)
P_{Electr}	7.2 (+)		$\dot{P}_{Real\ Estate}$	3.1 (+)	UC_{PV}	7.5 (-)	2.5 (-)
L_{NB}	4.6 (+)				AHP	7.5 (+)	3.0 (+)

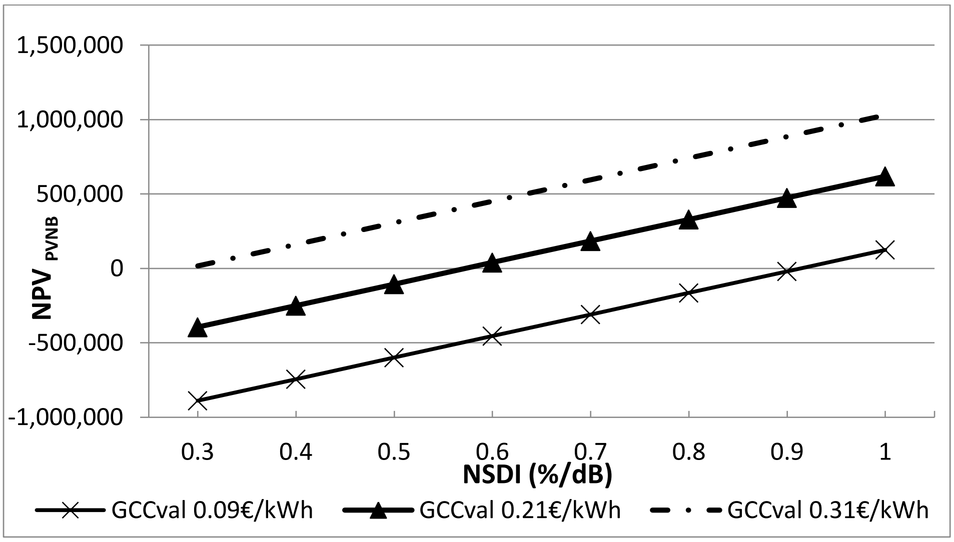

Figure 4 The impact of variations in the NSDI - value on the NPV of the PVNB

2.4 Conclusion and discussion

The current need for increased renewable energy production combined with the scarcity of available land in densely populated regions inspired this research concerning the profitability of photovoltaic noise barriers. Although a positive net present value is guaranteed for a PVNB at this location, this research stresses the importance of governmental PV subsidies –tradable green certificates in Belgium- which are most important in determining the profitability of the PV(NB) investment. Moreover, since PV is not yet viable without governmental support in the short term, PV subsidies should be guaranteed to be able to attract private investors. The methodology outlined above can be useful for policy decisions concerning the location of the noise barriers. Moreover, as governmental budgets are always limited, choices will have to be made on "optimal" locations, *i.e.* locations where residents suffer the most from noise pollution. By applying the noise sensitivity depreciation index to surrounding properties, these optimal locations can be determined.

It should be noted that due to a lack of data, this research does not cover possible economies of scope. However, it is stated in literature that mechanical and electrical prefabrication of complete photovoltaic sound barriers is exercised in most of the grid connected PV plants built along transport infrastructures (Nordmann and Clavadetscher 2004). It can be argued that "joint production" of an integrated PVNB is more beneficial than the production of the sound barrier and the PV array separately. Noise experts indicate that the cost of the noise barrier could increase when PV is added, since the sound barrier may need to be reinforced to be able to support the PV array in extreme weather conditions. Also, PV - modules included in a PVNB may be more costly due to additional noise reflection measures. Consequently, an interesting item for further investigation would be the assessment of the (dis)economies of scope (Bernheim and Whinston 2008) that could arise when combining solar panels and sound barriers into a PVNB.

When the government decides to place a noise barrier, additional PV is normally not taken into account. However, the construction of a sound barrier could in turn motivate the private sector to invest in PV panels that can be mounted on the sound barrier. This way, an extra amount of renewable energy can be produced -and thus a certain amount of CO_2 emission can be avoided- without requiring additional space. Further, the private investor could benefit from a profitable investment, while surrounding residents suffer less from noise nuisance, which is reflected in an increase in real estate prices. This study shows that the installment of PV on noise barriers brings about synergies and can create novel markets for public – private partnerships where three parties -government, residents, and private investors- can benefit from. This is a good example of technology fusion that can be stimulated for example via implementation of flexible governmental legislation regarding investment conditions of PV sound barriers.

3 Economic benefits of combining clean technologies under budgetary constraints: The case of solar PV and battery electric vehicles

Revised version currently under review

ABSTRACT

The combined use of clean technologies can lead amongst other benefits to reduced environmental impacts, better management of land scarcity, and diminishment of the effect of power variability of intermittent clean energy sources. Nonetheless, private investors will only invest in the combination of technologies if the latter is more profitable. The aim of this chapter is to provide a systematic model for decision makers that allows evaluating the profitability of any random combination of technologies under budgetary constraints, and to compare this profitability with that of the individual projects. This research goes beyond the state of art in the field of financial management and more specifically in the field of the rationing of capital amongst interdependent projects, by developing a method to calculate the payoff of interdependent projects undertaken together. Moreover, this research develops a computational model from the investor's point of view, of which the purpose is threefold. The model *(i)* allows to directly compare the economic payoff of individual complementary technologies with the economic payoff of their integrated combination, under budgetary constraints; *(ii)* calculates economic synergies labeled "benefits of combined technologies" (BOCT) when combining complementary technologies, *(iii)* explains the rationalization behind BOCT. The model exemplifies an ex ante CBA developed for business and non-governmental use. A four step methodology is proposed and illustrated with a case of PV solar power and battery electric vehicles (BEVs) for a small Belgian enterprise. Results show that at low electricity prices (<€0.112/kWh) it is most profitable to invest in BEVs. When the price of electricity rises (>€0.134/kWh), investment in exclusively PV becomes most attractive. In all other cases, it is more profitable to invest in the combination of both technologies.

3.1 Introduction

There are numerous reasons why an investor might prefer to undertake a combination of complementary clean technologies together rather than to invest in one single clean technology, including *(i) greenhouse gas emission reduction*; *e.g.* solar air-conditioning systems (Lu, Xia et al. 2013), electric vehicles powered with low carbon electricity (Doucette and McCulloch 2011); *(ii) appropriate management of land scarcity*; *e.g.* building integrated photovoltaics (Petter Jelle, Breivik et al. 2012), photovoltaic noise barriers (De Schepper, Van Passel et al. 2012); *(iii) diminishment of the effect of power variability of intermittent clean energy sources; e.g.* combining electric vehicles and wind power (Ekman 2011), combining solar PV with electric vehicles and heat pumps (Zhang, Tezuka et al. 2012), utilizing a spatially diverse solar farm portfolio rather than a single site farm (Tarroja, Mueller et al. 2013); combining solar PV with decentralized storage systems (Nykamp, Bakker et al. 2014); *(iv) grid independency*; *e.g.* solar powered consumer electronics (Lizin, Van Passel et al. 2012); solar powered LED lighting (Durlinger, Reinders et al. 2012); *(v) improved energy and exergy efficiencies*; *e.g.* renewable energy-based multi-generation systems (Dincer and Zamfirescu 2012), thermal management systems for electric vehicles (Hamut, Dincer et al. 2013). All these examples enhance a firm's corporate environmental responsibility (CER), though any rational investor will only opt for the combined clean technology when the latter has a nonnegative economic payoff that exceeds the payoff of the single technologies, given budgetary restrictions. We assume that companies seek to maximize economic returns while improving CER, given limited investment resources. This research quantifies the economic benefits of combining clean technologies given budgetary constraints, from an investor's point of view.

The aim of the chapter is to provide a systematic model for decision makers that allows them to evaluate the profitability of any random combination of technologies under budgetary constraints, and to compare this profitability with that of the individual projects in isolation. This research goes beyond the state of art in the field of financial management and more specifically, in the field of the rationing of capital in the sense of liquid resources. Moreover, one of the three major problems in the rationing of capital is how to select the most profitable project amongst mutually exclusive alternatives (Lorie and Savage 1949). While rationing capital models are fundamentally focused on investment projects that are mutually independent, these types of investment decisions may involve choices amongst investment projects that are not mutually independent or hence that are interdependent. That is, the economic payoff of any one project may depend on the other projects undertaken with it (Reiter 1963). Following this definition, complementary technologies as considered in this research are an example of interdependent projects. Several optimization methods have been developed to find the optimal (or nearly optimal) payoff of the joint undertaking of interdependent projects (Reiter and Sherman 1962; Reiter 1963; Weingartner 1963; Reiter and Rice 1966). Within these optimization methods, the interdependencies amongst different technologies or projects or in other words, the interactions between projects undertaken together, are assumed to be given data (Reiter 1963), either hypothetical data or data obtained from a collaborating company. We argue that this number is not obvious to assess. In literature, examples of the economic assessment of joint technologies can be found on a case-by-case basis (Shaw and Peteves 2008; Mousazadeh, Keyhani et al. 2009; Wu, Huang et al. 2009; 2012). However, a systematic method to calculate the joint payoff of a random combination of technologies is missing. Moreover, no information is provided on the comparison of investing in the integrated combination of complementary (interdependent) technologies with investing in their individual counterparts, given budgetary constraints. Filling this gap, this chapter develops a computational model to support the investors' decision making that *(i)* calculates the economic payoff of individual complementary technologies and their integrated combination under budgetary constraints; *(ii)* quantifies economic synergies labeled "benefits of combined technologies" (BOCT) when combining complementary technologies; *(iii)* explains the rationalization behind BOCT. Note that in this research we do not include an environmental impact target, the focus is on private investors that aim to enhance their profits from clean technologies.

The proposed framework is visualized in Figure 5 for two clean, complementary, interdependent technologies N_1 and N_2. Given limited investment resources, the investor can compare the joint economic payoff $V_{N1,N2}$ and the economic payoffs of the individual technologies V_{N1} and V_{N2}. To obtain these payoffs by means of a CBA, the net benefits of investing in N_i are compared with the net benefits of a reference R_i that would be displaced if the technologies under consideration were to proceed. The outputs of the technologies N_i to be assessed should equalize the respective outputs of the displaced technologies R_i to obtain correct CBA results (O_{Ni}=O_{Ri}). The displaced technology is called "the counterfactual", usually the status quo (Boardman, Greenberg et al. 2011). When comparing the payoffs of the joint and individual technologies, BOCT can be established due to characteristics of the technology itself, market conditions, and regulation that cause nonlinearities when combining technologies.

Section 3.2 elaborates on a stepwise methodology, which is illustrated by a comprehensive case study of PV solar power and battery electric vehicles (BEVs) in section 3.3. The chapter ends with a conclusion section (section 3.4).

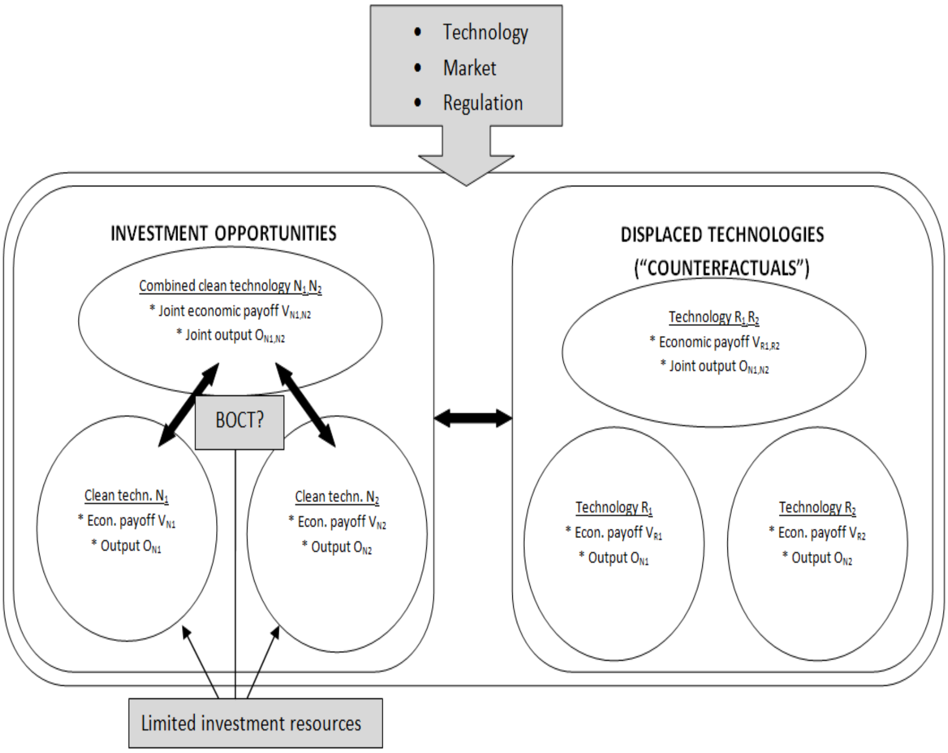

Figure 5 Framework regarding the assessment of economic benefits of combined technologies given limited investment resources, applied to clean complementary technologies N_1 and N_2

3.2 Methodology

3.2.1 Magnitude limited investment resource and technology sizes

Several business firms do not apply the firm's cost of capital to decide which projects should be undertaken but, instead, they determine the magnitude of their capital budget in some other way that results in fixing an absolute monetary limit on capital expenditures (Lorie and Savage, 1949). We focus on a basic case of limited investment resources, that is capital expenditures are required in one accounting period only. In this first step, the initial investment capital I_0 or in other words, the magnitude of the capital expenditure *c*, is to be determined according to the investor's preferences (Eq. 1).

$$I_0 = c = f(investor's\ preferences) \qquad (1)$$

3.2.1.1 Investment size any individual technology

Given a limited amount of investment resources, the size of any individual technology ($size_{Ni}$) can be calculated according to Eq. 2, where the denominator UC_{Ni}-UC_{Ri} represents the initial unit cost of technology N_i directly compared to the initial unit cost of displaced technology R_i. We assume that the unit cost of technology N_i exceeds the unit cost of displaced technology R_i.

$$size_{N_i} = \frac{I_0}{UC_{N_i} - UC_{R_i}} \; with \; UC_{N_i} > UC_{R_i} \qquad (2)$$

If the technologies N_i that need to be compared have the same lifetime, the denominator UC_{Ni}-UC_{Ri} is easily calculated as UC_{N1}-UC_{R1}, …, UC_{Nn}-UC_{Rn} for all *n* technologies. When the technology lifetimes are unequal, this calculation becomes more complex. We use the roll-over-method to compare projects with unequal lifetimes (Boardman, Greenberg et al. 2011); the project with the shorter lifetime is "rolled over" within the lifetime of the longer project: Given technology N_s with short lifetime n_{Ns} that needs to be compared with technology N_l with longer lifetime n_{Nl}, the number of times that project N_s needs to be "rolled over" (*z*) is given in Eq. 3. The calculation of the initial unit cost of investment in N_s as compared to the investment in any displaced technology R_s (UC_{Ns}-UC_{Rs}) is calculated according to Eq. 4, considering the annual price evolution of the technologies $\dot{P}$ and the discount rate *r*.

$$z = \frac{n_{N_l}}{n_{N_s}} \; with \; n_{N_l} > n_{N_s} \qquad (3)$$

$$UC_{N_s} - UC_{Rs} = \sum_{t=0*n_{N_s}}^{(z-1)*n_{N_s}} \left[\frac{UC_{N_s}*(1+\dot{P}_{N_s})^t}{(1+r)^t}\right] - \sum_{t=0*n_{Rs}}^{(z-1)*n_{Rs}} \left[\frac{UC_{Rs}*(1+\dot{P}_{Rs})^t}{(1+r)^t}\right] \qquad (4)$$

The calculation of the technology size necessitates the determination of the initial technology unit cost. Due to the existence of economies of scale, *i.e.* cost advantages that enterprises obtain with increasing scale (Pindyck and Rubinfeld 2009), the technology unit cost to be paid by the investor may vary for different technology sizes. An additional factor that can influence the technology unit cost is policy. Examples include subsidies which can be received only for installations of limited sizes or additional measures that imply additional costs, which are required for installations exceeding a certain threshold size.

3.2.1.2 Investment size of any joint combination of interdependent technologies

The investment size of any joint combination of interdependent technologies is calculated by solving a system of equations as outlined in Eq. 5. The first equation indicates that the investment cost I_0 is composed of the initial unit cost of all technologies directly compared to the initial unit cost of the displaced technologies (UC_{Ni}-UC_{Ri}) multiplied by their size ($size_{Ni} = size_{Ri}$). The other equations represent the technical interrelationships among the different technologies within the integrated combination.

$$\begin{cases} I_0 = \left(UC_{N_1} - UC_{R_1}\right) * size_{N_1} + \left(UC_{N_2} - UC_{R_2}\right) * size_{N_2} + \cdots + \left(UC_{N_n} - UC_{R_n}\right) * size_{N_n} \\ size_{N_2} = size_{N_1} * c_1 \\ size_{N_3} = size_{N_1} * c_2 \\ \ldots \\ size_{N_n} = size_{N_1} * c_{n-1} \end{cases} \quad (5)$$

The relationship among technology sizes is case specific and can be expressed as the size of a certain technology N_i within the combination multiplied by a capacity constant c_i. The latter can represent the number of solar cells needed to power PV LED lighting during one hour, the amount of solar panels needed to fuel a solar powered electric vehicle to drive one kilometer,… To determine the numerical value of this constant, information is needed on the demand required from the integrated technology. The latter should equalize the demand required from the displaced technology (see Figure 5). Note that due to possible interdependencies when combining technologies, the unit cost of any technology N_i within the joint technology N_1, N_2, …, N_n cannot simply be assumed to equal the unit cost of the individual technology N_i. Instead, this unit cost should be determined for each unique combination of technologies, considering all existent interdependencies.

3.2.2 Economic payoff of investment options

To measure the economic payoff, we make use of the net present value (NPV) criterion as recommended by Boardman et al. (2011). The NPV_N of technology *N* is calculated according to Eq. 6, where $CF_{N,t}$ is the cash flow at time *t*, *r* is the discount rate, and $I_{0,N}$ is the acquiring cost. The annual cash flow is calculated as the sum of the benefits $B_{N,t}$ (including subsidies) minus the costs $Q_{N,t}$, and the total amount of taxes $T_{N,t}$ to be paid in year *t* (Eq. 7). The taxes are computed in Eq. 8, where *deductable* $Q_{N,t}$ represent the costs that are allowed to be deducted from the taxable income in year *t*, $A_{N,t}$ stands for the total amount of amortization in year *t*, $T_{d\%,N}$ represents the tax deduction percentage, and t_r equals the company's tax rate (Mercken 2004). The total amount of amortization in year *t* ($A_{N,t}$) is calculated in this chapter using the declining balance amortization method (Mercken 2004). The NPV of technology *N* can be compared to the NPV of any displaced reference technology *R* ($NPV_{N\text{-}R}$) by means of Eq. 9. We note that for any technology N_s that needs to be rolled over *z* times for purposes of comparison, the investment cost should be rolled over as well. Moreover, the investment cost is then calculated following Eq. 10. The cash flow is calculated analogously.

$$NPV_N = \sum_{t=1}^{n} \frac{CF_{N_t}}{(1+r)^t} - I_{0_N} \quad (6)$$

$$CF_{N,t} = B_{N_t} - Q_{N_t} - T_{N_t} \quad (7)$$

$$T_{N,t} = \left[B_{N_t} - \left(deductable\ Q_{N_t} + A_{N_t}\right) * T_{d\%_N}\right] * t_r \quad (8)$$

$$NPV_{N-R} = NPV_N - NPV_R \quad (9)$$

$$I_{0_{Ns}} = \sum_{t=0*n_{N_s}}^{(z-1)*n_{N_s}} \left[size_{Ns} * \left[\frac{UC_{N_s}*(1+\dot{P}_{N_s})^t}{(1+r)^t}\right]\right] \quad (10)$$

3.2.3 Benefits of combined technologies (BOCT)

BOCT can be assessed by comparing the joint payoff of the combined technology with the economic payoffs of the individual technologies, given limited investment resources. Per definition, BOCT occur when the joint economic payoff of the combined technology exceeds the maximum of the individual economic payoffs of the complementary technologies (Eq. 11).

$$\exists\, BOCT \iff \mathrm{NPV}_{((\mathrm{N}_1,\mathrm{N}_2,\dots,\mathrm{N}_n)-(\mathrm{R}_1,\mathrm{N}_2,\dots,\mathrm{N}_n))} > MAX\,(\mathrm{NPV}_{\mathrm{N}_1-\mathrm{R}_1}, \mathrm{NPV}_{\mathrm{N}_2-\mathrm{R}_2}, \dots, \mathrm{NPV}_{\mathrm{N}_n-\mathrm{R}_n}) \quad (11)$$

3.2.4 *Rationalization behind BOCT*

As a final step, we describe how to find the parameters that explain BOCT for any combination of interdependent technologies. To this end, we assess the parameters *p* that cause nonlinearities when combining different technologies. In other words, we verify which parameters *p* determine the difference between the joint payoff of the combined technology and the relative linear combination of the payoffs of the individual technologies composed of the sizes of the technologies within the integrated combination divided by the size of the corresponding individual technologies (Eq. 12). These parameters *p* can be technological, they can relate to market conditions or to regulation (Figure 5).

$$Any\ parameter\ p\ impacts\ existing\ BOCT \iff \mathrm{NPV}_{\left((\mathrm{N}_1,\mathrm{N}_2,\dots,\mathrm{N}_n)-(\mathrm{R}_1,\mathrm{R}_2,\dots,\mathrm{R}_n)\right)}(\mathrm{p}) \neq \frac{size_{N_1}\ within\ \mathrm{N}_1,\mathrm{N}_2,\dots,\mathrm{N}_n}{size_{N_1}}\,\mathrm{NPV}_{N_1-\mathrm{R}_1}(\mathrm{p}) + \frac{size_{N_2}\ within\ \mathrm{N}_1,\mathrm{N}_2,\dots,\mathrm{N}_n}{size_{N_2}}\,\mathrm{NPV}_{N_2-\mathrm{R}_2}(\mathrm{p}) + \dots + \frac{size_{N_n}\ within\ \mathrm{N}_1,\mathrm{N}_2,\dots,\mathrm{N}_n}{size_{N_n}}\,\mathrm{NPV}_{N_n-\mathrm{R}_n}(\mathrm{p}) \quad (12)$$

3.3 Case Study

The case is based on a real-life example; *i.e.* a small steel processing company located in Flanders (Belgium), seeking to maximize economic returns while improving CER, given budgetary limits. The company considers two clean technologies within which to invest: solar PV panels and battery electric vehicles (BEVs). They consider these technologies because they have needs for both electricity generating and transport technologies. They are interested in PV in particular because *(i)* they have a large area available to install PV panels and *(ii)* the installation of this solar project does not require filing for an official permission, which would be the case for alternative energy technologies such as wind mills. The company considers BEVs for transport because they prefer a "zero-emission" vehicle that they can easily “fuel” with electricity that is available on their site, which would not be the case for alternative clean transport technologies such as hydrogen vehicles. We illustrate how the small and medium sized enterprise (SME) can apply the model to compare the economic payoff of solar panels (displacing grid electricity), battery electric vehicles (displacing gasoline fueled internal combustion engine vehicles), and the combined technology, *i.e.* solar powered BEVs (displacing gasoline fueled ICEVs), given limited investment resources. Results are summarized in Figure 6, numerical data about the technologies in Table 9. We note that the electric vehicle considered is the Nissan Leaf, which has a substantially lower purchase price than an “average” battery electric vehicle, due to the fact that the former is mass produced (Weiss, Patel et al. 2012). The methodology is applied to this case in subsections 3.3.1 - 3.3.4. We assume that the lifetime of the project equals the lifetime of the “longest living” technology; that is solar PV with a lifetime of 25 years.

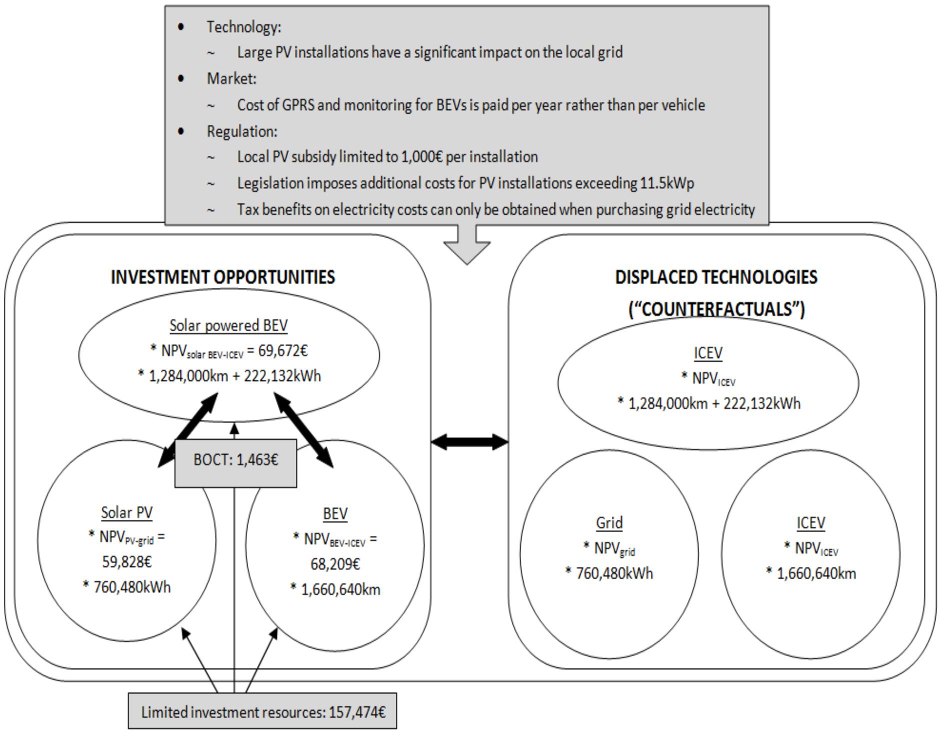

Figure 6 Framework regarding the economic assessment of benefits of combining technologies (BOCT) illustrated for a case of PV displacing grid electricity, and BEVs displacing ICEVs, under budgetary limits

3.3.1 Magnitude limited investment resource

The limited investment resource is to be determined according to the investor's preferences. The SME had envisioned a budget of €157,474 to invest in clean technologies. Hence, according to Eq.1, we note that $I_0 =$ €157,474.

Based on Eq. 2, we compute the size of the PV installation. We take into account economies of scale and the impact of policy measures; *i.e.* due to the fact that large PV installations can possibly overload the grid, legislation imposes the installation of a meter, a decoupling box, and a grid study. The numerical values of the PV and grid unit costs can be found in Table 9. The only feasible solution given the budgetary constraint implies an initial PV unit cost of €4,000/kWp. Accordingly, the size of the individual PV installation is

39.37kWp. The determination of the "size" of the BEVs, that is the number of BEVs, is more complex, as the lifetime of the BEVs (n_{BEV} = 5 y) differs from the lifetime of the PV installation (n_{PV} = 25y). Moreover, the investment in BEVs needs to be "rolled over" 5 times within the longer lifetime of the PV installation (Eq. 3). Hence, the initial unit cost of the BEVs directly compared to that of the ICEVs is calculated according to Eq. 4 and totals €40,608.07 per vehicle. We find that the number of battery electric vehicles to invest in equals 3.88. This means that the project starts with 3.88 BEVs that are replaced 5 times every 5 years, totaling a project lifetime of 25 years.

The size of the combined technology is calculated according to Eq. 5. In this case, the constant c_1 characterizes the relationship amongst the size of the solar installation and the number of BEVs to be powered using this installation. The required travel distance D_t equals 17,120km per vehicle per year, *i.e.* the travel distance of the displaced ICEVs (Table 9). Hence, the constant c_1 in our case equals 3.833kWp/vehicle. The unit cost of PV (BEVs) as compared to the grid (ICEVs) is calculated analogously to the procedure described for individual technologies, though the technology unit costs within this joint technology cannot be assumed to equal the unit cost of the individual technologies. By solving the system of equations based on the value of c_1 and the other numbers in Table 9, we find that the only feasible solution infers a PV unit cost of €3,100/kWp, a BEV unit cost of €29,403, and an ICEV unit cost of €16,487. The according technology sizes are 11.5kWp

3.3.2 Economic payoff of investment options

The economic payoff is measured using the *NPV* in Eq. 6 and Eq. 9. Benefits of the solar installation include tradable green certificates *(TGC)* and the local PV subsidy *(SUBSlocal)*. Besides the unit cost of the installation *(UC_{PV})*, also the costs of maintenance *(MaC_{PV})* and insurance *($INSC_{PV}$)* are accounted for. Note that an elevated investment deduction *(EID)* is granted for the investment of the installation. The solar electricity would replace the same amount of grid electricity so the cost of purchasing electricity from the grid *(P_{electr})* is avoided. The only benefit provided for the vehicles is the ecology subsidy *(SUBS)*. Costs to be paid for the vehicles are unit costs *(UC)*, annual traffic taxes *(T_n)*, one off vehicle registration taxes *(T_0)*, maintenance costs *(MaC)*, the costs of general packet radio service *(C_{GPRS})* and monitoring *(C_{mon})* and fuel costs *(P_{electr}, P_{gasol})*. Note that BEVs benefit from a higher tax deduction percentage *($T_{d\%}$)* than ICEVs. We assume that the vehicles are used during 5 years, with no residual value after this lifetime. For the current case, we find a *NPV* for the solar installation *($NPV_{PV\text{-}grid}$)* of €59,828; the *NPV* of the grid powered battery electric vehicles *($NPV_{BEV\text{-}ICEV}$)* equals €68,209, and the *NPV* of the solar powered BEVs *($NPV_{solarBEV\text{-}ICEV}$)* totals €69,672. In Figure 7 we show how these results differ for varying electricity prices. The payoff of the solar installation increases with rising grid electricity prices. Conversely, the payoff of the BEVs decreases with increasing electricity prices. The payoff of the joint technology is independent of the electricity price, as the generated PV electricity is fed into the grid, and used to power the BEVs afterwards. As legislation in Belgium imposes a "backwards going meter", that is the SME's electricity meter adds up when electricity is taken from the grid and it deducts the electricity that is fed into the grid, this implies a zero operation.

Table 9 Case: Data

Parameter	Value	Motivation
General		
t_r	33.99%	Company's tax rate on profit according to Wetboek der Inkomstenbelastingen 1992
r	4%	Discount rate according to (European Commission 2009)
PV installation		
β	850kWh/kWp	Irradiation factor in Belgium according to (Súri, Huld et al. 2007)
η	100%	Efficiency rate according to (Mondol, Yohanis et al. 2007), assuming an inclination angle of 30° and an azimuth angle of 0°
α	0.70%/y	Annual system performance deterioration rate according to the performance guarantee on PV modules
n_{PV}	25 y	Lifetime PV installation according to 4 Belgian PV companies
nA_{PV}	20 y	Amortization period PV equals the maximum period during which TGCs can be obtained
UC_{PV}	3,100€/kWp if P_{tot} <11.5kWp 4,000€/kWp if 11.5<P_{tot}<50kWp 3,600€/kWp if 50<P_{tot}<70kWp 2,900€/kWp if 70<P_{tot}<90kWp 2,700€/kWp if 90<P_{tot}<110kWp	Average initial unit cost of PV depends on the total power of the installation; numerical values according to 4 Belgian companies. For installations exceeding 11.5kWp, legislation imposes the additional costs of a grid study, a meter, and a decoupling box. For larger installations the unit cost decreases due to economies of scale.
$INSC_{PV}$	2.5‰ of PV investment cost	Average annual PV insurance cost according to 4 Belgian PV companies
MaC_{PV}	15€/kWp	Average annual PV maintenance cost according to 4 Belgian PV companies
TGC	0.33€/kWh	Value of tradable green certificates (PV subsidies), data available from www.energiepsaren.be
$SUBS_{local}$	15% of PV investment cost (max 1,000€)	Local PV subsidy, data available from www.energiesparen.be
$EID_{\%}$	13.5% of PV investment cost	Elevated investment deduction for PV installation, data available from www.energiesparen.be
Grid		
UC_{electr}	0€	The initial unit cost to invest in grid electricity is 0, assuming that the grid is already available at the site
P_{electr}	0.12€/kWh	Average electricity price for the SME
$\dot{P}_{Electr}$	2.24%	Annual evolution of electricity prices for industrial consumers in Belgium over the last 10 years, data available from Eurostat

Battery electric vehicle (Nissan Leaf) versus internal combustion engine vehicle (Nissan Note Tekna 1.6l)

n_{BEV}	5 y	Average lifetime of a company car in Belgium
n_{ICEV}	5 y	
nA_{BEV}	5 y	The amortization period of the vehicle equals the vehicle's lifetime
nA_{ICEV}	5 y	
D_t	17,120km/veh/y	Average annual travel distance of the displaced ICEVs
Td_{BEV}%	120%	Tax deduction percentage according to the Programmawet 23-12-2009, data available from www.ejustice.just.fgov.be
Td_{ICEV}%	75%	
$SUBS_{BEV}$	1%	Ecology subsidy according to http://ewbl-publicatie.vlaanderen.be
$SUBS_{ICEV}$	0%	
UC_{BEV}	29,403€ for <= 5 vehicles	Initial unit cost of the vehicles according to www.nissan.nl; quantity discount according to 2 Belgian Nissan distributors
UC_{ICEV}	26,463€ for 5<vehicles<50 16,487€ for <= 5 vehicles 14,838€ for 5<vehicles<50	
$\dot{P}_{BEV}$	-1.41%/y	Annual evolution of vehicle prices, calculated as the geometric mean of the evolution of car prices from 2003 till 2011, data available from http://ec.europa.eu
$\dot{P}_{ICEV}$	-1.41%/y	
T_{oBEV}	61.50€	One off vehicle registration tax, data available from http://koba.minfin.fgov.be
T_{oICEV}	123€	
T_{nBEV}	71.28€	Annual traffic tax, data available from http://koba.minfin.fgov.be
T_{nICEV}	248.29€	
$\dot{P}_{ToBEV}$	0%/y	Annual evolution of the one off vehicle registration tax; data available from www.minfin.fgov.be
$\dot{P}_{ToICEV}$	0%/y	
$\dot{P}_{TnBEV}$	1.02%/y	Annual evolution of the annual traffic tax; calculated as the geometric mean of the evolution of annual traffic taxes from 2005 till 2011, data available from www.minfin.fgov.be
$\dot{P}_{TnICEV}$	1.02%/y	
MaC_{BEV}	1,332€/5y	Maintenance cost of the vehicle according to 2 Belgian Nissan distributors
MaC_{ICEV}	4,440€/5y	
$Fuse_{BEV}$	0.173kWh/km	Fuel use of the vehicle according to www.nissan.be
$Fuse_{ICEV}$	6.8l/100 km	
P_{electr}	0.12€/kWh	Average electricity price for the SME
P_{gasol}	1.50€/l	Gasoline price, data available from www.petrolfed.be
$\dot{P}_{Electr}$	2.24%/y	Annual evolution of electricity prices for industrial consumers in Belgium over the last 10 years, data available from Eurostat. Annual evolution of gasoline prices; calculated as the geometric mean of the evolution of the average max price of Euro95 from 1990 till 2010, data available from www.petrolfed.be
$\dot{P}_{gasol}$	3.54%/y	
C_{GPRS}	120€/y	Annual average cost of subscription for general packet radio service transfer traffic for BEVs according to 4 Belgian companies
C_{mon}	480€/y	Annual average cost of data monitoring for BEVs according to 4 Belgian companies

To determine the sensitivity of the results, a Monte Carlo sensitivity analysis is conducted in which we vary the input data assuming a minimum (maximum) deviation of -10% (+10%) of the assumed parameter values in Table 9. The amount of solar radiation is not varied within the analysis. Results are presented in Table 10. The most important variables to determine the profitability of the investment options in our analysis are the unit costs of the PV installation (UC_{PV}) and the vehicles (UC_{BEV}, UC_{ICEV}), the value of the tradable green certificates *(TGC)*, the price of gasoline (P_{gasol}) and the electricity price (P_{electr}). In Table 11 we have calculated the according net present values for the company for the different investment options in 2009, 2012, and 2014. Note that the investment in solar panels for the SME in 2014 is profitable, despite the fact that tradable green certificates are no longer provided. This is mainly due to the fact that PV initial unit costs have fallen significantly in recent years. Nonetheless, the optimal timing to invest in solar panels was the year 2012, in which the subsidies were very generous compared to the decreasing costs of the solar installation. Since 2009 the economic attractiveness of battery electric vehicles is increasing as their initial purchase costs are falling rapidly.

3.3.3 Benefits of combined technologies (BOCT)

BOCT are now assessed according to Eq. 11, as the difference between the NPV of the combined technology minus the maximum of the NPV of the individual technologies. In the current case, we calculate the BOCT as the difference between the $NPV_{solarBEV\text{-}ICEV}$ and the $NPV_{BEV\text{-}ICEV}$, which equals €1,463. This means that the company would gain €1,463 more by investing in the combination of the technologies than if they would invest in the second most profitable investment opportunity in this case, *i.e.* the grid powered BEVs. The economic payoffs in function of the electricity price given the situation in Belgium on January 2011 are visualized in Figure 7. For low electricity prices (<€0.12/kWh) it is most profitable to invest in BEVs, that can be charged with low cost electricity. When the price of electricity rises (>€0.13/kWh) investment in exclusively PV becomes most attractive, due to a higher avoided cost of electricity. In all other cases, it is more profitable to invest in the combination of both technologies (upper part Figure 7). More precisely, BOCT are present at electricity prices between 0.112 and €0.134/kWh (bottom part Figure 7). In Tables 10 and 11 we demonstrate how the BOCT vary with varying input parameters. In 2009, the benefit of the combined technology was equal to €1,470, while this combined technology benefit is no longer existent in 2014. Note that the proposed methodology aims to compare the profitability of different investment options, yet the presence of BOCT is not guaranteed.

Table 10 Sensitivity analysis (Results for the SME in 2012)

	$NPV_{PV\text{-}grid}$		$NPV_{BEV\text{-}ICEV}$		$NPV_{solarBEV\text{-}ICEV}$		*BOCT*
Base case	59,828		68,209		69,672		1,463
Minimum	32,389		21,072		26,617		/
Maximum	90,303		115,331		106,865		/
Sensitivity	UC_{PV}	-37.1%	UC_{BEV}	-54.0%	UC_{BEV}	-52.2%	
with respect	TGC	33.3%	UC_{ICEV}	25.2%	UC_{ICEV}	24.3%	
to…	P_{electr}	16.1%	P_{gasol}	14.9%	P_{gasol}	13.9%	

Table 11 Results for the SME in 2009, 2012, and 2014

Year	2009	2012	2014
Input parameter values			
UC_{PV} (€/Wp)	5 - 6.4	3.1 – 4	1.1 - 1.3
TGC (€/kWh)	0.45	0.33	0
UC_{BEV} (€)	31.450	29,403	25,221
UC_{ICEV} (€)	17.089	16,487	16,190
P_{gasol} (€/l)	1.16	1.5	1.47
P_{electr} (€/kWh)	0.129	0.120	0.115
Results			
$NPV_{PV\text{-}grid}$ (€)	35,001	59,828	28,810
$NPV_{BEV\text{-}ICEV}$ (€)	29,961	68,209	95,307
$NPV_{solarBEV\text{-}ICEV}$ (€)	36,471	69,672	76,025
BOCT (€)	1,470	1,463	/

3.3.4 Rationalization behind BOCT

We recall from section 3.2.4 that per definition, the parameters *p* that determine the difference between the joint payoff of the combined technology and the relative linear combination of the payoffs of the individual technologies are the parameters that are responsible for BOCT (Eq. 12). We see from Table 9 that our case study contains several parameters *p* that cause nonlinearities when combining different technologies: *(i) PV unit cost*; when a PV installation in Belgium exceeds 11.5kWp, legislation requires the performance of a grid study and installation of both a meter and a decoupling box due to the fact that large PV installations may have a significant impact on the electricity grid. These additional measures bring about extra costs. Further, as long as the total installed power is smaller than about 70kWp, economies of scale might not be sufficient to spread out this additional cost; *(ii) local PV subsidy*; this subsidy does not vary linearly with the installed capacity, as in both cases the maximum subsidy of €1,000 can be obtained; *(iii) costs of general packet radio service and (iv) monitoring cost;* these do not vary proportionally with the number of vehicles; *(v) tax benefit on the electricity cost*; a tax benefit can be obtained on the cost of electricity when charging the electric vehicle with electricity purchased from the grid, while a tax benefit cannot be obtained when charging the electric vehicle with the PV generated electricity. Hence, the combination of the five parameters listed above is responsible for the presence of the combined technology benefits.

3.4 Conclusion

This research is the first to provide a method to calculate and compare the economic payoff of individual complementary technologies with the payoff of their integrated combination, under budgetary limits. The developed model exemplifies an ex ante CBA developed for business and non-governmental use. It is a partial equilibrium model that focuses on the equilibrium point of an investor, maximizing the investor's payoff subject to a given set of economic situations. While this model is sufficient from the viewpoint of an investor, for policy makers a general equilibrium model is required. The model is applicable to perform an economic assessment of any combination of complementary technologies, yet the existence of economic synergies or "benefits of combined technologies" (BOCT) is not guaranteed. Analogously to economies of scope, the existence of BOCT has to be verified for each combination of complementary technologies. The presence of BOCT depends on the policy measures provided for each technology, on the characteristics of the technology itself, and on the market conditions that may cause nonlinearities when combining technologies.

The method is illustrated with a case of solar PV and battery electric vehicles for a small Belgian company. It is found that economic BOCT or synergies are present for electricity prices between €0.112/kWh and €0.134/kWh. Hence, the company which currently pays €0.12/kWh for its electricity gains the most by investing in the combination of both technologies. The additional profit in this case amounts to €1,463. A Monte Carlo sensitivity analysis demonstrates how these results vary with changes in the key parameter values, which can be uncertain and time reliant. While economic BOCT are present at several scenarios, it is not clear to what extent this combined technology impacts emission reduction. To this end, the environmental life cycle impact should be assessed. These results need to be evaluated simultaneously with the results of the economic computational model. This calls for a multi objective optimization approach, which is an interesting topic for further investigation.

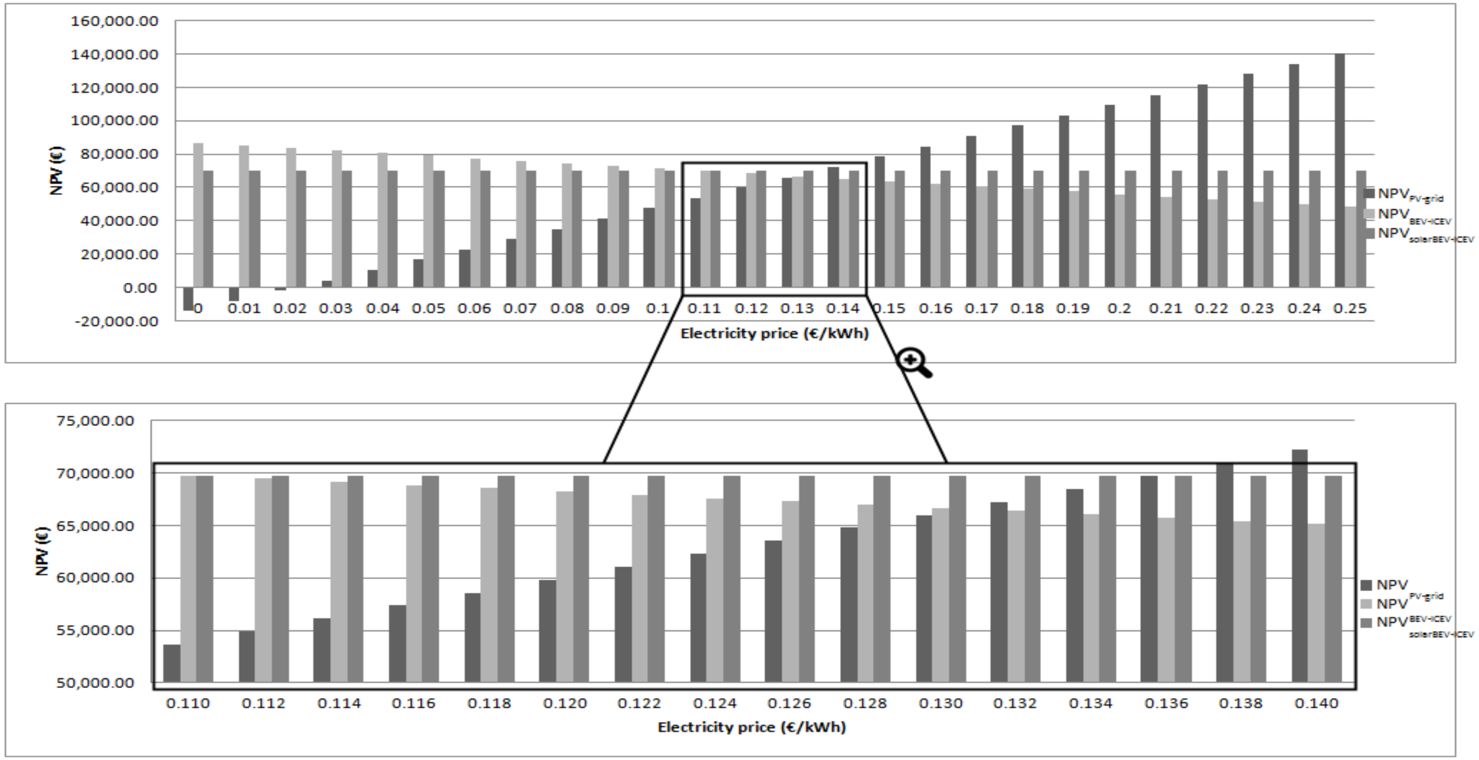

Figure 7 Comparison of the NPV of the investment options in function of the electricity price

4 Cost-efficient emission abatement of energy and transportation technologies: Mitigation costs and policy impacts for Belgium

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ABSTRACT

In the light of global warming, this chapter develops a framework to compare energy and transportation technologies in terms of cost-efficient GHG emission reduction. We conduct a simultaneous assessment of economic and environmental performances through life cycle costing and life cycle assessment. To calculate the GHG mitigation cost, we create reference systems within the base scenario. Further, we extend the concept of the mitigation cost, allowing to *(i)* compare technologies given a limited investment resource, and *(ii)* evaluate the direct impact of policy measures by means of the subsidized mitigation cost. The framework is illustrated with a case of solar photovoltaics (PV), grid powered battery electric vehicles (BEVs), and solar powered BEVs for a Belgian small and medium sized enterprise (SME). The study's conclusions are that the mitigation cost of solar PV is high, even though this is a mature technology. The emerging mass produced BEVs on the other hand are found to have a large potential for cost-efficient GHG mitigation as indicated by their low cost of mitigation. Finally, based on the subsidized mitigation cost, we conclude that the current financial stimuli for all three investigated technologies are excessive when compared to the CO_2 market value under the EU Emissions Trading Scheme.

4.1 Introduction

Aiming to mitigate climate change, the EU set targets to reduce GHG emissions with at least 20% by 2020 compared to 1990 levels (European Commission 2009). In 2010, two sectors produced nearly two-thirds of global CO_2 emissions; electricity and heat generation accounted for 41% while transport produced 22% (International Energy Agency 2012). Clean energy and transportation technologies are at hand to reduce polluting emissions, yet they often imply increased economic costs. Hence, there is a strong need to assess and compare clean energy and transportation (non-energy) technologies in terms of cost-efficient emission reduction. To this end, the economic costs and environmental impacts can be integrated into a mitigation assessment (Sathaye and Meyers 1995), and the technologies' costs for mitigation can be calculated accordingly.

The GHG mitigation cost is defined by Lazarus et al. (1995) in the manual "Long range energy alternatives planning" (LEAP) system; an integrated modeling tool to track energy consumption, production, and resource extraction in all sectors of an economy. It can be used to account for both energy and non-energy (*e.g.* transportation) GHG emission sources and sinks. The LEAP system model is not used as such in this research, yet the reasoning behind the model has the same structure. Moreover, we conduct a comparative life cycle assessment (LCA) to assess the mitigation potential of the technologies and we use life cycle costing (LCC) to assess the economic costs. Additionally, in our framework we extend the traditional mitigation cost as described in LEAP in two ways: *(i)* In the light of rationing capital amongst competing investment opportunities (Lorie and Savage 1949), we allow comparing the mitigation cost of different technologies –*i.e.* energy, transportation, or a combination of the former- given the constraint of a limited capital for investment; and *(ii)* As both energy (Badcock and Lenzen 2010) and transportation technologies (Delucchi and Murphy 2008) are generously subsidized, we assess the impact of policy by calculating the subsidized GHG mitigation cost, which accounts for all direct subsidies and taxes. The methodology is illustrated with a Belgian small and medium sized enterprise (SME). As a matter of fact, to pursue high environmental performance, economic and social effectiveness of companies, including SMEs is the key goal of sustainable development (Laurinkeviciute and Stasiskiene 2011). The company aims to reduce GHG emissions at the source by substituting fossil based with clean technologies (Ingwersen, Garmestani et al. 2013). More specifically, they seek to evaluate the cost of emission reduction of solar PV, grid powered battery electric vehicles, and solar powered battery electric vehicles under budgetary limits.

In section 4.2 we discuss how the framework is conceptualized. Section 4.3 provides a stepwise method to address the targeted objectives of the framework. In section 4.4 the methodology is applied to a Belgian company. The chapter ends with a conclusion section, incorporating policy recommendations.

4.2 Conceptual framework

A schematic overview of the conceptual framework is provided in Figure 8. A detailed explanation is given in the following subsections.

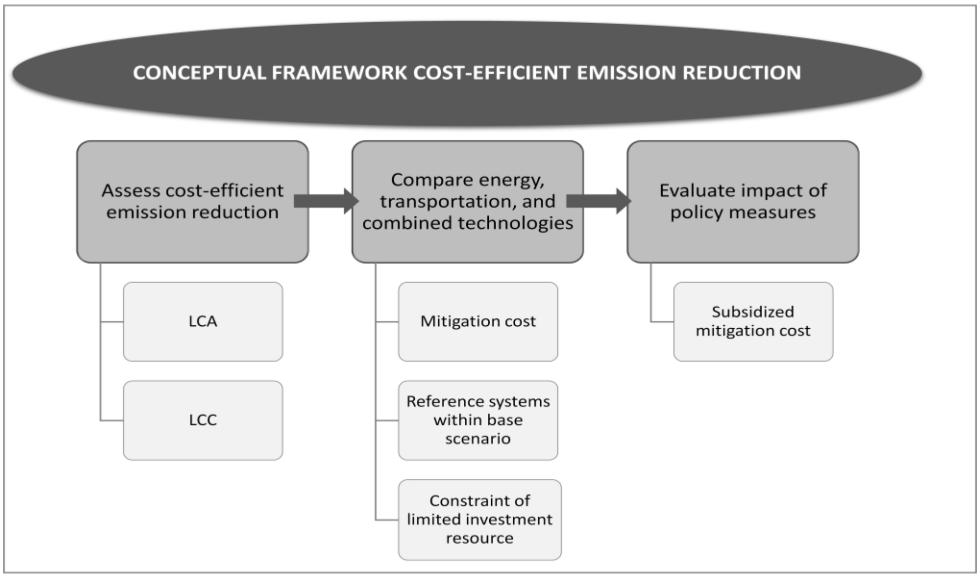

Figure 8 Conceptual framework to assess and compare cost-efficient emission reduction of clean energy and transport technologies under budgetary limits

4.2.1 Cost-efficient emission reduction

To assess the cost of emission reduction, it is necessary to evaluate *(i)* the emission reduction potential; and *(ii)* the economic costs compared to the conventional (*e.g.* fossil based) alternative over the whole life cycle of the technologies. To this end, we make use of life cycle assessment and life cycle costing. Life cycle assessment or LCA is a tool to assess environmental impacts of complete life cycles of products or functions. In this framework we use comparative LCA, *i.e.* the environmental impact of the clean technology is calculated and compared to the impact of a conventional technology. More specifically, we make use of attributional LCA -suited to describe the environmentally physical flows of a past, current, or future product system- rather than a consequential LCA, which is more appropriate for determining the emission impact of a change in consumption. The applied LCA methodology complies to the relevant ISO standards (14040-14044:2006). Life cycle costing or LCC is an assessment technique that takes into consideration all the cost factors relating to the asset during its operational life. The life cycle cost of an asset can, very often, be many times the initial purchase or investment cost (Woodward 1997). As any rational investor considers the life cycle cost rather than merely the cost of investment, it is important that policy makers are aware of the magnitude of lifetime costs since their final aim is to influence the investor's choice.

4.2.2 Energy, transportation, and combined technologies

For each technology we calculate the mitigation cost as defined by Lazarus et al. (1995) in the manual "Long range energy alternatives planning" (LEAP) system. To this end, both the LCA and the LCC must handle on the same functional unit. To compare energy and transportation technologies, we follow the LEAP approach that distinguishes "reference systems" (in which energy and non-energy technologies are separated) within the base scenario (which can contain both types). Amongst others, this approach is demonstrated by Kumar et al. (2003) who determined the GHG mitigation potential of biomass energy technologies in Vietnam. In the light of rationing capital amongst competing investment opportunities (Lorie and Savage 1949), we extend the mitigation cost as described in LEAP by comparing the mitigation cost of different technologies –*i.e.* energy, transportation (non-energy), or a combination of the former- given the constraint of a limited investment resource.

4.2.3 Impact of policy measures

Policy makers can make use of the mitigation cost to determine how much abatement can be achieved at a certain economic cost and to assess where policy intervention is needed in order to achieve certain emission reductions. Accordingly, the authors propose to include the impact of financial policy measures on the mitigation cost. Hence, we define the "subsidized mitigation cost" that takes into account all direct subsidies and/or taxes relating to a technology (or combination of technologies). Rather than predicting the economic cost of emission reduction to meet future CO_2 targets -as demonstrated amongst others by Chen et al. (2013)- this analysis evaluates the current impact of policy on the economic cost of mitigation.

4.3 Methodology

To address the aims of the developed framework, a three-step methodology is worked out (Figure 9). First, the base scenario and investment scenarios are defined. Second, the technology sizes within each scenario are calculated, given the constraint of a limited capital for investment. Then, the greenhouse gas mitigation cost of each technology including and excluding the impact of policy is determined. This is elaborated upon in the following subsections.

4.3.1 Base scenario and investment scenarios

For each technology that we want to assess, a reference technology or "reference system" needs to be defined. Indeed, without a reference it is impossible to calculate the mitigation cost. Then, the base scenario is composed of all the reference systems. Next, the investment scenarios can be defined by replacing the reference systems within the base scenario one by one with the according technology that needs to be assessed. If the combination of energy and transportation technologies is complementary, we additionally include in our framework the combination of the former.

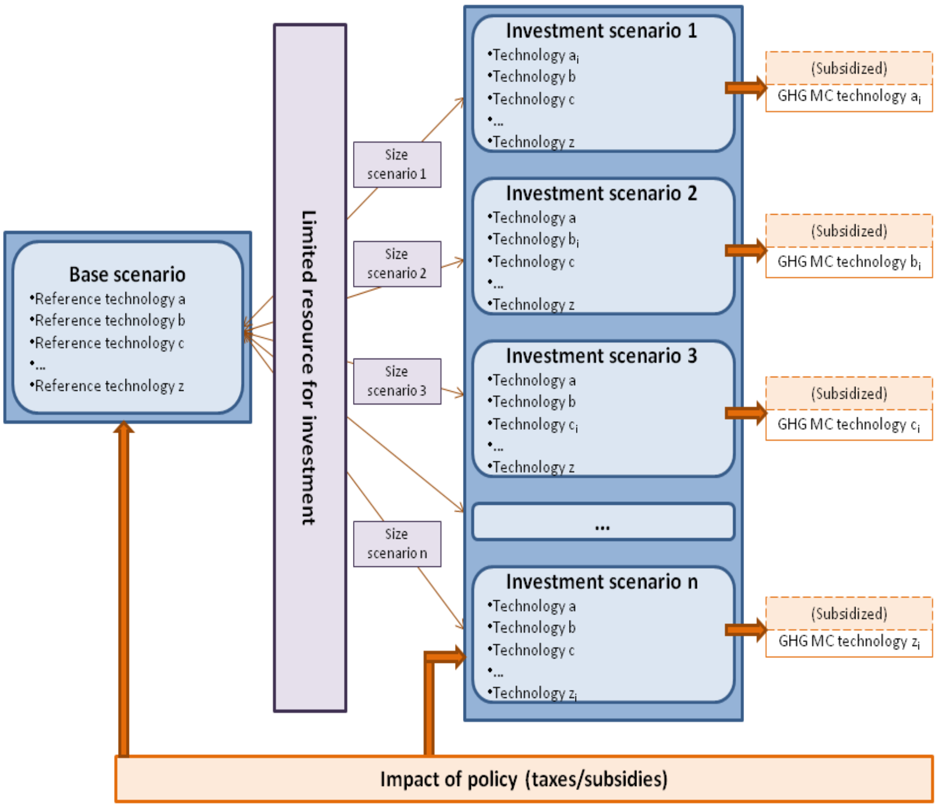

Figure 9 Methodology to calculate GHG mitigation costs under budgetary constraints

4.3.2 Investment sizes, given a limited investment resource

To calculate the technology sizes, we refer to Chapter 3 in which a model is developed to directly compare the economic payoff of individual complementary technologies with the economic payoff of their integrated combination under budgetary constraints. Given a limited amount of investment resources (I_0), the size of any individual technology *($size_{Ni}$)* can be calculated according to Eq. 1, where the denominator UC_{Ni}-UC_{Ri} represents the initial unit cost of technology N_i directly compared to the initial unit cost of displaced technology R_i. When the technology lifetimes are unequal, the roll-over-method (Boardman, Greenberg et al. 2011) is used; the project with the shorter lifetime is "rolled over" within the lifetime of the longer project: Given technology N_s with short lifetime n_{Ns} that needs to be compared with technology N_l with longer lifetime n_{Nl} ($n_{N_l} > n_{N_s}$), the number of times that project N_s needs to be "rolled over" *(z)* is given in Eq. 1a. The calculation of the initial unit cost of investment in N_s as compared to the investment in any displaced technology R_s $(UC_{Ns}$-$UC_{Rs})$ is then calculated according to Eq. 1b, by taking into account the real annual price evolution of the technologies $(\dot{P})$, and then discounting at discount rate *r*. The investment size of any joint combination of interdependent technologies is calculated by solving a system of equations as outlined in Eq. 2. The first line indicates that the investment cost I_0 is composed of the initial unit cost of all technologies directly compared to the initial unit cost of the displaced technologies $(UC_{Ni}$-$UC_{Ri})$ multiplied by their size ($size_{Ni}$ = $size_{Ri}$). The other lines represent the technical interrelationships among the different technologies within the integrated combination, which is characterized by a constant c_i.

$$\mathrm{size_{N_i}} = \frac{\mathrm{I_0}}{\mathrm{UC_{N_i}} - \mathrm{UC_{R_i}}} \text{ with } \mathrm{UC_{N_i}} > \mathrm{UC_{R_i}} \tag{1}$$

$$\mathrm{z} = \frac{\mathrm{n_{N_l}}}{\mathrm{n_{N_s}}} \text{ with } \mathrm{n_{N_l}} > \mathrm{n_{N_s}} \tag{1a}$$

$$\mathrm{UC_{N_s}} - \mathrm{UC_{Rs}} = \sum_{t=0*\mathrm{n_{N_s}}}^{(z-1)*\mathrm{n_{N_s}}} \left[\frac{\mathrm{UC_{N_s}}*(1+\dot{\mathrm{P}}_{\mathrm{N_s}})^{t}}{(1+r)^{t}}\right] - \sum_{t=0*\mathrm{n_{Rs}}}^{(z-1)*\mathrm{n_{Rs}}} \left[\frac{\mathrm{UC_{Rs}}*(1+\dot{\mathrm{P}}_{\mathrm{Rs}})^{t}}{(1+r)^{t}}\right] \tag{1b}$$

$$\begin{cases} \mathrm{I_0} = \left(\mathrm{UC_{N_1}} - \mathrm{UC_{R_1}}\right) * \mathrm{size_{N_1}} + \left(\mathrm{UC_{N_2}} - \mathrm{UC_{R_2}}\right) * \mathrm{size_{N_2}} + \cdots + \left(\mathrm{UC_{N_n}} - \mathrm{UC_{R_n}}\right) * \mathrm{size_{N_n}} \\ \mathrm{size_{N_2}} = \mathrm{size_{N_1}} * c_1 \\ \mathrm{size_{N_3}} = \mathrm{size_{N_1}} * c_2 \\ \cdots \\ \mathrm{size_{N_n}} = \mathrm{size_{N_1}} * c_{n-1} \end{cases} \tag{2}$$

4.3.3 Technological and subsidized GHG mitigation cost

The mitigation cost of any investment scenario *n* is calculated using Eq. 3, by dividing the additional economic cost of each investment scenario *n* as compared to the base scenario *b* $(Q_n–Q_b)$ by the average annual emission reduction $(GHG_b$-$GHG_n)$ over the whole lifetime (Lazarus, Heaps et al. 1995). The economic life cycle costs *Q* (including investment capital I_0, operation costs *OC* and maintenance costs *MaC*) of all investment scenarios and the base scenario throughout the lifetime of the technologies are calculated and annualized according to Eq. 4-5. To calculate the GHG emission reduction, we use the LCA software SimaPro® (PRé consultants, Amersfoort, The Netherlands). We note that the mitigation cost as such is based solely on technological parameters, excluding any financial legislative parameters such as direct taxes or subsidies. We refer to this cost as "technological mitigation cost".

$$MC_{GHG_n} = \sum_t \left[\frac{Q_{n,t} - Q_{b,t}}{GHG_{b,t} - GHG_{n,t}}\right] \quad (3)$$

$$Q_{b,t} = \frac{I_{0_{b,t}} + OC_{b,t} + MaC_{b,t}}{(1+i)^t} \quad (4)$$

$$Q_{n,t} = \frac{I_{0_{n,t}} + OC_{n},t + MaC_{n,t}}{(1+i)^t} \quad (5)$$

To assess the influence of monetary incentives, we define in Eq. 6 the subsidized GHG mitigation cost. The latter is calculated by correcting the economic costs *Q* for the direct subsidies received and the direct taxes to be paid *(SUBS)*. Taxes are considered as negative subsidies.

$$MC_{GHG_{SUBS,n}} = \sum_t \left[\frac{(Q_{n,t} - SUBS_{n,t}) - (Q_{b,t} - SUBS_{b,t})}{GHG_{b,t} - GHG_{n},t}\right] \quad (6)$$

4.4 Case study

The case is based on a Belgian SME with a demand for both electricity and road transport. Currently, required demands are met by means of grid electricity and gasoline powered internal combustion engine vehicles (ICEVs). The vehicles have an average travel distance of 17,120km/y. The company wants to assess the cost-efficient emission reduction of the following clean energy and transport technologies: *(i)* solar photovoltaics (PV); *(ii)* grid powered battery electric vehicles (BEVs); and *(iii)* solar powered BEVs (the combination of the former), given an initial capital for investment of €127,000. Economic data is summarized in Table 12. Data regarding the BEV is based on the Nissan Leaf; the ICEV referred to is the comparable gasoline powered Nissan Note Tekna auto 1.6l. For each numerical value, a motivation and reference is listed. We assume that the lifetime of the project equals the lifetime of the "longest living" technology;

that is solar PV with a lifetime of 25 years. Further we assume that the vehicles' CO_2 emissions are constant throughout the lifetime of the project.

4.4.1 Base scenario and investment scenarios

The scenarios are presented schematically in Figure 10.

Demand (=functional unit of the analysis)	**Base scenario**	**Investment scenario 1**	**Investment scenario 2**	**Investment scenario 3**
Transportation demand (kilometers)	gasoline ICEV (reference) 	gasoline ICEV 	grid powered BEV 	solar powered BEV 
Electricity demand (kilowatthours)	Grid (reference) 	PV 	Grid 	Grid 

Figure 10 Base scenario and investment scenarios

Table 12 Economic data case study

General data	Subsidies/Taxes (S/T)	Costs (Q_n)
r = 4% (European Commission 2009) n = 25 y (vehicles: 5 * 5 y)	t_r = 33.99%(FOD Financiën 1992)	I_0 can be any (positive) number. Here, I_0 is €127,000 and is varied by +-20% in the sensitivity analysis.
Base scenario: Grid electricity and gasoline fueled ICEVs		
$size_{ICEV}$ = 6; equals $size_{BEV}$ (scenario 2) $Fuse_{ICEV}$ = 6.02l/100km; data adapted from (Nissan 2013) Dt = 17,120km/y; assumption based on case study n_{ICEV} = 5 y (will be replaced 5 times) Electr = 44,327kWh/y; equals the average annual electricity produced by the solar PV installation (scenario 1)	$T_{o,ICEV}$ = 495€ (FOD Financiën 2013) $T_{n,ICEV}$ = 385.84€/y (FOD Financiën 2013) $\dot{P}_{To}$ = 0%; stable over the last 7 years and expected to remain stable in the coming years (FOD Financiën 2013) $\dot{P}_{Tn}$ = 2.10%; geometric mean of the evolution of annual traffic taxes from 2005 till 2011 (FOD Financiën 2013) T_{gasol} = 0.63€/l; Excise tax + APETRA/BOFAS/energy contribution on gasoline 95 price (Belgische Petroleum Federatie 2013) T_{electr} = 0.9544€/MWh; energy contribution due on electricity used for business purposes by end users connected to a distribution network <1kV, (FOD Financiën 2012) $S_{ID,ICEV}$=70% (Belgisch Staatsblad 2009) $S_{ID,fuel}$=75% (Belgisch Staatsblad 2009)	UC_{ICEV} = 16,686€/veh; price excl. 21% tax (Nissan 2013) $\dot{P}_{ICEV}$ = -1.45%/y; calculated as the geometric mean of the Belgian real car price evolution from 2005 till 2011 (European Union 2005-2011) MaC_{ICEV} = 4,440€/5y; Nissan's estimate UC_{gasol} = 0.84€/l; gasoline 95 price excl. taxes (Belgische Petroleum Federatie 2013) $\dot{P}_{gasol}$ = 3.85%/y; calculated as the geometric mean of gasoline price evolutions from 1990 till 2011 (Belgische Petroleum Federatie 2013) UC_{electr} = 0.0967€/kWh; electricity price excl. taxes for Belgian medium sized enterprises (Eurostat 2012) $\dot{P}_{electr}$ = 1.79%/y; calculated as the geometric mean of electricity price evolution for Belgian medium sized enterprises from 1991 till 2011 (Eurostat 2012)
Scenario 1: Solar PV and gasoline fueled ICEVs (Grid electricity substituted by solar PV)		
$size_{PV}$ = 57.37kWp; calculations in Table 14 β = 850kWh/kWp (Súri, Huld et al. 2007) α = 0.70%/y; according to the performance guarantee on PV modules n_{PV} = 25y $size_{ICEV}$ = 6 (as in the base scenario)	S_{TGC} = 230€/MWh for 20 y until 30.06.2012 (Flemish Energy Agency 2013) S_{EID} = 10% (Flemish Energy Agency 2013)	UC_{PV} = 2,300€/MWp if P_{tot}<11.5kWp, 2,900€/MWp if P_{tot}=11.6kWp, 2,900-2,300€/MWp if 11.6<P_{tot}<25kWp, 2,300-2,100€/MWp if 25<P_{tot}<100kWp, 2,100-1,900€/MWp if 100<P_{tot}<200kWp, 1,900-1,700€/MWp if 200<P_{tot}<300kWp; based on 4 tenders in Feb 2012, including legislation and EOS $UC_{INS,PV}$ = 0.23% of I_0; average based on 4 tenders in Feb 2012 MaC_{PV} = 11€/kWp; average based on 4 tenders in Feb 2012

Scenario 2: Grid electricity and grid powered BEVs (gasoline fueled ICEVs substituted by grid powered BEVs)		
$size_{BEV}$ = 6; calculations in Table 14 $Fuse_{BEV}$ = 0.173kWh/km (Nissan 2013) Dt = 17,120km/y; assumption based on case study n_{BEV} = 5 y (will be replaced 5 times) Electr = 44,327kWh/y (as in the base scenario)	$T_{o,BEV}$ = 0 (FOD Financiën 2013) $T_{n,BEV}$ = 73.79€/y (FOD Financiën 2013) $\dot{P}_{To,BEV}$ = 0%/y; stable the last 7 years and expected to remain stable in the coming years (FOD Financiën 2013) $\dot{P}_{Tn,BEV}$ = 2.10%/y; geometric mean of the evolution of annual traffic taxes from 2005 till 2011 (FOD Financiën 2013) T_{electr} = 0.9544€/MWh; energy contribution due on electricity used for business purposes by end users connected to a distribution network <1kV (FOD Financiën 2012) $S_{ID,BEV}$ = 120% (Belgisch Staatsblad 2009)	UC_{BEV} = 30,570€/veh; price excl. 21% tax (Nissan 2013) $\dot{P}_{BEV}$ = -5.39%/y; average of annual price decrease of BEVs forecasted by EU Coalition – Mc Kinsey (2010) and Weiss et al. (2012) MaC_{BEV} = 1,332€/5y; Nissan's estimate UC_{electr} = 0.0967€/kWh; electricity price excl. taxes for Belgian medium sized enterprises (Eurostat 2012) $\dot{P}_{electr}$ = 1.79%/y; calculated as the geometric mean of electricity price evolution for Belgian medium sized enterprises from 1991 till 2011 (Eurostat 2012)
Scenario 3: Grid electricity and solar powered BEVs (gasoline fueled ICEVs substituted by solar powered BEVs)		
$size_{BEV}$ = 4; calculations in Table 14 $size_{ICEV}$ = 2; calculations in Table 14 $size_{PV}$ = 15.38kWp; calculations in Table 14 Electr = 44,327kWh/y (as in the base scenario) Other data from the previous scenarios is applicable	Subsidies/taxes from previous scenarios are applicable	Costs from previous scenarios are applicable

4.4.2 *Investment sizes, given a limited investment resource*

The investor has foreseen a budget of €127,000 that can potentially be invested in either one of the investment scenarios (Table 14, row 1). The calculations of the investment sizes are listed in row 2. In scenario 1, the ICEVs from the base scenario are used for transport, and the capital is used to purchase PV panels. According to Eq. 1, we find that the size of the PV installation totals 57.37kWp, which is sufficient to displace an average of 44,327kWh/y of grid electricity in the base scenario. The latter is calculated as the average of the electricity generated by the solar panels annually. In scenario 2, the grid is used to meet electricity demands, and the gasoline ICEVs are replaced with grid powered BEVs for transport. The determination of the number of BEVs is more complicated, as the lifetime of the BEVs (5y) differs from that of the PV installation (25y). Hence, the investment in BEVs is rolled over 5 times within the longer PV lifetime (Eq. 1a). According to Eq. 1b we find that the number of BEVs equals 6, meaning that the project starts with 6 BEVs that are replaced 5 times every 5 years. We assume that these 6 BEVs replace an equal amount of ICEVs in the base scenario. Scenario 3 uses grid electricity and solar powered BEVs. The size of this combined technology given the budgetary limit of €127,000 is calculated by solving the system of equations as outlined in Eq. 2. The constant *c* in this case represents the power of solar panels needed to charge one BEV (kWp/vehicle), and is hence calculated by dividing the total electricity consumption of the BEV (kWh/vehicle) by the amount of electricity generated per unit of power of the solar panels (kWh/kWp). In this investment scenario, 4 BEVs are purchased (that are replaced 5 times every 5 years) accompanied with 15.38kWp of solar panels to power the vehicles. As the base scenario contains 6 ICEVs and the limited investment capital is sufficient to replace only 4 of them with BEVs; 2 ICEVs are kept in this scenario.

4.4.3 *Technological and subsidized GHG mitigation cost*

The calculation of the economic costs and the direct impact of policy can be found in Table 14, row 3. The life cycle inventory as modeled in SimaPro® is listed in Table 13. Unit processes are selected from the EcoInvent database, based on the best available match with the real projections at hand. The different scenarios are assessed for their impact on climate change using the IPCC 2007 GWP 100a v1.02 single issue method. Regarding the electricity, the LCA accounts for the GHG emissions of the generation and distribution phase. As regards the vehicles, we consider the impacts of *(i)* production and assembly, *(ii)* well-to-tank (WTT) (production and distribution of the energy carrier), and *(iii)* tank-to-wheel (TTW) (conversion from energy carrier to transport). Table 15 shows the CO_2eq emissions per unit of the different processes used.

An overview of the economic costs, the GHG emissions and the mitigation costs is presented in Table 16. The first two rows summarize the economic costs excluding and including the impact of policy. From the investor's point of view, scenario 2 (grid powered BEVs) is the most interesting option for investment, as it implies the lowest economic costs while receiving the highest amount of policy support. Scenario 1 (solar PV) on the other hand implies the highest costs. The third row shows total GHG emissions. In scenarios 1, 2, and 3, life cycle GHG emissions as compared to the base scenario are decreased with 24%, 45%, and 37%. Hence, from a climate change viewpoint, the limited investment resources would obtain the best (worst) results when allocated to grid powered BEVs (solar PV). The final row shows the technological and the subsidized mitigation costs. In both cases, grid powered BEVs (scenario 2) are the most cost-efficient technology to reduce greenhouse gases. A negative mitigation cost -*e.g.* technological mitigation cost of grid BEVs in scenario 2- indicates that the alternative is an economic option regardless of any emission reduction (Sims, Rogner et al. 2003) or hence, reducing greenhouse gases in this case leads to an economic gain. We note however that according to Weiss et al. (2012), the price of the Nissan LEAF is -just as the price of the Mitsubishi i-MiEV and the Citroën C-zero- substantially (*i.e.* about 41%) lower than the price of an "average" BEV, due to the fact that the former is mass produced. This draws the attention to the importance of economies of scale, reaching significant cost savings when producing large quantities. The subsidized mitigation cost indicates that all technologies are generously subsidized in Flanders, reaching values of about -300€ per ton CO_2eq avoided. Finally, we note that the choice of the discount rate is important (Baumol 1968). Based on a Monte Carlo sensitivity analysis, we conclude however that the discount rate in our analysis is not an important variable to determine the variability of the forecast variables, *i.e.* the technologies' greenhouse gas mitigation costs.

Table 13 Life cycle inventory

Unit process (available in EcoInvent)	**Quantity**	**Unit**	**Comment**
Base scenario			
Passenger car/RER/I U	30	piece	ICEV life cycle
Petrol, low-sulphur, at regional storage/RER U	154,482	kg	Storage and distribution of petrol
Petrol, low-sulphur, at refinery/RER U	154,482	kg	Production of petrol
Operation, passenger car, petrol, fleet average 2010/RER U	2,566,064	km	Combustion of petrol for transport
Electricity, low voltage, production BE, at grid/BE U	1,108,184	kWh	Electricity for any purpose from Belgian grids
Scenario 1			
Passenger car/RER/I U	30	piece	ICEV life cycle
Petrol, low-sulphur, at regional storage/RER U	154,482	kg	Storage and distribution of petrol
Petrol, low-sulphur, at refinery/RER U	154,482	kg	Production of petrol
Operation, passenger car, petrol, fleet average 2010/RER U	2,566,064	km	Combustion of petrol for transport
PV, 3 kWp slanted-roof, multi-Si, panel, CH U	1,108,184	kWh	Electricity for any purpose from PV installation
Scenario 2			
Passenger car, electric, LiMn2O4, at plant/RER/I U	30	piece	BEV life cycle
Electricity, low voltage, production BE, at grid/BE U	443,929	kWh	Electricity for transport (2,566,064 km) from Belgian grid
Electricity, low voltage, production BE, at grid/BE U	1,108,184	kWh	Electricity for any purpose from Belgian grids
Scenario 3			
Passenger car, electric, LiMn2O4, at plant/RER/I U	20	piece	BEV life cycle
Passenger car/RER/I U	10	piece	ICEV life cycle
PV, at 3 kWp slanted-roof, multi-Si, panel, CH U	297,112	kWh	Electricity for transport (1,717,411 km) from PV
Petrol, low-sulphur, at regional storage/RER U	51,091	kg	Storage and distribution of petrol
Petrol, low-sulphur, at refinery/RER U	51,091	kg	Production of petrol
Operation, passenger car, petrol, fleet average 2010/RER U	848,653	km	Combustion of petrol for transport
Electricity, low voltage, production BE, at grid/BE U	1,108,184	kWh	Electricity for any purpose from Belgian grids

Table 14 Investment capital (I_0), investment size (Size), economic costs (Q) and policy impact (SUBS)

	Base scenario (ICEV + grid)	Scenario 1 (ICEV + PV)	Scenario 2 (grid BEV + grid)	Investment scenario 3 (solar BEV + grid)
I_0	0€	€127,000	€127,000	€127,000
Size (Eq. 1-2)	$size_{ICEV} = size_{BEV} = 6$ $size_{grid}$ $(= electr_t)$ $= \frac{\sum_{t=1}^{25}[\beta * size_{PV} * (1-\alpha * t)]}{25}$ $= 44{,}327kWh/y$	$size_{PV} = I_0/(UC_{PV} - UC_{grid})$ $= 57.37kWp$ ❖ $UC_{PV} = 2{,}213.70$ €/kWp ❖ $UC_{grid} = 0€$	$size_{BEV} = I_0/(UC_{BEV} - UC_{ICEV}) = 6$ ❖ $UC_{BEV} = \sum_{t=0,5,10,15,20}\left[\frac{UC_{BEV,t=0}*(1+\dot{P}_{BEV})}{(1+r)^t}\right.$ $73{,}483.21€/veh$ ❖ $UC_{ICEV} \sum_{t=0,5,10,15,20}\left[\frac{UC_{ICEV,t=0}}{(1+}\right.$ $52{,}300.58€/veh$	$\begin{cases} I_0 = (UC_{PV} - UC_{grid}) * size_{PV} + (UC_{BEV} - UC_{ICEV}) * size_{BEV} \\ size_{PV} = size_{BEV} * c_1 \end{cases}$ $size_{PV} = 15.38kWp$; $size_{BEV} = 4$; $size_{ICEV} = 6 - 4 = 2$ ❖ $c_1 = \frac{D_t * n_{BEV} * z * F_{use_{BEV}}}{\sum_{t=1}^{n_{PV}}[\beta*(1-\alpha*t)]} = \frac{3.833kWp}{veh}$ ❖ $UC_{PV} - UC_{grid} = 2{,}730.67€/kWp$ ❖ $UC_{BEV} - UC_{ICEV} = 21{,}182.63€/veh$
Q (Eq. 4-5)	$Q_b = €289{,}682.99$ ❖ $OC_{ICEV_t} = D_t * F_{use_{ICEV}} * UC_{gasol_t} * (1+\dot{P}_{gasol})^t$ ❖ $MaC_{ICEV,t}$ ❖ $OC_{grid_t} = size_{grid} * UC_{electr} * (1+\dot{P}_{electr})^t$	$Q_{scenario\ 1} = €347{,}371.75$ ❖ $OC_{ICEV_t} = D_t * F_{use_{ICEV}} * UC_{gasol_t} * (1+\dot{P}_{gasol})^t$ ❖ $MaC_{ICEV,t}$ ❖ $OC_{PV_t} = UC_{INS,PV} * UC_{PV} * size_{PV}$ ❖ $MaC_{PV,t} = MaC_{PV} * size_{PV}$	$Q_{scenario\ 2} = €267{,}937.38$ ❖ $OC_{gridBEV_t} = D_t * F_{use_{BEV}} * UC_{electr_t} * (1+\dot{P}_{electr})^t$ ❖ $MaC_{gridBEV_t} = MaC_{BEV,t}$ ❖ $OC_{grid_t} = size_{grid} * UC_{electr} * (1+\dot{P}_{electr})^t$	$Q_{scenario\ 3} = €300{,}255.87$ ❖ $OC_{solarBEV_t} = UC_{INS,PV} * UC_{PV} * size_{PV}$ ❖ $MaC_{solarBEV_t} = MaC_{BEV,t} + MaC_{PV,t}$ ❖ $OC_{grid_t} = size_{grid} * UC_{electr} * (1+\dot{P}_{electr})^t$ ❖ $OC_{ICEV_t} = D_t * F_{use_{ICEV}} * UC_{gasol_t} * (1+\dot{P}_{gasol})^t$
SUBS	$SUBS_b = €11{,}103.45$	$SUBS_{scenario\ 1} = €168{,}074.23$	$SUBS_{scenario\ 2} = €186{,}658.42$	$SUBS_{scenario\ 3} = €171{,}031.45$
	❖ $T_{ICEV_t} = [T_{0_{ICEV}} *$ (1+ṖT0)t=0,5,10,15,20+TnICEV∗(1+ṖTn)t∗ $size_{ICEV} + D_t * F_{use_{ICEV}} * T_{gasol_t} * (1+\dot{P}_{gasol})^t$ ❖ $T_{grid_t} = size_{grid} * T_{electr} * (1+\dot{P}_{electr})^t$ ❖ $S_{ICEV_t} = t_r * [S_{ID,fuel} *$ OCICEVt+*SID,ICEV∗(*TICEVt+UCICEV,t=0,5,10,15,20∗sizeICEV+MaCICEVt)	❖ $T_{ICEV_t} = [T_{0_{ICEV}} *$ (1+ṖT0)t=0,5,10,15,20+TnICEV∗(1+ṖTn)t∗ $size_{ICEV} + D_t * F_{use_{ICEV}} * T_{gasol_t} * (1+\dot{P}_{gasol})^t$ ❖ $S_{PV_t} = S_{EID_{t=0}} * UC_{PV} * size_{PV} + electr_t * S_{TGC_t}$ ❖ $S_{ICEV_t} = t_r * [S_{ID,fuel} *$ OCICEVt+*SID,ICEV∗(*TICEVt+UCICEV,t=0,5,10,15,20∗sizeICEV+MaCICEVt)	❖ $T_{BEV(grid)_t} = [T_{0_{BEV}} *$ (1+ṖT0)t=0,5,10,15,20+TnBEV∗(1+ṖTn)t∗ $size_{BEV} + D_t * F_{use_{BEV}} * T_{electr_t} * (1+\dot{P}_{electr})^t$ ❖ $T_{grid_t} = size_{grid} * T_{electr} * (1+\dot{P}_{electr})^t$ ❖ $S_{BEV(grid)_t} = t_r *$ $[S_{ID,fuel} * OC_{BEV(grid)_t} +$ *SID,BEV∗(*TBEV(grid)t+UCBEV,t=0,5,10,15,20∗sizeBEV+MaCBEV(grid)t)	❖ $T_{BEV(PV)_t} = [T_{0_{BEV}} * (1+\dot{P}_{T_0})^{t=0,5,10,15,20} + T_{n_{BEV}} *$ (1+ṖTn)t∗ sizeBEV ❖ $T_{grid_t} = size_{grid} * T_{electr} * (1+\dot{P}_{electr})^t$ ❖ $T_{ICEV_t} = [T_{0_{ICEV}} * (1+\dot{P}_{T_0})^{t=0,5,10,15,20} + T_{n_{ICEV}} *$ (1+ṖTn)t∗ $size_{ICEV} + D_t * F_{use_{ICEV}} * T_{gasol_t} * (1+\dot{P}_{gasol})^t$ ❖ $S_{BEV(PV)_t} =$ $t_r * [S_{ID,BEV} * (T_{BEV(PV)_t} + UC_{BEV,t=0,5,10,15,20} * size_{BEV} +$ MaCBEVPVt+*SID,fuel∗*OCICEVt+*SID,ICEV∗*TICEVt+UCICEV,t=0,5,10,15,20∗sizeICEV+MaCICEVt+SEIDt=0∗ $UC_{PV} * size_{PV} + electr_t * S_{TGC_t}$

Table 15 CO_2eq emissions (kg) per unit of the different processes used in the scenarios

Passenger car/RER/I U	4,199.18	kg CO_2eq/veh
Petrol, low-sulphur, at regional storage/RER U	0.729	kg CO_2eq/kg
Petrol, low-sulphur, at refinery/RER U	0.703	kg CO_2eq/kg
Operation, passenger car, petrol, fleet average 2010/RER U	0.237	kg CO_2eq/km
Electricity, low voltage, production BE, at grid/BE U	0.363	kg CO_2eq/kWh
Electricity, PV, at 3 kWp slanted-roof, multi-Si, panel, mounted, CH U	0.064	kg CO_2eq/kWh
Passenger car, electric, LiMn2O4, at plant/RER/I U	5,695.76	kg CO_2eq/veh

Table 16 Costs, GHG emissions, and mitigation costs

		Transportation			**Electricity generation**		
Costs (€)		Investment		O&M	Investment	O&M	**LCC (€)**
Excl. policy	Base	0		205,949	0	83,733.17	289,682.99
	Scenario 1	0		205,949	127,000	14,421.93	347,371.75
	Scenario 2	127,000		57,204	0	83,733.17	267,937.38
	Scenario 3	127,000		89,522	0	83,733.17	300,255.87
		Investment + O&M			Investment + O&M		**LCC (€)**
Incl. policy	Base	193,177.84			85,401.69		278,579.53
	Scenario 1	193,177.84			-13,880.32		179,297.52
	Scenario 2	-4,122.73			85,401.69		81,278.96
	Scenario 3	43,822.72			85,401.69		129,224.421
GHG emissions (ton CO_2eq)		Production	WTT	TTW	Generation & distribution		**Total (ton CO_2eq)**
	Base	125.77	220.96	608.16	402.27		1,357.16
	Scenario 1	125.77	220.96	608.16	70.59		1,025.48
	Scenario 2	170.71	177.26	0	402.27		750.25
	Scenario 3	155.85	92.00	201.13	402.27		851.26
MITIGATION COST (€/ton CO_2eq)		Technological mitigation cost (excluding policy)			Subsidized mitigation cost (including policy)		
	Scenario 1	173.93			-299.33		
	Scenario 2	-38.60			-325.09		
	Scenario 3	20.40			-295.22		

4.4.4 Impact of policy measures including sensitivity analysis

The impact of policy on the mitigation cost is visualized in Figure 11. The vertical axis shows the GHG mitigation cost; the horizontal axis reflects the additional amount of subsidies as compared to the base scenario. Where this additional amount of subsidization equals zero (the y-axis); one can find the technological GHG mitigation cost. The larger data points are projections of the current situation (June 2012) for Belgian SMEs, reflecting the subsidized mitigation cost. The horizontal line indicates the targeted market value of CO_2 emissions according to the EU Emission Trading Scheme in 2020 (European Commission 2012). The solar PV technology for SMEs without any type of direct subsidization or taxes -even after a market presence of over 35 years (Nielsen, Cruickshank et al. 2010)- largely exceeds the projected CO_2 market value. Mass produced BEVs on the contrary approximately achieve this targeted value.

To verify the robustness of these results, a sensitivity analysis is performed. This is a partial sensitivity analysis in which we simultaneously vary the investment resource, the travelled distance, and the generated electricity (as these are all interrelated). Moreover, we let the investment resource fluctuate with +20% and -20%. The effect on the GHG mitigation cost is shown in Figure 12. We see that the analysis is robust for a change in the aforementioned parameters, as the reciprocal ranking of the technologies is maintained.

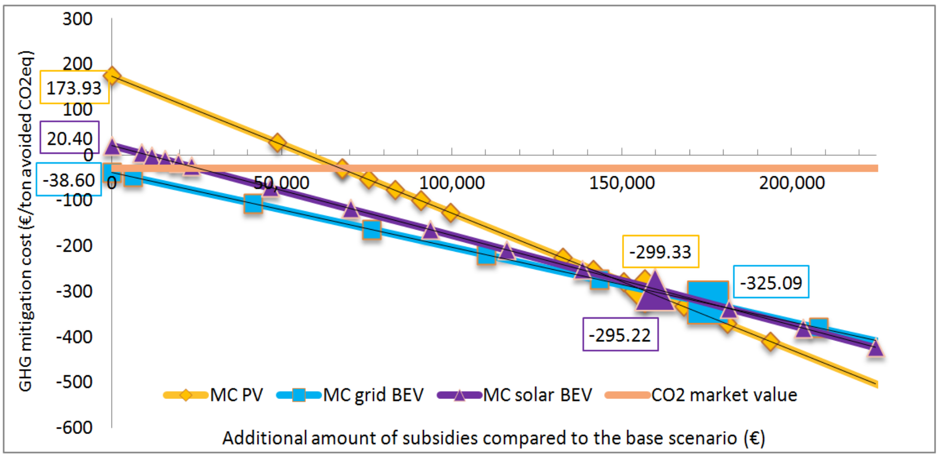

Figure 11 Impact of financial incentives on the GHG mitigation cost; larger data points reflect current (June 2012) situation for Belgian SMEs

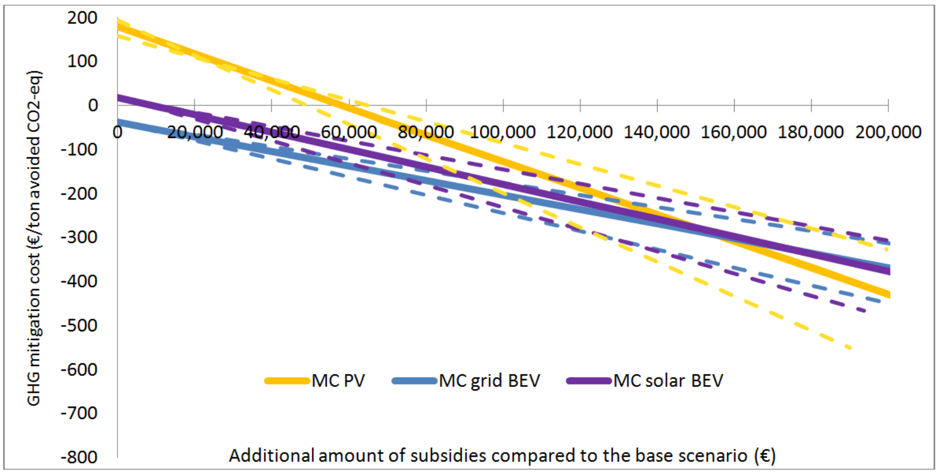

Figure 12 Sensitivity analysis - Dashed lines indicate upper and lower limits due to a variation in the initial investment resource of +20% and -20% respectively

4.5 Conclusion

We develop a framework to compare the cost-efficient emission reduction of clean energy and transport technologies and to evaluate the impact of policy, given limited investment resources. The analysis is static, intended to assess the current impact of policy on the mitigation cost. The prediction of future measures falls beyond the scope of this framework. While the framework approaches increased CO_2 emissions as a mere monetary problem, we recognize that the overall impacts of global warming go well beyond this monetary valuation.

We illustrate the framework with a case of PV solar power, grid powered (mass produced) battery electric vehicles (BEVs), and solar powered (mass produced) BEVs for a Belgian SME. In terms of cost-efficient emission reduction, the company gains more by replacing petrol fueled vehicles with grid powered BEVs than with installing solar panels. The analysis is robust to changes in the amount of the limited investment capital, the amount of electricity generated and the amount of kilometers travelled, as indicated by the partial sensitivity analysis. The analysis only considers economic and environmental parameters. Particularly related to BEVs, there are other inconveniences –*e.g.* limited driving range, long charging times- that fall beyond the scope of this framework. The results are valid for Belgium, a rather cloudy region in Europe with a relatively low electricity intensity mix. Results differ with location, depending on the amount of solar irradiation and the electricity intensity mix. We studied a Belgian SME rather than a household. Knowing that households face electricity prices that are about 70% higher, solar PV becomes the most cost-efficient technology to reduce emissions.

The current financial stimuli for these technologies are found to be generous. Moreover, the subsidized value of one ton carbon dioxide avoided by means of solar PV, grid powered BEVs, and solar powered BEVs equals more than ten times the market value of CO_2 certificates under the EU Emissions Trading Scheme. Excessive subsidization might be temporarily justified for emerging technologies with a high potential for cost-efficient emission abatement, aiming to reward "early adopters" who pave the way for broader adoption, which in turn can lead to mass production and cost reductions. Finally, we point to the importance of a sound long-term incentive scheme to ensure a stable environment for investors.

5 Economic and environmental performances of small-scale rural PV solar projects under the Clean Development Mechanism: The case of Cambodia

ABSTRACT

The two core objectives of the Clean Development Mechanism (CDM) are cost-effective emission reduction and sustainable development. Despite their large potential to contribute to both the objectives, solar projects play a negligible role under the CDM. In this research, the greenhouse gas mitigation cost is used to evaluate the economic and environmental performances of small-scale rural photovoltaic solar projects. In particular, we compare the use of absolute and relative mitigation costs to evaluate the attractiveness of these projects under the CDM. We encourage the use of relative mitigation costs, implying consideration of baseline costs that render the projects profitable. Results of the mitigation cost analysis are dependent on the baseline chosen. To overcome this drawback, we complement the analysis with a multi-objective optimization approach, which allows quantifying the trade-off between economic and environmental performances of the optimal technologies without requiring a baseline. Our main suggestion is developing guidelines to create an additional revenue stream of avoided baseline costs. We discourage the use of absolute limits on the crediting period. Rather, we advise to deliver certified emission reduction units over the operational lifetime in order to stimulate technological development. We encourage increased use of standardized baselines to avoid manipulation of the system. Inclusion of these guidelines can boost the use of small-scale off-grid solar projects under the CDM.

5.1 Introduction

Countries committed to the Kyoto Protocol must meet GHG emission reduction targets primarily through national measures. As an additional means of compliance, the Kyoto Protocol launched three market-based mechanisms, thereby creating the "carbon market". These mechanisms are *(i)* Emissions Trading (ET), *(ii)* Joint Implementation (JI), and *(iii)* the Clean

Development Mechanism (CDM). The ET allows countries that have spare emission units to sell this excess capacity to countries that are over their targets. The JI and CDM are both project-based mechanisms which feed the carbon market. The former enables industrialized countries to carry out joint projects with other developed countries, while the latter involves investment in sustainable development projects that reduce emissions in developing countries (UNFCCC 2014). Moreover, in the CDM, projects can earn saleable certified emission reduction (CER) credits -each equivalent to one ton of CO_2- that can be used towards meeting the Kyoto targets (UNFCCC 2014).

In particular, the CDM is designed to meet two objectives, namely to help Annex I parties (developed countries with specific limitation targets for GHG emissions) to cost-effectively meet part of their reduction targets and to assist non-Annex I parties (developing countries under the Kyoto Protocol without legally binding emission reduction targets) in achieving sustainable development (UNFCCC 2012). In literature, it is argued that both objectives are contradictory, with the cost-effective reduction objective overshadowing the sustainable development goal. Amongst others, Sutter and Parreño (2007) find a trade-off strongly in favor of the cost-effective emission reduction objective, while neglecting the sustainable development goal. Based on a literature review, Olsen (2007) confirms that a trade-off between the CDM's twin objectives exists and that when left to market forces, the CDM does not significantly contribute to sustainable development. Moreover, Pearson (2007) states that the CDM fails to promote sustainable development, a problem of which the cause is fundamental and stems from the CDM structure in which the search for least-cost carbon credits is the paramount consideration. Hence, he argues that most industrialized countries use the CDM merely to reduce their cost of compliance, searching for projects that deliver large volumes of cheap credits. Over the years, most issued CERs came from hydrofluorocarbons (HFC) and nitrous oxide (N_2O) projects (Table 17), which are argued to yield the least sustainable development benefits (Sutter and Parreno 2007; Olsen and Fenhann 2008).

Renewable energy projects on the other hand are less commonly implemented under the CDM, despite their large potential to contribute to sustainability. Especially solar technologies are underrepresented, claiming on average 0.05% of all the issued CERs (Table 17). Pearson (2007) states that questioning whether the CDM is promoting sustainable development can be framed primarily in terms of whether it is promoting renewables in developing countries. Del Rio (2007) encourages the deployment of renewable electricity projects such as solar PV, as -apart from contributing to the GHG emission reduction- they provide substantial local economic, social and environmental sustainability benefits to host countries. Kim et al. (2013) find that technologies whose primary benefits are sustainable development (such as solar PV) are more likely to be neglected under the CDM. The scarce amount of CER credits from solar projects mainly results from on-grid solar (96% of all registered solar projects are grid-connected installations). Since the deployment of the CDM, no more than 14 off-grid photovoltaic (PV) solar projects (all small-scale projects) have been registered (UNFCCC 2013). On average, these small-scale projects are found to contribute to a slightly higher number of sustainable development benefits than large-scale projects. In particular, they deliver more economic and social benefits than large scale projects (Olsen and Fenhann 2008). Hence, in this research, we focus on small-scale rural PV technologies, which play a negligible role under the CDM.

Table 17 Trend of CERs issued/issuing according to project type as a percentage of the total amount of CERs issued/issuing (UNFCCC 2014)

Year	Hydro	Wind	Solar	Biomass	HFC	N_2O	Methane	Other
2006	5.92%	3.49%	0.00%	13.75%	59.94%	7.80%	6.31%	2.79%
2007	2.51%	2.47%	0.00%	6.09%	46.27%	25.61%	5.15%	11.89%
2008	3.53%	4.35%	0.00%	2.56%	56.43%	22.18%	7.39%	3.55%
2009	5.25%	5.98%	0.00%	2.65%	57.97%	19.25%	3.93%	4.97%
2010	8.63%	8.18%	0.00%	1.28%	36.07%	31.44%	4.80%	9.61%
2011	12.15%	8.78%	0.04%	1.40%	38.78%	20.93%	7.11%	11.16%
2012	16.36%	12.98%	0.03%	2.59%	30.06%	15.31%	9.54%	13.12%
2013	20.30%	16.49%	0.36%	4.53%	14.83%	12.43%	15.73%	15.77%
Average	9.33%	7.84%	0.05%	4.36%	42.54%	19.37%	7.50%	9.11%

A possible measure to assess the attractiveness of CDM projects is the mitigation cost, that is the average cost per ton CO_2 reduced (mathematical formulae in section 5.2.1). A comprehensive analysis of the mitigation cost implies *(i)* the assessment of the economic costs of the project and *(ii)* the assessment of the amount of CO_2 equivalent emissions avoided by the project over its lifetime. Low mitigation cost projects imply low economic costs as well as highly avoided CO_2 emission reductions, which are in turn rewarded with saleable CER units. Hence, projects with low mitigation costs are most attractive for the investors to implement, as they enable low-cost procurement of CER credits (Kim, Popp et al. 2013). The United Nations Framework Convention on Climate Change (UNFCCC) finds solar photovoltaics to be the most expensive technology deployed in the CDM, with an average mitigation cost of $326 per ton CO_2 equivalents (UNFCCC 2012). In this research, we evaluate the mitigation cost of small-scale rural solar PV projects. In particular, we compare "absolute" and "relative" mitigation costs. With absolute mitigation costs, we refer to the mitigation cost defined by the UNFCCC (2012), in which the complete omission of baseline costs is assumed. To calculate relative mitigation costs on the other hand, avoided baseline costs are deducted from project costs (Lazarus, Heaps et al. 1995).

The mitigation cost analysis allows ranking technologies or projects in order of decreasing cost of emissions abatement or hence in order of increasing attractiveness for the potential CDM project implementer. We note however that the results of this analysis are always dependent on the baseline or reference technology chosen (Sathaye and Meyers 1995). To overcome this drawback, we propose to complement the mitigation cost analysis with a multi-objective approach in which economic and environmental objectives are simultaneously optimized. Multi-objective optimization is of particular interest when the objectives to be optimized are conflicting (Steuer 1986). In this case, plural optimal solutions exist. In this research, we use multi-objective optimization to simultaneously optimize off-grid solar technologies from economic and environmental viewpoint. The project implementer can then choose amongst these optimal solutions, according to personal preferences.

In section 5.1, we described the need for evaluating small-scale rural PV projects under the CDM by means of a mitigation cost analysis, and to complement this analysis with a multi-objective optimization approach. Section 5.2 demonstrates the methods used, including the absolute versus relative costs of mitigation. In section 5.3, we apply these methods to two types of small-scale rural PV projects, *i.e.* solar light emitting diode (LED) lighting and small solar home systems (SHS). Based on our findings, policy recommendations are formulated in section 5.4. We end the chapter with a conclusion and discussion of the findings in section 5.5.

5.2 Methodology

5.2.1 Mitigation cost analysis

5.2.1.1 Absolute mitigation cost

To calculate the absolute mitigation cost, we assume complete omission of avoided baseline costs. This approach is used by the UNFCCC (2012), in which the methodology for calculating the mitigation costs of CDM projects is described as follows:

"The mitigation cost is the total cost of the project, including initial outlay of capital, the annual operational expenditure and revenues per CER expected for each project. As shown in equation 1 below, project mitigation cost is defined as the net present value of a project´s annual operations costs less its non-CDM related revenues (e.g. income from electricity sales for wind projects), plus the capital expenditures, all divided by the amount of GHG emission reductions it expects to achieve over its crediting period." (p 93).

$$MC(absolute)_i = \frac{\sum_{t=1}^{cp}\frac{\left(OC_{i,t}-R_{i,t}\right)}{(1+r)^t}+I_{0,\mathrm{i}}}{\sum_{t=1}^{cp}A_{i,t}} = \frac{\sum_{t=1}^{cp}\frac{\left(OC_{i,t}-R_{i,t}\right)}{(1+r)^t}+I_{0,\mathrm{i}}}{\sum_{t=1}^{cp}\mathrm{E_{b,t}}-\mathrm{E_{i,t}}} \quad \text{(Eq. 1)}$$

Where:

MC(absolute)$_i$ is the absolute mitigation cost of project *i* (in \$/t CO_2eq);
t denotes a given year during the project crediting period;

cp is the length of its crediting period(s) (up to 10 or 21 years);

$OC_{i,t}$ is the operating cost of project *i* in year *t* (in $);

$R_{i,t}$ is the non-CER revenue of project *i* in year *t* (in $);

$I_{0,i}$ is the initial investment of project *i* (in $);

$A_{i,t}$ is the abatement (expected emission reduction) achieved by project *i* in year *t* (in t CO_2eq), which is defined as the difference between the baseline emissions ($E_{b,t}$) and the project emissions ($E_{i,t}$) according to CDM baseline methodologies;

r is the discount rate (expressed as a decimal; 1% = 0.01)

As mentioned before, this definition implies the omission of the baseline costs, *i.e.* costs related to the baseline technology that are avoided due to implementation of the project. Further, the crediting period rather than the operational lifetime is used for the calculation, also in cases in which the operational lifetime exceeds the crediting period. The project participants may choose between two options for the length of a crediting period: *(i)* a "fixed" crediting period with no possibility of renewal or extension with a length of maximum 10 years or *(ii)* a "renewable" crediting period with single crediting periods of maximum 7 years which may be renewed two times at most (maximum 21 years). The amount of expected emission reductions is determined as the difference between baseline and project emissions, using prescribed CDM baseline methodologies. Note that the mitigation cost defined as such is calculated from the viewpoint of the project developer.

5.2.1.2 Relative mitigation cost

To calculate the relative mitigation cost, avoided baseline costs are deducted from project costs. This is according to the definition of Lazarus et al. (1995), in which the greenhouse gas mitigation cost of technology *i* is defined as the economic cost per ton carbon dioxide equivalents (CO_2eq) avoided when using technology *i* to replace the baseline technology *b*. The mitigation cost is considered from the project developer's point of view. To calculate this cost, we determine the GHG mitigation potential and the additional economic costs of the project technology *i* as compared to the reference or baseline technology *b* over the technologies' lifetime *n* (Eq. 2). For purposes of comparison, we apply the terminology used in Eq. 1. The differences with the absolute mitigation cost in Equation 1 are indicated in grey.

$$MC(relative)_i = \frac{\sum_{t=1}^{n}\frac{(OC_{i,t}-R_{i,t})}{(1+r)^t}+I_{0,\mathrm{i}} - \sum_{t=1}^{n}\frac{(OC_{b,t}-R_{b,t})}{(1+r)^t}+I_{0,\mathrm{b}}}{\sum_{t=1}^{n}A_t} = \frac{\sum_{t=1}^{n}\frac{(OC_{i,t}-R_{i,t})}{(1+r)^t}+I_{0,\mathrm{i}} - \sum_{t=1}^{n}\frac{(OC_{b,t}-R_{b,t})}{(1+r)^t}+I_{0,\mathrm{b}}}{\sum_{t=1}^{n}\mathrm{E_{b,t}}-\mathrm{E_{i,t}}} \quad \text{(Eq. 2)}$$

Where:

$MC(relative)_i$ is the relative mitigation cost of project *i* (in \$/t CO_2eq);
t denotes a given year during the project lifetime;
n is the operational lifetime of the project;
i refers to the project implemented;
b refers to the replaced baseline technology;
OC_t is the operating cost in year *t* (in \$);
R_t is the non-CER revenue in year *t* (in \$);
I_0 is the initial investment (in \$);
A_t is the abatement (expected emission reduction) achieved in year *t* (in t CO_2eq), which is defined as the difference between the baseline emissions ($E_{b,t}$) and the project emissions ($E_{i,t}$) determined by means of a life cycle analysis (LCA) model;
r is the discount rate (expressed as a decimal; 1% = 0.01)

According to this definition, the avoided baseline costs are deducted from the project's costs. In this research, the replaced baseline technology is determined according to the applicable CDM methodology for purposes of comparison with the absolute mitigation cost. Economic costs are calculated over the technologies' operational lifetime (rather than over the crediting period) by means of life cycle costing. To calculate the amount of emission abatement, we make use of life cycle analysis (LCA); a method to quantify the environmental impact of a product or service over their full life cycle (ISO 14044:2006). When undertaking an LCA, there are a number of methodological choices that need to be made. Choosing either an attributional or a consequential modeling approach may have a great influence on the overall outcomes of the study (European Commission - Joint

Research Centre - Institute for Environment and Sustainability 2010). Each approach however has its own benefits and drawbacks. It may be argued that a consequential approach may be the more appropriate choice for this study, since this research attempts to support future decision-making. However, a consequential LCA requires detailed data on marginal changes in the technological system as a consequence of a choice for a certain product. In this light, one may wonder for example how the PV production technology would be affected by an increasing demand for solar lanterns, or where the crude oil would come from if energy demand were to increase. As many of this required data is either unavailable or very uncertain, the authors have opted to use an attributional LCA model in this study. Hence, we make use of average values for current technologies, as available in the EcoInvent database. To calculate the mitigation cost correctly, both the economic analysis and the environmental life cycle analysis must relate to the same functional unit. This approach has been demonstrated in Chapter 4.

5.2.2 Multi-objective optimization

Results of the mitigation cost analysis are dependent upon the baseline technology chosen. We propose to overcome this drawback by complementing the analysis with a multi-objective optimization approach. Multi-objective optimization is concerned with the simultaneous optimization of plural objective functions. For a nontrivial multi-objective optimization problem, no single solution exists that optimizes all objectives at the same time. In that case, the objective functions are said to be conflicting and plural optimal solutions exist. These solutions are also referred to as "Pareto optimal" or "efficient" solutions. A feasible solution $\hat{x} \in X$ is called efficient or Pareto optimal if there is no other $x \in X$ that performs better with respect to all objectives and strictly better on at least one objective. The set of all efficient solutions is called the efficient set. We use the following mathematical formulation (Steuer 1986; Ehrgott 2010):

$Min\ z_k(x)$	$k = 1, \dots, p$	*p* objective functions
$subject\ to\ g_j(x) \begin{Bmatrix} \leq \\ = \end{Bmatrix} 0$	$j = 1, \dots, m$	*m* constraints
$x_i \in \mathbb{R}^n$	$i = 1, \dots, n$	*n* variables

In our research, we want to determine the optimal combinations of technologies to provide a certain demand, while simultaneously minimizing economic costs and environmental emissions. To formulate a mathematical model that represents the optimization of the combined use of different technologies of the same type from economic and environmental viewpoint, we refer to Chapter 6. The decision variables, *i.e.* the amount of technology i used in the combination of technologies, are denoted by x_i. The model contains two objectives: *(i)* minimizing economic costs and *(ii)* minimizing environmental emissions. As regards the economic objective function, we distinguish between *(i)* Minimizing lifecycle costs, as is the case for any rational investor and *(ii)* Minimizing solely the cost of investment, as the latter may constitute a huge implementation barrier for poor households. The economic lifecycle (investment) costs and environmental emissions implied by one unit of technology *i* are represented respectively by the data c_i^1 ($c_i^{1'}$) and c_i^2. Furthermore, a required demand *d* has to be satisfied. In this constraint, q_i is defined as the amount of output provided by one unit of technology *i*. We note that the demand *d* in our multi-objective optimization problem must correspond to the functional unit of the mitigation cost analysis in order to establish the link between the mitigation cost analysis and the multi-objective optimization approach. Hence, assuming linear relations, the optimization of the use of technologies *i* to satisfy required demand *d* can be formulated as a multi-objective linear programming problem (MOLP), which can be solved using a multi-objective simplex method. The MOLP is defined as follows:

$Min \sum_{i=1}^{n} c_i^1 x_i$	Economic objective function
$Min \sum_{i=1}^{n} c_i^2 x_i$	Environmental objective function
$Subject\ to \sum_{i=1}^{n} q_i x_i = d$	Demand constraint
$x \in X$	
$X \subset \mathrm{R}_+^n$	

5.3 Case: Small-scale rural solar PV projects under the CDM

In our research, we focus on two types of small-scale rural solar PV projects with lighting purposes, which play a negligible role under the CDM in spite of their large sustainability potential. More specifically, we consider small-scale portable solar LED lanterns and small off-grid solar home systems (SHS). In particular, we consider a case in Cambodia, where the electrification rate is merely 24% (IEA 2011) and the market for modern off-grid lighting is nascent (IFC 2012). The Kamworks company is one of the few that provides off-grid lighting to local villagers. They produce and distribute portable solar lanterns -*a.k.a.* "*The Moonlight*"- as well as the SHS. In practice, the SHS produce more electricity than is needed for lighting purposes only. Nonetheless, to compare the SHS with the other lighting systems in our analysis, we assume that all available energy is used for lighting. This approach is, amongst others, also used in (Durlinger, Reinders et al. 2012). The case is hypothetical and did not apply for registration under the CDM. For each type of technology, we discuss *(i)* The projects and methodologies approved under the CDM; *(ii)* A brief description, including economic and technical data; and *(iii)* The calculation of the absolute and relative greenhouse gas mitigation cost, including a sensitivity analysis of the results. This structure is presented schematically in Figure 13. As functional unit of our GHG mitigation cost calculation, we consider the provision of light of 100,000 households with typical lighting needs in Cambodia, *i.e.* the provision of household lighting with a strength of 90 lumens for 3.5 hours a day, 365 days per year, during a period of 10 years (the lifetime of the project technologies). Hence, our functional unit totals 114,975 million lumen-hours over a 10-year time span.

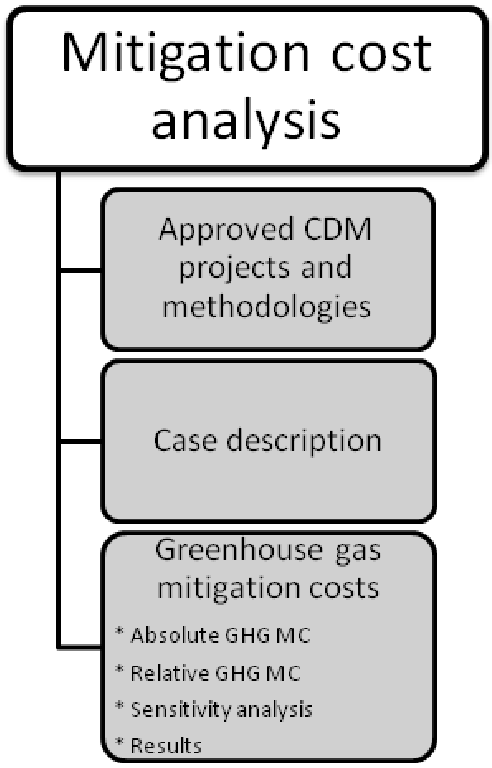

Figure 13 Structure of the mitigation cost analyses applied to (i) Portable solar LED lanterns and (ii) Small-scale rural SHS

5.3.1 Mitigation cost analysis: Portable solar LED lanterns

5.3.1.1 Approved CDM projects and methodologies

For portable solar LED systems, two CDM methods are applicable. In January 2003, the Approved Methodology for Small-scale CDM project activities (AMS) I.A "*Electricity generation by the user*" (UNFCCC 2012) was launched, applicable to renewable electricity generation such as solar, hydro, wind, or biomass gasification implemented to replace fossil-fuel-fired generation. In November 2010, a specific standardized baseline method AMS-III.AR for "*Substituting fuel based lighting with LED/CFL lighting systems*" was introduced (UNFCCC 2012). To date, no more than 12 solar LED lantern projects have been registered. Table 18 (A) shows an overview of the registered solar LED lighting projects sorted by date. We note that since its introduction, eight out of nine solar LED lighting projects were approved under AMS-III.AR. Accordingly, in this research, we apply the approved baseline AMS-III.AR to determine the solar LED lantern's absolute mitigation cost. We note that the solar lanterns under consideration fulfill the criteria required by this methodology, *i.e.* the project activity replaces portable fossil fuel based lamps with LED based lighting systems in residential applications, the project lamps are charged with a photovoltaic system and have a minimum lifetime of 10,000 hours with a warranty of more than one year, no more than five lamps per household -three to be precise- are distributed, and measures are limited to emission reductions of less than 60kt CO_2 equivalents annually. Note that this methodology assumes kerosene lanterns as a standardized baseline technology to be replaced by solar lanterns.

Table 18 Overview of portable solar LED lanterns and small-scale rural SHS projects registered under the CDM sorted by "Date"; "Reductions" are the estimated emission reductions in metric tonnes of CO_2eq/y (UNFCCC 2013)

Title	Methodology	Date	Reductions
(A) Registered solar LED lighting projects			
Rural Education for Development Society CDM PV Lighting Project	AMS-I.A	10/8/09	21,060
D.light Rural Lighting Project	AMS-I.A	30/10/09	30,052
Barefoot Power Lighting Programme	AMS-III.AR	25/7/12	9,749
Tough Stuff Solar Panel and Lamp Sales Madagascar Project	AMS-III.AR	9/8/12	25,704
Nuru Lighting Programme	AMS-III.AR	3/10/12	34,294
Project to replace fossil fuel based lighting with Solar LED lamps in Africa	AMS-III.AR	3/12/12	21,393
CarbonSoft Open Source PoA, LED Lighting Distribution: Emerging Markets	AMS-III.AR	24/12/12	3,968
Bundled project on distribution of solar energy lamps and replacement of incandescent light bulbs with CFL lamps	AMS-I.A	26/12/12	28,961*
Southern African Solar LED Programme	AMS-III.AR	31/12/12	12,236
TATS Solar Lantern Programme of Activities	AMS-III.AR	31/12/12	13,823
Greenlight Solar PV Lighting India	AMS-III.AR	31/12/12	56,397
CarbonSoft Open Source PoA, LED Lighting Distribution: Pan Africa	AMS-III.AR	1/10/13	41,850
(B) Registered rural SHS projects			
Photovoltaic kits to light up rural households in Morocco	AMS-I.A	28/4/06	38,636
Installation of solar home systems in Bangladesh	AMS-I.A	26/6/12	45,713

*This is the emission reduction attributable to the solar energy lamps

5.3.1.2 Case description

Portable solar LED lanterns are considered an alternative for kerosene lanterns in developing countries. An estimated 1.06 million households in

Cambodia use kerosene as their primary source for lighting. These are primarily poorer households (IFC 2012). Hence, in this research, we consider kerosene lanterns as the baseline technology to be replaced by solar LED lanterns, which is in correspondence with AMS-III.AR of the CDM. Economic and technical data regarding the lanterns is presented in the first two columns of Table 19. The total light output of one solar lantern with a lighting strength of 30 lumens that is used 3.5h/day, 365 days/y, over a lifetime of 10 years equals 383,250 lumen-hours. Hence, to provide the total of 114,975 million lumen-hours, 300,000 project solar lanterns are distributed to 100,000 households.

Table 19 Data provided by the Kamworks company (December 2013)

	Kerosene lantern (base technology)	Solar LED lantern	Battery powered with diesel generator (base technology)	Solar home system
Economic data				
Initial investment *(I_0)*	Lantern: $0.70 Wicks: $0.125	Lantern: $10 Battery: $5	Battery: $45 Fluorescent tube: $5	SHS including installation: $345
Operational lifetime *(n)*	Lantern: 2y Wicks: 0.5y	Lantern: 10y Battery: 2y	Battery: 1y	Solar system: 10y Battery: 3y
Operating costs *(OC)*	Kerosene: 0.74$/l (IFC 2012); 0.03l/h (UNFCCC 2012) Wicks: $0.125	Battery replacement: $5	Electricity: $0.95/kWh (IFC 2012)	Battery: $30 Assembly & maintenance: $25
Crediting period *(cp)*	-	7 y (UNFCCC 2012)	-	10 y (UNFCCC 2012)
Discount rate *(r)*	4% (European Commission 2009)	Idem	idem	idem
Technical data				
Light output	45 lm (Durlinger, Reinders et al. 2012)	30 lm	900lm	1050lm
Light source	Fuel (0.03l/h)	6 LEDs	1* 18W CFL (50lm/W)	3*7W CFL (50lm/W)
Solar panel	-	0.7 Wp, a-Si	-	40 Wp, mc-Si
Battery capacity	-	2Ah	70Ah	48Ah
Battery type	-	2xNiCd AA (1.5V)	Lead acid (12V)	Lead acid (12V)
Electricity generation	-	-	279.6Wh/day	117Wh/day
Density	0.8026kg/l (OECD/IEA 2004)	-	-	-
Size of the systems to provide the functional unit (FU) of 114,975 million lumen-hours over a 10 y time span				
lm-h per system	114,975lm-h	383,250 lm-h	5,102,700lm-h	21,352,500lm-h
Systems needed to provide FU	1,000,000	300,000	22,532	5,384

5.3.1.3 Greenhouse gas mitigation costs

5.3.1.3.1 Absolute greenhouse gas mitigation cost

We start by calculating the absolute GHG mitigation cost of solar LED lanterns as defined in Eq. 1 (section 5.2.1.1). Additionally, as higher purchase prices constitute a huge barrier for implementation, we calculate the absolute mitigation cost when considering merely the cost of investment rather than the full LCC. Economic parameter values (operating costs OC_t, initial investment costs I_0, crediting period *cp*, and discount rate *r*) can be found in the second column of Table 19. Note that there are no operational revenues R_t from electricity generation, as the project lamps are not grid-connected. Reduced emissions are calculated as the difference between baseline and project emissions according to AMS-III.AR (UNFCCC 2012). The expected emission reduction A_t is detailed in Eq. 3, which is adapted from Paragraph 24 in AMS-III.AR (note that references to *"Paragraph x"* in the remainder of this section always refers to paragraphs in AMS-III.AR). In this equation, N_i stands for the number of solar lanterns distributed and $OF_{t,i}$ represents the percentage of project lamps distributed to end users that are still operating and in service in the year *t*. The latter is fixed to 100% for years 1,2, and 3. For project lamps that claim emission reductions for up to 7 years, ex-post monitoring surveys must be conducted to determine the percentage of project lamps that are still operating and in service in years 4, 5, 6, and 7. We assume in our analysis that this number equals to 100% throughout the whole lifetime of the product. We note though that assuming that all lamps are operational up to year 7 represents an overestimation of the actual number of lamps in service. Baseline emissions, *i.e.* avoided emissions from the equivalent baseline lighting system, are calculated according to Paragraph 18, which provides a default emissions factor of 0.092t CO_2eq per project lamp, assuming a utilization rate of 3.5h/day, 365days/y, and a fuel use rate of 0.03l/h for kerosene lanterns. Project emissions of solar lanterns are nonexistent (Paragraph 21). Results are presented in the first column of Table 21. Additionally, we have calculated the absolute mitigation cost of solar LED lanterns over a hypothetical crediting period of 10 years (column 2). These results will be used in the multi-objective optimization analysis (section 5.3.3).

$$A_t = N_i * \left(Baseline\ emission_{t,i} - Project\ emission_{t,i}\right) * (OF_{t,i}) \qquad \text{(Eq. 3)}$$

5.3.1.3.2 Relative greenhouse gas mitigation cost

In this section, we calculate the relative GHG mitigation cost of portable solar LED lanterns according to Eq. 2 (section 5.2.1.2). The project costs are calculated identically to those in Eq. 1, with the only exception being the lifetime, which is assumed to be 10 years (Table 19). Additionally, this calculation requires determination of the baseline costs, *i.e.* the avoided costs of using kerosene lanterns that would have provided the equivalent amount of lighting. Economic parameter values of kerosene lanterns are provided in the first column of Table 19. Emission reductions A_t are calculated as the difference between baseline and project emissions by means of life cycle assessment. To this end, we updated the model described by Durlinger in (2012) and (2012), which is an attributional LCA model. Ecoinvent v2.2 data was used to model the background data (Frischknecht, Jungbluth et al. 2007). The impact assessment method ReCiPe (Goedkoop, Heijungs et al. 2012) was used to generate characterized results. More precisely, this study applies the result of the mid-point impact category “Climate Change”. The software SimaPro 7.2.2 (PRé consultants, Amersfoort, The Netherlands) was used to model the LCA and to generate results. The life cycle inventory as modeled in SimaPro® is listed in Table 20. For purposes of comparison, we also calculate the mitigation cost according to Eq. 2 over a lifetime of 7 years, which is the maximum crediting period prescribed under AMS-III.AR *(n = cp = 7)*. Results are listed in the last two columns of Table 21. Project costs of the solar lanterns under both methods (absolute and relative) are now equal.

5.3.1.3.3 Sensitivity analysis

To verify the sensitivity on the deterministic values used in this approach, a Monte Carlo sensitivity analysis is conducted on the GHG mitigation cost considering LCC (500,000 trial runs). For each economic parameter value (Table 19) and for all environmental LCE, a triangular distribution is assumed with minimum and maximum deviations of -10% and +10% with respect to the assumed values. Results are presented in Table 21 (B). We indicate the range of GHG mitigation cost values and the sensitivity information as the percent of the mitigation cost variance due to the spread in the three most influencing parameters. Note that a negative (positive) sign indicates that the GHG mitigation cost will decrease (increase) with an increase of this parameter.

5.3.1.3.4 Results

From our analysis in which we compared absolute and relative GHG mitigation costs of solar LED lanterns, we conclude the following: It is a major difference whether or not baseline costs are included. The absolute mitigation cost assumes the complete omission of baseline costs, even though the avoided costs of kerosene lanterns are approximately 5 times higher than those of solar lanterns to provide the equivalent amount of lighting. Moreover, sensitivity analysis of the relative mitigation cost indicates that the baseline costs are the most important parameters to determine the mitigation cost.

Table 20 Life cycle inventory

Emissions due to…	Unit process (Available in EcoInvent)	Quantity	Comment
Battery (Lead acid battery 100Ah)			
Energy input	Electricity, at cogen 200kWe diesel SCR, allocation exergy/CH U	146kWh	Proxy for energy delivered by diesel aggregate
Battery	Lead, primary, at plant/GLO U	17kg	Lead plates and bridges
	Polyethylene, HDPE, granulate, at plant/RER U	3kg	Casing and plate seperators
	Sulphuric acid, liquid, at plant/RER U	2.5kg	
	Water, completely softened, at plant/RER U	4.7kg	
Copper wire	Wire	0.5m	5/10y
	Copper, at regional storage/RER U	19.5g	39 kg/km from FireLCA report
	Polyvinylchloride, at regional storage/RER U	44g	
Transport	Transport, van <3.5t/RER U	0.03264 ton*km	
	Transport, transoceanic freight ship/OCE U	0.33069 ton*km	
	Transport, lorry >16t, fleet average/RER U	0ton*km	
Solar Led Lantern (Moonlight)			
Batteries	Steel, low-alloyed, at plant/RER U	24g	6 x NiCd battery 1000 mAh
	Nickel, 99.5%, at plant/GLO U	42g	6 x NiCd battery 1000 mAh
	Cadmium, primary, at plant/GLO U	42g	6 x NiCd battery 1000 mAh
	Polyethylene, HDPE, granulate, at plant/RER U	21g	6 x NiCd battery 1000 mAh
	Water, completely softened, at plant/RER U	18g	6 x NiCd battery 1000 mAh
	Potassium hydroxide, at regional storage/RER U	12g	6 x NiCd battery 1000 mAh
Electronic parts	Photovoltaic panel, a-Si, at plant/US/I U	0.01257m²	Solar panel 0.7 Wp
	Flat glass, uncoated, at plant/RER U	0.064kg	Solar panel 0.7 Wp
	Converter, chromium steel 18/8, at plant/RER U	0.015kg	Solar panel 0.7 Wp
	Printed wiring board, mixed mounted, unspec., solder mix, at plant/GLO U	6g	Circuit board
	Light emitting diode, LED, at plant/GLO U	1g	LEDs
Miscellaneous parts	Nylon 66, at plant/RER U	4g	Moonlight cord
	Solid bleached board, SBB, at plant/RER U	3.4g	Moonlight reflector
	Aluminium, primary, at plant/RER U	0.1g	Moonlight reflector
	Steel, converter, chromium steel 18/8, at plant/RER U	6g	Moonlight screws
	Steel product manufacturing, average metal working/RER U	6g	Moonlight screws
	Polystyrene, general purpose, GPPS, at plant/RER U	0.088kg	Moonlight Shell
	Injection moulding/RER U	0.088kg	Moonlight Shell
Transport	Transport, van <3.5t/RER U	0.0421875ton*km	
	Transport, transoceanic freight ship/OCE U	0.344975ton*km	
	Transport, lorry >16t, fleet average/RER U	0.0214375ton*km	
Solar Home System (Battery 3*40Ah)			
Lead Acid Battery	Lead, primary, at plant/GLO U	20.4kg	Lead plates and bridges
	Polyethylene, HDPE, granulate, at plant/RER U	3.6kg	Casing and plate seperators
	Sulphuric acid, liquid, at plant/RER U	3kg	
	Water, completely softened, at plant/RER U	5.64kg	
Electronic parts	Photovoltaic panel, multi-Si, at plant/RER/I U	0.46352m²	Multi-Si 40 Wp
	Inverter, 500W, at plant/RER/I U	1p	Proxy for charge controller
	Copper, at regional storage/RER U	117g	Proxy for simple parts and wires
	Polyvinylchloride, at regional storage/RER U	264g	Proxy for simple parts and wires
Transport	Transport, van <3.5t/RER U	0.2502ton*km	
	Transport, transoceanic freight ship/OCE U	1.65345ton*km	
	Transport, lorry >16t, fleet average/RER U	0.06342ton*km	
Kerosene Lantern			
Fuel use	Adapted process: Light fuel oil, burned in boiler 10kW condensing, non-modulating/CH U	33l	Annual fuel use: 0.03 l/h, 3h/day, 365days/y. Only emissions per kg fuel were taken from this process, and fuel supply chain was remodelled to fit region of interest

Table 21 GHG mitigation costs of solar LED lanterns versus kerosene lanterns

	Absolute (7 y)	Absolute (10 y)	Relative (10 y)	Relative (7 y)
(A) MITIGATION COST ANALYSIS				
(1) Project inv cost ($): $I_{0,\mathrm{i}}$	4,500,000.00	4,500,000.00	4,500,000.00	4,500,000.00
(2)Project O&M cost ($): $\sum_t \frac{(OC_{i,t}-R_{i,t})}{(1+r)^t}$	3,706,261.92	4,760,142.02	4,760,142.02	3,706,261.92
(3)Baseline inv cost($): $I_{0,\mathrm{b}}$	not applicable	not applicable	584,279.92	485,917.78
(4) Baseline O&M cost ($): $\sum_t \frac{(\mathrm{O}C_{b,t}-R_{b,t})}{(1+r)^t}$	not applicable	not applicable	46,411,356.74	34,344,357.03
(1)+(2)-(3)-(4) Additional project cost ($)	**8,206,261.92**	**9,260,142.02**	**-37,735,494.64**	**-26,624,012.89**
(5) Project emission (t CO_2eq)	0.00	0.00	1,602.00	1,518.00
(6)Baseline emission (t CO_2eq)	193,158.00	275,940.00	283,605.00	198,523.50
(6)-(5) Emission reduction: $\sum_t A_t$ (t CO_2eq)	**193,158.00**	**275,940.00**	**282,003.00**	**197,005.50**
((1)+(2)-(3)-(4))/((6)-(5)) ***GHG MC LCC ($/t CO_2eq)***	***42.48***	***33.56***	***-133.81***	***-135,14***
((1)-(3))/((6)-(5)) GHG MC I_0 ($/t CO_2eq)	***23.30***	***16.31***	***13.89***	***20.38***
(B) MONTE CARLO SENSITIVITY ANALYSIS ON GHG MC LCC				
Range($/t CO_2eq)	[35.49; 50.87]	[27.98; 40.24]	[-186.04; -93.68]	[-190.07; -92.38]
Sensitivity with respect to…	Kerosene emission (-67.7%)	Kerosene emission (-67.7%)	Fuel use rate (-34.8%)	Fuel use rate (-34.8%)
	I_0 solar lantern (+19.0%)	I_0 solar lantern (+16.7%)	Cost of kerosene (-34.8%)	Cost of kerosene (-34.8%)
	Battery cost (+12.8%)	Battery cost (+14.8%)	Kerosene emissions (+23.4%)	Kerosene emissions (+21.3%)

This provides a clear motivation for using relative rather than absolute mitigation costs to assess the attractiveness of projects. Nonetheless, the UNFCCC defined and applies the absolute mitigation cost for this purpose.

They recognize however that baseline costs can be significant for many projects, and that the avoided costs of fossil-fired generation render renewable energy projects viable despite their high mitigation costs (UNFCCC 2012). Indeed, in our analysis of the solar LED lighting, absolute mitigation costs are found positive while relative mitigation costs are negative. The sensitivity analysis indicates that these signs are maintained despite maximal variations in the parameter values between +10% and -10%. Note that a negative sign in this case means that replacing kerosene with solar LED lanterns provides net benefits to society, with the financial benefits outweighing the costs even before considering the value of reduced emissions. A second difference is the use of a limited crediting period under AMS-III.AR. Moreover, AMS-III.AR restricts the crediting period to a maximum of 7 years, while Kamworks assures a solar LED technology operational lifetime of 10 years. Avoided kerosene (baseline) emission is an important parameter in determining the mitigation cost, particularly in determining the absolute mitigation cost. This points to the importance of providing a good estimate of kerosene emissions under AMS-III.AR. Kerosene emissions according to AMS-III.AR (193,158 t CO_2eq) deviate no more than 2% from the emissions assessed using our LCA model (197,006 t CO_2eq), assuming equal utilization, fuel use rates, and lifetimes. We note though that in reality, results can differ due to other fuel consumption rates or use patterns. Furthermore, as our LCA indicates that project emissions (1,518 t CO_2eq) represent less than 1% of avoided baseline emissions (198,524 t CO_2eq), it seems reasonable to assume that they are negligible, as is the case in AMS-III.AR. Finally, we note that the purchase price of the solar lanterns (+16.7%) and the batteries (+14.8%) -which constitutes a huge barrier for widespread implementation- indeed has an important impact on the mitigation cost. Nonetheless, the sensitivity analysis indicates that the avoided kerosene emissions have the greatest impact on the mitigation cost (-67.7%).

5.3.2 Mitigation cost analysis: Small-scale rural solar home systems

5.3.2.1 Approved CDM projects and methodologies

Under the CDM, small-scale rural solar home systems (SHS) can be registered under two methodologies. One option is to register under AMS-I.A "Electricity generation by the user", which is in place since January 2003 (UNFCCC 2012). Another option is to register under AMS-I.L "Electrification of rural communities using renewable energy", which was introduced in March 2012 (UNFCCC 2013). At this moment, only 2 small-scale rural SHS projects have been registered, both under AMS-I.A (Table 18 B). Accordingly, we apply this method to determine the SHS absolute mitigation cost. With a capacity of 40Wp per system or 343kWp in total (Table 19), this project falls largely under the CDM limit of 15MW for small-scale systems. We note that AMS-I.A does not specify a baseline for solar home systems. Indeed, in their project design documents, we find that the two registered SHS projects use different baselines. Moreover, "Photovoltaic kits to light up rural households in Morocco" (SceT-Maroc & GERERE 2005) assumes diesel generators for baseline calculations, while "Installation of solar home systems in Bangladesh" (CDM - Executive Board 2012) assumes the usage of kerosene and batteries charged at shops from small diesel generators as baseline technologies.

5.3.2.2 Case description

In Cambodia, the key off-grid lighting sources are kerosene and batteries powered by diesel generators at local shops (IFC 2012). Hence, these technologies are considered as baseline for solar home systems. Assuming a lifetime of 10 years, electricity production of 117Wh/day and a luminous efficacy of 50lm/W (data in Table 19), each SHS provides 21,352,500 lumen-hours. Thus, 5,384 SHS are needed to provide the total functional unit of 114,975 million lumen-hours. To provide the equivalent amount of lighting, 22,532 batteries charged with diesel generators or 1,000,000 kerosene lanterns are required.

5.3.2.3 Greenhouse gas mitigation costs

5.3.2.3.1 Absolute greenhouse gas mitigation cost

We start with calculating the absolute GHG mitigation cost of solar home systems according to Eq. 1. Additionally, we calculate the absolute mitigation cost when considering merely the cost of investment rather than the full life cycle costs. Economic parameter values of the SHS are presented in Table 19. As the systems are not grid-connected, there are no operational revenues ($R_t = 0$). The expected emission abatement A_t is calculated as the difference of baseline and project emissions minus potential leakage over the crediting period according to AMS-I.A (UNFCCC 2012). The energy baseline is the fuel consumption that would have been used in the absence of the project activity to provide the equivalent quantity of lighting. We compare the choice of *(i)* kerosene and *(ii)* batteries powered at diesel stations as baselines.

The kerosene baseline is calculated according to option 3 of AMS-I.A (Paragraph 8). In the remainder of this section, all *"Paragraph"* references refer to the paragraphs in AMS-I.A. In correspondence with Paragraph 10, the baseline emissions in year *t* ($E_{b,t}$) due to the replacement of kerosene consumption is calculated in Eq. 4, with N_t the number of kerosene lamps replaced in year *t* (1,000,000 lamps with a lifetime of 2 year over a period of 10 years or hence 200,000 lamps each year), FC_t the amount of kerosene consumption per lamp in year *t (0.03l/h * 3.5h/day * 365days/y * 0.8026kg/l = 30.76kg/y)*, *NCV* the net caloric value of kerosene (43.8TJ/Gg (IPCC 2006)) , and EF_{CO2} the CO_2 emission factor of kerosene (71.9kgCO_2/GJ (IPCC 2006)). This leads to an annual emission of 0.097t CO_2eq/kerosene lamp. We note that this differs from the default value described under AMS-III.AR (0.092t CO_2eq/project lamp), although it relates to the exact same baseline technology. Baseline emissions of kerosene lanterns in year *t* equal 19,374t CO_2eq. There are no project emissions (Paragraph 13). Leakage is assumed to be zero. Results are shown in the first column of Table 22 (A).

$$E_{b,t} = N_t * FC_t * NCV * EF_{CO2} \qquad \text{(Eq. 4)}$$

When considering batteries powered at diesel stations as baseline, emissions *($E_{b,t}$)* are calculated according to option 2 of AMS-I.A (Paragraph 8) in Eq. 5 as the sum of the annual output of all *i* renewable energy technologies implemented as part of the project activity ($\sum_i EG_i$), considering average annual distribution losses (l) that would have been observed in diesel-powered mini-grids. Each SHS produces 117Wh/day (Table 19) and no distribution losses are considered ($l = 0$). Given a total of 5,384 SHS, the energy baseline thus equals 229,950kWh per year. Baseline emissions can then be calculated according to Paragraph 9 as the energy baseline times a default emissions factor (Eq. 6 below). For the latter, we use the prescribed default value of 0.8kgCO_2eq/kWh, which is derived from diesel generation units (Paragraph 9). We note however that this value can easily be altered: "…*with adequate justification, a higher emission factor from Table I.F.1 under the category AMS-I.F may be used*". Indeed, the Bangladesh SHS project (CDM - Executive Board 2012) uses the default value of 0.8kg CO_2eq/kWh (leading to a very small potential for CO_2 savings that is eventually ignored for final baseline calculations), while the Moroccan SHS (SceT-Maroc & GERERE 2005) project applies a value of 1.9kg CO_2eq/kWh. Hence, the annual baseline emissions in this case equal 229,950kWh/y * 0.8kg CO_2eq/kWh or 183,960kg CO_2eq per year or 1,839t CO_2eq over the period of 10 years. Indeed, as in the Bangladesh project, we agree that this amount is negligible compared to the baseline emissions of the kerosene lanterns (193,740t CO_2eq). Results are presented in the third column of Table 22 (A).

$$E_{BL,t} = \sum_i EG_{i,t}/(1-l) \qquad \text{(Eq. 5)}$$

$$BE_{CO2,t} = E_{BL,t} * EF_{CO2} \qquad \text{(Eq. 6)}$$

5.3.2.3.2 "Relative" greenhouse gas mitigation cost

In this section, we calculate the relative GHG mitigation cost of SHS according to Eq. 2, assuming kerosene lanterns as baseline. The project costs are calculated identically to those in Eq. 1, as the lifetime and the crediting period are equal in this case *(n = cp = 10y)*. For the calculation of baseline costs and baseline emissions of kerosene, we refer to section

5.3.1.3.2. The life cycle inventory is presented in Table 20. Results are presented in the second column of Table 22.

Finally, we calculate the relative GHG mitigation cost of SHS (Eq. 2) when considering batteries powered with diesel generators as baseline. Project costs are again identical to those in Eq. 1. Baseline costs are calculated using the parameter values in Table 19. The life cycle inventory is presented in Table 20. Project and baseline emissions are assessed with the LCA model described in 3.1.3.2. Results are shown in the last column of Table 22.

5.3.2.3.3 Sensitivity analysis

A Monte Carlo sensitivity analysis is conducted on the life cycle GHG mitigation cost, assuming 500,000 trial runs. To this end, all economic and environmental parameter values are assumed to vary with minimally -10% and maximally +10% according to a triangular distribution. Results are listed in Table 22 (B). We indicate the range of GHG mitigation cost values and the sensitivity of the mitigation cost with respect to the spread in the three most influencing parameters.

Table 22 GHG mitigation costs of solar home systems versus *(i)* kerosene or *(ii)* batteries powered with diesel generators

	Absolute	Relative	Absolute	Relative
	Baseline: Kerosene		Baseline: Batteries powered with diesel generator at local shop	
(A)MITIGATION COST ANALYSIS				
Project inv cost ($): $I_{0,\mathrm{i}}$	1,857,480.00	1,857,480.00	1,857,480.00	1,857,480.00
Project O&M cost ($): $\sum_t \frac{(OC_{i,t}-R_{i,t})}{(1+r)^t}$	478,151.48	478,151.48	478,151.48	478,151.48
Baseline inv cost ($): $I_{0,\mathrm{b}}$	n.a.	584,279.92	n.a.	826,302.86
Baseline O&M cost ($): $\sum_t \frac{(OC_{b,t}-R_{b,t})}{(1+r)^t}$	n.a.	46,411,356.74	n.a.	2,534,828.98
Additional proj cost ($)	**2,335,631.48**	**-44,660,005.18**	**2,335,631.48**	**-1,025,500.37**
Project emissions (t CO_2eq)	0	990.77	0.00	990.77
Baseline emissions (t CO_2eq)	193,740.00	283,600.00	1,839.60	3,752.85
Emission reductions: $\sum_t A_t$ (t CO_2eq)	**193,740.00**	**282,609.23**	**1,839.60**	**2,762.08**
GHG mitigation cost LCC ($/t CO_2eq)	***12.06***	***-158.03***	***1,269.64***	***-371.28***
GHG mitigation cost I_0 ($/t CO_2eq)	***9.58***	***4.51***	***1009.72***	***373.33***
(B)MONTE CARLO SENSITIVITY ANALYSIS				
Range($/t CO_2eq)	[13.64; 27.45]	[-171.8;-137.5]	[1,070.73; 1,519.54]	[-687.90; -2.28]
Sensitivity with respect to…	Light output SHS (-22.2%) Lifetime SHS (-21.9%) Light output kerosene lantern (+21.5)	Emissions kerosene (+98.3%)	Electr production SHS (-61.2%) Purchase price SHS (+37.4%)	Electricity from diesel generator (-21.1%) Electricity cost (-20.4%) Lifetime SHS (-17.9%)

5.3.2.3.4 *Results*

Our mitigation cost analysis confirms that SHS projects are unattractive for CDM investors when absolute mitigation costs are considered, in particular when diesel powered batteries are considered as baseline to be replaced (mitigation cost of 1,269.64$/t CO_2eq). When comparing the absolute and relative mitigation costs of SHS, we conclude again that it is a major difference whether baseline costs are included. Even in the most extreme cases, absolute mitigation costs are positive while relative mitigation costs are negative, pointing to the fact that avoided baseline costs render the solar projects profitable. A second key difference is the choice of the baseline technology, which -in contrast to the default emission value per project lantern implemented under AMS-III.AR- is clearly not standardized under AMS-I.A. Within the current system, investors can easily increase the amount of CER units obtained by preferring kerosene over batteries as baseline to be replaced, even though it relates to the exact same project technology (*i.e.* implementation of SHS). This is largely due to the fact that kerosene lanterns emit much more (about 100 times) CO_2 equivalents than batteries to produce the equivalent amount of lighting. Indeed, the greenhouse gas mitigation cost values are highly dependent upon the baseline chosen. The sensitivity analysis indicates that parameters related to the SHS (light output or electricity production, lifetime, purchase price) are most important in determining the absolute GHG mitigation cost. When considering relative mitigation costs however, we see that baseline (either kerosene or batteries powered with diesel generators) rather than project (SHS) parameters are the largest influencers.

5.3.3 *Multi-objective optimization*

5.3.3.1 *Multi-objective linear programming (MOLP) models and coefficients*

In this section, we apply the multi-objective optimization model described in section 5.2.2 to the case of small-scale rural solar off-grid lighting. In particular, in our analysis, we consider four continuous decision variables x_i between 0 and 1, representing the amount of lighting technology i (percentage of the total) used in the combination of lighting technologies as follows: i = 1 represents kerosene lanterns, i = 2 stands for solar LED lanterns, i = 3 stands for batteries powered with diesel generators and i = 4 stands for SHS. Following the mitigation cost analysis described in section 5.3.1 and 5.3.2, we distinguish 4 types of multi-objective linear programming problems (MOLPs). Moreover, we distinguish between considering relative or absolute mitigation costs, and between considering complete life cycle costs (LCC) or merely the costs of investment (IC). The models are labeled A (relative, LCC), B (relative, IC), C (absolute, LCC) and D (absolute, IC). Each model is subject to a constraint regarding the lighting demand, *i.e.* $x_1 + x_2 + x_3 + x_4 = 1$ or hence the lighting demand needs to be completely satisfied. Note that this lighting demand corresponds to the functional unit of the mitigation cost analysis, *i.e* 114,975 million lumen-hours over a 10-year time span. The model coefficients are listed in Table 23. Economic coefficients represent the lifecycle or investment costs in kilo dollars (k$) and are summarized in $c_i^1 \text{ or } c_i^{1\prime}$. Environmental coefficients c_i^2 summarize the greenhouse gas life cycle emissions in tCO_2eq. The numerical values of these coefficients can be taken from Tables 21 and 22. Note that the emissions of the kerosene lanterns $c_1^{2(C)} \text{ and } c_1^{2(D)}$ are taken from Table 22 (based on AMS-I.A) rather than from Table 21 (based on AMS-III.AR), as only in AMS-I.A a 10-year lifetime is allowed.

Table 23 Decision variables and coefficients of the multi-objective linear programming (MOLP) models

i	Decision variable	Technology	MOLP A: Relative MC analysis, LCC		MOLP B: Relative MC analysis, IC		MOLP C: Absolute MC analysis, LCC		MOLP D: Absolute MC analysis, IC	
			$c_i^{1(A)}$	$c_i^{2(A)}$	$c_i^{1'(B)}$	$c_i^{2(B)}$	$c_i^{1(C)}$	$c_i^{2(C)}$	$c_i^{1'(D)}$	$c_i^{2(D)}$
1	x_1	Kerosene	46,996	283,605	584	283,605	0	193,740	0	193,740
2	x_2	Solar LED	9,260	1,602	4,500	1,602	9,260	0	4,500	0
3	x_3	Batteries	3,361	3,753	826	3,753	0	1,840	0	1,840
4	x_4	SHS	2,335	991	1,857	991	2,335	0	1,857	0

5.3.3.2 MOLP optimal solution frontiers

An overview of all Pareto optimal solutions for each model is presented in Figure 14. When considering life cycle costs and the relative mitigation cost methodology (MOLP A), we see that the use of solar home systems to fulfill lighting demands represents a single optimal solution from economic and environmental point of view. Said differently, in this case, there is no trade-off between economic and environmental performances, which can also be seen in Table 23. This is in correspondence with the relative mitigation life cycle cost analysis, as the cost of solar LED lanterns (-133.81$/t CO_2eq) exceeds the mitigation cost of SHS for both baselines (-158.03 and -371.28$/t CO_2eq). When considering life cycle costs and the absolute mitigation cost methodology (excluding baseline costs) on the other hand, the optimal solution front implies a trade-off between the use of SHS and batteries (MOLP C). The same conclusion is valid when considering investment costs and the absolute mitigation cost methodology (MOLP D). In both cases, the mitigation cost analysis provides ambiguous results when comparing solar LED lanterns and SHS. Moreover, in the absolute life cycle cost analysis (corresponding to MOLP C) the mitigation cost of solar LED lanterns (33.56$/t CO_2eq) exceeds that of SHS when kerosene is considered as baseline (12.06$/t CO_2eq) but is smaller than if batteries were the baseline (1,269.64$/t CO_2eq). This is also valid when considering the absolute investment cost analysis (MOLP D); the mitigation cost of solar LEDs (16.31$/t CO_2eq) lies between that of SHS when the baseline would be kerosene (9.59$/t CO_2eq) or batteries (1,009.72$/t CO_2eq). When considering merely the cost of investment and the relative mitigation cost methodology (MOLP B), the exclusive use of kerosene lanterns represents the economic lexicographic optimum. A relatively small increase in investment cost (+41%) is required to largely decrease the life cycle emissions (-7456%). To reach the environmental lexicographic optimum (that comprises the sole use of SHS) however, the investment cost requires to be increased with 124% to lower emissions with an additional 278%. Hence, the use of multi-objective optimization allows quantifying the trade-off between economic and environmental performances of the optimal solutions.

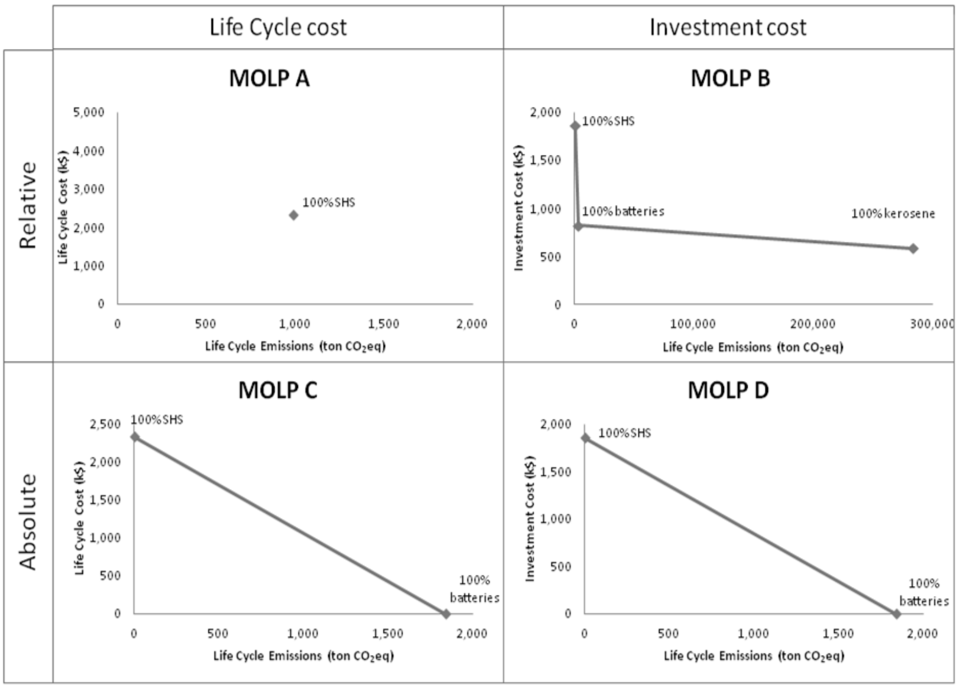

Figure 14 Optimal solution frontiers of the multi-objective linear programming (MOLP) models

5.3.3.3 The added value of complementing the mitigation cost analysis with multi-objective optimization

The results of the mitigation cost analysis are clear and concise, yet the drawback is that they are highly dependent on the baseline technology. Moreover, the mitigation cost analysis allows ranking technologies in order of increasing cost of emission abatement only if the same baseline technology is assumed to be replaced. If a project technology can replace plural baselines (*e.g.* SHS can replace kerosene lanterns and batteries), the mitigation cost analysis can lead to ambiguous results. The multi-objective linear programming approach on the other hand -which in this case is very straightforward- allows ranking technologies in order of increasing cost of emission abatement, without requiring a baseline. Considering the aforementioned example, we can see from MOLP B that SHS always outperform solar LED lanterns, as the latter do not appear in the optimal solution frontier. Moreover, the use of multi-objective optimization enables quantifying the trade-off between economic and environmental performances of the optimal technologies. This allows the decision maker to opt for one of these optima based on personal preferences. We note that in our analysis, the solar LED lanterns are never part of the optimal solution frontier; in all cases they are outperformed by SHS.

5.4 Policy recommendations

Despite their large potential to lower the costs for local villagers while decreasing GHG emissions, deployment of small-scale rural photovoltaic solar projects in developing countries is hampered by elevated initial investment costs. Hence, we stimulate the uptake of these projects under the CDM. Accordingly, based on our mitigation cost and multi-objective optimization analysis, we formulate the following recommendations for CDM policy makers: First, specifically for rural renewable electricity projects, we point to the importance of considering avoided baseline costs by creating an additional revenue stream to ensure the economic project viability, which is a necessary condition for project implementation. We illustrate this idea in Figure 15: Under the CDM, a project developer implements a project in the host country in order to receive CER credits delivered by the CDM Executive Board. The CER credits are sold to an Annex I entity; a developed country who can use the credits for compliance. To ensure climate integrity, the project must pass through vigilant approval, monitoring and evaluation procedures that create additional transaction costs. In our research, we focus on costs and revenues related to the technologies; costs and revenues inherent to the CDM structure (*e.g.* transaction costs and CER revenues) fall beyond the scope. Operational revenues might consist of income from the electricity sale of on-grid wind or solar projects, in which generated electricity is directly fed into the national grid and thus easily quantifiable. In case of small-scale rural solar projects however, generated electricity is stored temporarily in batteries and is then used by the local villagers, who reap the benefits from project implementation as they no longer have to bear the costs from (more polluting) alternatives. Hence, the economic benefits of avoided baseline costs (*e.g.* the avoided costs of kerosene and diesel generators) accrue to the villagers rather than to the project developer, rendering the project economically unviable for the latter and hence hindering project implementation under the CDM. We argue that in this case, an additional revenue stream should be created, representing avoided baseline costs. Our analysis indicates that avoided baseline costs are often five times more expensive than the costs of project implementation. To ensure economic viability, it is in this case sufficient that approximately one fifth (Table 21: ((1)+(2)/(3)+(4)) ≈ 1/5) of these economic benefits are returned to the project developer. The remaining benefits accrue to the end user, creating a win-win situation for both parties. Despite the fact that the creation of a revenue stream of avoided baseline costs is not addressed in the CDM methodologies, we note that both registered SHS projects and one of the registered solar LED lantern projects already include such a revenue stream, in the form of a monthly or annual operational rent.

Second, we discourage the use of limited time periods during which CERs can be obtained. While we recognize the Board's concern of inferior products that will no longer be operational after *t* years, we argue that limiting the crediting period undermines the search for superior technologies. Moreover, by fixing an absolute time limit during which CER credits can be obtained, investors have no motivation to invest in longer living -more expensive- technologies and hence technological development is being countered. It is the mandatory use of the monitoring methodology, which imposes ex-post surveys to determine the percentage of project lamps operating and in service in year *t*, that should discourage investors to file deceiving lifetimes.

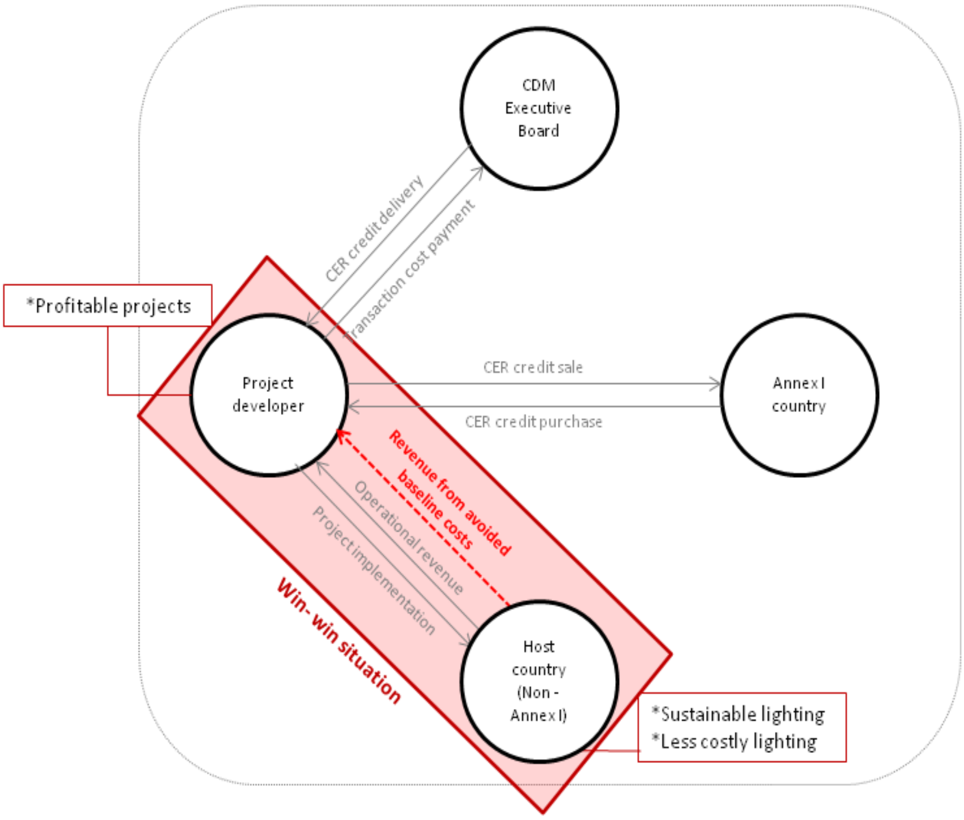

Figure 15 CDM working principle

Third, we encourage the use of standardized baselines under the CDM to avoid misuse of the system by manipulating baseline emissions. For solar LED lanterns, a good estimate of the avoided baseline (kerosene) emissions is given in AMS-III.AR. For SHS on the other hand, no (standardized) baseline is provided, allowing the project developer to easily manipulate the amount of CERs obtained. Based on the results of our sensitivity analysis, we point to the crucial importance of providing a good estimate of this baseline. Such an estimation baseline for SHS should consist of a combination of kerosene and batteries powered at diesel stations or hence diesel generators, as in practice, solar home systems are likely to replace both. Besides countering the CER manipulation, the use of standardized baseline methodologies helps lowering transaction costs (Hogarth 2012). In this regard, Spalding-Fecher and Michaelowa (2013) also emphasized that standardized baselines in the CDM should be mandatory. Nonetheless, a limited amount of flexibility should be maintained. Examples include standardized baselines per country or region and the possibility to use different values, as long as justification is provided.

We encourage continuing the use of mitigation costs -in particular relative mitigation costs- to make an ex-post evaluation of the attractiveness of CDM projects. This ex-post evaluation is useful for project implementers as well as for policy makers to verify which projects allow the procurement of CER credits in an economically feasible manner. Additionally, we stimulate the use of multi-objective optimization to make an ex-ante evaluation of the economic and environmental performances of the technologies that are promoted under the CDM. The knowledge of optimal solutions provides a good basis for policy decisions, for example when considering project differentiation strategies among project types (Bakker, Haug et al. 2011). Moreover, projects that appear in the optimal solution frontiers are optimal from economic and environmental viewpoints and are hence assumed to have a larger contribution to sustainable development than all other dominated solutions (projects). Given that in our analysis SHS always outperform solar LED lanterns, a possible strategy would be to reward SHS for example by applying CER discounting.

5.5 Conclusions and discussion

The results of this research encourage the use of relative rather than absolute mitigation costs to assess the attractiveness of CDM projects**.** This implies that avoided baseline costs are to be taken into account, often rendering the projects economically viable. Due to the inherent CDM structure however it is currently more obvious to apply absolute mitigation costs, as project investors do not automatically receive an operational return from implemented rural projects. Consequently, economic viability -which is a necessary condition for project implementation- is not automatically realized. This is a mere structural problem, which can be altered to a win-win situation for both parties by including guidelines to stimulate an additional revenue stream of the avoided baseline costs. Correcting this metric accordingly will especially influence the evaluation of small-scale renewable energy projects, as the avoided costs of fossil fuels render these projects profitable. In case of lighting, this would correspond to a "lighting as a service model", in which the project developer will pay upfront lighting costs and is compensated through a performance contract, *i.e.* the energy savings due to the new lighting technology. It has already been demonstrated in literature that these projects make a significant contribution to the sustainability of host countries. When reconsidering the mitigation cost as such, the CDMs twin objectives -*i.e.* assisting at cost-effective emission reduction and contributing to sustainable development- are more likely to be reconciled rather than opposed. One drawback of the mitigation cost analysis is that results are always dependent on the baseline chosen. In case of plural potential baseline technologies, we stimulate the use of a multi-objective approach. Moreover, multi-objective optimization enables quantifying the trade-off between economic and environmental performances of the optimal technologies, without requiring a baseline.

We note that the mitigation cost does not consider CER credit revenues. Accordingly, a negative mitigation cost -as is the case with rural solar projects- means that the project is viable without CER revenue. A natural interpretation would be to state that the project is not "additional", *i.e.* that the emission reduction would have occurred anyways, without registration as a CDM project. However, to demonstrate "additionality" in this case (*i.e.* to demonstrate that the project wouldn't have occurred without CDM provisions), barrier analysis should be applied. More specifically, the high investment cost of the solar technologies clearly provides a barrier to widespread market penetration. Besides using the income of CER units to help finance the higher initial purchase price, CER revenues in this case could be used to cover the risk of non-payment of the avoided baseline revenue stream. Finally, we note that the multi-objective optimization in our analysis might represent a simplification of the studied case. Nevertheless, our analysis is a good start and could be completed by including the economies of scale (*i.e.* cost advantages that are obtained with increasing scale) using multi-objective mixed integer programming.

6 Multi-objective optimization to evaluate the impact of Belgian policy on solar power and electric vehicles

Revised version currently under review

ABSTRACT

This research uses multi-objective optimization to determine the optimal mixture of energy and transportation technologies, while minimizing economic and environmental impacts. We demonstrate the added value of using multi-objective mixed integer linear programming (MOMILP) considering economies of scale versus using continuous multi-objective linear programming (MOLP) assuming average cost intervals. This research is the first to apply the improved version of the unique algorithm to solve MOMILPs exactly (Vincent, et al. 2013). To differentiate optimal solutions with and without subsidies, the impact of policy on the Pareto frontier is assessed. We distinguish between minimizing economic life cycle costs (complete rationality) and required investments (bounded rationality). The approach is illustrated using a Belgian company with demands for electricity and transport. Electricity technologies are solar photovoltaics and the grid; transportation includes internal combustion engine vehicles (ICEVs), grid powered battery electric vehicles (BEVs), and solar powered BEVs. The impact of grid powered BEVs to reduce GHG emissions is limited, yet they are less costly then solar panels to decrease emissions. Current policy measures are found to be properly targeting rational investors who consider life cycle costs, while private (potentially bounded rational) investors often focus on required investments only.

6.1 Introduction

In the light of climate change, Europe has put in place legislation to reduce greenhouse gas (GHG) emissions to 20% below 1990 levels by 2020 (European Commission 2009). In 2010, the combined share of electricity and heat generation and transport represented nearly two-thirds of global emissions (International Energy Agency 2012). Recognizing that the former sectors are the world's largest contributors to climate change, the use of clean energy sources and alternative transportation technologies is widely stimulated. Unfortunately, better environmental performances often imply a trade-off with increased economic costs. Hence, clean energy and transportation technologies require assessment from both economic and environmental point of view. A possible way to address this is combining economic costs and environmental impacts into a mitigation assessment (Sathaye and Meyers 1995), and calculating the technologies' cost for mitigation accordingly. This methodology allows ranking different technologies or projects in order of increasing cost of emission abatement. Amongst others, this approach has been demonstrated in Chapters 4 and 5. One drawback however is that the mitigation cost assessment is always dependent on a baseline or reference technology (Sathaye and Meyers 1995). Moreover, as assumptions regarding the baseline affect both the additional costs and the reduced emissions of the implemented technology, a technology's mitigation cost can vary widely depending on the baseline chosen. A second shortcoming is that while the mitigation cost clearly indicates the cost per ton of emissions avoided for each separate technology, it does not provide any information on determining an optimal mixture of different technologies to satisfy required demands. In this research we propose to overcome these drawbacks by means of a multi-objective optimization approach (see section 5.2.2 for more information about the use of multi-objective optimization).

In literature, we find numerous examples regarding the use of multi-objective optimization to determine the optimal mix of energy technologies within an energy system. A review of the use of multi-criteria approaches in energy systems has been provided in Wang et al. (2009). In a basic form, energy systems are limited to the generation of electricity. For example, in Arnette and Zobel (2012) a multi-objective model is developed to determine the optimal mix of renewable energy sources (wind, solar, biomass) and existing fossil fuel facilities on a regional basis, considering generation costs and greenhouse gas emissions. In a more complex form, energy systems may include other generation technologies besides electricity such as heating or co-production technologies, implying a more complicated multi-objective optimization model to determine the optimal design of the system (Liu, Pistikopoulos et al. 2010). While multi-objective optimization has been extensively used to determine the optimal mixture of energy (*e.g.* electricity and heat generating) technologies, it has not been applied yet to find the optimal mix of energy and transportation technologies. Nonetheless, we argue that it is valuable to consider energy and transportation simultaneously, for three main reasons: *(i)* These are the world's two most polluting sectors (International Energy Agency 2012); *(ii)* Nearly all entities (*e.g.* multinationals, small & medium sized enterprises or SMEs, households,…) have needs regarding both; *(iii)* When combined, synergies might be exploited such as additional emission reduction (Doucette and McCulloch 2011) and diminishment of the effect of power variability of intermittent clean energy sources such as solar PV (Zhang, Tezuka et al. 2012) or wind power (Hennings, Mischinger et al. 2013; Liu, Hu et al. 2013). Hence, in this research we use multi-objective optimization to determine the optimal mixture of energy and transportation technologies given required energy and transportation needs, while minimizing economic costs and environmental emissions.

To obtain realistic results, economies of scale -cost advantages that enterprises obtain with increasing scale (Pindyck and Rubinfeld 2009)- are considered. As noted by Mavrotas et al. (2008), this inherently discrete phenomenon implies the use of mixed integer programming. We demonstrate the added value of using multi-objective mixed integer linear programming (MOMILP) considering economies of scale versus using continuous multi-objective linear programming (MOLP) assuming average cost intervals. This research is the first to apply the improved version of the exact multiple objective branch and bound algorithm for mixed 0-1 linear programming as described in Vincent et al. (2013). We note that thus far, this algorithm is the only method available to find all the optimal solutions of a MOMILP problem exactly. Hence, other attempts found in literature provide no more than an approximation of the optimal solution frontier. For example, Arnette and Zobel (2012) propose a MOMILP optimization model for renewable energy development. Whilst this is a very interesting contribution, the optimal solution frontier is simply approximated by means of a linear relaxation of five supported solutions. Further, we point to the impact of policy measures. Badcock and Lenzen (2010) indicated in their review regarding subsidies for electricity generating technologies that the global energy sector receives among the highest financial support provided to any sector of the global economy. Likewise, policymakers provide strong financial incentives for sustainable road transport (Santos, Behrendt et al. 2010). To assess the impact of policy or hence, to distinguish between the optimal solutions with and without subsidies and taxes, we visualize the impact of policy measures on the Pareto frontier. Finally, we compare minimizing full economic life cycle costs (including initial investment as well as operation costs) and minimizing solely the initial required investments. Moreover, in complex and uncertain circumstances, humans make decisions under the constraints of limited knowledge, resources, and time; which is defined as "bounded rationality" (Gigerenzer and Selten 2002). Hence, a comparison is made between completely rational versus bounded rational investors. The approach is illustrated with a Belgian SME seeking to find the optimal combination of technologies to satisfy electricity and transportation demands, while minimizing environmental emissions and economic costs. Two technologies are at hand for electricity generation: *(i)* the local grid and *(ii)* solar photovoltaics (PV); and three for transportation: *(i)* internal combustion engine vehicles (ICEVs), *(ii)* grid powered battery electric vehicles (BEVs), and *(iii)* solar powered BEVs. The motivation for this choice of technologies is given in section 6.4.1.

In section 6.1, we discussed the need for using a multi-objective optimization approach to find the optimal mixture of energy and transport technologies considering economic and environmental objectives. In the following section, the optimization model is discussed. Section 6.3 elaborates on the solution method. In section 6.4, the results of the case and the limitations of the model are discussed. The chapter ends with a conclusion of the findings including policy implications in section 6.5.

6.2 Optimization Model

6.2.1 Basic model

The aim of this basic model is to mathematically represent the optimization of the combined use of *n* different technologies of the same type (*e.g.* energy generating technologies or transportation technologies) from an economic and environmental point of view. Consider the case where all technologies are energy generating ones (the case of transportation technologies is analogous). The decision variables are denoted by x_i. They represent the proportion of technology *i* used in the combination of energy generating technologies. The two competing objectives in the model are *(i)* to minimize economic costs and *(ii)* to minimize environmental emissions. The economic costs (*e.g.* purchase price, operating and maintenance costs, taxes) and environmental emissions (*e.g.* greenhouse gas emissions) implied by one unit of technology *i* are represented respectively by means of the data c_i^1 and c_i^2. The economic coefficient c_i^1 is calculated using life cycle costing (LCC), which is an assessment technique that takes into consideration all the cost factors relating to the asset during its operational life. The life cycle cost of an asset can, very often, be many times the initial purchase or required investment (Woodward 1997). The environmental coefficient c_i^2 can be determined using life cycle analysis (LCA), a tool to assess environmental impacts of complete life cycles of products or functions. Furthermore, a required energy demand *d* -determined according to the investor's preferences- has to be satisfied. In this constraint, q_i is defined as the amount of energy provided by one unit of technology *i*. Hence, assuming linear relations, the optimization of the use of technologies *i* to satisfy required demand *d* can be formulated as a multi-objective linear programming (MOLP) problem as follows:

$Min\ \sum_{i=1}^{n} c_i^1\, x_i$	Economic objective function
$Min\ \sum_{i=1}^{n} c_i^2\, x_i$	Environmental objective function
$Subject\ to\ \sum_{i=1}^{n} q_i\, x_i = d$	Satisfy demand constraint
$x \in X$	
$X \subset \mathrm{R}_{+}^{\mathrm{n}}$	

6.2.2 Economies of scale

Due to the existence of economies of scale -cost advantages that enterprises obtain with increasing scale (Pindyck and Rubinfeld 2009)- the technology unit cost to be paid by the investor may vary for different technology sizes. Accordingly, technology *i* should be subdivided into *k* intervals, each having a lower and upper bound. Furthermore, to indicate the interval *k* that is active for technology *i*, binary variables y_{ik} (with value 0 or 1) need to be introduced in the developed MOLP, turning the latter into a multi-objective mixed integer linear programming (MOMILP) problem. Hence, the previous model should be adapted as follows:

Variables x_{ik} and y_{ik} are added to the model, implying the following constraints:

$\sum_{k \in interval\ i} x_{ik} = x_i \ \forall\ i = 1, \dots, n$ Each technology x_i subdivided in *k* intervals

$\sum_{k \in interval\ i} y_{ik} = 1 \ \forall i = 1, \dots, n$ Exactly one interval active for technology x_{ik}

The variables x_{ik} are bounded by the following constraint, which ensures that x_{ik} = 0 if its associated interval is not active (y_{ik}=0):

$lb_{ik} y_{ik} \leq w_{ik} x_{ik} \leq ub_{ik} y_{ik}$ Lower and upper bound interval *k* of technology *i*

$\forall\ i = 1, \dots, n\, ; k\ \in interval\ i$

Finally, the objective functions are the following:

$Min\ \sum_{i=1}^{n} \sum_{k \in interval\ i} c_{ik}^{1} x_{ik}$ Economic objective function

$Min\ \sum_{i=1}^{n} \sum_{k \in interval\ i} c_{ik}^{2} x_{ik}$ Environmental objective function

6.2.3 Energy versus transportation technologies

In this chapter, we develop a model that allows comparing energy generating technologies versus transportation technologies, the latter being possibly energy consuming. To this end, we need to explicitly distinguish between variables and data regarding energy technologies *E* on the one hand, and transportation technologies *T* on the other. Moreover, an additional demand (for transportation) has to be satisfied. Accordingly, the following variables and data need to be split:

$$x = \begin{bmatrix} x_E \\ x_T \end{bmatrix}, \qquad Q = \begin{bmatrix} q_E^T \\ q_T^T \end{bmatrix}, \qquad d = \begin{bmatrix} d_E \\ d_T \end{bmatrix}$$

We specify the number of technologies *n*, assuming *m* energy generating and *p* transport technologies:

$$x_E = \begin{bmatrix} x_{E_1} \\ x_{E_2} \\ \cdots \\ x_{E_m} \end{bmatrix} \ and \ x_T = \begin{bmatrix} x_{T_1} \\ x_{T_2} \\ \cdots \\ x_{T_p} \end{bmatrix}$$

Hence, considering energy and transportation technologies simultaneously leads to the following demand constraints:

$\sum_{i \epsilon E} q_i x_i = d_E$ Satisfy energy demand constraint

$\sum_{i \epsilon T} q_i x_i = d_T$ Satisfy transportation demand constraint

Finally, an additional set of constraints that allows linking energy generating and transportation technologies must be added to the MOMILP. Accordingly, factor e_{ij} is introduced, representing the quantity of energy technology *i* required to supply one unit of transportation technology *j*. Let $PoweredBy_i$ with $i \in E$ be the set of transportation technologies *j* that can be powered by *i*. We assume that two different energy technologies *i* and *i'* cannot supply the same transportation technology *j*. It hence implies the following constraints:

$\forall\ i \ \epsilon \ E$: $\sum_{k \in Interval_i} x_{ik} = x_i + \sum_{j \in PoweredBy_i} e_{ij}\, x_j$ Total amount of energy generation

$\forall\ i \ \epsilon \ T$: $\sum_{k \in Interval_i} x_{ik} = x_i$ Total amount of transportation resources

The linking of energy and transportation technologies is represented schematically in Figure 16. The transport technologies *(x_j)* require an amount of energy to be fueled, which is given using the relation *"PoweredBy".* The coefficient e_{ij} transforms the amount of transportation technology *j* into a corresponding amount of energy technology *i*. Note however that the demand for energy *(d_E)* is not increased due to this energy consumption of the vehicles. Consequently, x_{ik} comprises both the amount of energy technology *i* used to fulfill energy demand d_E and the amount of energy used to power the transport technologies *j*. We note that for energy technologies the interval *k* is related to the capacity of the system, as the unit cost decreases with larger capacities due to economies of scale. For transportation technologies, *k* is related to the amount of vehicles as quantity reductions can be obtained from vehicle distributors.

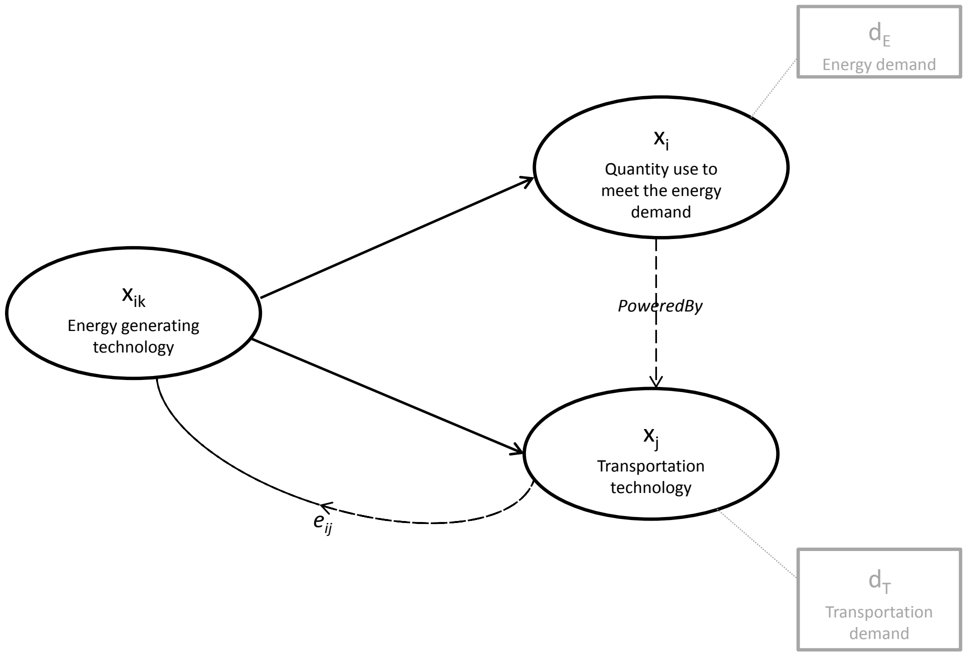

Figure 16 Schematic representation of the link between energy and transportation technologies

6.3 Solution Method

Solving a multi-objective optimization problem is not as straightforward as solving single-objective optimization problems. A simplified overview of types of multi-objective problems and according solution methods is provided in Figure 17, which is developed by the authors. The figure is structured based on linearity of the problem (*i.e.* linear or non-linear) and the type of the decision variables (*i.e.* continuous, discrete, or mixed). The different types of problems are shown in rectangles; the according solution methods are listed in circles. Further, it is indicated in bold, capital letters whether the problem is easy or hard to solve. If we assume linear relations and exclusively continuous decision variables (see 6.2.1 Basic model), the multi-objective linear programming (MOLP) problem is relatively easy to solve by means of a multi-objective simplex. However, when considering economies of scale, the introduction of binary variables is required. This transforms the MOLP into a multi-objective mixed integer linear programming (MOMILP) problem (see 6.2.2 Economies of scale), which is more complicated to solve. To this end, Mavrotas and Diakoulaki (1998; 2005) proposed a multi-objective branch and bound algorithm, which was recently improved and corrected for the bi-objective case by Vincent et al. (2013).

In this research, the improved version of this algorithm is used to solve the MOMILP problem (Figure 18). This algorithm aims at finding all the efficient solutions. Per definition, a subset $S \in X$ is called efficient if there does not exist another feasible solution $S' \in X$ such that $z^j(S') \leq z^j(S)$ for all $j = 1,...,Q$ with strict inequality for at least one of the objectives. The corresponding vector $z(S)=(z^1(S),...,z^Q(S))$ is called non-dominated (Ehrgott and Gandibleux 2000). In other words, an efficient or Pareto optimal solution is a feasible solution that is not dominated by any other feasible solution (*i.e.* it performs better on all the objectives at the same time). The developed algorithm is a branch and bound algorithm that explores a binary tree, *i.e.* a tree which enumerates all the possible combinations of values for the binary variables. The algorithm starts at the root node, that is the ancestor of all nodes that represents the original problem (Figure 18, step 0). Then it visits the tree following a depth-first search scheme. All other nodes of the tree represent a subproblem where some of the binaries have been fixed. For instance, in step 2, x_0 and x_1 are both fixed at 0. The binary variables which have not been fixed yet are called free variables. At any stage of the algorithm, a list of solutions called the incumbent list is updated by storing all the potentially efficient solutions. The incumbent list is initially empty and it is updated whenever a final node or "leaf node" is visited. In such a node, all the binary variables are fixed and hence, the corresponding subproblem is a simple MOLP. This MOLP is then solved using a multi-objective simplex and if the solutions are efficient to the global problem, they are added to the incumbent list. Additionally, the incumbent list serves the role of upper bound set (UBS) on the global problem. Hence, only the solutions that are not dominated by this UBS are potentially efficient.

We note that the binary tree grows exponentially with the number of binary variables. Moreover, given *n* binary variables, the binary tree consists of 2^{n+1} nodes. Fortunately, the algorithm allows to fathom nodes (either by infeasibility or by dominance), and hence it is not necessary to explore all nodes. When a node is visited, the linear relaxation of the according subproblem is considered, *i.e.* the free binary variables are temporarily supposed continuous in the interval [0,1]. This linear relaxation can either be feasible or infeasible. If it is infeasible -that is some constraints are not respected- the node is fathomed by infeasibility (*e.g.* step 5). If it is feasible, a lower bound set (LBS) of the linear relaxation is computed. This LBS represents an optimistic evaluation of the solution set that can be obtained from the current node and it is compared to the upper bound set of the global problem. If at least a part of the LBS is dominated by the UBS (*e.g.* step 10), the node can be fathomed by dominance. If the LBS is not dominated by the UBS (*e.g.* step 6), the node is not fathomed and its child nodes are generated by fixing one additional binary variable at a time. These child nodes must be explored as well. At the termination of the algorithm, the incumbent list contains all the efficient solutions.

Vincent et al. (2013) proposed a new representation of the solution set for the bi-objective case to correct errors that lead to keeping dominated solutions. Further, the authors introduced the use of an actual lower bound set instead of a single lower bound point, allowing to fathom nodes more efficiently. Another improvement is a preprocessing that determines in which order the variables should be fixed. This allows the algorithm to find good solutions sooner, leading to a better fathoming, less visits of nodes and thus reduced solution times.

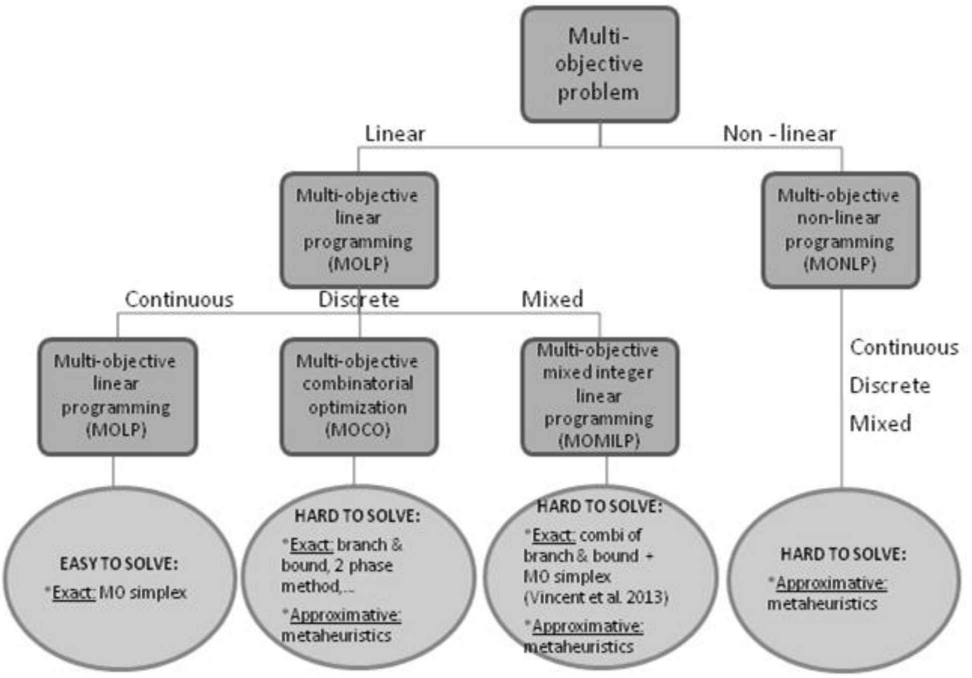

Figure 17 Types of multi-objective problems (in rectangles) and according solution methods (in circles)

6.4 Case Study

6.4.1 Model formulation

We studied a small steel processing company in Flanders (in the northern part of Belgium), with a specific annual demand for energy -in this case only electricity- and transportation. To fulfill electricity needs, the firm has two technologies at hand: (i) grid electricity (which is already in place, *i.e.* grid electricity is their current manner of obtaining electricity), and (ii) roof mounted photovoltaic solar panels. They are interested in PV in particular because they have a large, optimally oriented roof area available to install PV panels and because the installation of this solar project does not require the lengthy, often expensive process of filing for an official permission, which would be the case for alternative energy technologies such as wind mills. For transportation and more particularly, for the commuting of their staff, the company considers three different types of vehicles: (i) gasoline powered internal combustion engine vehicles (ICEVs) (their current vehicles), (ii) grid powered battery electric vehicles (BEVs), and (iii) solar powered BEVs. The latter technology exemplifies the concept of electric vehicle workplace charging using PV panels (Tulpule, Marano et al. 2013). Moreover, the company considers a simple grid-connected solar PV parking structure for their BEVs at the main entrance of their buildings to enhance the visibility of their corporate environmental responsibility (CER) strategy. The vehicles are all comparable in size, *i.e.* medium sized vehicles for the commuting of employees. Note that we do not consider diesel vehicles; currently the SME only uses gasoline ICEVs as travel distances are relatively short. This renders battery electric vehicles with limited driving ranges an interesting alternative. The company considers BEVs for transport because they prefer "zero-emission" vehicles that they can easily power with electricity that is available on their site, which would not be the case for alternative clean transport technologies such as hydrogen vehicles. One could argue that an alternative strategy for the company to minimize economic costs and environmental emissions could be to trade CO_2 permits under the EU ETS system. However, the steel company only monitors the emissions that are required by law, *i.e.* emissions that are directly related to their installations including emissions of the raw materials, conventional fuels, process gases, consumption of graphite electrodes, other fuels and waste gas scrubbing (European Commission 2012). Hence, the emissions of electricity for their offices and transport for their staff are not monitored under their EU ETS compliance. Therefore, we do not consider the purchase of tradable CO_2 permits as an alternative option to decrease costs and emissions. We acknowledge that the results of the study are case and situation specific, yet the proposed methodology is applicable to other cases in which economies of scale are present.

6.4.1.1 Decision variables.

From the model presented in section 6.2, we redefine the decision variables x_{ik} by distinguishing energy generating and transportation technologies. This leads to the variables x_{ijk} as defined in Table 24. In addition, we note that the variables that represent the same type of technology are measured in the same unit. In this research, we use kilowatt-hours per year (kWh/y) for energy generating technologies, and kilometers per year (km/y) for transportation technologies. The data are then normalized with respect to the annual demand for energy and transport. For example, considering the use of solar panels for electricity generation (*i.e.* $i = 1$, $j = 1$), we first assess the annual amount of solar electricity generated (kWh/y). Next, we normalize this amount with respect to the total annual energy demand (kWh/y). Therefore, x_{ijk} takes a value within the interval [0,1] and hence represents the portion of annual demand d covered by technology j, in interval k. This normalization allows describing the mix of technologies used to satisfy demand d. For instance, $x_{11k} = 0.5$ implies that 50% of the electricity demand is covered by means of solar panels. The boolean variable y_{ijk} represents the activity of interval k -given the corresponding level of economies of scale- for technology j of type i.

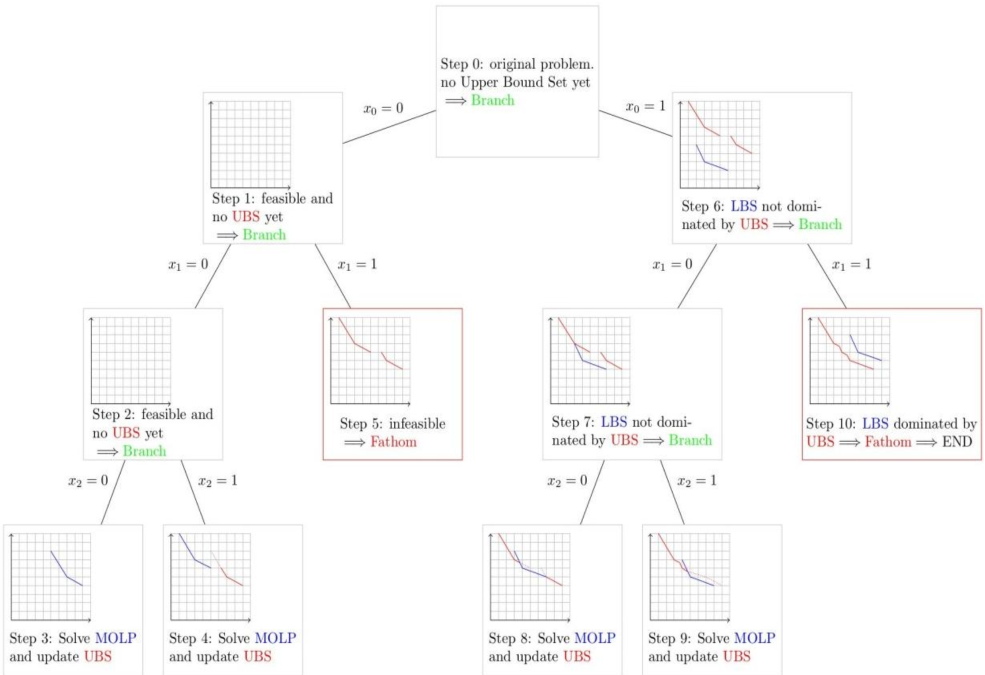

Figure 18 Tree exploration within the exact multi-objective branch and bound algorithm for the bi-objective case

Table 24 Decision variables x_{ijk}

Energy versus transportation technology		Type of technology	Number of intervals for each technology	
i = 1	electricity	j = 0 grid	k = 1	One interval
		j = 1 PV	k = 1, 2, …7	Seven intervals
i = 2	vehicles	j = 0 ICEV	k = 1, 2, 3	Three intervals
		j = 1 grid BEV	k = 1, 2, 3	Three intervals
		j = 2 solar BEV	k = 1, 2, 3	Three intervals

6.4.1.2 Objective functions

6.4.1.2.1 Economic objective function

The economic costs of the technologies are calculated using life cycle costing (LCC). We assume that the lifetime of the project equals the lifetime of the "longest living" technology; that is solar PV with a lifetime of 20 years (data in Table 25). Technologies should always be compared over the same discounting period so that they have the same opportunity to accumulate costs and benefits. In this chapter we use the roll-over-method to compare projects with unequal lifetimes (Boardman, Greenberg et al. 2011); *i.e.* the project with the shorter lifetime is "rolled over" within the lifetime of the longer project: Given technology T_s with short lifetime n_{Ts} that needs to be compared with technology T_l with longer lifetime n_{Tl} , the number of times that technology T_s needs to be "rolled over" *(z)* is given in Eq. 1. The calculation of the initial unit cost of investment in T_s *(UC_{Ts})* is then calculated according to Eq. 2, by taking into account the real annual price evolution of the technologies *($\dot{P}$)*, and then discounting at discount rate r. Hence, given a vehicle lifetime of 5 years, the investment in the vehicles is "rolled over" 4 times within the longer 20 year lifetime of the PV installation in years $t = 0,5,10,15$.

$$z = \frac{n_{T_l}}{n_{T_s}} \text{ with } n_{T_l} > n_{T_s} \quad (1)$$

$$UC_{T_s} = \sum_{t=0*n_{T_s}}^{(z-1)*n_{T_s}} \left[\frac{UC_{T_s}*(1+\dot{P}_{T_s})^t}{(1+r)^t}\right] \quad (2)$$

Life cycle cost data (including the initial cost of investment and operation and maintenance costs over the technologies' lifetime) is summarized in the coefficient c_{ijk}^1. We also calculate the optimal solutions when considering exclusively the cost of investment, for example due to bounded rationality. Data regarding the investment cost is summarized in $c_{ijk}^{1'}$. The coefficients are calculated according to Eq. 3a to 7b. We consider the time value of money by discounting at discount rate *r*. The meaning and values of the symbols (including and excluding the impact of policy) are listed in Table 25. The cost of grid electricity is computed in Eq. 3a and 3b, considering an annual increase of the electricity price $\dot{P}_{electr}$. The costs of solar PV comprise the initial cost of investment minus the elevated investment deduction (Eq. 4a), and operating costs of maintenance and insurance minus the tradable green certificates (Eq. 4b). Note that the latter are obtained over a period of ten years, rather than over the whole lifetime of 20 years of the installation. To satisfy the average demand of 150,000kWh/y exclusively with photovoltaics, an installation with a capacity of 190.47kWp (P_{tot}) would be required. Initial investment of the vehicles is calculated in Eq. 5a, 6a, 7a according to the procedure explained in Eq. 1-2 above. Note that tax benefits in the form of investment deductions are deducted from the initial unit cost. Operating costs of the internal combustion engine vehicles include fuel costs of gasoline, maintenance costs, registration and traffic taxes minus the tax benefits obtained (Eq. 5b). Operating costs of the grid powered battery electric vehicles are calculated simultaneously in Eq. 6b, yet they include fuel costs of electricity rather than gasoline. Solar powered battery electric vehicles imply no fuel costs over the lifetime of the vehicle, fuel costs of solar electricity are reflected in a higher initial purchase price. Solar powered vehicles have the additional advantage of obtaining tradable green certificates (Eq. 7b). Numerical values of the coefficients in each interval *k* are presented in the upper part of Table 26 (in euros).

To demonstrate the added value of incorporating economies of scale using mixed integer programming in a MOMILP rather than simply assuming one cost interval for each technology in a MOLP, we compare the results of both approaches. Hence, in the MOLP (model described in section 6.2.1 with the decision variables as redefined in Table 24) we assume an "average" cost interval for all technologies. In particular, the grid electricity only has one interval *(k = 1)*, we assume solar PV to be in the fourth cost interval *(k = 4)*, and all the vehicles are assumed to be in the second cost interval *(k = 2).* The according cost coefficients are listed in the lower part of Table 26. Hence, the economic objective function is as follows:

$Min \sum_{i=1}^{m} \sum_{j=1}^{p} \sum_{k \in interval\ i} c_{ijk}^{1} x_{ijk}$ Economic objective function

6.4.1.2.2 Environmental objective function

The environmental impacts are determined using life cycle assessment (LCA). To this end, we use the model described in Chapter 4. Moreover, we conduct an attributional LCA, which serves to assess the environmentally physical flows of a past, current, or future product system. Hence, we make use of average values for current technologies, as available in the EcoInvent database. The applied LCA methodology complies to the relevant ISO standards (14040-14044:2006). Unit processes are selected from the EcoInvent database, based on the best available match with the real projections at hand. The different scenarios are assessed for their impact on climate change on a 100 year time dimension (kg CO_2eq) using the IPCC 2007 GWP 100a v1.02 single issue method. As the sectors of heat and electricity and transport are the two largest contributors to global GHG emissions (International Energy Agency 2012), we focus on CO_2eq emissions. Other category impacts such as fossil depletion, human toxicity, particulate matter formation,… are beyond the scope of the bi-objective optimization model. Regarding the transportation technologies, we consider *(i)* the life cycle impact of the production and assembly of the vehicle, including the environmental impact of battery production *(ii)* the well-to-tank (WTT) impact, *i.e.* production and distribution of the energy carrier, and *(iii)* the tank-to-wheel (TTW) impact, *i.e.* conversion from energy carrier to transport. As regards the energy technologies, we take into account the GHG emissions of *(i)* the generation and *(ii)* the distribution phase. Data regarding life cycle environmental emissions is represented by means of c_{ijk}^{2}. The numerical value of the coefficients (in ton CO_2eq) can be found in Table 26. The environmental objective function is expressed the following way:

$Min \sum_{i=1}^{m} \sum_{j=1}^{p} \sum_{k \in interval\ i} c_{ijk}^{2} x_{ijk}$ Environmental objective function

$$c_{101}^{1'} = UC_{electr} \tag{3a}$$

$$c_{101}^{1} = c_{101}^{1'} + \sum_{t=1}^{n} \frac{d_E * P_{electr} * (1+\dot{P}_{electr})^t}{(1+r)^t} \tag{3b}$$

$$c_{11k}^{1'} = P_{tot} * UC_{PV(k)} * (1 - EID_{\%}) \tag{4a}$$

$$c_{11k}^{1} = c_{11k}^{1'} + \sum_{t=1}^{n} \frac{P_{tot} * (MC_{PV,t} + INSC_{PV,t} * UC_{PV})}{(1+r)^t} - \sum_{t=1}^{n_{TGC}} \frac{\beta * P_{tot} * (1-\alpha * t) * TGC}{(1+r)^t} \tag{4b}$$

$$c_{20k}^{1'} = \sum_{t=0,5,10,15} \left[\frac{UC_{ICEV(k)} * (1+\dot{P}_{ICEV})^t * (1 - ID_{\%ICEV} * t_r)}{(1+r)^t} \right] \tag{5a}$$

$$c_{20k}^{1} = c_{20k}^{1'} + \sum_{t=1}^{n} \frac{d_T * F_{use_{ICEV}} * P_{gasol} * (1+\dot{P}_{gasol})^t * (1 - ID_{\%fuel} * t_r) + V * (1 - ID_{\%ICEV} * t_r) * \left[MC_{ICEV} + T_{0_{ICEV}} * \left(1+\dot{P}_{T_{0_{ICEV}}}\right)^t + T_{n_{ICEV}} * \left(1+\dot{P}_{T_{n_{ICEV}}}\right)^t \right]}{(1+r)^t} \tag{5b}$$

$$c_{21k}^{1'} = \sum_{t=0,5,10,15} \left[\frac{UC_{grBEV(k)} * (1+\dot{P}_{BEV})^t * (1 - ID_{\%BEV} * t_r)}{(1+r)^t} \right] \tag{6a}$$

$$c_{21k}^{1} = c_{21k}^{1'} + \sum_{t=1}^{n} \frac{d_T * F_{use_{BEV}} * P_{electr} * (1+\dot{P}_{electr})^t * (1 - ID_{\%fuel} * t_r) + V * (1 - ID_{\%BEV} * t_r) * \left[MC_{grBEV} + T_{0_{BEV}} * \left(1+\dot{P}_{T_{0_{BEV}}}\right)^t + T_{n_{BEV}} * \left(1+\dot{P}_{T_{n_{BEV}}}\right)^t \right]}{(1+r)^t} \tag{6b}$$

$$c_{22k}^{1'} = \sum_{t=0,5,10,15} \left[\frac{UC_{solBEV(k)} * (1+\dot{P}_{BEV})^t * (1 - ID_{\%BEV} * t_r)}{(1+r)^t} \right] \tag{7a}$$

$$c_{22k}^{1} = c_{22k}^{1'} + \sum_{t=1}^{n} \frac{V * (1 - ID_{\%BEV} * t_r) * \left[MC_{solBEV} + T_{0_{BEV}} * \left(1+\dot{P}_{T_{0_{BEV}}}\right)^t + T_{n_{BEV}} * \left(1+\dot{P}_{T_{n_{BEV}}}\right)^t \right]}{(1+r)^t} - \sum_{t=1}^{n_{TGC}} \frac{\beta * P_{solBEV} * (1-\alpha * t) * TGC}{(1+r)^t} \tag{7b}$$

Table 25 Case study: Data economic costs; parameter values excluding and including policy measures

Parameter	Symbol	Value excl. policy	Value incl. policy	Motivation
General				
Tax rate	t_r	0%	33.99%	(FOD Financiën 1992)
Discount rate	r	4%	Idem	(European Commission 2009)
Electricity demand	d_E	150,000kWh/y; 190.47kWp (P_{tot})	Idem	SME's electricity need
Transport demand	d_T	14,996.3km/y,veh 8 vehicles;	Idem	SME's transportation need
Lifetime	n	20y	Idem	Lifetime longest living technology, *i.e.* solar PV
Solar PV installation				
Irradiation factor	β	850kWh/kWp	Idem	(Súri, Huld et al. 2007)
PV deterioration rate	α	0.70%/y	Idem	4 Belgian PV companies
Lifetime	n_{PV}	20 y	Idem	4 Belgian PV companies
Unit cost in function of PV capacity	UC_{PV}	2,150€/kWp	Idem	If 0<P_{tot} <11.5kWp
		2,150€/kWp	2,250€/kWp	If 11.5<P_{tot}<25kWp
		2,100€/kWp	Idem	If 25<P_{tot}<50kWp
		1,900€/kWp	Idem	If 50<P_{tot}<100kWp
		1,600€/kWp	Idem	If 100<P_{tot}<200kWp
		1,400€/kWp	Idem	If 200<P_{tot}<300kWp
		1,300€/kWp	Idem	If P_{tot}>300kWp
	Average unit cost depends on the total power of the installation; values according to 4 Belgian companies. For installations > 11.5kWp, legislation imposes the additional costs of a grid study, a meter, and a decoupling box. For larger installations the unit cost decreases due to economies of scale.			
Insurance cost	$INSC_{PV}$	0.23%/y of I_0PV	Idem	4 Belgian PV companies
Maintenance cost	MC_{PV}	11€/kWp,y	Idem	4 Belgian PV companies
Tradable green certificates	TGC	0€/kWh	0.093€/kWh	(Flemish Energy Agency 2013)
Lifetime TGC	N_{TGC}	0 y	10 y	(Flemish Energy Agency 2013)
Elevated investment deduction	$EID_{\%}$	0% of I_0PV	15.50%	(Flemish Energy Agency 2013)
Grid				
Unit cost electricity	UC_{electr}	0€	Idem	Grid available at the site
Electricity price	P_{electr}	0.093€/kWh	0.095€/kWh	(Eurostat 2012)
Annual evolution electricity price	$\dot{P}_{Electr}$	1.76%/y	Idem	(Eurostat 2012)
Grid powered battery electric vehicle, Nissan Leaf (grid BEV)				
Lifetime	n_{BEV}	5 y	Idem	Lifetime Belgian company car
Unit cost	UC_{grBEV}	29,194€	Idem	for 0<vehicles<5
		28,430€	Idem	for 5<vehicles<50
		27,818€	Idem	for >50 vehicles
	Unit cost(Nissan 2013); discounts according to 2 Belgian Nissan distributors			
Annual price evolution	$\dot{P}_{BEV}$	-5.39%/y	Idem	(EU Coalition - McKinsey 2010; Weiss, Patel et al. 2012)
Fuel use	$Fuse_{BEV}$	0.173kWh/km	Idem	(Nissan 2013)
Electricity price	P_{electr}	0.093€/kWh	0.095	(Eurostat 2012)
Annual evolution electricity price	$\dot{P}_{Electr}$	1.76%/y	Idem	(Eurostat 2012)
Maintenance cost	MaC_{grBEV}	266.4€/veh/y	Idem	2 Belgian Nissan distributors
Vehicle registration tax	T_{oBEV}	0€	Idem	(FOD Financiën 2013)
Price evolution registration tax	$\dot{P}_{ToBEV}$	0%/y	Idem	Geometric mean 2005 - 2012 (FOD Financiën 2013)

Annual traffic tax	T_{nBEV}	0€/y	75.8€/y	(FOD Financiën 2013)
Price evolution traffic tax	$\dot{P}_{TnBEV}$	0%/y	2.31%/ y	Geometric mean 2005 -2012 (FOD Financiën 2013)
Investment deduction	$ID\%_{BEV}$	0%	120%	(Belgisch Staatsblad 2009)
Gasoline powered internal combustion engine vehicle, Nissan Note Tekna 1.6l (ICEV)				
Lifetime	n_{ICEV}	5 y	Idem	Average lifetime of a company car in Belgium
Unit cost	UC_{ICEV}	13,953€ 13,787€ 13,455€	Idem Idem Idem	for 0<vehicles<5 for 5<vehicles<50 for >50 vehicles
	Unit cost(Nissan 2013); quantity reductions according to 2 Belgian Nissan distributors			
Annual price evolution	$\dot{P}_{ICEV}$	-1.45%/y	Idem	Geometric mean from 2005 till 2011 (European Union 2005-2011)
Fuel use	$Fuse_{ICEV}$	6.8l/100 km	Idem	(Nissan 2013)
Gasoline price	P_{gasol}	0.7428€/l	1.33€/l	(Belgische Petroleum Federatie 2013)
Evolution gasoline price	$\dot{P}_{gasol}$	4%/y	Idem	(Belgische Petroleum Federatie 2013)
Maintenance cost	MaC_{ICEV}	888€/veh/y	Idem	2 Belgian Nissan distributors
Vehicle registration tax	T_{oICEV}	0€	123€	(FOD Financiën 2013)
Price evolution registration tax	$\dot{P}_{ToICEV}$	0%/y	Idem	Geometric from 2005 till 2012 (FOD Financiën 2013)
Annual traffic tax	T_{nICEV}	0€/y	263.87€	(FOD Financiën 2013)
Price evolution traffic tax	$\dot{P}_{TnICEV}$	0%/y	2.31%	Geometric mean from 2005 till 2012 (FOD Financiën 2013)
Investment deduction	$ID\%_{ICEV}$	0%	70%	(Belgisch Staatsblad 2009)
Investment deduction gasoline fuel	$ID\%_{fuel}$	0%	75%	(Belgisch Staatsblad 2009)
Solar powered battery electric vehicle, Nissan LEAF (solar BEV)				
Lifetime	n_{BEV}	5 y	Idem	Average lifetime of a company car in Belgium
Unit cost	UC_{solBEV}	33,476 – 36,276€ 32,712 - 35,512€ 32,100 – 34,900€	<36,606€ <35,842€ <35,230€	for 0<veh<5 for 5<veh<50 for >50 vehicles
	In function of PV size; Unit cost (Nissan 2013); quantity reductions according to 2 Belgian Nissan distributors; cost PV according to 4 Belgian companies			
Annual price evolution	$\dot{P}_{BEV}$	-5.39%/y	Idem	(EU Coalition - McKinsey 2010; Weiss, Patel et al. 2012)
Fuel use	$Fuse_{BEV}$	0.173kWh/km	Idem	(Nissan 2013)
Solar power	$Psol_{BEV}$	3.29kWp	Idem	Solar power needed to power the BEV over lifetime
Tradable green	TGC	0€/kWh	0.093€/kWh	(Flemish Energy Agency 2013)
Lifetime TGC	n_{TGC}	0 y	10 y	(Flemish Energy Agency 2013)
Maintenance cost	MaC_{solBEV}	318.55€/veh/y	Idem	2 Belgian Nissan distributors and 4 Belgian PV companies
Vehicle registration tax	T_{oBEV}	0€	Idem	(FOD Financiën 2013)
Price evolution registration tax	$\dot{P}_{ToBEV}$	0%/y	Idem	Geometric from 2005 till 2012 (FOD Financiën 2013)
Annual traffic tax	T_{nBEV}	0€/y	75.77€/y	(FOD Financiën 2013)
Price evolution traffic tax	$\dot{P}_{TnBEV}$	0%/y	2.31%/y	Geometric mean from 2005 till 2012 (FOD Financiën 2013)
Investment deduction	$ID\%_{BEV}$	0%	120%	(Belgisch Staatsblad 2009)

Table 26 Numerical values of the economic LCC (€) and environmental LCE (ton CO_2eq) coefficients in the MOMILP and the MOLP model

			Including policy			Excluding policy		
Techn *(i)*	Type *(j)*	Interval *(k)*	Econ. LCC(c^1_{ijk})	Econ. IC ($c^{1'}_{ijk}$)	Env. LCE (c^2_{ijk})	Econ. LCC (c^1_{ijk})	Econ. IC ($c^{1'}_{ijk}$)	Env. LCE (c^2_{ijk})
Multi-objective mixed integer linear programming (MOMILP)								
i = 1	*j* = 0	*k* = 1	224,592.31	0.00	1,089.00	220,079.66	0	1,089.00
i = 1	*j* = 1	*k* = 1	269,593.89	346,036.63	191.10	450,785.26	409,510.81	191.10
i = 1	*j* = 1	*k* = 2	286,303.98	362,131.36	191.10	450,785.26	409,510.81	191.10
i = 1	*j* = 1	*k* = 3	261,268.84	337,989.27	191.10	440,964.07	399,987.30	191.10
i = 1	*j* = 1	*k* = 4	227,888.66	305,799.82	191.10	401,679.31	361,893.27	191.10
i = 1	*j* = 1	*k* = 5	177,818.37	257,515.63	191.10	342,752.16	304,752.23	191.10
i = 1	*j* = 1	*k* = 6	144,438.18	225,326.18	191.10	303,467.40	266,658.20	191.10
i = 1	*j* = 1	*k* = 7	127,748.09	209,231.45	191.10	283,825.02	247,611.19	191.10
i = 2	*j* = 0	*k* = 1	495,097.43	237,668.85	909.53	524,958.18	311,872.73	909.53
i = 2	*j* = 0	*k* = 2	492,268.02	234,839.44	909.53	521,245.32	308,159.87	909.53
i = 2	*j* = 0	*k* = 3	486,609.24	229,180.66	909.53	513,819.84	300,734.39	909.53
i = 2	*j* = 1	*k* = 1	357,822.42	311,584.33	332.76	585,633.37	526,218.21	332.76
i = 2	*j* = 1	*k* = 2	349,665.76	303,427.67	332.76	571,858.02	512.442.86	332.76
i = 2	*j* = 1	*k* = 3	343,140.44	296,902.34	332.76	560,837.75	501,422.59	332.76
i = 2	*j* = 2	*k* = 1	390,013.07	366,928.81	182.08	610,526.40	581,562.70	182.08
i = 2	*j* = 2	*k* = 2	381,856.41	358,772.16	182.08	596,751.05	567,787.35	182.08
i = 2	*j* = 2	*k* = 3	375,331.08	352,246.83	182.08	585,730.78	556,767.07	182.08
Multi-objective linear programming (MOLP)								
i = 1	*j* = 0	*k* = 1	224,592.31	0.00	1,089.00	220,079.66	0	1,089.00
i = 1	*j* = 1	*k* = 4	227,888.66	305,799.82	191.10	401,679.31	361,893.27	191.10
i = 2	*j* = 0	*k* = 2	492,268.02	234,839.44	909.53	521,245.32	308,159.87	909.53
i = 2	*j* = 1	*k* = 2	349,665.76	303,427.67	332.76	571,858.02	512.442.86	332.76
i = 2	*j* = 2	*k* = 2	381,856.41	358,772.16	182.08	596,751.05	567,787.35	182.08

6.4.2 Sensitivity analysis

To determine the sensitivity of the economic model coefficients, a Monte Carlo sensitivity analysis is conducted in which we vary the input data assuming a minimum (maximum) deviation of -10% (+10%) of the assumed parameter values in Table 25. Results are presented in Table 27. The first three lines indicate the base case, the minimum and the maximum value obtained after varying all the input parameters. The last three lines give the sensitivity with respect to the three most influencing model parameters. Note that a positive (negative) sign indicates that the LCC will increase (decrease) with an increase of the respective parameter. The absolute value indicates the percentage of the spread in the life cycle cost that is due to a variation of $\pm10\%$ of the assumed parameter value. The most important parameter to determine the LCC of the grid electricity is the unit cost of electricity *(UC_{electr})* to be paid by the company. We find three parameters with a large influence on the LCC of solar PV, *i.e.* the amount of solar radiation *(β),* the unit cost of the installation *(UC_{PV})*, and the tradable green certificates *(TGC)*. The LCC of the internal combustion engine vehicles is largely determined by the unit cost of the vehicles *(UC_{ICEV})*, the fuel use of the vehicles *($Fuse_{ICEV}$)*, and the gasoline price *(P_{gasol})*. We find two parameters that are large influencers of the LCC of the BEVs, being the unit cost *(UC_{BEV})* and the investment deduction of the vehicles *($ID\%_{BEV}$)*. In conclusion, we see that for both the energy technologies and the vehicles, the initial purchase price is a large influencer of the total life cycle costs and the inclusion of cost intervals is hence recommended.

Table 27 Monte Carlo sensitivity analysis of the life cycle cost LCC model coefficients (in €)

	LCC grid (c^1_{101})		LCC PV (c^1_{114})		LCC ICEV (c^1_{202})		LCC grBEV (c^1_{212})		LCC solBEV (c^1_{222})	
Base case	224,592.31		227,888.66		492,268.02		349,665.76		381,856.41	
Minimum	194,872.07		156,510.60		429,635.56		291,749.67		337,897.67	
Maximum	256,920.39		303,820.35		549,818.08		400,684.59		452,237.50	
Sensitivity with respect to	UC_{elect}	87.2%	β	-50.5%	UC_{ICEV}	43.4%	UC_{grBEV}	62.0%	UC_{solBEV}	65.2%
	r	-11.0%	UC_{PV}	42.2%	$Fuse_{ICEV}$	19.3%	$ID\%_{BEV}$	-32.9%	$ID\%_{BEV}$	-29.3%
	$\dot{P}_{electr}$	1.8%	TGC	-5.4%	P_{gasol}	19.2%	$\dot{P}_{ToBEV}$	4.2%	$\dot{P}_{ToBEV}$	4.3%

6.4.2.1 Constraints

Following the model from Section 6.2, we can establish the link between *(i)* grid electricity and grid powered battery electric vehicles (BEVs) and *(ii)* solar PV electricity and solar powered BEVs as follows:

$\sum_{k\in Interval_{1,0}} x_{10k} = x_{10} + e_{grid} x_{21}$ Relation grid electricity – grid BEV

$\sum_{k\in Interval_{1,1}} x_{11k} = x_{11} + e_{PV} x_{22}$ Relation PV electricity – solar BEV

The existence of economies of scale for vehicles implies the following constraint:

$\sum_{k\in Interval_{2,j}} x_{2jk} = x_{2j} \ \forall\, j = 0, \dots, 2$ Economies of scale for vehicles

Considering economies of scale, intervals for the according technologies are established as follows:

$\sum_{k\,\in\, Interval_{i,j}} y_{ijk} = 1$ Exactly 1 interval active for technology *i,j*

$lb_{ijk}y_{ijk} \leq x_{ijk} \leq ub_{ijk}y_{ijk} \; \forall \, i,j; \; k \in Interval_{ij}$ Interval bounds for technology *i,j*

Finally, due to normalization, we express the demand constraints the following way:

$x_{10} + x_{11} = 1$ Electricity demand

$x_{20} + x_{21} + x_{22} = 1$ Transportation demand

6.4.3 Results and discussion

We start with a discussion of the results that are obtained using multi-objective mixed integer linear programming (MOMILP). Figures 19 and 20 respectively show the Pareto frontier when minimizing the total economic life cycle cost and the required investment, while satisfying the constraints on electricity & transportation demand. The according numerical values of the optimal solutions can be found in the upper part of Tables 28 and 29, *i.e.* the life cycle costs *(LCC)* and the required investment *(IC) in k€*, the life cycle emissions *(LCE) in ton* CO_2eq, the percentage change compared to the economic lexicographic optima *(%ΔLCC, %ΔIC, %ΔLCE)*, the proportion of electricity demand to be supplied by the grid *(%grid)* and by solar photovoltaics *(%PV*), and the proportion of transportation demand to be met by internal combustion engine vehicles *(%ICEV)*, by grid powered battery electric vehicles *(%gridBEV)* and by solar powered battery electric vehicles *(%solarBEV)*. A distinction is made between the optimal solutions for the SME including policy measures and the optima excluding the impact of policy. Assuming rational decisions based on the full life cycle cost (LCC) and assuming the impact of current policy (Figure 19 bottom left), there is only one optimal solution (*G*) for the SME: the current electricity demand is fulfilled completely by means of solar PV, and transportation demand is met for 100% with solar BEVs. This solution is optimal from economic and environmental perspective. However, when the impact of policy is excluded (Figure 19 upper right), we see clearly that the use of environmentally beneficial technologies implies a trade-off with the economic performance. When solely optimizing the economic objective (independently of the environmental objective), we find the economic lexicographic optimum; solution *A*. Here, demands are met entirely with grid electricity and ICEVs, implying a life cycle cost of 741.33k€ and life cycle emissions of 1,998.53ton CO_2eq. When tolerating a slight increase of the LCC with 3.21%-8.69%, the ICEVs can be gradually replaced by grid powered BEVs, implying an emission decrease with 10.68-31.56% respectively (B_1-B_2). If the LCC is allowed to increase with 10.62-13.26%, the grid BEVs will be partially accompanied with solar PV electricity, leading to emission reductions up to 40.65% (D_1-D_2). With a further increase of the LCC (14.95%-19.63%), solar panels can be used to satisfy electricity demands and solar BEVs are used for transport, leading to a maximal reduction of emissions of 80% (F_1-F_2).

If, due to bounded rationality, the SME would base its decision on the initial investment rather than on the full life cycle cost, there are plural optimal solutions (Figure 20, Table 29). If we exclude policy measures, we note that the lexicographic optima H and K_2 respectively correspond to the previously discussed lexicographic optima A and F_2. However, a large increase in required investment (26.18%-52.41%) has to be tolerated to decrease emissions by means of grid powered electric vehicles. Moreover, the grid BEVs will serve to meet no more than 78.68% of transportation demand (I_1-I_2). With a further increase of the initial investment (52.41%-98.89%), solar PV electricity is used in combination with ICEVs (J_1-J_2). Only if the required investment is allowed to increase with more than 116%, solar BEVs are used in combination with solar PV electricity (K_1-K_2). If the impact of policy is included, transportation needs are met completely with solar BEVs (L, M_1-M_2). The uptake of solar PV panels to meet electricity demand however implies an increase in the required investment of maximally 119.36%, allowing an emission reduction of 75.25% (M_1-M_2). Hence, policy measures do not necessarily push bounded rational investors towards the environmental optimum.

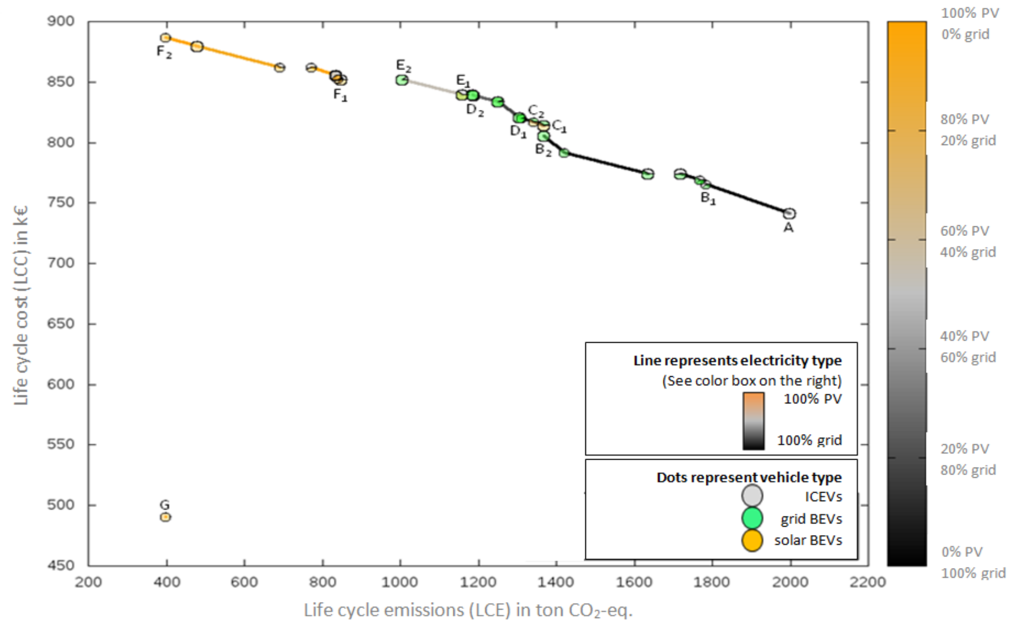

Figure 19 Pareto optimal solutions when simultaneously minimizing LCE and LCC. Upper right: excluding policy impact–Bottom left: including policy impact

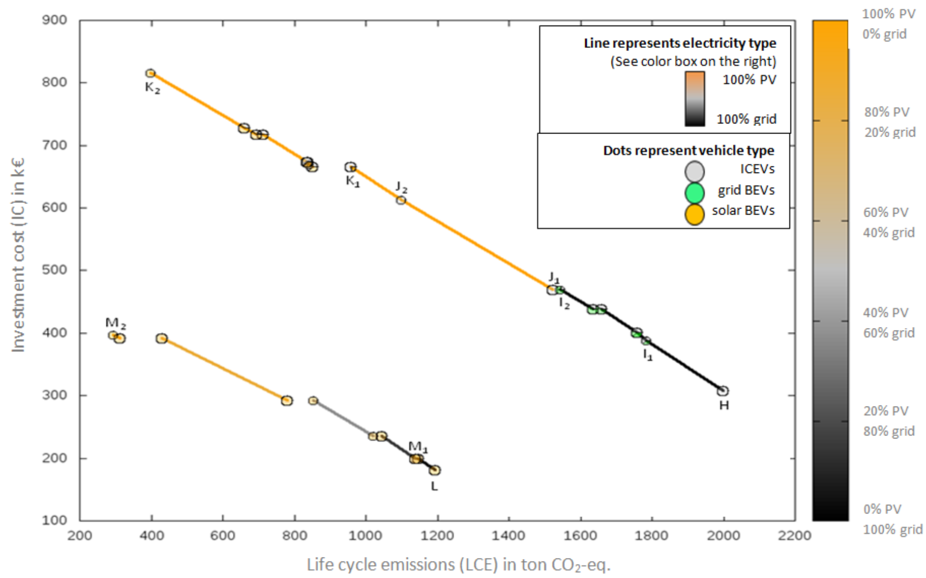

Figure 20 Pareto optimal solutions when simultaneously minimizing LCE and IC. Upper right: excluding policy impact – Bottom left: including policy impact

In the introduction, we discussed the need of incorporating economies of scale into the analysis, an inherent discrete phenomenon that implies the use of mixed integer programming. If on the contrary we would assume an average cost interval for all technologies, we could solve the problem using multi-objective linear programming. Compared to mixed integer programming, this has the advantage of being easier to solve, both in terms of computation times and complexity. For purposes of comparison we have included the optimal solutions using MOLP in our analysis. Results are presented in Figure 21, numerical values of the solutions can be found in the lower part of Tables 28 and 29. This clearly shows the interest of taking economies of scale (using MOMILP) into account. We see that MOLP can give either optimistic or pessimistic results compared to the MOMILP, the latter being much more accurate. Moreover, while we can conclude from the MOMILP analysis that policy measures effectively push rational investors towards one solution (solution G) that is optimal from economic and environmental viewpoint, the MOLP erroneously indicates that the use of grid electricity and grid BEVs (solution *e*) is also part of the efficient solution set. One could argue that it all depends on the value of the "average" coefficients chosen, but in reality this is not the main point of focus. Due to the fact that MOLPs have continuous and strictly convex solution sets, they can’t provide efficient solution sets that accurately follow the non-continuous solution sets of MOMILPs. Moreover, as we provide more and more realistic input data into the MOMILP, it is clear that this will provide us more precise solution sets.

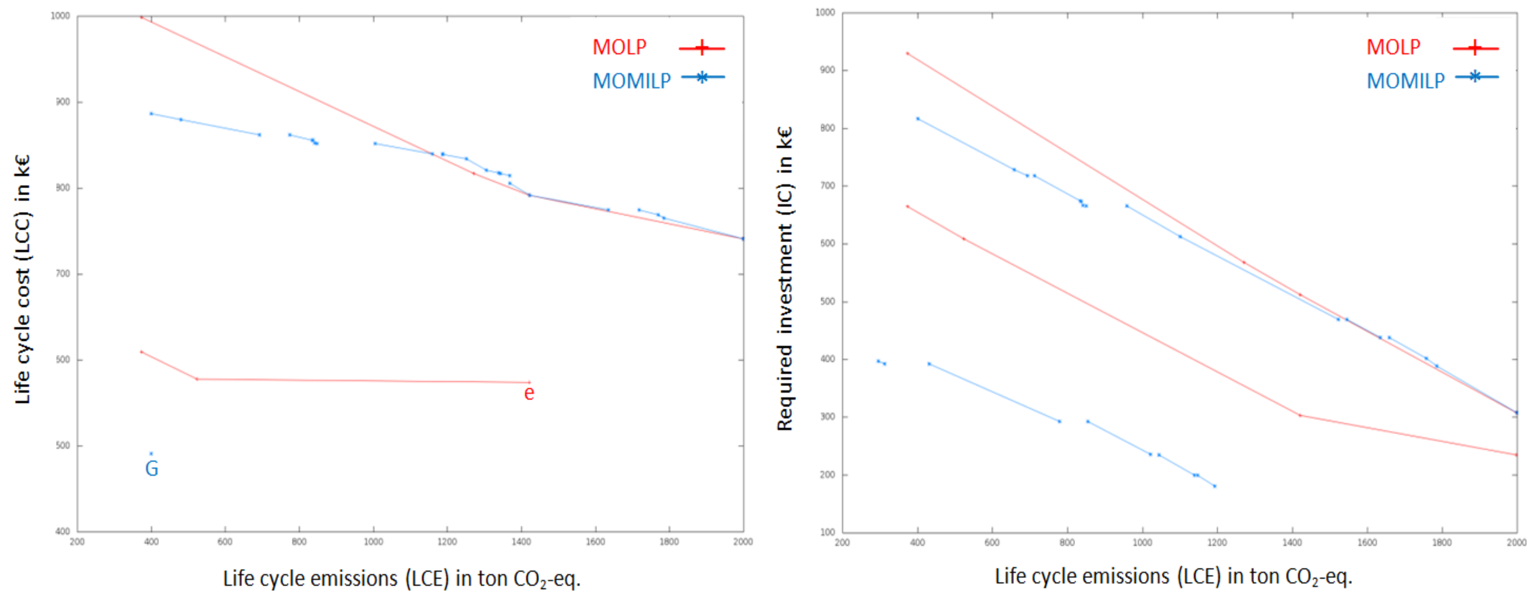

Figure 21 Pareto optimal solutions of multi-objective linear programming (MOLP) versus multi-objective mixed integer linear programming (MOMILP)

Table 28 Pareto optimal solutions when minimizing life cycle costs LCC (in k€) and life cycle emissions LCE (in ton CO_2eq)

Solution	LCC	%ΔLCC$_A$	LCE	%ΔLCE$_A$	%grid	%PV	%ICEV	%gridBEV	%solarBEV
Multi-objective mixed integer linear programming (MOMILP)									
Excluding policy measures									
A	741.33		1998.53		100.00%	0.00%	100.00%	0.00%	0.00%
B_1	765.15	3.21%	1785.13	-10.68%	100.00%	0.00%	63.00%	37.00%	0.00%
	769.11	3.75%	1769.71	-11.45%	97.63%	2.37%	63.00%	37.00%	0.00%
	769.11	3.75%	1769.71	-11.45%	100.00%	0.00%	39.67%	60.33%	0.00%
	774.59	4.49%	1717.66	-14.05%	100.00%	0.00%	51.30%	48.70%	0.00%
	774.59	4.49%	1635.16	-18.18%	100.00%	0.00%	37.00%	63.00%	0.00%
	791.94	6.83%	1421.76	-28.86%	100.00%	0.00%	0.00%	100.00%	0.00%
B_2	805.78	8.69%	1367.89	-31.56%	94.00%	6.00%	0.00%	100.00%	0.00%
C_1	814.58	9.88%	1367.89	-31.56%	100.00%	0.00%	4.23%	32.77%	63.00%
C_2	817.15	10.23%	1343.49	-32.78%	100.00%	0.00%	0.00%	37.00%	63.00%
D_1	820.06	10.62%	1312.30	-34.34%	93.19%	6.81%	0.00%	100.00%	0.00%
	820.06	10.62%	1312.30	-34.34%	87.00%	13.00%	9.64%	90.36%	0.00%
	820.65	10.70%	1305.03	-34.70%	87.00%	13.00%	0.00%	100.00%	0.00%
	834.11	12.52%	1250.33	-37.44%	80.09%	19.91%	0.00%	100.00%	0.00%
	834.11	12.52%	1250.33	-37.44%	74.00%	26.00%	6.53%	93.47%	0.00%
	839.15	13.20%	1188.31	-40.54%	74.00%	26.00%	0.00%	100.00%	0.00%
D_2	839.60	13.26%	1186.09	-40.65%	73.75%	26.25%	0.00%	100.00%	0.00%
E_1	839.60	13.26%	1159.28	-41.99%	55.72%	44.28%	37.00%	0.00%	63.00%
	839.60	13.26%	1159.28	-41.99%	47.00%	53.00%	37.00%	63.00%	0.00%
E_2	852.15	14.95%	1004.96	-49.72%	47.00%	53.00%	10.24%	89.76%	0.00%
F_1	852.15	14.95%	847.31	-57.60%	0.00%	100.00%	63.86%	0.00%	36.14%
	852.81	15.04%	841.26	-57.91%	0.00%	100.00%	63.00%	0.00%	37.00%
	855.65	15.42%	836.56	-58.14%	0.26%	99.74%	62.00%	0.00%	38.00%
	855.65	15.42%	836.56	-58.14%	0.00%	100.00%	62.00%	1.86%	36.14%
	855.87	15.45%	834.25	-58.26%	0.00%	100.00%	62.00%	0.00%	38.00%
	862.14	16.30%	773.33	-61.31%	0.00%	100.00%	53.31%	0.00%	46.69%
	862.14	16.30%	692.37	-65.36%	3.72%	96.28%	37.00%	0.00%	63.00%
	879.50	18.64%	478.97	-76.03%	8.84%	91.16%	0.00%	0.00%	100.00%
F_2	886.86	19.63%	399.62	-80.00%	0.00%	100.00%	0.00%	0.00%	100.00%
Including policy measures									
G	490.94		399.62		0.00%	100.00%	0.00%	0.00%	100.00%
Multi-objective linear programming (MOLP)									
Excluding policy measures									
a	741.32		1998.53		0.00%	100.00%	0.00%	0.00%	100.00%
b	791.94	6.83%	1421.76	-28.86%	100%	0%	0%	100%	0%
c	816.83	10.19%	1271.09	-36.40%	100%	0%	0%	0%	100%
d	998.43	34.68%	373.33	-81.32%	0%	100%	0%	0%	100%
Including policy measures									
e	574.26		1421.76		100%	0%	0%	100%	0%
f	577.55	0.57%	523.09	-63.21%	0%	100%	0%	100%	0%
g	609.74	6.18%	373.33	-73.74%	0%	100%	0%	0%	100%

Table 29 Pareto optimal solutions when minimizing required investment IC (in k€) and life cycle emissions LCE (in ton CO_2eq)

Solution	IC	%ΔIC_H	LCE	%ΔLCE_H	%grid	%PV	%ICEV	%gridBEV	%solarBEV
Multi-objective mixed integer linear programming (MOMILP)									
Excluding policy measures									
H (=A)	308.16	0.00%	1998.53	0.00%	100.00%	0.00%	100.00%	0.00%	0.00%
I_1	388.84	26.18%	1785.13	-10.68%	100.00%	0.00%	63.00%	37.00%	0.00%
	401.48	30.28%	1757.43	-12.06%	97.08%	2.92%	63.00%	37.00%	0.00%
	401.48	30.28%	1757.43	-12.06%	100.00%	0.00%	41.80%	58.20%	0.00%
	438.23	42.21%	1658.52	-17.01%	100.00%	0.00%	38.57%	61.43%	0.00%
	438.23	42.21%	1635.16	-18.18%	100.00%	0.00%	37.00%	63.00%	0.00%
I_2	469.68	52.41%	1544.74	-22.71%	100.00%	0.00%	21.32%	78.68%	0.00%
J_1	469.68	52.41%	1522.64	-23.81%	47.00%	53.00%	100.00%	0.00%	0.00%
J_2	612.91	98.89%	1100.63	-44.93%	0.00%	100.00%	100.00%	0.00%	0.00%
K_1	666.03	116.13%	957.88	-52.07%	0.00%	100.00%	79.63%	0.00%	20.37%
	666.03	116.13%	850.38	-57.45%	0.00%	100.00%	64.29%	0.00%	35.71%
	669.31	117.20%	841.37	-57.90%	0.00%	100.00%	63.00%	0.00%	37.00%
	673.32	118.50%	837.20	-58.11%	0.00%	100.00%	62.00%	2.29%	35.71%
	674.17	118.77%	834.37	-58.25%	0.00%	100.00%	62.00%	0.00%	38.00%
	718.22	133.07%	711.71	-64.39%	0.00%	100.00%	44.50%	0.00%	55.50%
	718.22	133.07%	693.49	-65.30%	3.82%	96.18%	37.00%	0.00%	63.00%
	728.41	136.37%	659.19	-67.02%	0.00%	100.00%	37.00%	0.00%	63.00%
K_2 (=F_2)	816.43	164.94%	399.62	-79.99%	0.00%	100.00%	0.00%	0.00%	100.00%
Including policy measures									
L	180.85		1193.26		100.00%	0.00%	0.00%	0.00%	100.00%
M_1	199.73	10.44%	1146.43	-3.92%	94.78%	5.22%	0.00%	0.00%	100.00%
	199.73	10.44%	1138.65	-4.58%	93.92%	6.08%	0.00%	0.00%	100.00%
	235.30	30.11%	1044.16	-12.50%	83.39%	16.61%	0.00%	0.00%	100.00%
	235.30	30.11%	1021.93	-14.36%	80.92%	19.08%	0.00%	0.00%	100.00%
	292.28	61.62%	854.63	-28.38%	62.29%	37.71%	0.00%	0.00%	100.00%
	292.28	61.62%	779.49	-34.68%	53.92%	46.08%	0.00%	0.00%	100.00%
	392.39	116.97%	430.43	-63.93%	15.04%	84.96%	0.00%	0.00%	100.00%
	392.39	116.97%	312.59	-73.80%	1.92%	98.08%	0.00%	0.00%	100.00%
M_2	396.71	119.36%	295.36	-75.25%	0.00%	100.00%	0.00%	0.00%	100.00%
Multi-objective linear programming (MOLP)									
Excluding policy measures									
h	234.84		1998.53		100%	0%	100%	0%	0%
i	303.43	29.21%	1421.76	-28.86%	100%	0%	0%	100%	0%
j	609.23	159.42%	523.09	-73.83%	100%	0%	0%	0%	100%
k	664.57	182.99%	373.33	-81.32%	0%	100%	0%	0%	100%
Including policy measures									
l	308.16		1998.53		100%	0%	100%	0%	0%
m	512.44	66.29%	1421.76	-28.86%	100%	0%	0%	100%	0%
n	567.79	84.25%	1271.09	-36.40%	100%	0%	0%	0%	100%
o	929.68	201.69%	373.33	-81.32%	0%	100%	0%	0%	100%

When dealing with energy systems, an important aspect to consider is variability. This is of special importance when renewable energy sources such as solar PV are employed. In this research however, we focus on economic costs and environmental emissions rather than on technical aspects. Hence, we assumed a simplified average annual demand and supply of electricity. Inclusion of daily or hourly electricity demand and supply data (considering peak versus off-peak periods) and inclusion of a third objective related to load management (considering grid-to-vehicle and vehicle-to-grid concepts (Loisel, Pasaoglu et al. 2014) are interesting topics for further research. Moreover, Steinhilber et al. (2013) point out that the full environmental potential of electric vehicles will only be realized if they are not simply used to substitute ICEVs, but also as a tool for load management in the electricity grid. Further, we note that even though grid powered battery electric vehicles are found to be the least costly option to decrease greenhouse gas emissions, the uptake of this technology is negligible in Belgium, with a total of 562 new electrified vehicles compared to 145,640 petrol vehicles in 2012 (FOD mobiliteit en transport - FEBIAC 2013). Hence, in addition to the subsidization of electric vehicles to overcome higher purchase prices, policy should continue stimulating technological development to address other inconveniences such as limited driving ranges and long charging times.

6.5 Conclusions and policy implications

This research proposes the use of multi-objective optimization from economic and environmental viewpoint to find the optimal mixture of energy and transportation technologies, given required energy and transport demands. To obtain realistic results, economies of scale are taken into account. This inherently discrete phenomenon implies the use of mixed integer programming. While the use of continuous multi-objective linear programming (MOLP) is easier to solve than multi-objective mixed integer linear programming (MOMILP) in terms of complexity and computation times, we demonstrate that MOLP is unable to provide the correct results that include the cost intervals or economies of scale for the different technologies. This research is the first to apply the improved version of the only algorithm available to solve MOMILPs exactly (Vincent, Seipp et al. 2013). Other attempts found in literature provide no more than an approximation of the optimal solution frontier. A comparison is made between complete rationality -*i.e.* minimizing economic life cycle costs- and bounded rationality- *i.e.* minimizing solely the required investment. To distinguish between the optima with and without subsidies, the impact of policy measures on the Pareto frontier is assessed. The approach is illustrated with a Belgian SME that seeks to find the optimal combination of technologies to satisfy electricity and transportation demands, while minimizing environmental emissions and economic costs. Technologies at hand are solar PV and grid electricity to cover electricity needs, and internal combustion engine vehicles (ICEVs), grid powered battery electric vehicles (BEVs) and solar powered BEVs to cover transportation requirements. The Pareto frontiers clearly illustrate a tradeoff between economic and environmental performances. Results demonstrate that at the time of writing, electricity from solar panels is still more expensive than purchasing electricity from the grid in the absence of energy policies. Likewise, the use of battery electric vehicles is still more costly than the use of petrol fueled internal combustion engine vehicles. It is demonstrated that the impact of grid powered battery electric vehicles to reduce greenhouse gas emissions is limited, yet they are less costly then solar panels to decrease emissions. When battery electric vehicles are powered with electricity generated from solar panels rather than with electricity from the Belgian grid, the environmental performance is largely improved, albeit at a higher economic cost.

Using MOMILP, current policy is found to be targeting rational investors who consider full life cycle costs. Moreover, under the current policy rational investors are pushed towards one single environmental optimum, which implies the use of solar panels for electricity generation and the use of solar powered battery electric vehicles for transportation. However, assuming that a bounded rational investor solely takes into consideration the initial required investment (for instance a private investor who manages a budget for one year only), the environmental optimum is not necessarily achieved. It is therefore important that policy makers point to the importance of considering life cycle costs. To this end, they could match the financial support for a PV installation with the support needed to make that installation breakeven (rather than providing one single certificate price and elevated investment deduction percentage for all installations). One of the major drawbacks of the current Belgian policy to stimulate the uptake of BEVs relates to the subsidization of the higher initial purchase price of the vehicles. Moreover, under current regulation an investment deduction of 120% for the vehicles is granted. Whilst this represents a large financial incentive, we note that only companies (rather than individuals) can profit from this measure. Further, besides the focus on the high purchase price of the vehicles, policy should stimulate technological development to overcome major drawbacks such as limited driving ranges and long charging times. Note that implementation of solar power and electric vehicles in this case can reduce greenhouse gas emissions with maximally 80%; the remaining 20% is due to the production of the vehicles and the solar panels and is hence unavoidable. This aspect should not be overlooked when assessing the technologies' climate change mitigation potential.

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7 Conclusions

7.1 Research questions

Solar photovoltaics (PV), which captures solar energy and converts it directly to electricity, has been on the market for more than 35 years. With a very low carbon footprint, the use of solar PV technologies provides significant environmental benefits compared to traditional fossil-fuel technologies. Hence, a wide range of governmental policies have been developed to stimulate growth in the photovoltaic sector. The occurrence of grid parity however, *i.e.* the moment when the cost of generating electricity with solar PV is equal to or lower than the cost of purchasing electricity from the grid, goes hand in hand with the phasing out of policy measures in Europe. We see throughout the chapters of this dissertation that the unit costs of solar PV panels have dropped significantly over the last years, from €3.1/MWp in the beginning of 2012 (Table 9) to €2.3/MWp in June 2012 (Table 12), 2.15€/MWp in 2013 (Table 25), and €1.1/MWp in 2014 (Table 11). Following this drop in unit costs, the subsidies for solar panels in Flanders have steadily been decreasing, from 0.33€/kWh in the beginning of 2012 (Table 9) to 0.23€/kWh in June 2012 (Table 12), 0.093€/kWh in 2013 (Table 25), and eventually zero subsidies at the time of writing in 2014 (Table 11). Indeed, dedicated financial support as the main driver for PV development is progressively vanishing. In the coming years, deployment strategies will depend much more on the capacity of PV power to actively participate in the electricity system. One way to enhance the integration of solar PV systems is by fusing them with other technologies. Technology fusion refers to the blending of several previously separate fields of existing technology, creating novel markets and growth opportunities. In the case of fusing solar PV with alternative technologies, greenhouse gas emission reductions and other advantages such as the savings of scarce land area, grid independency, diminishment of the effect of power variability of intermittent clean energy sources, and increased system performances can be established. These social and technical advantages however often come at increased economic costs, implying a barrier for wide-scale implementation. Moreover, any rational investor will only invest in a combination of technologies if this is economically profitable. Furthermore, the policy makers' major concern is the technologies' cost-efficiency to decrease polluting emissions. Hence, there is a strong need for private investors as well as for policy makers to evaluate economic and environmental performances of combined technologies. This dissertation answers the main research question:

How can the economic and environmental performances of solar PV combined with alternative technologies be evaluated to support decision making?

This research question is operationalized by answering the subquestions in section 7.1.1-7.1.5.

7.1.1 How can economic and environmental costs and benefits of combined technologies be integrated into one monetary measure?

Economic and environmental performances of combined technologies can be integrated into a single monetary measure if external environmental aspects are quantified in monetary terms or hence monetized. Such a technology assessment can be conducted by using an environmental cost benefit analysis (CBA). This approach is demonstrated in Chapter 2, in which economic and environmental performances of a photovoltaic noise barrier (PVNB) are combined into monetary measures. Moreover, the twofold environmental benefits of this combined technology, *i.e.* noise and emission reduction, are evaluated in terms of economic profits. The benefit of emission reduction is negligible in monetary terms. The benefit of noise reduction however indicates that, due to an increase in housing and lot prices thanks to the established noise reduction, the PVNB is a profitable investment for the society. We note that the valuation of environmental aspects, either by using stated or revealed preference valuation techniques, is case-specific and subject to lots of criticism due to the high subjectivity of the matter. A possible way to overcome this issue is addressed in Section 7.1.3. Further, we note that the environmental CBA fails to compare the profitability of different projects under budgetary constraints. This problem of rationing capital amongst competing investment opportunities is tackled in

Section 7.1.2. Nonetheless, the monetization of environmental aspects provides a clear-cut basis to support decision making. In our case choices will have to be made on "optimal" locations to install noise barriers, *i.e.* locations where residents suffer the most from noise pollution. By applying the noise sensitivity depreciation index to surrounding properties, these optimal locations can be determined. The best way to capture the full potential of the combined technology, *i.e.* to include solar panels that generate clean electricity without requiring additional space, is to establish a public – private partnership in which a private party is attracted to invest in the solar panels.

7.1.2 How can the profitability of combined technologies be assessed, given the constraint of a limited investment resource?

Whether fusing solar PV with alternative technologies comes at increased economic costs is an essential issue for wide-scale implementation. Despite the existence of rationing capital models, a systematic method to calculate the joint payoff of a random combination of technologies is missing in literature. In Chapter 3, research is presented that is the first to provide a method to calculate and compare the economic payoff of individual complementary technologies with the payoff of their integrated combination, under budgetary limits. If the profitability of the combined technology exceeds that of the individual technologies, economic synergies or benefits of combined technologies (BOCT) are said to be present. The developed model exemplifies an ex ante CBA developed for business and non-governmental use. It is a partial equilibrium model that focuses on the equilibrium point of an investor, maximizing the investor's payoff subject to a given set of economic constraints. The method is illustrated with a case of solar PV and battery electric vehicles (BEVs). BOCT are calculated in function of the electricity price. It is found that for low electricity prices (<€0.12/kWh) it is most profitable to invest in BEVs that can be charged with low cost electricity. When the price of electricity rises (>€0.13/kWh) investment in exclusively PV becomes most attractive, due to a higher avoided cost of electricity. In all other cases, it is more profitable to invest in the combination of both technologies. The model is applicable to perform an economic evaluation of any combination of complementary technologies, yet the existence of BOCT is not guaranteed. Analogously to economies of scope, the existence of BOCT has to be verified for each combination of complementary technologies. The presence of BOCT depends on the policy measures provided for each technology, on the characteristics of the technology itself, and on the market conditions that may cause nonlinearities when combining technologies. Apart from the presence of BOCT, it is not clear to what extent the combined technology impacts emission reduction. To this end, the environmental life cycle impact should be assessed. These results need to be evaluated simultaneously with the results of the economic computational model. This is elaborated upon in subquestion 7.1.4.

7.1.3 How can economic and environmental performances of combined technologies be integrated into one measure without monetizing the environmental impacts?

While integrating environmental performances into one monetary measure is a relatively straightforward way to support decision making, opponents argue that the result of monetization is highly dependent on the valuation approach and that it is improper to express environmental externalities in monetary terms. Recognizing these drawbacks, we propose in this doctoral thesis to assess combined technologies using a mitigation cost assessment. Such an assessment allows evaluating the technologies' cost-efficiency to decrease polluting emissions, while disregarding the aspect of monetization. In Chapter 4, we elaborate upon the traditional mitigation cost assessment by developing a framework that enables the comparison of the mitigation cost of individual and combined technologies, given the constraint of a limited capital for investment. To this end, the economic performances (evaluated using the computational model developed in Chapter 3) and the environmental performances (evaluated using a life cycle assessment conducted with the software SimaPro®) are calculated and integrated for each technology, considering an equal functional unit for each analysis. The framework is illustrated with a case of PV solar power, grid powered battery electric vehicles (BEVs), and solar powered BEVs for a Belgian, medium sized enterprise. In terms of cost-efficient emission reduction, the company gains more by replacing petrol fueled vehicles with grid powered BEVs than with installing solar panels. Moreover, the mitigation cost of BEVs is found to be negative, meaning that the alternative is an economic option regardless of any emission reduction or hence, reducing greenhouse gases by replacing ICEVs with BEVs leads to an economic gain. We note however that the price of the BEV considered (the Nissan LEAF) is substantially lower than the price of an “average” BEV, due to the fact that the former are mass produced. This draws the attention to the importance of economies of scale, *i.e.* cost advantages that are obtained with increasing scale. This concept is considered in more detail in subquestion 7.1.5.

7.1.4 How can the integrated assessment of economic and environmental performances of combined technologies be used to evaluate the impact of policy and to develop policy recommendations accordingly?

Aiming to mitigate climate change, the reduction of greenhouse gas emissions in a cost-efficient manner is a major concern for policy makers. Accordingly, a wide range of policy measures -including feed in tariffs, tradable green certificates, CO_2 pricing and investment deductions- have been developed to stimulate wide-scale implementation of clean technologies. Emerging technologies with a high potential for emission reduction often require subsidization in their early stages, aiming to reward “early adopters” who pave the way for broader adoption, which in turn can lead to mass production and cost reductions. Excessive subsidization throughout the mature stages of these technologies however is untenable in the long term, often leading to a poor reputation of the technology and to excruciating high costs for society. The latter is exactly what happened to the Belgian solar PV industry in 2011: Even though grid parity was reached, the use of solar panels was still generously subsidized by disproportionately high priced tradable green certificates, leading to a negative public opinion. This was answered with repetitive, drastic subsidy reductions, which -in combination with other phenomena such as a large oversupply of the panels- eventually lead to a collapse of the solar PV market. This points to the importance of a sound, long-term incentive scheme, ensuring a safe and stable environment for investors. Such an environment can be created by timely evaluating the impact of policy measures -considering economic and environmental objectives- and by implementing policies accordingly. This dissertation proposes two methods to fill this gap, which are both applicable to combined technologies.

A first way is to calculate the greenhouse gas mitigation cost to support decision making. The GHG mitigation cost allows ranking technologies in order of increasing cost of emission abatement. Policy makers can make use of the mitigation cost to determine how much abatement can be achieved at a certain economic cost and to assess where policy intervention is needed in order to achieve certain emission reductions. Chapter 4 demonstrates this approach by evaluating the impact of policy on the mitigation cost of solar PV, grid powered battery electric vehicles (BEVs) and solar powered BEVs. The current financial stimuli for all these technologies are found to be generous. Moreover, the subsidized value of one ton carbon dioxide avoided by means of solar PV, grid powered BEVs, or solar powered BEVs equals more than ten times the market value of CO_2 certificates under the EU Emissions Trading Scheme. Chapter 5 uses the mitigation cost to evaluate the attractiveness of rural solar lighting projects under the Clean Development Mechanism (CDM). The appearance of extremely high mitigation costs for PV lighting projects under the CDM points out the necessity for policy makers to intervene. Nonetheless, the mitigation cost calculation shows that this implementation barrier is a mere structural problem inherent to the CDM, which can be altered to a win-win situation for project implementers and host countries by including guidelines to stimulate an additional revenue stream of the avoided baseline costs.

A second method to evaluate the impact of policy by means of assessment of the economic and environmental performances, is to compare optimal solution frontiers of multi-objective problems with and without the impact of policy. This approach is of particular interest when the implemented technology can replace plural baselines. In this case, comparing technologies using the mitigation cost analysis can lead to ambiguous results. The use of multi-objective optimization however allows evaluating technologies without considering a baseline technology. Moreover, this approach enables evaluating the impact of policy on the optimal mixture of technologies, while accounting for economic and environmental objectives. This is demonstrated in Chapter 6 for the Belgian case of solar power and electric vehicles. Results of the analysis can be used as a static ex-post decision making tool to evaluate policy. Current policy is found to be targeting rational investors who consider full life cycle costs. Moreover, under current policy rational investors are pushed towards one single environmental optimum, which implies the use of solar panels for electricity generation and the use of solar powered battery electric vehicles for transportation. However, assuming that a bounded rational investor solely takes into consideration the initial cost of investment (for instance a private investor who manages a budget for one year only), the environmental optimum is not necessarily achieved.

7.1.5 How can the trade-off between economic and environmental performances of combined technologies be quantified in order to determine the optimal mixture of technologies?

While the mitigation cost analysis allows evaluating the cost-efficiency to decrease polluting emissions, it does not allow quantifying the trade-off between economic and environmental impacts. This dissertation encourages the use of multi-objective optimization (MOO) to overcome this drawback. MOO is an area of multiple criteria decision making that is concerned with the mathematical optimization of multiple objective functions, subject to a set of constraints. The use of MOO is of particular interest when optimal decisions need to be taken in the presence of trade-offs between conflicting objectives. For a nontrivial MOO problem, there does not exist one single solution that simultaneously optimizes each objective. In that case, the objective functions are said to be conflicting and plural optimal solutions exist. Optimal solutions (also referred to as efficient, non-dominated or Pareto optimal) exist if there is no other feasible solution which would improve an objective without causing a simultaneous degradation of at least one other objective. The set of all optimal solutions is called the Pareto optimal solution set. The decision maker can opt for one of these optima based on personal preferences. In Chapter 5, we clearly demonstrate the added value of complementing the mitigation cost analysis with a multi-objective approach, applied to two types of rural solar lighting projects, *i.e.* portable solar LED lanterns and small-scale rural solar home systems (SHS). The relatively simple multi-objective linear programming analysis shows that solar LED lanterns are never part of the optimal solution frontier; in all cases they are outperformed by SHS. In Chapter 6, we extend the multi-objective approach by accounting for economies of scale. This inherently discrete phenomenon implies the use of mixed integer programming. Assuming linear relations, this implies a multi-objective mixed integer linear programming (MOMILP) problem. We demonstrate the added value of using MOMILP considering economies of scale versus using continuous multi-objective linear programming (MOLP) assuming average cost intervals. This research is the first to apply the improved version of the only algorithm available to solve MOMILPs exactly (2013). Other attempts found in literature provide no more than an approximation of the optimal solution frontier. Note that this is the only chapter to explicitly account for economies of scale. The other chapters assume a given budget which implies projects on a certain scale and hence, in previous chapters the prevalence of economies of scale falls beyond the scope. The approach is illustrated with a Belgian company that seeks to find the optimal combination of technologies to satisfy electricity and transportation demands under budgetary constraints, while minimizing environmental emissions and economic costs. Technologies at hand are solar PV and grid electricity to cover electricity needs, and internal combustion engine vehicles (ICEVs), grid powered battery electric vehicles (BEVs) and solar powered BEVs to cover transportation requirements. The Pareto frontiers clearly illustrate a tradeoff between economic and environmental performances. Grid BEVs are the least costly option to decrease environmental emissions, followed by solar PV panels and solar BEVs. The multi-objective model can serve as an ex-ante decision making tool for the investor. Based on personal preferences, the SME can opt for one of the optimal solutions with the aid of multi-criteria decision making (MCDM) for example by determining a compromise solution based on weighted criteria or by means of an a posteriori method. For more information regarding the use of MCDM in sustainable energy decision making, we refer the interested reader to (Wang, Jing et al. 2009).

7.2 Policy recommendations

This doctoral thesis provides a clear motivation for evaluating the use of solar PV combined with alternative technologies, which leads to plentiful social and technical advantages. Particularly in the light of climate change, there is a strong need for evaluating these combined technologies from economic and environmental point of view to support decision making. This dissertation proposes four methods to fill this gap. A schematic presentation of these methods is provided in Figure 22. In its most basic form, decision makers can compare the economic profitability of combined technologies by monetizing externalities using an environmental cost benefit analysis (CBA). If the decision maker wants to compare these projects under budgetary constraints, the methodology to calculate benefits of combined technologies (BOCT) can be integrated into the environmental CBA. We note though that the process of monetization is not always straightforward. An alternative approach is using the GHG mitigation cost to evaluate the projects. Moreover, this method is of particular interest when the emphasis is put on cost-efficient emission reduction rather than on mere economic profits. The mitigation cost evaluation allows the decision maker to determine *(i)* how much abatement can be achieved at a certain economic cost and *(ii)* where policy intervention is needed to establish a certain level of emission reductions. Moreover, the GHG mitigation cost methodology described in this dissertation allows the decision maker to rank technologies in terms of cost-efficient emission reduction, given budgetary restrictions. A final, comprehensive method to evaluate combined technologies is the multi-objective optimization. Additional to ranking technologies in terms of cost-efficient emission reduction, this method *(i)* provides an overview of *all* the solutions that are optimal from economic and environmental viewpoint, *(ii)* allows the decision maker to quantify the trade-off amongst economic and environmental performances, and *(iii)* allows determining the optimal mixture of combined technologies under limited budgetary resources.

Additionally, the multi-objective approach is the sole methodology that does not require a baseline or reference technology and it can be used to model economies of scale. The major drawback of this latter method is that complex problems are often hard to model, leading to expensive solution procedures. Hence, to determine the appropriate solution method -given the aim of the policy makers- trade-offs should be made in terms of cost and time on the one hand, and completeness of the solutions on the other.

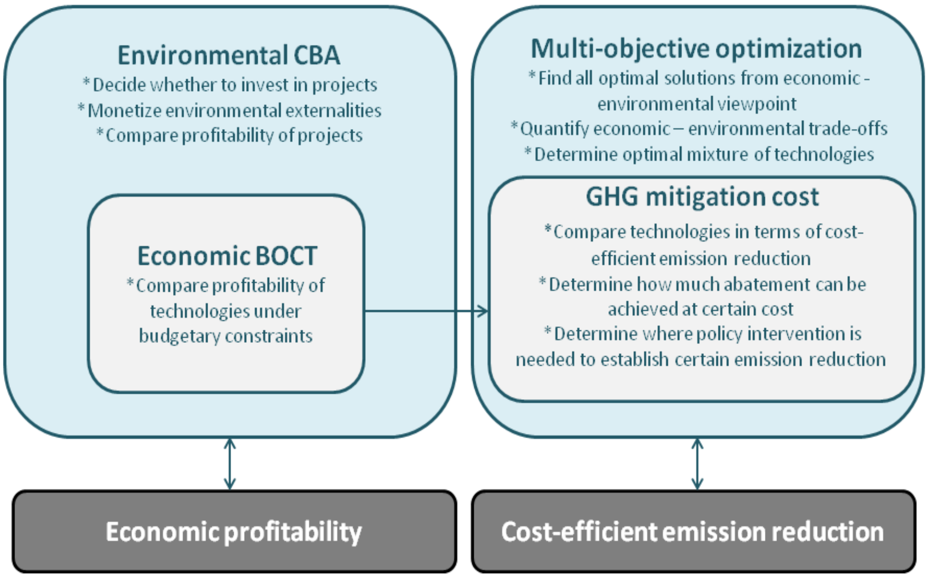

Figure 22 Economic and environmental assessment methods of combined technologies to support decision making

7.3 Future research

This dissertation evaluates the economic and environmental performances of solar PV combined with alternative technologies. As this is a dissertation in the field of applied economics, the modeling of technological performances falls beyond the scope of the study. Nonetheless, the rate of technological improvement has an influence on the adoption rate of the technologies, which in turn can contribute to mass production and cost reductions. Additionally, the fusion of technologies can lead to improved system performances. Hence, a thorough estimation and evaluation of the technological performance of combined technologies over time is an interesting topic for further investigation. A possible method is to include technological performance (in terms of technological output or efficiency) as a third objective in the multi-objective approach, additional to optimizing economic and environmental impacts. In this context, an interesting up-to-date objective would be to optimize the load management of the electrical grid. To solve this problem exactly, the multiple objective branch and bound algorithm for mixed 0-1 linear programming of Vincent et al. (2013) would need to be extended for the three-objective case.

An additional topic that is worthwhile to include in the analysis is the social advantage related to job creation, one of the most important drivers of economic growth. Moreover, the inclusion of the social aspect additional to the economic and the environmental aspects that have already been dealt with in this dissertation, would complete the sustainability assessment of solar PV fused with alternative technologies. The value chain of the PV sector comprises two categories of jobs. On the one hand, there are "direct jobs" such as PV producers, inverter manufactures, installers, and recycling companies. "Indirect jobs" on the other hand support the PV industry by providing more generic components and services, including suppliers of raw material, electrical devices, and production equipment. It is found that the manufacturing of PV modules creates about 3 to 7 direct jobs in production zones and 12 to 20 indirect jobs per Megawatt Peak produced. It is worth noting that this job creation within the PV industry is truly "additional", *i.e.* it does not lead to job losses in other energy sectors as these are complementary jobs which are created (European Photovoltaic Industry Association 2012). The value of job creation could be included into our analysis by monetizing the impact into a social cost benefit analysis (Hoogmartens, Van Passel et al. 2014) or by including "job creation" as an additional objective to be maximized into the multi-objective approach.

In this dissertation, the proposed methodologies are applied to three different cases: solar noise barriers, solar powered battery electric vehicles, and rural solar powered lighting systems. Note though that solar PV is easily integrateable with lots of other technologies including consumer electronics, textile, windows, toys, boats, parking meters, airplanes, ATMs, tents and many more. In fact, this dissertation only deals with cases of technology fusion in which solar PV is combined with alternative technologies, while technology fusion can refer to the blending of all types of technologies. Evaluation of other integrated technologies to support decision making regarding the optimization of technology fusion are interesting topics for further investigation.

Note that the environmental evaluations in this dissertation focus on the impact on climate change, *i.e.* the assessment of greenhouse gas emissions. This is in line with current European regulations regarding the 20-20-20 targets, in which targets are set to reduce GHG emissions with at least 20% by 2020 compared to 1990 levels (European Commission 2009). Nonetheless, other category impacts such as ozone depletion, acidification, fossil fuel depletion, human toxicity, particulate matter formation,… are all relevant to the environmental assessment of clean technologies. This would require a multi-criteria approach that goes beyond the bi-objective model of this dissertation.

This dissertation provides several models to evaluate the economic and environmental performances of combined technologies. This research could be valorized by developing a user-friendly software that, based on input parameters to be determined by the user, enables the evaluation of a random combination of technologies from economic and environmental viewpoint. The most straightforward approach is to define the GHG mitigation cost excluding versus including the impact of policy as output parameters in the model, possibly under a budgetary constraint. Such a software would go further than the traditional life cycle analysis software (*e.g.* SimaPro®) by integrating economic performances. This would be of particular interest for policymakers, who could use the developed tools to assess the impact of policy (*e.g.* evaluate the impact of providing feed in tariffs versus tradable green certificates).

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