

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 paper 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 (i) comparison of technologies given a limited investment resource, and (ii) evaluation of 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. 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 CO₂ market value under the EU Emission Trading Scheme.

Keywords Energy policy · Transportation policy · Photovoltaics · Battery electric vehicles · Life cycle (cost) assessment

List of symbols

α (%/year)	Annual system performance deterioration rate
β (kWh/kWp)	Irradiation factor
BEV (number of vehicles)	Battery electric vehicle
D_t (km/year)	Annual travel distance
(E)ID (%)	(Elevated) investment deduction
Electr (kWh)	Electricity
Fuse (l/100 km)	Fuel use
Gasol (l)	Gasoline
GCC (€/MWh)	Green current certificates
GHG (CO ₂ -eq.)	Greenhouse gas
ICEV (number of vehicles)	Internal combustion engine vehicle
INS (€)	Insurance cost
I_0 (€)	Investment cost (capital)
MaC (€)	Maintenance cost
MC (€/ton avoided CO ₂ -eq.)	Mitigation cost
n (year)	Lifetime
OC (€)	Operation cost
\dot{P} (%/year)	Real annual price increase
PV (kWp)	Photovoltaics
Q (€)	Economic life cycle cost
r (%)	Discount rate

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S/T (€)	Subsidies/taxes
T_n (€/year)	Annual traffic tax
T_0 (€)	One off vehicle registration tax
t_r (%)	Tax rate
UC (€)	Unit cost (excluding direct taxes and subsidies)

Introduction

Aiming to mitigate climate change, the EU set targets to reduce greenhouse gas (GHG) emissions with at least 20 % by 2020 compared to 1990 levels (European Commission 2009a). In 2010, two sectors produced nearly two-thirds of global CO₂ 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 of clean technologies 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. LEAP is an integrated modeling tool that can be used 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 (including transportation) GHG emission sources and sinks. The LEAP system model is not used as such in this paper, although 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 among competing investment opportunities (Lorie and Savage 1955), we allow 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 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 (i.e. source reduction) by substituting fossil based with clean technologies (Ingwersen et al. 2013). More specifically, they seek to evaluate the cost of emission reduction of solar photovoltaics, grid powered battery electric vehicles, and solar powered battery electric vehicles under budgetary limits.

In the following section (“[Conceptual framework](#)”), we discuss how the framework is conceptualized. The “[Methodology](#)” section provides a stepwise method to address the targeted objectives of the framework. In the section “[Case study](#)”, the proposed methodology is applied to a Belgian company. The paper ends with a “[Conclusion](#)” section, incorporating policy recommendations.

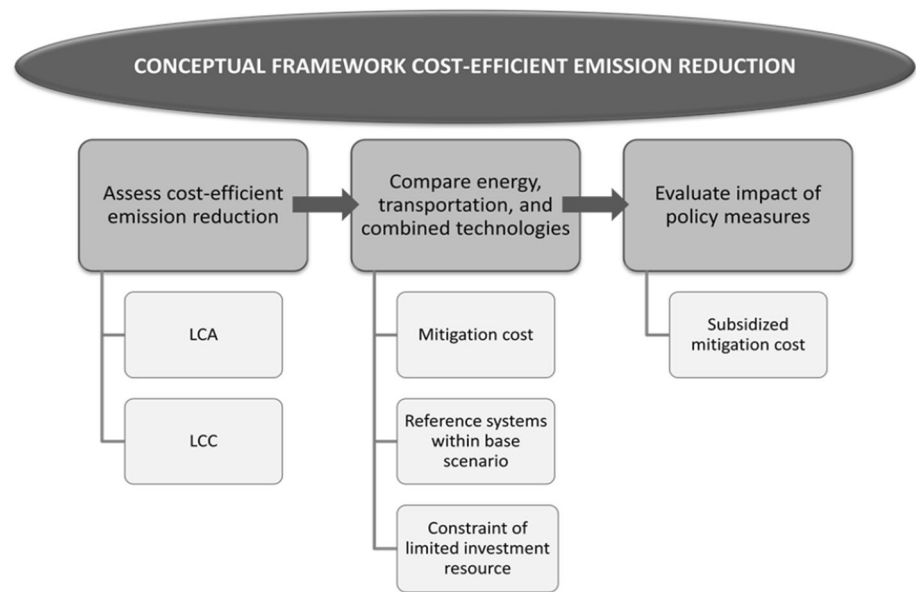
Conceptual framework

A schematic overview of the conceptual framework is provided in Fig. 1. A detailed explanation is given in the following subsections.

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.

Fig. 1 Conceptual framework to assess and compare cost-efficient emission reduction of clean energy and transport technologies, given the constraint of a limited investment resource



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). Among 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 among competing investment opportunities (Lorie and Savage 1955), 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.

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 CO₂ targets—as demonstrated among others by

Chen et al. (2013)—this analysis evaluates the current impact of policy on the economic cost of mitigation.

Methodology

To address the aims of the developed framework, a three-step methodology is worked out (Fig. 2). 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.

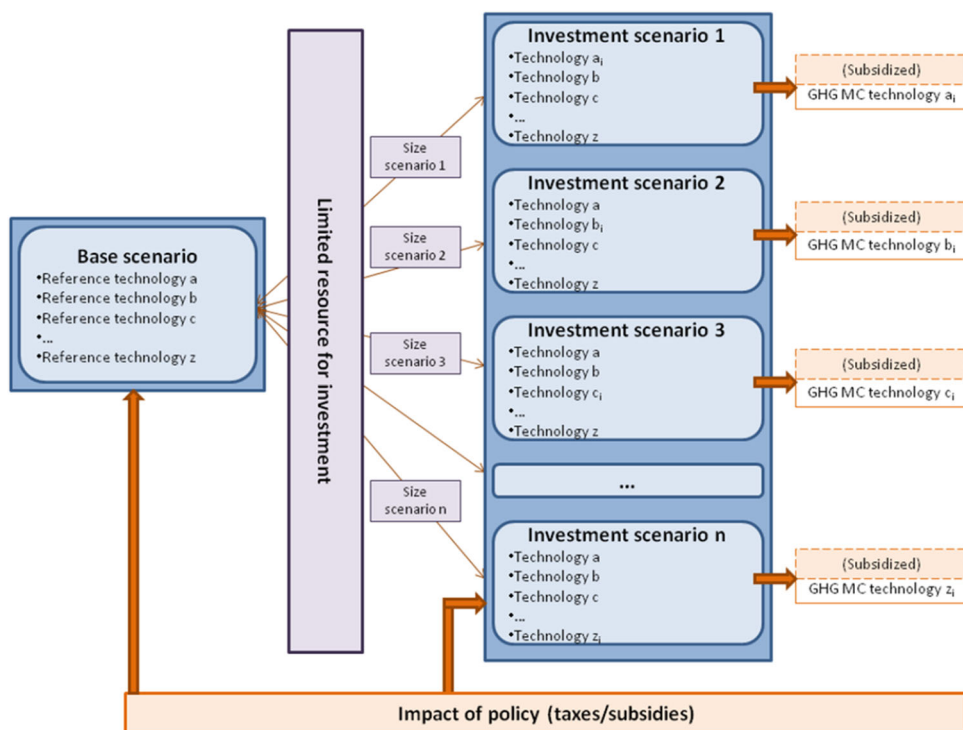
Base scenario and investment scenarios

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.

Investment sizes, given a limited investment resource

To calculate the technology sizes, we refer to De Schepper et al. (2012) who developed a model to directly compare the economic payoff of individual complementary technologies

Fig. 2 Methodology



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 ($size_{N_i}$) can be calculated according to Eq. 1, where the denominator $UC_{N_i} - UC_{R_i}$ 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 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_{N_s} that needs to be compared with technology N_1 with longer lifetime n_{N_1} ($n_{N_1} > n_{N_s}$), 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 ($UC_{N_s} - UC_{R_s}$) 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 (2). 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 ($UC_{N_i} - UC_{R_i}$) multiplied by their size ($size_{N_i} = size_{R_i}$). The other equations represent the technical interrelationships among the different technologies within the integrated combination, which is characterized by a constant c_i .

$$Size_{N_i} = \frac{I_0}{UC_{N_i} - UC_{R_i}} \quad \text{with } UC_{N_i} > UC_{R_i} \quad (1)$$

$$z = \frac{n_{N_1}}{n_{N_s}} \quad \text{with } n_{N_1} > n_{N_s} \quad (1a)$$

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

$$\left\{ \begin{array}{l} I_0 = (UC_{N_1} - UC_{R_1}) * size_{N_1} + (UC_{N_2} - UC_{R_2}) * size_{N_2} + \dots + (UC_{N_n} - UC_{R_n}) * size_{N_n} \\ \quad \quad \quad size_{N_2} = size_{N_1} * c_1 \\ \quad \quad \quad size_{N_3} = size_{N_1} * c_2 \\ \quad \quad \quad \dots \\ \quad \quad \quad size_{N_n} = size_{N_1} * c_{n-1} \end{array} \right. \quad (2)$$

Table 1 Economic data

General data	Subsidies/taxes (S/T)	Costs (Q_t)
$r = 4\%$ (European Commission 2009b) $n = 25$ years (vehicles: $5 * 5$ years)	$t_1 = 33.99\%$ (Federale Overheidsdienst Financiën 1992)	I_0 can be either (positive) number; it is constant for all investment scenarios (as compared to the base scenario). In this case, I_0 amounts to €127,000 and it is varied by +20 and -20 % in the sensitivity analysis
<i>Base scenario: grid electricity and gasoline fueled ICEVs</i>	$T_{0,ICEV} = 495€$ (Federale Overheidsdienst Financiën 2011–2012) $T_{n,ICEV} = 385,84€/year$ (Federale Overheidsdienst Financiën 2011–2012) $\dot{P}_{T_1} = 0\%$; has been stable over the last 7 years and is expected to remain stable in the coming years (Federale Overheidsdienst Financiën 2005–2011) $\dot{P}_{T_2} = 2.10\%$; calculated as the geometric mean of the evolution of annual traffic taxes from 2005 till 2011 (Federale Overheidsdienst Financiën 2005–2011) $T_{gasol} = 0.63€/l$; Excise tax + APETRA/BOFAS/energy contribution on gasoline 95 price (Belgische Petroleum Federatie 2012) $T_{electr} = 0.9544€/MWh$; energy contribution due on electricity used for business purposes by end users, connected to a distribution network <1 kV, (Federale Overheidsdienst 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 2012a) $\dot{P}_{ICEV} = -1.45\%/year$; calculated as the geometric mean of the Belgian real car price evolution from 2005 till 2011 (European Union 2005–2011) $MaC_{ICEV} = 4,440€/5$ years; Nissan's estimate $UC_{gasol} = 0.84€/l$; gasoline 95 price excl. taxes (Belgische Petroleum Federatie 2012) $\dot{P}_{gasol} = 3.85\%/year$; calculated as the geometric mean of gasoline price evolutions from 1990 till 2011 (Belgische Petroleum Federatie 2012) $UC_{electr} = 0.0967€/kWh$; electricity price excl. taxes for Belgian medium sized enterprises (Eurostat 2012) $\dot{P}_{electr} = 1.79\%/year$; calculated as the geometric mean of electricity price evolution for Belgian medium sized enterprises from 1991 till 2011 (Eurostat 2012)
<i>Scenario 1: solar PV and gasoline fueled ICEVs (grid electricity substituted by solar PV)</i>	$S_{GCC} = 230€/MWh$ for 20 years until 30.06.2012 (Vlaams Energieagentschap 2012) $S_{EID} = 10\%$ (Vlaams Energieagentschap 2012)	$UC_{PV} = 2,300€/MWh$ if $P_{tot} < 11.5$ kWp, 2,900€/MWh if $P_{tot} = 11.6$ kWp, 2,900–2,300 €/MWh if $11.6 < P_{tot} < 25$ kWp, 2,300–2,100€/MWh if $25 < P_{tot} < 100$ kWp, 2,100–1,900€/MWh if $100 < P_{tot} < 200$ kWp, 1,900–1,700€/MWh if $200 < P_{tot} < 300$ kWp; based on 4 tenders in February 2012, ranges due to legislation and scale economies $UC_{NS,PV} = 0.23\%$ of I_0 ; average based on 4 tenders in February 2012 $MaC_{PV} = 11€/kWp$; average based on 4 tenders in February 2012
<i>Scenario 2: grid electricity and grid powered BEVs (gasoline fueled ICEVs substituted by grid powered BEVs)</i>	$T_{0,BEV} = 0$ (Federale Overheidsdienst Financiën 2011–2012) $T_{n,BEV} = 73.79€/year$ (Federale Overheidsdienst Financiën 2011–2012) $\dot{P}_{T_{grid}}$ = 0 %/year; has been stable over the last 7 years and is expected to remain stable in the coming years (Federale Overheidsdienst Financiën 2005–2011) $\dot{P}_{T_{solar}}$ = 2.10 %/year; calculated as the geometric mean of the evolution of annual traffic taxes from 2005 till 2011 (Federale Overheidsdienst Financiën 2005–2011) $T_{electr} = 0.9544€/MWh$; energy contribution due on electricity used for business purposes by end users, connected to a distribution network <1 kV (Federale Overheidsdienst Financiën 2012) $S_{ID,BEV} = 120\%$ (Belgisch Staatsblad 2009)	$UC_{BEV} = 30,570€/veh$; price excl. 21 % tax (Nissan 2012a) $\dot{P}_{BEV} = -5.39\%/year$; average of annual price decrease of BEVs forecasted by EU Coalition – McKinsey (2010) and Weiss et al. (2012) $MaC_{BEV} = 1,332€/5$ year; Nissan's estimate $UC_{electr} = 0.0967€/kWh$; electricity price excl. taxes for Belgian medium sized enterprises (Eurostat 2012) $\dot{P}_{electr} = 1.79\%/year$; calculated as the geometric mean of electricity price evolution for Belgian medium sized enterprises from 1991 till 2011 (Eurostat 2012)
<i>Scenario 3: Grid electricity and solar powered BEVs (gasoline fueled ICEVs substituted by solar powered BEVs)</i>	Subsidies/taxes from previous scenarios are applicable	Costs from previous scenarios are applicable
$Size_{BEV} = 4$; calculations in Table 2 $Size_{ICEV} = 2$; calculations in Table 2 $Size_{PV} = 15.38$ kWp; calculations in Table 2 Electr = 44,327 kWh/year (as in the base scenario) Other data from the previous scenarios is applicable		

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 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 Eqs. 4 and 5. To calculate the GHG emission reduction, we use the professional 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”.

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

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

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

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.

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

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 or gasoline ICEVs. The vehicles have an average travel distance of 17,120 km/year. 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 1. Data regarding the BEV is based on the Nissan Leaf; the ICEV referred to is the comparable gasoline powered Nissan Note Tekna auto 1.6 l. 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’ CO₂ emissions are constant throughout the lifetime of the project.

Base scenario and investment scenarios

The scenarios are presented schematically in Fig. 3.

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 2, row 1). The calculations of the investment sizes are listed in row 2. In scenario 1, the ICEVs from the base scenario are used to meet transportation demands, and the capital is used to purchase PV panels. According to Eq. 1









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 

Fig. 3 Base scenario and investment scenarios

Table 2 Investment capital (I_0), investment size (size), economic costs (Q), and policy impact (SUBS)

	Base scenario (ICEV + grid)	Investment scenario 1 (ICEV + PV)	Investment scenario 2 (grid powered BEV + grid)	Investment scenario 3 (solar powered BEV + grid)
I_0	€0	€127,000	€127,000	€127,000
Size (Eqs. 1–2)	$\text{Size}_{\text{ICEV}} = \text{size}_{\text{BEV}} = 6\text{vehicles}$ $\text{Size}_{\text{grid}} (= \text{electr}) = \frac{\sum_{t=1}^{25} \beta^t * \text{size}_{\text{PV}} * (1 - \alpha * t)}{25}$ $= 44,327 \text{ kWh/year}$	$\text{Size}_{\text{PV}} = I_0 / (\text{UC}_{\text{PV}} - \text{UC}_{\text{grid}}) = 57.37 \text{ kWp}$	$\text{Size}_{\text{BEV}} = I_0 / (\text{UC}_{\text{BEV}} - \text{UC}_{\text{ICEV}}) = 6\text{vehicles}$	$I_0 = (\text{UC}_{\text{PV}} - \text{UC}_{\text{grid}}) * \text{size}_{\text{PV}} + (\text{UC}_{\text{BEV}} - \text{UC}_{\text{ICEV}}) * \text{size}_{\text{BEV}}$ $\text{size}_{\text{PV}} = \text{size}_{\text{BEV}} * c_1$ $\text{Size}_{\text{PV}} = 15.38 \text{ kWp}; \text{size}_{\text{BEV}} = 4\text{vehicles}; \text{size}_{\text{ICEV}} = 6 - 4 = 2\text{vehicles}$
Q (Eqs. 4 and 5)	$Q_b = €89,682.99$	$Q_{\text{scenario 1}} = €347,371.75$	$Q_{\text{scenario 2}} = €267,937.38267$	$Q_{\text{scenario 3}} = €300,255.87$
	$\text{OC}_{\text{ICEV}} = D_1 * \text{Fuse}_{\text{ICEV}} * \text{UC}_{\text{gasol}} * (1 + \dot{P}_{\text{gasol}})^t$ $\text{MaC}_{\text{ICEV,t}}$ $\text{OC}_{\text{grid}} = \text{size}_{\text{grid}} * \text{UC}_{\text{electr}} * (1 + \dot{P}_{\text{electr}})^t$	$\text{OC}_{\text{ICEV}} = D_1 * \text{Fuse}_{\text{ICEV}} * \text{UC}_{\text{gasol}} * (1 + \dot{P}_{\text{gasol}})^t$ $\text{MaC}_{\text{ICEV,t}}$ $\text{OC}_{\text{PV,t}} = \text{UC}_{\text{INS,PV,t}} * \text{UC}_{\text{PV}} * \text{size}_{\text{PV}}$ $\text{MaC}_{\text{PV,t}} = \text{MaC}_{\text{PV}} * \text{size}_{\text{PV}}$	$\text{OC}_{\text{gridBEV}} = D_1 * \text{Fuse}_{\text{BEV}} * \text{UC}_{\text{electr}} * (1 + \dot{P}_{\text{electr}})^t$ $\text{MaC}_{\text{gridBEV,t}}$ $\text{OC}_{\text{grid}} = \text{size}_{\text{grid}} * \text{UC}_{\text{electr}} * (1 + \dot{P}_{\text{electr}})^t$	$\text{OC}_{\text{solarBEV}} = \text{UC}_{\text{INS,PV,t}} * \text{UC}_{\text{PV}} * \text{size}_{\text{PV}}$ $\text{MaC}_{\text{solarBEV,t}} = \text{MaC}_{\text{BEV,t}} + \text{MaC}_{\text{PV,t}}$ $\text{OC}_{\text{grid}} = \text{size}_{\text{grid}} * \text{UC}_{\text{electr}} * (1 + \dot{P}_{\text{electr}})^t$ $\text{OC}_{\text{ICEV,t}} = D_1 * \text{Fuse}_{\text{ICEV}} * \text{UC}_{\text{gasol}} * (1 + \dot{P}_{\text{gasol}})^t$
SUBS	$\text{SUBS}_b = €11,103.45$	$\text{SUBS}_{\text{scenario 1}} = €168,074.23$	$\text{SUBS}_{\text{scenario 2}} = €186,658$	$\text{SUBS}_{\text{scenario 3}} = €171,031.45$
	$T_{\text{ICEV}} = [T_{0,\text{ICEV}} * (1 + \dot{P}_{T_0})^{t=0.5,10,15,20} + T_{\text{ngbev}} * (1 + \dot{P}_{T_n})^t] * \text{size}_{\text{ICEV}}$ $+ D_1 * \text{Fuse}_{\text{ICEV}} * T_{\text{gasol}} * (1 + \dot{P}_{\text{gasol}})^t$ $T_{\text{grid}} = \text{size}_{\text{grid}} * T_{\text{electr}} * (1 + \dot{P}_{\text{electr}})^t$ $S_{\text{PV}} = S_{\text{EID},=0} * \text{UC}_{\text{PV}} * \text{size}_{\text{PV}} + \text{electr} * S_{\text{GCC}}$ $S_{\text{ICEV}} = t_r * [S_{\text{ID,fuel}} * \text{OC}_{\text{ICEV}} + S_{\text{ID,ICEV}} * (T_{\text{ICEV}} + \text{UC}_{\text{ICEV},t=0.5,10,15,20} * \text{size}_{\text{ICEV}} + \text{MaC}_{\text{ICEV}})]$	$T_{\text{BEV(grid),t}} = [T_{0,\text{BEV}} * (1 + \dot{P}_{T_0})^{t=0.5,10,15,20} + T_{\text{ngbev}} * (1 + \dot{P}_{T_n})^t] * \text{size}_{\text{BEV}}$ $+ D_1 * \text{Fuse}_{\text{BEV}} * T_{\text{electr}} * (1 + \dot{P}_{\text{electr}})^t$ $T_{\text{grid}} = \text{size}_{\text{grid}} * T_{\text{electr}} * (1 + \dot{P}_{\text{electr}})^t$ $T_{\text{ICEV}} = [T_{0,\text{ICEV}} * (1 + \dot{P}_{T_0})^{t=0.5,10,15,20} + T_{\text{ngbev}} * (1 + \dot{P}_{T_n})^t] * \text{size}_{\text{ICEV}} + D_1 * \text{Fuse}_{\text{ICEV}} * T_{\text{gasol}} * (1 + \dot{P}_{\text{gasol}})^t$ $S_{\text{BEV(PV),t}} = t_r * [S_{\text{ID,BEV}} * (T_{\text{BEV(PV),t}} + \text{UC}_{\text{BEV},t=0.5,10,15,20} * \text{size}_{\text{BEV}} + \text{MaC}_{\text{BEV(PV),t}}) + S_{\text{ID,fuel}} * \text{OC}_{\text{ICEV}} + S_{\text{ID,ICEV}} * (T_{\text{ICEV}} + \text{UC}_{\text{ICEV},t=0.5,10,15,20} * \text{size}_{\text{ICEV}} + \text{MaC}_{\text{ICEV}})] + S_{\text{EID},=0} * \text{UC}_{\text{PV}} * \text{size}_{\text{PV}} + \text{electr} * S_{\text{GCC}}$	$T_{\text{BEV(PV),t}} = [T_{0,\text{BEV}} * (1 + \dot{P}_{T_0})^{t=0.5,10,15,20} + T_{\text{ngbev}} * (1 + \dot{P}_{T_n})^t] * \text{size}_{\text{BEV}}$ $T_{\text{grid}} = \text{size}_{\text{grid}} * T_{\text{electr}} * (1 + \dot{P}_{\text{electr}})^t$ $T_{\text{ICEV}} = [T_{0,\text{ICEV}} * (1 + \dot{P}_{T_0})^{t=0.5,10,15,20} + T_{\text{ngbev}} * (1 + \dot{P}_{T_n})^t] * \text{size}_{\text{ICEV}} + D_1 * \text{Fuse}_{\text{ICEV}} * T_{\text{gasol}} * (1 + \dot{P}_{\text{gasol}})^t$ $S_{\text{BEV(PV),t}} = t_r * [S_{\text{ID,BEV}} * (T_{\text{BEV(PV),t}} + \text{UC}_{\text{BEV},t=0.5,10,15,20} * \text{size}_{\text{BEV}} + \text{MaC}_{\text{BEV(PV),t}}) + S_{\text{ID,fuel}} * \text{OC}_{\text{ICEV}} + S_{\text{ID,ICEV}} * (T_{\text{ICEV}} + \text{UC}_{\text{ICEV},t=0.5,10,15,20} * \text{size}_{\text{ICEV}} + \text{MaC}_{\text{ICEV}})] + S_{\text{EID},=0} * \text{UC}_{\text{PV}} * \text{size}_{\text{PV}} + \text{electr} * S_{\text{GCC}}$	

as discussed in the section “[Methodology](#)”, we find that the size of the PV installation totals 57.37 kWp, which is sufficient to displace an average of 44,327 kWh/year 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 (5 years) differs from that of the PV installation (25 years). Hence, the investment in BEVs is rolled over 5 times within the longer PV lifetime (Eq. 1a). Following 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 will replace an equal amount of ICEVs in the base scenario. Scenario 3 makes use of grid electricity and solar powered BEVs. The size of the latter combined technology given the budgetary limit of €127,000 is calculated by solving the system of

equations as outlined in Eq. 2 which can be found in the section “[Methodology](#)”. 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.

Technological and subsidized GHG mitigation cost

The calculation of the economic costs as well as the direct impact of policy can be found in Table 2, row 3. The life cycle inventory as modeled in SimaPro[®] is listed in Table 3. Unit processes are selected from the EcoInvent

Table 3 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-sulfur, at regional storage/RER U	154,482	kg	Storage and distribution of petrol
Petrol, low-sulfur, 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 mixed sources on Belgian grids
Scenario 1			
Passenger car/RER/I U	30	Piece	ICEV life cycle
Petrol, low-sulfur, at regional storage/RER U	154,482	kg	Storage and distribution of petrol
Petrol, low-sulfur, 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, PV, at 3 kWp slanted-roof, multi-Si, panel, mounted, CH U	1,108,184	kWh	Electricity for any purpose from PV installation
Scenario 2			
Passenger car, electric, LiMn ₂ O ₄ , 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 mixed sources on Belgian grids
Scenario 3			
Passenger car, electric, LiMn ₂ O ₄ , at plant/RER/I U	20	Piece	BEV life cycle
Passenger car/RER/I U	10	Piece	ICEV life cycle
Electricity, PV, at 3 kWp slanted-roof, multi-Si, panel, mounted, CH U	297,112	kWh	Electricity for transport (1,717,411 km) from PV installation
Petrol, low-sulfur, at regional storage/RER U	51,091	kg	Storage and distribution of petrol
Petrol, low-sulfur, 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 mixed sources on Belgian grids

database, based on the best available match with the real projections at hand. The different scenarios are assessed for their impact on climate change (kg CO₂-eq.) using the IPCC 2007 GWP 100a v1.02 single issue method. Regarding the electricity, the LCA takes into account the GHG emissions of the generation and the distribution phase. To assess the impact of 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 4 shows the CO₂-eq. 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 5. 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 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 are mass produced. This draws the attention to the importance of scale economies, 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 CO₂-eq. avoided. Finally, we note that the choice of the discount rate is important (Baumol 1968). Based on a Monte Carlo sensitivity analysis, we conclude 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.

Impact of policy measures including sensitivity analysis

The impact of policy measures on the mitigation cost is visualized in Fig. 4. 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 CO₂ 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 et al. 2010)—largely exceeds the projected CO₂ 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. Accordingly, 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 Fig. 5. We see that the analysis is robust for a change in the aforementioned parameters, as the reciprocal ranking of the technologies is maintained.

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

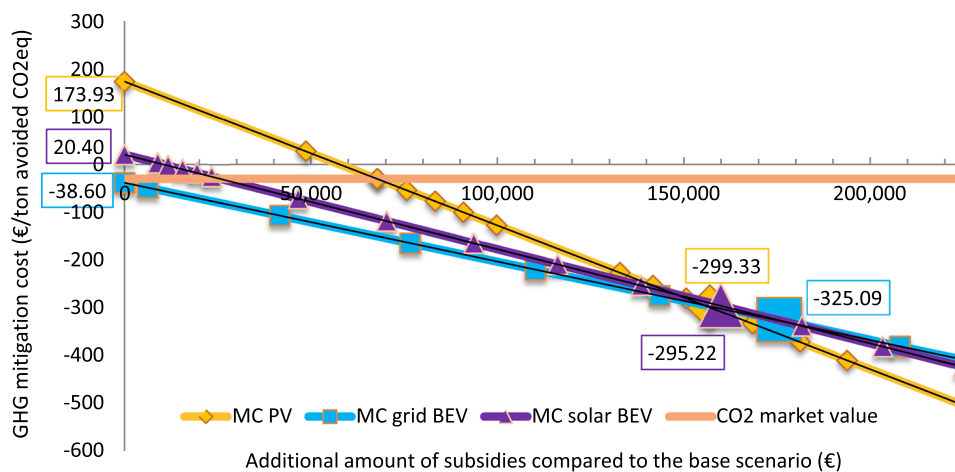
Table 4 CO₂-eq. emissions (kg) per unit of the different processes used in the scenarios

Passenger car/RER/I U	4,199.18 kg CO ₂ -eq./vehicle
Petrol, low-sulfur, at regional storage/RER U	0.729 kg CO ₂ -eq./kg
Petrol, low-sulfur, at refinery/RER U	0.703 kg CO ₂ -eq./kg
Operation, passenger car, petrol, fleet average 2010/RER U	0.237 kg CO ₂ -eq./km
Electricity, low voltage, production BE, at grid/BE U	0.363 kg CO ₂ -eq./kWh
Electricity, PV, at 3 kWp slanted-roof, multi-Si, panel, mounted, CH U	0.064 kg CO ₂ -eq./kWh
Passenger car, electric, LiMn ₂ O ₄ , at plant/RER/I U	5,695.76 kg CO ₂ -eq./vehicle

Table 5 Economic costs, GHG emissions, and mitigation costs

Economic costs (€)	Transportation		Electricity generation		Total LCC (€)
	Investment	Operation & maintenance	Investment	Operation & maintenance	
Excl. policy					
Base scenario	0	205,949.82	0	83,733.17	289,682.99
Scenario 1	0	205,949.82	127,000	14,421.93	347,371.75
Scenario 2	127,000	57,204.21	0	83,733.17	267,937.38
Scenario 3	127,000	89,522.70	0	83,733.17	300,255.87
Economic costs (€)	Total transportation		Total electricity generation		Total LCC (€)
Incl. policy					
Base scenario		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 ₂ -eq.)	Production	WTT	TTW	Generation & distribution	Total (ton CO ₂ -eq.)
Base scenario	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 ₂ -eq.)	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		

Fig. 4 Impact of financial incentives on the GHG mitigation cost; larger data points reflect current (June 2012) subsidized GHG mitigation cost for Belgian SMEs

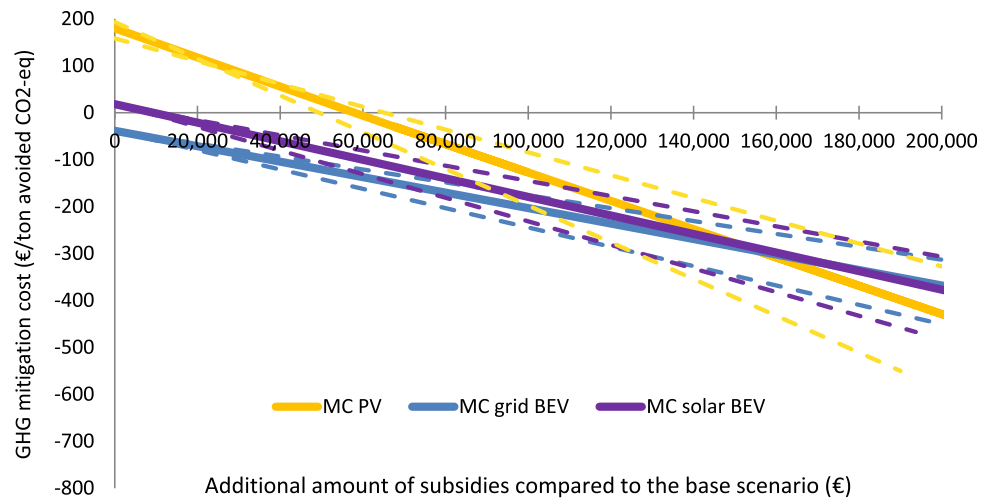


increased CO₂ emissions as a mere monetary problem, we recognize that the overall impacts of global warming go well beyond this monetary valuation.

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

Fig. 5 Sensitivity analysis—*dashed lines* indicate upper and lower limits due to a variation in the initial investment resource of +20 and −20 %, respectively



travelled, as indicated by the 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 twice as high, 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 CO₂ 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 insure a stable environment for investors.

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