Assessment of energy technologies based on carbon price developments

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***Abstract.* The aim of the paper is to assess energy technologies in power and transport sectors. The main tasks are to develop the framework for comparative assessment of energy technologies based on future carbon prices imposed on economy by post-Kyoto climate change mitigation regimes. The assessment framework allows to compare power generation and transport technologies in terms of their environmental and economic impacts. The main indicators selected for technologies assessment are: private costs and external costs of GHG emissions. The ranking of energy technologies based on total social costs allows to identify the most perspective technologies in future taking into account international climate change mitigation constraints and to promote these technologies by policy tools. The main results presented in this paper were obtained during EU financed Framework 7 project "PLANETS" dealing with probabilistic long-term assessment of new energy technology scenarios.**

Key words: energy technologies, comparative assessment, carbon price.

I. Introduction

Climate change is the dominating environmental concern of the international environmental political discussion of today. Global warming is not only an issue for the environment, but rather for human society as a whole, since rising global temperatures might have serious consequences not only on the environment, but on our economy and social life as well. In 2012 the Kyoto protocol will come to end. The very struggle to reach agreement at Copenhagen COP 15 in December 2009, demonstrates that climate diplomacy has finally come of age. The negotiations at Copenhagen were so contentious because of the very real impact the proposals on the table will have, not only on the environment, but also on national economies. In combating climate change – energy technologies play the major role as energy sector are the main source of GHG emissions.

As climate change mitigation is the central environmental policy in EU and all over the world the long-term assessment of new energy technologies based on various long-run policy scenarios is useful for policy makers taking into account just 2 main criteria for technologies assessment: private costs and external costs of GHG emissions.

The aim of the paper is to assess the main relevant future electricity generation and transport technologies by integrating price of carbon obtained by policy scenarios run using various energy models in calculating GHG emission externalities for the main future power and transport technologies. Such comparison and ranking of energy technologies based on total social costs allows to identify the most perspective energy technologies seeking to implement GHG emission restrictions in 2020 imposed for energy sector by possible post-Kyoto climate change mitigation regimes.

II. Comparative assessment of energy technologies

The main indicators for energy technologies assessment used in this study are private costs and external costs of GHG emissions. The life cycle GHG emissions indicator reflects the potential negative impacts of the global climate change caused by emissions of greenhouse gases for the production of 1 kWh of electricity or ride of 1 vehicle km. It follows the methodology of IPCC [1] and covers complete energy carrier chains. This indicator was used in almost all main studies on energy technologies assessment performed all over the world [2, 3, 4, 5, 6, 7, 8, 9, 10, 11].

Seeking to integrate long-term technology assessment with results of long-term policy scenarios run in assessing the main relevant power and transport technologies the carbon price obtained by various policy scenarios runs will be used in the calculation of the GHG emission externalities of selected energy technologies in power and transport sectors. These two main fossil fuel burning sectors were selected based on IPCC methodology as they are the major sources of GHG emission from this GHG emission sector [1].

Within EU Framework 7 project Planets [12] aiming at probabilistic long-term assessment of future energy technologies scenarios the assessment of energy technologies was performed based on carbon price development. Seeking to assess energy technologies based on future energy and climate change mitigation policies the information on carbon price developments is crucial in terms of technologies ranking.

The policy scenarios integrating various GHG emission reduction commitments and climate change mitigation targets can provide information on carbon price developments over time frame. The policy oriented assessment of the main selected power and transport technologies in this paper will be provided for 2020 and 2050 for the 5 regions various regions (World, OECD, Energy Exporting EEX – Russia and mid-East, Developing Asia, DevAsia, Rest of the World, ROW) covered by models (ETSAP-TIAM, DEMETER, GEMINI and WITCH) [13].

10 policy scenarios runs were performed for 4 energy models:

- First best scenarios: FB-3p2 and FB-3p5 setting alternative targets after 2050: 3.2 W/m^2 and 3.5 W/m^2.
- Second best policy scenarios:
  1. SC1-3p2 –To reach commitments indicated in Table 1 for SC1 linearly declining from business as usual from start date (Table 1) to the indicated of 2005 emissions. The target after 2050: 3.2 W/m^2
  2. SC1-3p5- To reach commitments indicated in Table 1 for SC1 linearly declining from business as usual from start date (Table 1) to the indicated of 2005 emissions. The target after 2050: 3.5 W/m^2
  3. SC2-3p2- To reach commitments indicated in Table 1 for SC2 linearly declining from business as sual from start date (Table 1) to the indicated of 2005 emissions. The target after 2050: 3.2 W/m^2
  4. SC2-3p5 - To reach commitments indicated in Table 1 for SC2 linearly declining from business as usual from start date (Table 1) to the indicated of 2005 emissions. The target after 2050: 3.5 W/m^2.

The set of 4 variant second best policy scenarios are the same as for four second best scenarios, but with a limitation on the purchasing of carbon permits between 2020 and 2050, during which period at least 80% of abatement (defined as business usual minus the allocation) has be undertaken domestically by each region, and at most 20% of the abatement can be done with international offsets (purchase of permits).

TABLE 1
GHG REDUCTION COMMITMENTS APPLIED IN POLICY SCENARIOS

Regions	Starting date of commit-ments	Commitments SC1 in 2050 comparing with year 2005	Commitments SC2 in 2050 comparing with year 2005
OECD	2015	-80%	-90%
ENERGY EXPORTING (EEX)	2025	-50%	0%
DEVELOPING ASIA (Dev. Asia)	2025	+25%	0%
REST OF THE WORLD (ROW)	2025	+55%	+100%
WORLD		-28%	-26%

The main indicators or criteria for energy technologies assessment according various policy scenarios will be private costs of energy generation and external costs of GHG emissions integrating carbon price. The following energy technologies were selected for assessment:

In power and heat sector:

- hard coal
- natural gas
- oil
- nuclear
- biomass

In transport: oil and biofuels.

In power sector just base load technologies were assessed. In transport sector some technologies such as hybrid electric vehicles and hydrogen based cars were not assessed in this report because of the lack of consistent data on GHG emissions life cycle and fuel costs. Though hydrogen could capture 10-15% of the transportation fuel market by 2050 however, important obstacles remain on the vehicle side, and in the transition to a hydrogen fuelled transportation sector which is highly uncertain. Hybrid electric vehicles (HEVs) have recently gained a lot of interest. These vehicles use a combustion engine to generate electricity. This electricity is used to drive an electric motor. The energy efficiency of this type of vehicles is up to 50% higher than for conventional vehicles.

In the following chapters of paper based on recent scientific literature review and results of various EU funded projects the range of life cycle GHG emissions and private costs for the selected electricity generation and transport technologies will be derived.

The average values of life cycle GHG emissions and private costs were further used for electricity generation and transport technologies policy oriented assessment and ranking. The most competitive energy technologies will be identified based on external costs of GHG emissions and total social costs for the main policy scenarios.

Policy oriented energy technologies assessment can provide information on the most attractive future energy technologies taking into account climate change mitigation targets and GHG emission reduction commitments for world regions. The average values of life cycle GHG emissions and private costs were further used for electricity generation technologies policy oriented assessment and ranking. The most competitive energy technologies will be identified based on external costs of GHG emissions and total costs for the main policy scenarios. Policy oriented energy technologies assessment can provide information on the most attractive future energy technologies taking into account climate change mitigation targets and GHG emission reduction commitments for world regions.

Carbon price developments obtained by 10 policy scenario runs for ETSAP-TIAM, DEMETER, GEMINI and WITCH models are presented in Table 2.

TABLE 2
GHG PRICE IN 2020 AND 2050 EUR (2005)/METRIC TONNE OF $CO_{2\ EQ}$,

Fuel or energy type	2020					2050				
	Global	OECD	EEX	DEV Asia	ROW	Global	OECD	EEX	DEV Asia	ROW
REF	0	0	0	0	0	0	0	0	0	0
FB-3p2 scenario	21-89	21-48	21-48	21-48	21-48	176-573	195-573	195-573	195-573	195-573
FB-3p5 scenario	13-52	13-48	13-48	13-48	13-48	89-297	195-297	195-297	195-297	195-297
SC1-3p2 scenario	3-21	3-21	3-21	3-21	3-21	107-248	107-248	107-248	107-248	3-107
SC1-3p5 scenario	3-44	3-13	3-13	3-13	3-13	110-289	110-289	110-289	110-289	110-289
SC2-3p2 scenario	3-14	3-14	3-14	3-14	3-14	110-229	110-229	110-229	110-229	110-229
SC2-3p5 scenario	3-13	3-13	3-13	3-13	3-13	110-268	110-268	110-268	110-268	110-268
VAR1-3p2scenario	0-14	0-14	0-17	0-12	0-12	111-192	113-192	125-192	103-192	103-192
VAR1-3p5 scenario	3-13	3-14	3-15	3-11	3-11	110-238	114-238	120-238	103-238	103-238
VAR2-3p2 scenario	0-13	0-15	0-12	0-12	0-12	105-164	115-164	101-164	101-164	101-164
VAR2-3p5 scenario	3-11	3-15	3-10	3-10	3-10	105-203	114-203	101-203	101-203	101-203

Further the policy oriented power and transport technologies assessment will be performed for various policy scenarios (10 scenarios) for 2020 and 2050 time frame and for various regions by calculating external costs of GHG emission using data on carbon price development over time and space obtained by various models (Table 2).

III. LIFE CYCLE GHG EMISSIONS AND PRIVATE COSTS OF FUTURE ELECTRICITY GENERATION TECHNOLOGIES

The data on life cycle GHG emissions for specific fuel cycles is necessary seeking to assess external costs of GHG emissions for different energy technologies using information about CO_2 prices over the time and space delivered by various models by running policy scenarios. Life cycle CO2 emissions from power sector depend strongly upon details of supply chain, production techniques, forestry and agriculture practices, transport distance etc. Life cycle emissions of GHG emissions in kg (CO2-eq.)/kWh are selected to assess electricity generation technologies according EU environmental policy priority – climate change mitigation. Climate change is the dominating environmental concern of the international environmental political discussion of today. Global warming is not only an issue for the environment, but rather for human society as a whole, since rising global temperatures might have serious consequences not only on the environment, but on our economy and social life as well. Among the potential consequences are more frequent extreme weather events like heat waves, storms, flooding and droughts, stress due to higher temperatures for plants and humans, rising sea level, and altering occurrence of pathogenic organisms. The indicator reflects the potential negative impacts of the global climate change caused by emissions of greenhouse gases for the production of 1 kWh of electricity.

The principle factors determining the GHG emissions from a fossil fuel power plant is the type of technology (and hence choice of fuel) and its thermal efficiency. In addition, thermal efficiency increases with the load factor (although efficiency reductions can be observed towards achieving full load operation) and therefore GHG emissions from a particular fossil fuel technology will depend on the mode of its operation (e.g. peak load management, base load supply, combined heat and power supply etc.). The ranges of life cycle GHG emissions for power and heat generation technologies are presented in Table 3. Life cycle GHG emission ranges (from minimal to maximal values) were presented based information provided by various sources [14; 15; 16; 17; 18, 19]. The range of direct CO_2 emissions from combustion and total life cycle GHG emissions per technology were calculated in kg/MWh. Further this data will be used for external costs calculation of power generation technologies using carbon price data (EUR/tCO_2) produced by various models for various policy scenarios, regions and time frames.

TABLE 3
LIFE CYCLE GHG EMISSIONS OF THE MAIN ENERGY TECHNOLOGIES IN POWER SECTOR

Fuel or energy type	Direct CO_2 emissions from combustion		Life cycle CO_2 emissions		Average value, of life cycle GHG emissions, kg/MWh
	kg/GJ	kg/MWh	kg/GJ	kg/MWh	
Nuclear	2.5÷30.3	9÷110	2.8÷35.9	10÷130	65
Oil	126.9÷300.7	460÷1090	137.9÷331.0	500÷1200	850
Natural gas	96.6÷179.31	350÷650	110.3÷215.2	400÷780	590
Hard coal	193.1÷262.1	700÷950	206.9÷344.8	750÷1250	1000
Hard coal IGCC with CO_2 capture	*52.4÷60.7*	*190÷220*	*38.6÷46.9*	*140÷170*	*155*
Large scale wood chips combustion	-	-	21.0÷23.0	76.0÷83.3	79.6
Large scale wood chips gasification	-	-	6.0÷8.0	21.6÷29.0	25.3
Large scale biomass IGCC with CO_2 capture	*-139.4÷-143.5*	*-505÷-520*	*-35.9÷-41.4*	*-130÷-150*	*-140*
Large scale straw combustion	-	-	62.0÷70.0	223.2÷252.0	237.6
Biomass (wood chips) CHP large scale	-	-	6÷10	21.6÷36.0	28.8
Biomass (wood chips gasification) CHP small scale	-	-	3÷6	10.8÷21.6	16.2

As one can see from information provided in Table 3 biomass wood chips gasification technologies have the lowest life cycle GHG emissions followed by wood chips CHP large scale. Hard coal technologies have the highest life cycle GHG emissions followed by oil and natural gas technologies. Hard coal IGCC with CO_2 capture technologies have quite low life cycle GHG emission comparable even with Large scale wood chips gasification technologies. Nuclear technologies have lower life cycle GHG emission than some biomass technologies for example large scale straw combustion technologies and large scale wood chips combustion technologies. Biomass technologies with CO_2 capture have negative life cycle GHG emissions. Especially high negative GHG emissions are during combustion processes of Biomass IGCC with CO_2 capture.

The private costs in EURcnt/kWh are based on the Average Levelised Generating Costs (ALLGC) methodology. The methodology calculates the generation costs (in EuroCents/kWh) on the basis of net power supplied to the station busbar, where electricity is fed to the grid. This cost estimation methodology discounts the time series of expenditures to their present values in 2005, which is the specified base year, by applying a discount rate. According to the methodology used in the IEA study in 2005, the levelised lifetime cost per GWh of electricity generated is the ratio of total lifetime expenses versus total expected outputs, expressed in terms of present value equivalent. The total lifetime expenses include the value of the capital, fuel expenses and operation and maintenance expenses, inclusive the rate of return equal to discount rate. The capital (investment) expenditures in each year include construction, refurbishment and decommissioning expenses. As suggested by OECD the methodology used defines the specific overnight construction cost in €/kW and the expense schedule from the construction period. The overnight construction cost is defined as the total of all costs incurred for building the plant immediately. The operating and maintenance costs (O&M) contribute by a small but no negligible fraction to the total cost. Fixed O&M costs include costs of the operational staff, insurances, taxes etc. Variable O&M costs include cost for maintenance, contracted personnel, consumed material and cost for disposal of normal operational waste (excluding radioactive waste). The range of current and long-term private costs (ALLGC) for the same power generating technologies were selected from various information sources [4; 8, 10]. In Table 4 the range of current private costs of the selected power generation technologies is presented.

TABLE 4
LONG-TERM PRIVATE COSTS OF POWER GENERATION TECHNOLOGIES (2030-2050), EUR/MWH

Fuel or energy type	Costs, EUR/MWh		Average private costs, EUR/MWh
	Min	Max	
Nuclear	24	42	33
Oil	79	100	90
Natural gas	53	60	57
Hard coal	21	44	33
Hard coal IGCC with CO_2 capture	40	43	42
Large scale wood chips combustion	35	38	37
Large scale wood chips gasification	42	49	46
Large scale biomass IGCC with CO_2 capture	57	60	59
Large scale straw combustion	44	48	46
Biomass (wood chips) CHP large scale	37	60	49
Biomass (wood chips gasification) CHP small scale	37	60	49

As one see from information provided in Table 4 the cheapest technologies in long-term perspective are: nuclear and hard coal technologies followed by large scale biomass combustion and biomass CHPs. The most expensive technologies in terms of private costs are: oil and natural gas technologies. Therefore the energy technologies having the lowest life cycle GHG emissions are not the most expensive but not the cheapest one in terms of private costs. Therefore the ranking of technologies in terms of competitiveness would highly depend on the carbon price implied by various policy scenarios integrating specific GHG emission reduction commitments taken by countries and set climate change mitigation targets.

IV. Ranking of future electricity generation technologies based on carbon price developments

Seeking to compare electricity generation technologies based on carbon price developments several most reliable scenarios were selected: first best and second best scenarios. The average data for global region (the average over four regions: OECD, EEX, DevAsia, ROW) on carbon price was applied in analysis. The first best scenarios (FB-3p2 and FB-3p5) include specific targets: 3.2 W/m^2 and 3.5 W/m^2. The second best scenarios (SC) also include 3.5 W/m^2 and 3.2 W/m^2 targets and 2 options for GHG emission reduction commitments for world regions: (SC2) include GHG emission reduction commitments just for OECD – GHG emission reduction in 2050 by 90% from 2005 levels and (SC1) include different commitments for OECD (80% reduction in 2050 from 2005 level); energy exporting countries (50% reduction in 2050 from 2005 level); Developing Asia countries (25% increase in 2050 from 2005 level) and for the rest of the world (55% increase in 2050 from 2005 level).

The ranking of 11 main future electricity generation technologies for 2020 and 2050 based on external costs of GHG emissions is the same as the same life cycle GHG emissions were applied for technologies assessment in all time frames. The most attractive technologies according external costs of GHG emissions in 2020 are: biomass IGCC with CO_2 capture, small scale biomass CHP (wood chips gasification), large scale wood chips gasification, large scale biomass CHP (wood chips combustion), nuclear, large scale wood chips combustion, hard coal IGCC with CO_2 capture. Less attractive technologies are: large scale straw combustion, natural gas, oil and hard coal. The ranking of electricity generation technologies based on external and private costs for the first best scenario in 2020 and 2050.

In Fig. 1 and Fig. 2 the range and average values of total (private and external costs of GHG emissions) costs of electricity generation technologies are presented in 2020 and 2050 respectively according the more strict first best policy scenario FB-3p2.

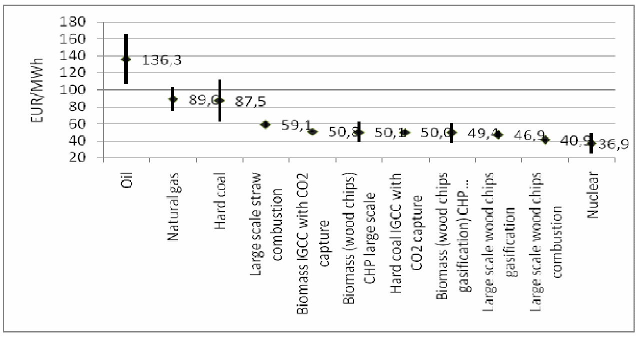

Fig. 1. The range of social costs of electricity generation in 2020 according the first best policy scenario FB-3p2.

As one see from Fig. 1 because of large uncertainties related with life cycle GHG emission and private costs of power generation technologies the ranking of electricity generation technologies is quite complicated however from Fig. 1 is obvious that the best electricity generation option in 2020 is nuclear following by large scale wood chips combustion and other biomass technologies. Oil based technologies are the least attractive following natural gas and coal technologies. The most expensive biomass based technology in 2020 is large scale straw combustion technology. Hard coal with CO_2 capture technology is ranked in the same order like most biomass based technologies including biomass with CO_2 capture.

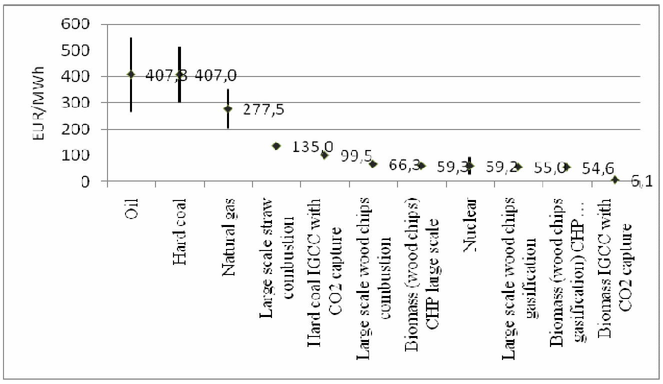

Fig. 2. The range of social costs of electricity generation in 2050 according the first best policy scenario FB-3p2.

In 2050 the ranking of electricity generation technologies according the same scenario (Fig. 2) even taking into account big uncertianties and wide range of total costs for electricity generation technologies provides completeley different results. The most competetive technology in 2050 is biomass ICGG with CO_2 capture, following by other large scale biomass technologies and nuclear. Oil, hard coal and natural gas based technologies are the least competetive technologies in 2050. Hard coal with CO_2 capture is less attractive technology comparing with variety of biomass based technologies except large scale straw combustion.

Therefore the ranking of 11 future electricity generation technologies based on total costs in 2020 and 2050 is quite different. This is related with the fact that the high carbon prices in 2050 have significant impact on technologies ranking as external costs of GHG emissions overweigh private costs of electricity generation technologies. The most competitive technologies according total costs (private and external costs of GHG emissions) in 2020 are: nuclear, large scale wood chips combustion, large scale wood chips gasification, biomass (wood chips gasification) CHP small scale, hard coal IGCC with CO_2 capture, biomass (wood chips) CHP large scale and biomass IGCC with CO_2 capture. Total costs of these first ranked technologies are quite similar except nuclear. The less attractive technologies are: large scale straw combustion, hard coal, natural gas and oil. In 2050 the following ranking of the same electricity generation technologies based on total costs is provided: biomass IGCC with CO_2 capture, biomass (wood chips gasification) CHP small scale, large scale wood chips gasification, nuclear, biomass wood chips CHP large scale, large scale wood chips combustion, hard coal IGCC with CO_2 capture, large scale straw combustion, natural gas, hard coal and oil.

The ranking of electricity generation technologies according external costs of GHG emissions and total costs (private and external) costs is similar for less strict first best policy scenario where 3.5 W/m^2 target is imposed instead of 3.2 W/m^2. For all policy scenarios electricity generation technologies ranking in 2020 and 2050 based on external GHG costs provides the same results because of the same life cycle GHG emission data of electricity generation technologies. The most competetive technology according the second best scenario SC1-3p2 in 2020 like in the case the first best policy scenario is nuclear folowed by large scale wood chips combustion technologies however the hard coal based technologies are ranked in the same order. This is because of low carbon price in 2020 according this scenario as private costs of hard coal based technologies overweight impacts of external GHG emission costs. Biomass IGCC with CO_2 capture technologies because of quite high private costs are less competetive in 2020 according this scenario. The most expensive technologies like in the case of first best scenario are oil, hard coal and natural gas based technologies.

The most competitive electricity generation technology in 2050 according the second best policy scenario like in the case of the first best policy scenario is biomass IGCC with CO2 capture however the nuclear is ranked as second best technology. The lower carbon price of second best scenario has impact on the competitiveness of electricity generation technologies as external costs of GHG emissions according this scenario do not overweight private costs of some technologies like in the case of first best scenario therefore provides for different ranking in first bets and second best policy scenarios.

Though quite different ranking of electricity generation technologies is obtained for various scenarios and time frame the results obtained in technologies ranking based on external GHG emission costs and total costs are similar just for FB-3p2 scenario in 2050 because of very high carbon price (375 EUR/tCO_2 eq). External costs of GHG emissions in FB-3p2 scenario in 2050 overweight impact on private costs in technologies ranking.

For all other policy scenarios electricity generation technologies ranking based on total costs and GHG emission costs provides for different results in technologies ranking. The most expensive technology in terms of total costs for all main policy scenarios in 2020 and 2050 is oil. The most competitive technology for all scenarios in 2020 is nuclear and in 2050 – biomass IGCC with CO_2 capture. Biomass IGCC with CO_2 capture is the most competitive in technologies assessment based on total GHG emission costs. The hard coal, oil and natural gas technologies are among the most expensive for all policy scenarios and all time frames. In 2050 because of the high carbon prices in all scenarios natural gas technologies are more competitive and in 2020 coal technologies are more competitive than natural gas technologies as private costs overweight external costs of GHG emissions in comparative assessment of technologies. In the ranking of technologies based on external costs of GHG emissions the coal technologies are the last attractive one. The ranking of biomass technologies based on total costs is different for specific scenarios and time frame and depends on carbon price obtained by specific scenarios. Very high carbon prices make more competitive technologies having low life cycle GHG emission such as biomass IGCC with CO_2 capture, biomass wood chips gasification and biomass CHPs technologies though these technologies in terms of private costs are more expensive than other biomass technologies external costs of GHG emissions in high carbon price scenarios overweight the private costs in technologies ranking. Hard coal with CO_2 capture technologies are ranked in the middle and in 2050 have similar total costs as large scale straw combustion technologies.

V. Life cycle GHG emissions and private costs of transport technologies

The range of life cycle GHG emissions of transport technologies in g/vehicle km were obtained by gathering data on GHG emissions from transport sector from various sources [14, 20, 21, 22, 23] evaluating direct CO_2 emissions from combustion and total life cycle GHG emissions for specific transport technologies (Table 5).

Fuel GHG intensity is the key factor which represents the net lifecycle emissions impact associated with the consumption of a unit of fuel. Sometimes termed a fuel's "carbon footprint," it can be expressed in units of grams of carbon dioxide-equivalent per megajoule (gCO_2 eq/MJ) of energy delivered to vehicles or other transportation equipment. Fuel GHG intensity is but one factor among many that contribute to transportation emissions.

For our assessment of transport technologies GHG life cycle and direct GHG emissions from combustion will be evaluated in g CO_2 per vehicle km. Conversion of GHG emission data from g CO_2 /l to g CO_2/vehicle km for various fuels is presented in Table 5 as well.

TABLE 5
LIFE CYCLE GHG EMISSIONS OF TRANSPORT TECHNOLOGIES

Fuel	CO_2 **emissions on combustion**				**Life cycle GHG emissions,** CO_2 **eq**					Average life cycle GHG emissions g/vehicle km
	g/litre	kg/gal	g/MJ	g/mile at 4.5 MJ/mile	g/litre	kg/gal	g/MJ	g/mile at 4.5 MJ/mile[1]	g/vehicle km[2]	
Petrol	2328	10.6	72.8	328	2600	11.8	81-110	366-495	227.4-307.6	268
Diesel	2614	11.9	72.6	327	3128	14.2	87-90	391-405	243.0-251.7	247
Bioethanol from sugar beet	1503	6.8	71.6	322	724	3.3	37-43	166.5-193.5	103.5-120.2	112
Bioethanol from wheat	1503	6.8	71.6	322	511	2.3	27-31	121.5-139.5	75.5-86.7	81
Biodiesel from rapeseed	2486	11.3	75.3	338	1334	6.1	39-43	175.5-193.5	109.1-120.2	115
Biodiesel from waste vegetable oil	2486	11.3	75.3	338	437	2.0	11-15	49.5-67.5	30.8-41.9	36

[1] 4.5 MJ/mile is equivalent to 32.5 mpg for a petrol car or 36.4 mpg for a diesel car. However, this makes no allowance for differences in combustion efficiency between different engine designs. For example, diesel engines run at higher compression ratio than petrol engines and therefore are typically more efficient (fewer MJ per mile).

[2] To convert miles per gallon of a particular fuel to grams of CO_2 per km divide the figure for g/litre of CO_2 (either directly from combustion or lifecycle) by the mpg (miles per gallon) figure multiplied by 0.354 (to convert to km/litre):
g/km = (g/l)/(mpg x 0.354) = (g/l x 2.825)/mpg

As one can see from information provided in Table 5 biodiesel from waste vegetable oil has the lowest life cycle GHG emission followed by bioethanol from wheat. Petrol based transport technologies have s the highest life cycle GHG emissions followed by diesel based transport technologies.

The range of current and long-term private costs of transport technologies were evaluated in EURcnt/vehicle km .

based on information about costs of fuels provided by various data sources [20, 21, 22] presented in Table 6.

The price of gasoline and diesel is based on cost of crude oil c.$50/barrel (FOB Gulf cost). These costs for biofuels vary widely depending on location for existing bioethanol and biodiesel technologies.

TABLE 6

CURRENT PRIVATE AND LONG COSTS OF TRANSPORT FUEL TECHNOLOGIES, EURCNT/VEHICLE KM

Fuel	Private costs					Average private costs, EURcnt/ vehicle km
	EURcnt/ litre	Energy density MJ/litre	EURcnt/ MJ	EURcnt/mile at 4.5 MJ/vehicle mile	EURcnt/ vehicle km	
Petrol	27.6-47.3	32	0.86-1.08	3.87-4.86	2.41-3.02	2.72
Diesel	27.6-47.3	36	0.77-1.31	3.47-5.90	2.16-3.67	2.92
Bioethanol from sugar beet	47.3-63.0	21	2.25-3.0	10.13-13.50	6.30-8.39	7.35
Bioethanol from wheat	55.1-74.8	21	2.62-3.56	11.79-16.02	7.33-9.96	8.65
Biodiesel from rapeseed	31.5-43.3	33	0.95-1.31	4.28-5.90	2.66-3.67	3.17
Biodiesel from waste vegetable oil	55.1-78.8	33	1.67-2.39	7.52-10.80	4.67-6.71	5.69

As one can see from information provided in Table 20 the most expensive in terms of fuel costs are bioethanol technologies and the cheapest are transport technologies based on petrol and diesel. Therefore the transport technologies having lowest life cycle GHG emission are among the most expensive terms of fuel costs.

Seeking to conduct policy oriented assessment of energy technologies external costs of GHG emissions will be evaluated for electricity generation and transport technologies based on carbon price developments provided by range policy scenarios runs.

It is important to stress that the ranking of energy technologies based on costs (private, external and total) points to a general problem in having costs as the main parameter for comparison of different technologies since these energy technologies do not compete on the same markets. For example, biomass technologies show a large span in costs and efficiencies and different processes yield different installed capacities therefore it is problematic to compare such processes if comparison is only made on cost basis since the different processes are suitable for different markets however comparison of different energy technologies based on total costs and carbon price enables to develop some important policy recommendations even taking into account high uncertainties in private and external costs if appropriate interpretation of results is provided.

VI. RANKING OF TRANSPORT TECHNOLOGIES BASED ON CARBON PRICE

Seeking to compare transport technologies based on carbon price developments several most reliable scenarios were selected as in the case of policy oriented electricity generation technologies ranking: first best and second best scenarios. The average data for global region (the average over four regions: OECD, EEX, DevAsia, ROW) on carbon price was applied in analysis. As the first best scenarios and second best scenarios include specific targets: 3.2 W/m^2 and 3.5 W/m^2 the scenarios with stricter target as in the case of electricity generation technologies were used in transport technologies assessment.

Transport technologies were compared based on external costs and total costs in 2020 and 2050. The same ranking of transport technologies based on external costs of GHG emissions was achieved for all policy scenarios considered and for both time framewoks: 2020 and 2050 as the same life cycle GHG emissions costs were applied. The most competetive transport technologies based on external GHG costs are technologies having the lowest life cycle GHG emissions, i. e. biodiesel from waste vegetable oil based technologies followed by bioethanol from wheat and from sugar beet based technologies.

In Fig. 4 and Fig. 5 the range of total costs and average total costs of transport technologies is provided in 2020 and 2050 respectively according the first best scenario FB-3p2.

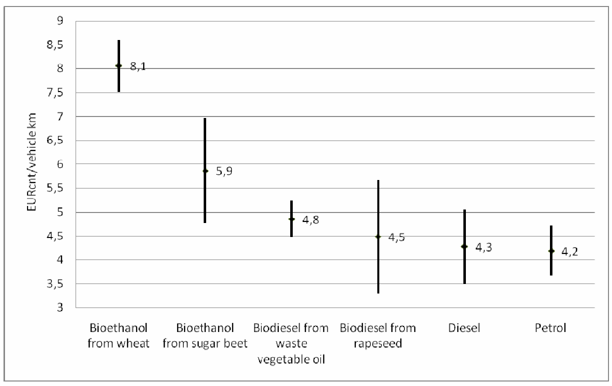

Fig. 4. The average and range of total costs of transport technologies in 2020 according FB-3p2 scenario.

As one can see from Fig. 4 the high uncertainties are relevant to total costs assessment of transport technolgies however even taking into account wide range of total costs of transport technologies in 2020 it is obviuos that petrol and diesel fuel based technologies are the most competetive in 2020 as carbon price and external costst of GHG emissions do not overweight fuel price differences in transport technologies assessment. Therefore even taking quite big uncertainties biomass based technologies are more expensive comparing with conventional transport technologies in 2020.

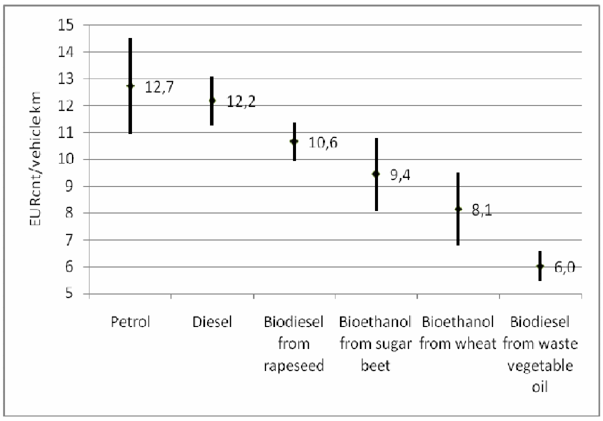

Fig. 5. The average and range of total costs of transport technologies in 2050 according FB-3p2 scenario.

However as one can see from Fig. 5 the high carbon price in 2050 accoring first best policy scenario makes transport technologies based on biofuels more competetive than those fossil fuel based.

The ranking of transport technologies based on total costs according the first best scenario in 2020 and 2050 provides oposite results. Because of the high carbon price in 2050 the petrol and diesel based transport technologies are ranked as the least atractive in this year though in 2020 these transport technologies are ranked as the most competetive. At the same time biodiesel from waste wegetable and bioethanol from wheat based transport technologies are the most competetve in 2050 though these technologies in 2020 were ranked as the least attractive because of the high fuel costs.

Further transport technologies ranking based on total costs will be provided for the second best policy scenarios. In Fig. 6 and Fig.7 the range of total costs and average total costs of transport technologies is provided in 2020 and 2050 respectively according the second best policy scenario SC1-3p2.

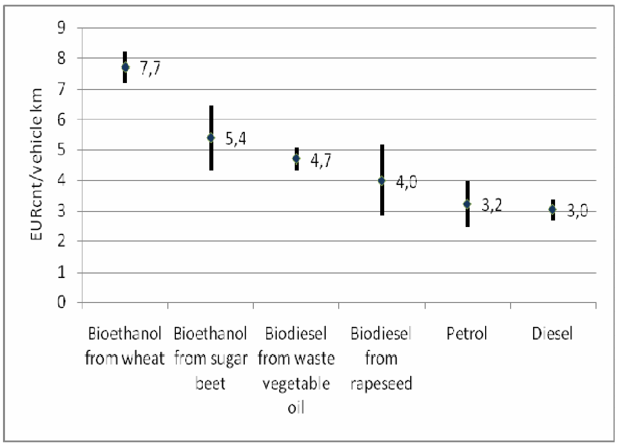

Fig. 6. The average and range of social costs of transport technologies in 2020 according the SC1-3p2 scenario.

As one can see from Fig. 6 the most expensive technologies according the second best scenario like in the case of the first best scenario in 2020 are transport technologies based on biofuels.

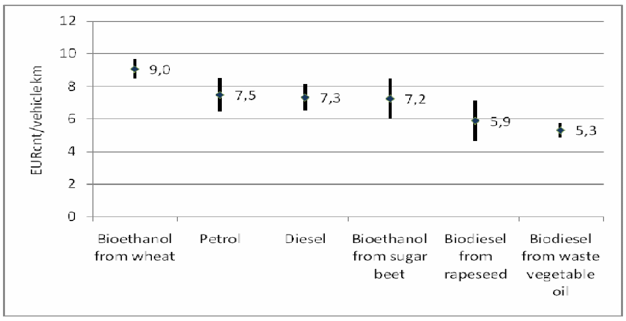

Fig. 7. The average and range of total costs of transport technologies in 2050 according the SC1-3p2 scenario.

As one can see from Fig. 7 even taking into account big uncertainties according the second best scenario like in the case of the first best scenario the most expensive technologies in 2050 are based on conventional fuels and the most competetive technologies are based on biofuels however in the case of second best scenario as lower carbon prices were obtained for this scenario the most expenive technology is bioethanol from wheat as carbon price is not high enough to overwight the high costs of fuel in technologies assessment.

As the seond best policy scenarios have almost twice lower carbon prices (178 EUR/tCO2 eq and 170 EUR/tCO2eq) in 2050 comparing with first best scenario (375 EUR/tCO2 eq) it provides very different ranking of transport technologies comparing with the first best scenario. Though in 2020 the most competetive transport technologies are those based on petrol and diesel like in the case of first best scenario however the least attractive transport technololgies according these scenarios are based on bioethanol from wheat. This is related with the fact that carbon prices obtainaed during the second best policy scenarios runs in all time frame are too low to overweight the high costs of bioethanol from wheat.

Though in year 2020 carbon prices in first best scenario are significantly higher (55 EUR/tCO2) than in second best scenarios (12 EUR/tCO2 eq in SC1-3p2 and 9 EUR/tCO2eq in SC2-3p2) the ranking of transport technologies in 2020 obtained by applying carbon prices provides very similar ranking of transport technologies for all scenarios as high carbon price in first best policy scenario is not able to overweight the mpact of private fuel costs in technologies ranking.

The most competteive transport technologies in 2020 for all policy scenarios are based on petrol. The least comptetive technologies in 2020 are based on bioetanol from wheat. In 2050 the most competetive transport technologies for all scenarios are based on bioethanol from waste vegetbale oil and the least competetive transport technologies are based on bioethanol from wheat excpet FB-3p2. In the case of this scenario the bioethanol form wheat is ranked among the most transport technologies because of high carbon price in 2050 overweighting high fuel cost of bioethanol.

Because of very high carbon prices in 2050 in FB-3p2 scenario the ranking of transport technologies based on total costs and GHG emission costs are very similar for this scenario but very different for all other policy scenarios especially in year 2020 where fuel costs are dominating in transport technologies ranking because of comparatively low carbon prices. However in 2050 the carbon price is the main determinant in transport technologies ranking. Especially first best policy scenario provides the competitive advantage for low carbon transport technologies such as biodiesel and bioethanol.

VII. Conclusion

The long-term assessment of new energy technologies was performed in the paper for various long-run policy scenarios taking into account 2 main criteria: private costs (ALLGC) and external GHG emission costs. Such policy oriented energy technologies assessment based on carbon price and private costs of technologies can provide information on the most attractive future energy technologies taking into account climate change mitigation targets and GHG emission reduction commitments for world regions.

The ranking of energy technologies based on costs (private, external and total) points to a general problem in having costs as the main parameter for comparison of different technologies since these energy technologies do not compete on the same markets. Energy technologies show a large span in costs and efficiencies and different processes yield different installed capacities therefore it is problematic to compare such processes if comparison is only made on cost basis since the different processes are suitable for different markets however comparison of different energy technologies based on total costs and carbon price enables to develop some important policy recommendations even taking into account high uncertainties in private and external costs.

Analysis of life cycle GHG emissions and private costs of the main future electricity generation technologies performed in the paper indicated that biomass technologies except large scale straw combustion technologies followed by nuclear have the lowest life cycle GHG emission. The cheapest future electricity generation technologies in terms of private costs in long-term perspective are: nuclear and hard coal technologies followed by large scale biomass combustion and biomass CHPs. The most expensive technologies in terms of private costs are: oil and natural gas technologies. As the electricity generation technologies having the lowest life cycle GHG emissions are not the most expensive but not the cheapest one in terms of private costs the ranking of technologies in terms of competitiveness highly depend on the carbon price implied by various policy scenarios integrating specific GHG emission reduction commitments taken by countries and set climate change mitigation targets.

The assessment of the main selected power technologies based on external costs of GHG emissions and total costs was performed in 2020 and 2050 for the first best (FB-3p2) and second best scenarios (SC1-3p2; SC2-3p2). Scenarios with more strict targets (3.2 M/m2) were selected for technologies assessment.

11 main future electricity generation technologies were selected: nuclear, oil, natural gas, hard coal including hard coal technologies with CO_2 capture and various biomass technologies (wood chips combustion, gasification, CHP, straw combustion, biomass IGCC with CO_2 capture). For all policy scenarios electricity generation technologies ranking in 2020 and 2050 based on external GHG costs provides the same results as the same data on life cycle GHG emissions were applied for technologies ranking. The most competetive technology according all policy scenarios based on external GHG costs in 2020 and 2050 is biomass IGCC with CO_2 capture biomass followed by other biomass technologies. Nuclear is ranked in the middle.

Though quite different ranking of electricity generation technologies is obtained for various scenarios and time frames the results obtained in technologies ranking based on external GHG emission costs and total costs are similar just for FB-3p2 scenario in 2050 because of very high carbon price (375 EUR/tCO_2 eq). External costs of GHG emissions in FB-3p2 scenario in 2050 overweight impact on private costs in technologies ranking. For all other policy scenarios electricity generation technologies ranking based on total costs and GHG emission costs provides for different results in technologies ranking. The most expensive technology in terms of total costs for all main policy scenarios in 2020 and 2050 is oil. The most competitive technology for all scenarios in 2020 is nuclear followed by large scale wood chips combustion technologies and in 2050 biomass IGCC with CO_2 capture followed by biomass wood chips gasification CHP small scale having the lowest life cycle GHG emissions among analyzed technologies except biomass with CO_2

capture. This technology is the most competitive in technologies assessment based on total GHG emission costs as well. The hard coal and natural gas technologies are among the most expensive for all policy scenarios.

In 2050 because of the high carbon prices in all policy scenarios natural gas technologies are more competitive than coal and in 2020 coal technologies are more competitive than natural gas technologies as private costs overweight external costs of GHG emissions in comparative assessment of technologies. In the ranking of technologies based on external costs of GHG emissions the coal technologies are the least attractive one. The ranking of biomass technologies based on total costs is different for specific scenarios and time frames and depends on carbon price obtained by specific scenarios. Very high carbon prices make more competitive technologies having low life cycle GHG emission such as biomass IGCC with CO_2 capture and biomass wood chips gasification technologies though these technologies in terms of private costs are more expensive than other biomass technologies nevertheless the external costs of GHG emissions in high carbon price scenarios overweight the private costs in technologies ranking.

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REFERENCES

[1] *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories,* IPCC WGI Technical Support Unit, UK, 1997.

[2] C. Gough, N. Castells and S. Funtowicz, “Integrated assessment: an emerging methodology for complex issues**,”** *Environmental Modeling and Assessment,* vol. 3, pp. 19–29, 1998.

[3] J. Walker and J. Johnston, *Guidelines for the assessment of indirect and cumulative impacts as well as interactions.* Luxemburg: Office for Official publications of the European Communities, 1999.

[4] N. Wrisberg, H. A. Udo, U. de Haes, P. Triebswetter and R. Clif, “Analytical tools for a environmental design and management in a systems perspective,” *Eco-efficiency in Industry and Science.* Dordrecht: Kluwer Academic Publishers, 2002.

[5]. EU Framework 6. New Energy Externalities Developments for Sustainability, *Report on Environmental, economic and social criteria and indicators for sustainability assessment of energy technologies,* NEEDS, 2007.

[6] Stanford University, *Global Climate and Energy Project: Integrated Assessment of Energy Technologies*, Technical report, 2007.

[7] International Atomic Energy Agency (IAEA), *Energy indicators for sustainable development: guidelines and methodologies*, Vienna, 2005.

[8] EU Framework 6. European Sustainable Electricity, *Comprehensive Analysis of Future European demand and Generat*ion of European Electricity and its Security of Supply. EUSUSTEL. Final technical report, 2007.

[9] PSI, *Integrated Assessment of Sustainable Energy Systems in China - The China Energy Technology Program (CETP) - A Framework for Decision Support in the Electric Sector of Shandong Provinc*e, 2003.

[10] EU Framework 6. Cost Assessment of Sustainable Energy System, *Development of a set of full cost estimates of the use of different energy sources and its comparative assessment in EU countries.* Report, CASES, 2008.

[11] EU Framework 6. Cost Assessment of Sustainable Energy Systems, *Report on policy instruments assessment methods and comparative analyses,* CASES, 2008.

[12] EU Framework 7. Probabilistic Long term assessment of new energy technology scenarios, *PLANETS Deliverable No. 9. Report on Technology assessment-I,* 2008.

[13] EU Framework 7. Probabilistic Long term assessment of new energy technology scenarios, *PLANETS. Deliverable No. 6. Report on Baseline scenarios*, 2008.

[14] P. Gluch, H. Baumann, “The life cycle costing (LCC) approach: a conceptual discussion of its usefulness for environmental decision-making,” *Building and Environment,* vol. 39, pp. 571–580, 2004.

[5] T. Ekvall, “Key methodological issues for life cycle inventory analysis of paper recycling,” *Journal of Cleaner Production*, vol. 7, pp. 281–294, 1999.

[16] U. R. Fritsche and S. S. Lim, *Comparison of GHG emissions and abatement costs of nuclear and alternative energy options from a life cycle perspective*. Oko-Institut, 2006.

[17] D. Weiser, *A guide to life-cycle GHG emissions from electric supply technologies*. Vienna: IAEA, 2008.

[18] K. Mollersten, J. Yan and J. R. Moreira, “Potential market niches for biomass energy with CO2 capture and storage-Opportunities for energy supply with negative CO2 emissions,” *Biomass and Bioenergy,* vol. 25, pp. 273-285, 2003.

[19] J. S. Rhode, “Engineering economic analysis of biomass IGCC with carbon capture and storage,” *Biomass and Bioenergy* vol. 29, pp. 440-450, 2005.

[20] R. Gross and A. Bauen, “Alternative fuels for transport and low carbon electricity generation: a technical note,” *Synthesis of energy technology medium-term projections,* ICEPT, October 2005.

[21] D. Rajagopal and D. Zilberman, *The use of environmental life-cycle analysis for evaluating biofuels,* Gianini Foundation of Agricultural Economics, University of California, 2008.

[22] The Royal Society, *Sustainable biofuels: prospects and challenges*, Policy document, January 2008.

[23] EPA. Office of Transportation and Air Quality, *Average carbon dioxide emissions resulting from gasoline and diesel fuel,* February 2005.