Internalisation of external cost in the power generation sector: Analysis with Global Multi-regional MARKAL Model

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Abstract: The Global MARKAL-Model (GMM), a multi-regional "bottom-up" partial equilibrium model of the global energy system with endogenous technological learning, is used to address impacts of internalisation of external costs from power production. This modelling approach imposes additional charges on electricity generation, which reflect the costs of environmental and health damages from local pollutants (SO_2, NO_x) and climate change, wastes, occupational health, risk of accidents, noise and others. Technologies allowing capturing of pollutants emitted from power plants are introduced into the energy system, for example desulphurisation, NO_x removal, and CO_2 scrubbers. The model indicates substantial changes in the electricity production system (new technologies penetration and fuel switching), caused by internalisation of external costs and also efficiency loss due to the use of scrubbers. There is significant environmental impact concerning the local pollution and CO_2 emissions reduction over the whole modelled time period. Finally, the detailed analysis of the total generation cost of different technologies including the effect of internalisation of external cost has been performed in order to evaluate the competitiveness of present and future energy systems.

Keywords: External cost, technology learning, energy systems, carbon removal, total generation cost.

1. Introduction

Internalisation of external costs into the full energy production cost is considered as a potentially efficient policy instrument with regard to energy for reducing its negative impacts and move towards a more sustainable energy supply and use. The convenience of merging production (or generation) cost with external cost into a total specific cost is in the fact that this approach can serve as a comparative indicator for evaluation of economic and environmental performance of optional energy technologies. Consideration of externalities is useful for providing an indication of damages/benefits associated with different energy options, for assessing trade-offs between different energy options, for ranking energy options and it can serve as a basis for the introduction of economic instruments to reflect the social costs of energy [1].

Although such an instrument is omitting other important aspects of the policy- and decision-making processes, for instance the political and social acceptance of certain energy systems [2], it is important to know, what the possible effects are of internalisation of externalities in the energy system.

To be able to study this phenomenon, the "bottom-up" optimisation model with sufficient representation of technologies is an applicable tool. This study has been performed with the Global Multi-regional MARKAL (GMM) model with Endogenous technological learning (ETL) developed at Paul Scherrer Institute. Since the strength of the GMM model is the richness of representation of the power generation sector (including ETL specification of selected technologies), and due to the data availability on the external cost from the electricity production [3], this modelling experiment has been performed with consideration of only the electric power sector. The paper describes the economic, environmental and structural impacts of a full internalisation of external costs in the electricity generation, assuming that the additional charges reflect the environmental and

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health damages from local pollution, climate change, risk of accidents and other burdens.

Three main scenarios were comparatively analysed with the research objective as specified above - Business-As-Usual Case without inclusion of the external cost; Case with internalised external costs resulting from local air pollution; and finally the scenario where the external costs are charged including both local air pollutants plus climate change impacts[1].

2. Description of the modelling framework

The analysis presented in this paper has been executed by using the Global Multi-regional MARKAL (GMM) model with Endogenous technological learning (ETL), developed by Barreto [4], and further upgraded by the authors. MARKAL is a dynamic linear programming, “bottom-up”, energy planning model allowing detailed representation of energy technology options on both demand and supply side of the energy system [5].

Five world regions are considered in the GMM model (see Figure 1). Two regions shape industrialised countries of North America (NAME) and the rest of the OECD (OOECD). One region covers transition-economies of Central & Eastern Europe and the Former Soviet Union (EEFSU). Two additional regions represent the developing world: the developing countries in Asia (ASIA) and Latin America, Africa and the Middle East (LAFM).

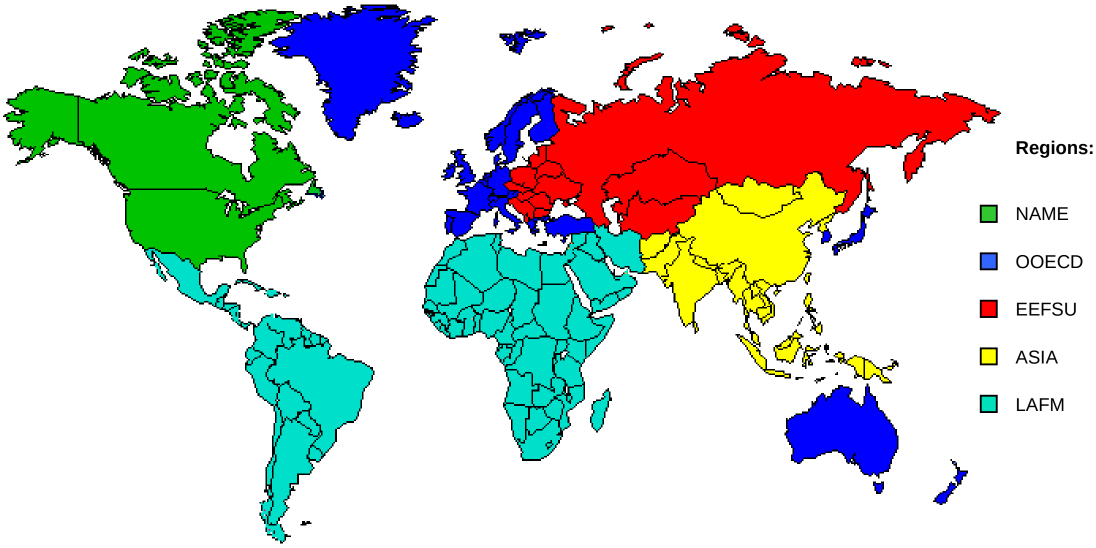

Fig. 1. Definition of the regions in the GMM model.

There are six end-use demand sectors in the GMM model. Industrial and residential & commercial sectors are divided into thermal and electric uses. The transportation sector merges together passenger and freight transport means. Finally, the non-commercial use of biomass and non-energy feedstock is represented. In each of the demand sector, a set of generic end-use devices is defined.

The supply sector is represented with some detail. Technologies for the production of

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[1] In both scenarios with internalised external cost, impacts from following burdens are always considered beside the air emissions: solid wastes, liquid wastes, risk of accidents, occupational exposure to hazardous substances, noise, others (e.g. exposure to electro-magnetic fields, emissions of heat) [3].

electricity, heat and a variety of final fuels (oil products, alcohol, hydrogen, natural gas) from several fossil and non-fossil sources are included, as well as the corresponding transmission and distribution (T&D) chains. Investment, fixed O&M and variable O&M costs are considered for all the different supply technologies. A schematic representation of the standard Reference Energy System (RES) used for all the regions, containing all the possible energy chains that can be chosen by the model, is shown in Figure 2.

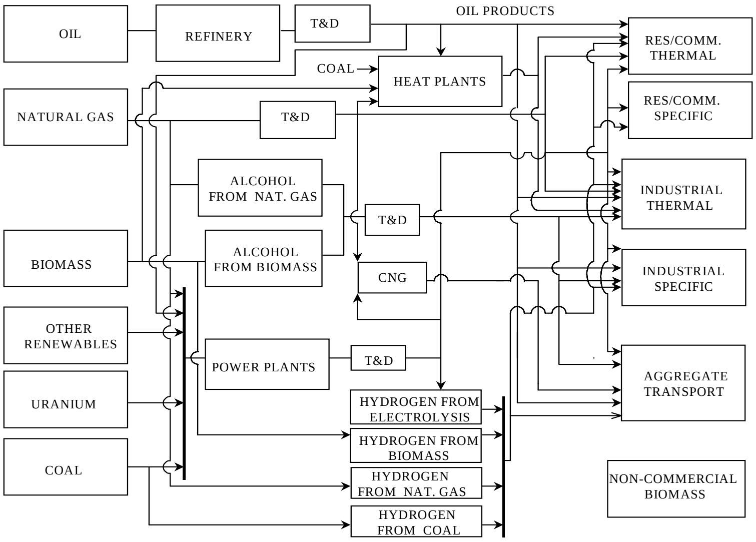

Fig. 2. Reference energy system applied in GMM model. Figure taken from [4].

Important characteristic of the GMM model is its ability to address the treatment of technology dynamics in energy-system development through the incorporation of learning curves of selected technologies within the model. Endogenisation of the technological learning (ETL) enables the modeller to analyse how the specific investment cost of a “learning” technology declines with accumulated installed capacity of the respective technology [6]. The detailed description and mathematical formulation of the learning-by-doing modelling approach applied in the MARKAL model can be found e.g. in Barreto [7]. The technological and learning specification of electricity generation technologies represented in the GMM model are given in Table 1.

The GMM model version used for this analysis applies the ETL option in combination with a partial equilibrium algorithm, that adjusts demands for energy services to the increased marginal cost of services due to the imposition of a policy constraint [9]; in our case it is the extra charge (external cost or tax) on the electricity generated from different technologies. The MARKAL model with elastic demands (referred to as the MARKAL-ED) is making use of a procedure, where the energy end-use demands are not fixed, but they are elastic to their own prices, endogenously computed by the model in the Baseline, and self adjusted if modified scenario conditions affect the prices (see Figure 3). The computation obtains equilibrium when the sum of producer and consumer surpluses is maximised. Consequently, the model's objective function now comprises two terms: the energy/technology costs, and the loss of welfare due to demand reduction [10]. Internalisation of externalities results in allocation of resources through the integration of externalities in energy prices. It can be expected, that the tax imposed on the power generation is recycled back into economy and used for different purposes. Total amount of tax (external cost) levied on the electricity sector is shown separately in Section 5.3.2.

Additionally, the GMM model allows simulation of the global trade of selected energy or environmental commodities (e.g. fuels, electricity, emission permits), and defines a shadow price of the commodity globally traded among regions.

Technology	Start year	Life time	Load factor		Efficiency		Investment cost	Fixed O&M cost	Variable O&M cost	Progress ratio
			start	2050	start	2050	$/kW	$/kW/a	$/GJ	
Fossil based power plants										
Coal conventional electric	1990	30	0.65	0.75	0.370	0.380	1050	69	0.72	
Coal conventional electric with DeSulf/DeNOx	2000	30	0.65	0.75	0.360	0.370	1150	79	1.22	
Coal conv. with DeSulf/DeNOx and CO2 scrubber	2010	30	0.65	0.75	0.296	0.304	2000	80	1.53	
Coal advanced electric	1990	30	0.65	0.8	0.429	0.500	1584	67.5	0.75	0.94
Coal advanced electric with CO2 scrubber	2010	30	0.65	0.8	0.365	0.425	1900	90	1.13	0.93
Coal IGCC (CHP)	2000	20	0.85	0.85	0.425	0.500	1584	36.6	3	0.94
Coal IGCC (CHP) with CO2 scrubber	2010	20	0.85	0.85	0.361	0.425	1900	90	3.9	0.93
Gas combined cycle	1990	20	0.65	0.75	0.510	0.588	600	36.6	0.63	0.9
Gas combined cycle with CO2 scrubber	2010	20	0.65	0.75	0.459	0.529	1000	50	0.88	0.9
Gas turbine	1990	20	0.2	0.2	0.360	0.360	350	58.5	0.51	
Gas steam conventional	1990	20	0.375	0.65	0.386	0.410	987.7	50.63	0.56	
Cogenaration gas turbine	1990	20	0.4	0.46	0.370	0.370	750	51.6	0.63	
Gas fuel cell	2000	20	0.65	0.65	0.599	0.649	2463	43.5	0.63	0.82
Hydrogen fuel cell (CHP) in industry	2000	20	0.85	0.9	0.4	0.6	3500	20	7.5	0.82
Hydrogen fuel cell (CHP) in res&com.	2000	20	0.85	0.9	0.4	0.5	3500	20	5.8	0.82
Oil electric	1990	20	0.65	0.65	0.303	0.400	991	63.6	0.57	
Nuclear and renewable power plants										
LWR Nuclear plant	1990	30	0.7	0.75	0.327	0.327	2500	114	0.19	
LWR Advanced nuclear plant	2000	30	0.85	0.85	0.345	0.345	2500	114	0.19	0.96
Hydro-electric plant	1990	50	0.42	0.43	0.385	0.471	3563	49.5	0.12	
Solar photovoltaics	1990	20	0.2	0.25	0.400	0.400	4600	9	1.25	0.81
Solar thermal electric	2000	20	0.2	0.2	0.400	0.400	2900	9	1.25	
Wind turbine	1990	20	0.3	0.3	0.330	0.330	1150	13.5	0.83	0.9
Biomass power plant	1990	20	0.42	0.65	0.333	0.333	3075	7.8	2.92	
Geothermal electric	1990	20	0.42	0.42	0.381	0.381	3075	7.8	0.9	

Table 1: Specification of electric power technologies used in GMM model. All costs are given in $(1998). The progress ratio (pr) is the rate at which the cost declines each time the cumulative production doubles. The data presented in the table comes from various sources: IIASA MESSAGE model database, literature reviews. Characteristics of technologies with CO_2 removal are adopted from [8].

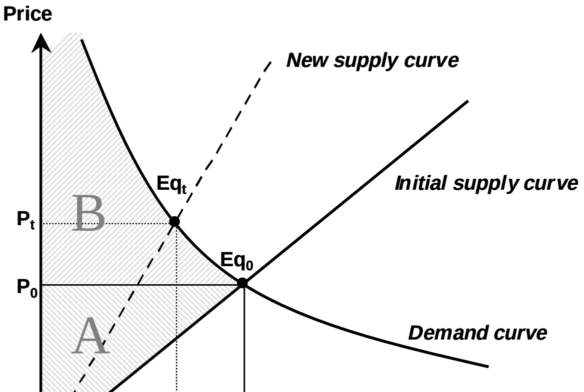

Fig. 3. Illustration of Partial equilibrium between demand and supply [adopted from 11]. Eq_0 is the initial equilibrium (defined by initial demand Q_0 and initial price P_0). External cost will increase the cost of supply (electricity) and the new equilibrium price moves to Pt. Equilibrium is shifted to the point Eq_t (defined by new demand Q_t and new price P_t). The equilibrium is found, when the area composed by producer surplus (A) and consumer surplus (B) is maximised.

3. External cost specification

External cost values used in this study have been derived from the outcomes of the European Commission (EC) ExternE Project. The methodology used for this project attempts to apply the impact pathway approach, i.e. the pathways of polluting substances are followed from the release source to the point of damage occurrence. The consecutive negative impacts (damage) are quantified using damage function. Economic valuation of the damage is obtained by the “willingness to pay” of the affected individual to avoid a negative impact resulting from energy production from an actual power plant. This ‘bottom-up’ approach emphasizes detailed site-specific characterization of technologies, enabling consideration of every important stage in different energy chains and comparison between different fuel-cycles and different types of burden and impact within a fuel-cycle [3].

For the purpose of internalisation of the external cost within the total electricity cost for different technologies in different world regions, the ExternE results had to be adjusted according to the GMM level of aggregation. The determinants for scaling the externalities were the population density in regions; fuel quality expressed as the content of the sulphur in coal and oil; technology specification with respect to installation of the emissions control systems; and finally, the possible improvement in conversion efficiency of the power generating systems over the modelled time horizon.

Table 2 summarises basic assumptions made for the adjustment of external cost. The world regions are grouped in two population density categories according to present statistical data [12]. ASIA and OOECD are located within the category of High density of population, and the remaining regions are assumed to have Medium population density. Changes in the population density over the time horizon are not considered. Sulphur content in coal is assumed to be 1% in all world regions. Even though there is no standardised statistical data available, according to the literature review made by the authors, this value represents the typical average of all different coal types used for power production.

Region	Population density	Sulphur content in coal [%]	Starting year of externality charges
NAME	Medium	1	2010
OOECD	High	1	2010
REEU	Medium	1	2010
ASIA	High	1	2010
LAFM	Medium	1	2010

Table 2: Basic assumptions made for the external cost calculation.

External cost was further scaled as a function of conversion efficiency so that exogenously given efficiency improvements could be taken into consideration. The following formula has been used for adjusting external cost with respect to the efficiency change:

$$ExtCost_t = ExtCost_{original,t=0} * \frac{\eta_{orig,t=0}}{\eta_t}$$

if

$$\eta_t > \eta_{orig,t=0}$$

where is the conversion efficiency of respective power plant.

The resulting external costs are displayed in Table 3. Two different types of externalities were considered: external cost due to local air pollutants (SO_2, NO_x, particulates) but excluding CO_2 impacts, and external cost merging damages from local pollutants and global climate change (see also Note 1 on Page 2). Ranges in the values of external cost represent regional differences due to assumptions and scaling as explained above.

Technology	**External costs (¢EUR95 / kWh)**	
	excl CO2	***incl CO2***
Fossil based power plants		
Coal conventional electric	5.7 - 11.7	7.5 - 13.6
Coal conventional electric with DeSulf/DeNOx	0.7- 1.0	2.5 - 3.0
Coal conv. with DeSulf/DeNOx and CO2 scrubber	0.9 - 1.3	1.3 - 1.9
Coal advanced electric	0.8 - 1.2	2.1 - 2.8
Coal advanced electric with CO2 scrubber	0.9 - 1.5	1.2 - 1.9
Coal IGCC (CHP)	0.6 - 0.9	2.4 - 3.0
Coal IGCC (CHP) with CO2 scrubber	0.8 - 1.0	1.1 - 1.4
Gas combined cycle	0.3 - 1.2	0.9 - 1.9
Gas combined cycle with CO2 scrubber	0.3 - 1.4	0.4 - 1.6
Gas turbine	1.3 - 1.8	2.3 - 2.9
Gas steam conventional	2.0 - 3.2	3.0 - 4.2
Cogenaration gas turbine	1.4 - 1.9	2.4 - 3.0
Gas fuel cell	0.3	0.9
Hydrogen fuel cell (CHP) in industry	0.3	0.9
Hydrogen fuel cell (CHP) in res&com.	0.3	0.9
Oil electric	1.4 - 2.7	2.7 - 4.4
Nuclear and renewable power plants		
LWR Nuclear plant	0.5	0.5
LWR Advanced nuclear plant	0.5	0.5
Hydro-electric plant	0.1	0.1
Solar photovoltaics	0.1	0.3
Solar thermal electric	0.1	0.3
Wind turbine	0.1	0.1
Biomass power plant	0.3	0.5
Geothermal electric	0.2	0.5

Table 3: External cost for different power technologies.

3.1 Treatment of External costs in MARKAL model

External costs, calculated with assumptions described in the previous section and presented in Table 3, are implemented in the GMM model in the following procedure. For each of the electricity producing technologies, an extra balance is introduced to represent the amount of electric power generated from each power plant during each time period. Subsequently, the electric power production is multiplied with corresponding external cost. In this way, it is assured that the matching external costs are charged to every unit of output from each power plant. Sum of discounted annual extra charges (tax) is directly reflected in the total discounted system cost (objective function).

In our model runs, the external costs are applied in all world regions from the same time period (2010).

An alternative approach to implement the externalities in the GMM model is to estimate the damage costs for different pollutants as environmental tax in different regions. This damage cost would be charged directly per unit of pollutant emitted by all relevant technologies present in the system (i.e. including demand devices, transport sector etc.). In this case, emissions factors for each technology would have needed to be specified in the model database. For the purpose to study externalities impact only to the power generation sector, the approach explained in the previous paragraph has been chosen.

The GMM model has different response options, how to react to the extra charges on the power generation with the aim of minimising the total energy system cost: A) to pay (or not) an external charge on power production from a technology; B) to install (or not) a (costly) system with $DeNO_x$, $DeSO_x$, or Carbon-capturing & sequestration; C) to reduce (or not) the energy/electricity consumption in different demand sectors and substitute the electricity use by other fuels; D) to apply (or not) the inter-fossil fuel switching and technological change towards technologies with lower external cost (renewables and nuclear power plants).

4. Scenarios analysed

As already mentioned in Section 1 and summarised in Table 4, three scenarios were explored in this study, all of them including endogenous technological learning (ETL) and partial equilibrium:

Acronym	Scenario definition
BNNL	Business-As-Usual, No local, No global externalities, with ETL
BXLL	BAU, External costs from Local pollutants, with ETL
BXGL	BAU, External costs incl. Local pollutants and Global warming impacts, with ETL

Table 4: Scenarios definition and acronyms used.

The underlying story-line for the reference development refers to the SRES-IIASA B2 scenario. B2 is a "dynamics-as-usual" scenario where differences in the economic growth across regions are gradually reduced and concerns for environmental and social sustainability at the local and regional levels rise along the horizon. Population growth is consistent with the United Nations median projection increasing to 9.4 billion people in 2050 in a continuation of historical trends. Economic growth is gradual, with world GDP increasing at an average rate of 2.8% per annum between 1990 and 2050. Income per capita grows at a global average of 1.8% per year for the same period reaching an average value of 11700 USD (1990) per capita in the year 2050 (at market exchange rates) [13].

The demand projections and potentials for fossil fuel [14] and renewable resources use correspond to those of the characterization of the SRES-B2 storyline performed with the MESSAGE model [13, 15]. The base year is 1990. The model horizon is 1990-2050. Ten-year periods are considered. A discount rate of 5% is applied to the calculations. Due to different geographic coverage of the world regions and different specification of technologies in the MESSAGE model compared to GMM, the results of the Baseline scenario should not be expected to match with those presented in SRES [13] and/or Riahi and Roehrl [15]. Neither is it claimed here that a consistent characterisation of the SRES-B2 storyline is provided. However, within the limitations and scope of this work, it can be considered a plausible development of the energy system [16].

An optimistic assumption has been made, that a global policy of imposing the external costs on the electricity production starts from the same time period (2010) in all regions. Simultaneously, it is expected that a global spill over of experience and know-how transfer from North to the South takes place.

5. Results

Although the energy system of five world regions is fully modelled, results are presented here with emphasis on the global power generation sector (fuel mix, choice of technologies, costs) and on the environment (SO_2 and NO_x emissions from the power production, total CO_2 emissions). Changes in the rest of the energy system are summarised in the form of primary and final energy use and the system costs.

5.1 System changes

5.1.1 Electricity production

The power generation in the Baseline scenario is dominated by systems based on coal combustion. Different types of coal power plants contribute by more than 50% to the total global power generation in the end of the time horizon. From the year 2030, the conventional coal plants are replaced by advanced coal ‘learning’ systems (i.e. supercritical plants, Pressurized fluidised bed combustion - PFBC), and Integrated Coal Gasification Combined Cycle (IGCC) technologies. The second most competitive system in 2050 is the NGCC, contributing to more than 17% of total power production. Around 30% of the electric power is supplied by the carbon-free nuclear and renewable sources in the year 2050 (see Figure 4).

Introduction of external costs into total production cost influences significantly the structure of the power generation mix. In the case of internalised local externalities (BXLL), coal remains the major contributor to total power production, however its share is reduced in 2050 by 10% relative to the Baseline. Moreover, the conventional pulverised coal combustion is steadily being replaced by systems with SO$_2$ and NO$_x$ emissions control (Flue Gas Desulfurization-FGD, low NO$_x$ burners etc.). The IGCC systems with carbon capturing are becoming competitive and appear in the solution between 2040 and 2050. The NGCC plants with other natural gas based systems increase their share in power production to a level of 23% of the total electricity supply by 2050. The share of renewables and nuclear plants is increased by 6 % relative to the Baseline because of lower external cost charged on these systems (see Figure 5).

When the external cost resulting from local and global impacts are included, the electric power system changes become more radical (Figure 6). The generation from coal reaches only 17.5% while natural gas fired power stations produce around 22% of total electricity in 2050. Nuclear energy supplies 18 % of electricity in 2050, and it can be seen, that the light water reactor (LWR) nuclear plants are playing a significant role in the power supply during the whole time horizon after implementing external cost. In the BXGL case, different technologies based on renewable sources contribute 40% of total generation in 2050, having wind turbines and Solar Photovoltaic (SPV) systems (both undergoing strong cost reduction due to ETL) major market players.

As a result of rising cost of electricity, the overall power generation in 2050 is decreased by 5.6% in BXLL and by 12.7% in BXGL, relative to the Baseline (effect of reduced demand for electricity due to partial equilibrium).

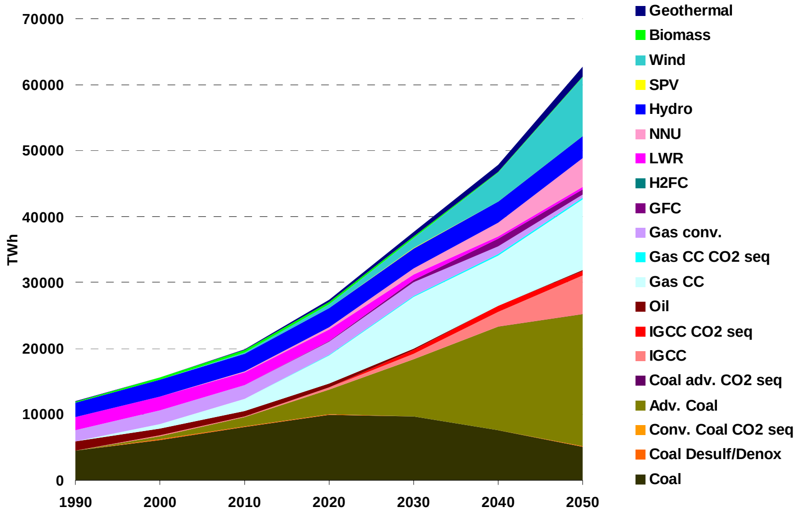

Fig. 4. Development in the electricity production by sources in the reference scenario.

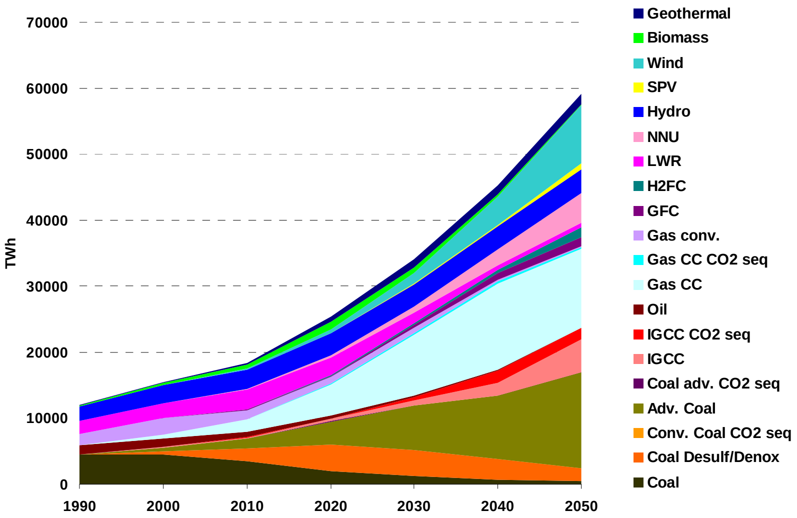

Fig. 5. Development in electricity production by sources in the scenario including external cost from local air pollution (BXLL).

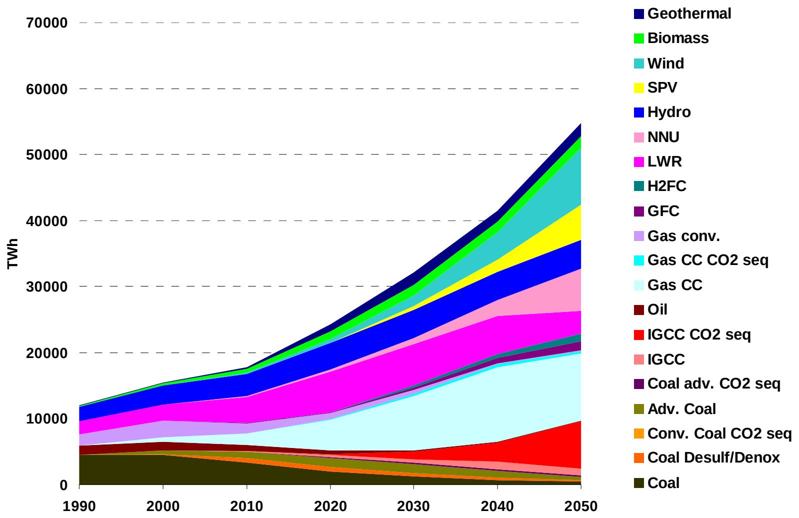

Fig. 6. Development in electricity production by sources in the scenario with included external cost from local air pollution and climate change impacts (BXGL).

Figure 7 illustrates the power generation profile in 2050 in all considered scenarios. It is noteable that coal systems with DeNO$_x$ systems and DeSO$_x$ scrubbers produce a considerable amount of electricity only in the case of local external cost. On the other hand, when local and global external costs are imposed, the systems with CO$_2$ capturing become competitive, and the IGCC technology with carbon capturing is the third largest power producer on the global level. This finding indicates, that internalised external cost makes the IGCC with C-removal an attractive technological option towards carbon mitigation strategies.

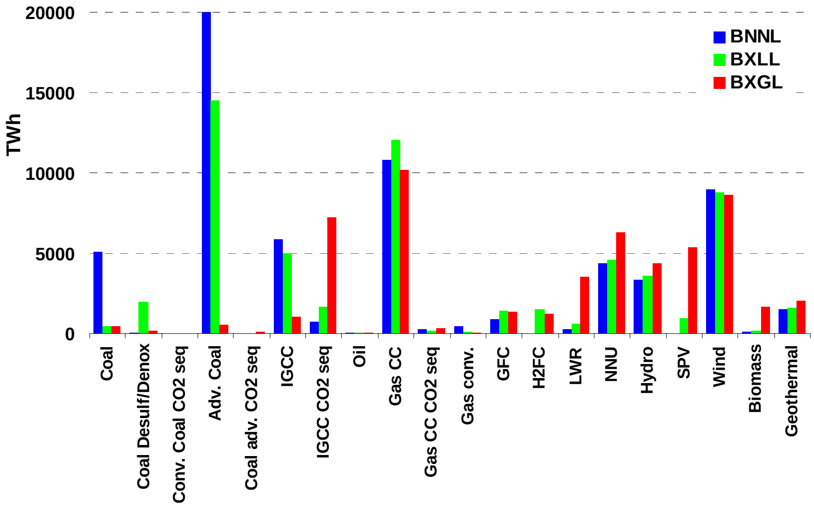

Fig. 7. Power generation profile in 2050 in all considered scenarios.

5.1.2 Primary energy consumption

Total global primary energy consumption remains almost unaffected if external costs of power generation are included. There is a 1.5% reduction in total primary energy consumption in the BXLL case and a 0.5% increase in the BXGL case (this is due to the use of fossil equivalent for calculation of the contribution of non-fossil sources to primary consumption and due to switch to other fuels than electricity in the final energy demand). Nevertheless, from Figures 8 and 9, substantial changes in consumption of different fuels can be observed. The BXLL case is characterised by a large reduction in coal use, which is replaced by oil, renewables and nuclear energy. This trend is even more obvious in the case of local and global externalities, where coal use (primarily for power generation) is substituted with nuclear energy, and there is a large increase in renewable electricity consumption in the end of the time horizon.

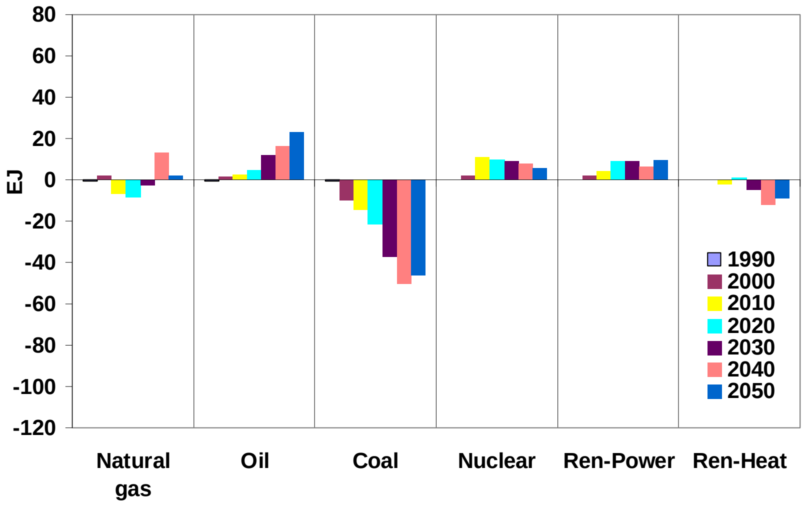

Fig. 8. Change in primary energy consumption in BXLL case compared to the Baseline.

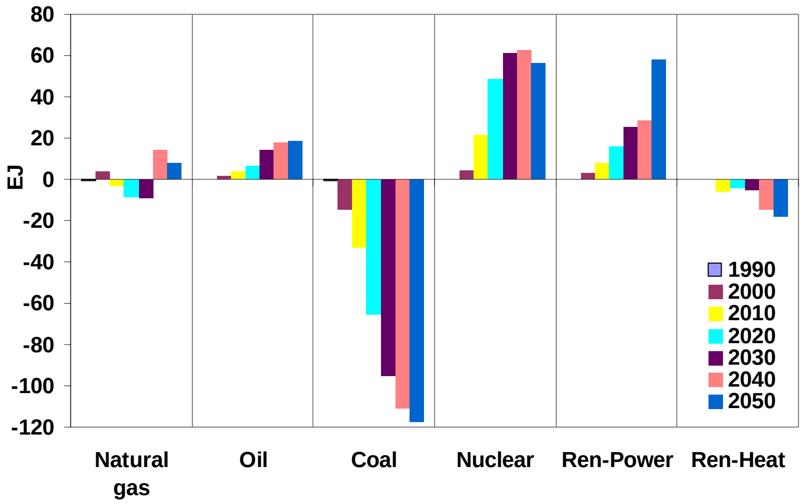

Fig. 9. Change in primary energy consumption in BXGL case compared to the Baseline.

Relative importance of different primary energy sources is shown in Figure 10. The share of coal is reduced in favour of increased contribution from oil, nuclear and renewables consumption in 2050. Importance of natural gas is slightly lowered in the BXLL case, but increased again in the global externalities case.

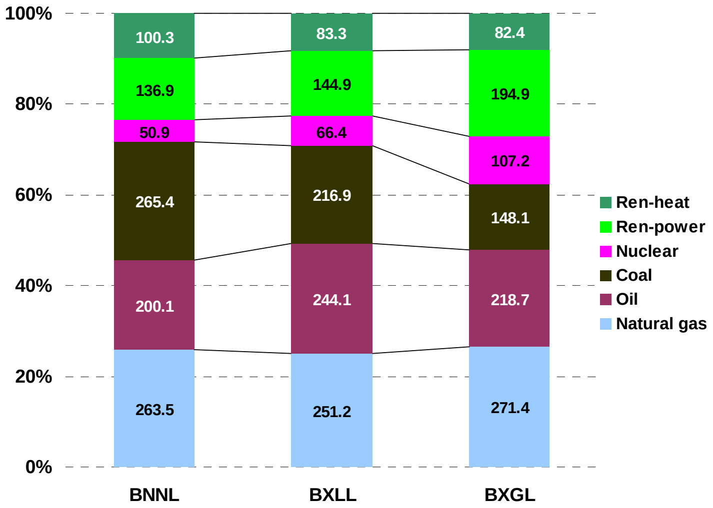

Fig. 10. Relative fuel shares in the total primary energy consumption in 2050 in all scenarios.

5.1.3 Final energy demand

In both externality cases, the total final energy consumption slightly increases (0.8 – 1%) compared to the reference development in 2050. Comparison of the fuel mix in the final demand in all cases (see Figure 11) shows, that the consumption of oil, natural gas, heat and biomass increases relative to the Baseline, while demand for electricity is reduced. This is due to fact that the external costs are applied only to the power sector. Subsequently, electricity that is more expensive is substituted by other fuels, which are often used by the less efficient end-use devices. Therefore, the overall final demand rises.

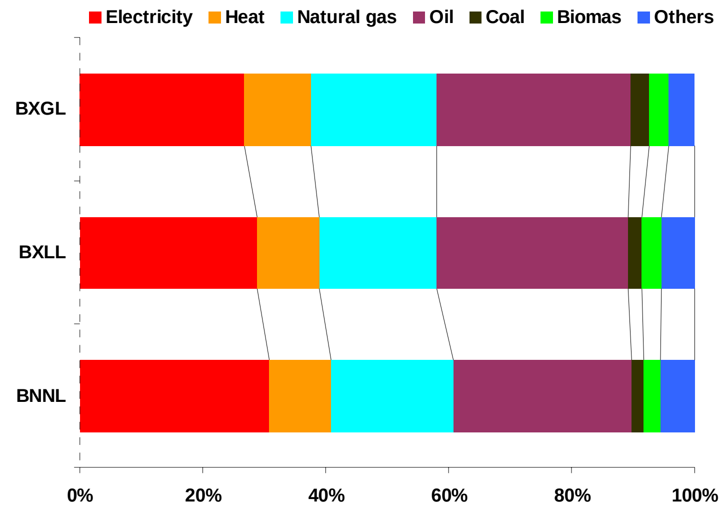

Fig. 11. Relative fuel shares in total final energy demand in 2050 in all scenarios.

Since the external cost is applied only to power generation, it is important to see the development of the final electricity consumption by different demand sectors. Figure 12 illustrates that the consumption of electricity is reduced in all sectors due to the increase in electricity price (effect of the partial equilibrium). However, the largest reduction may be observed in the industrial sector (by 13.4% in BXLL and 23.6% in BXGL over the Baseline) in 2050.

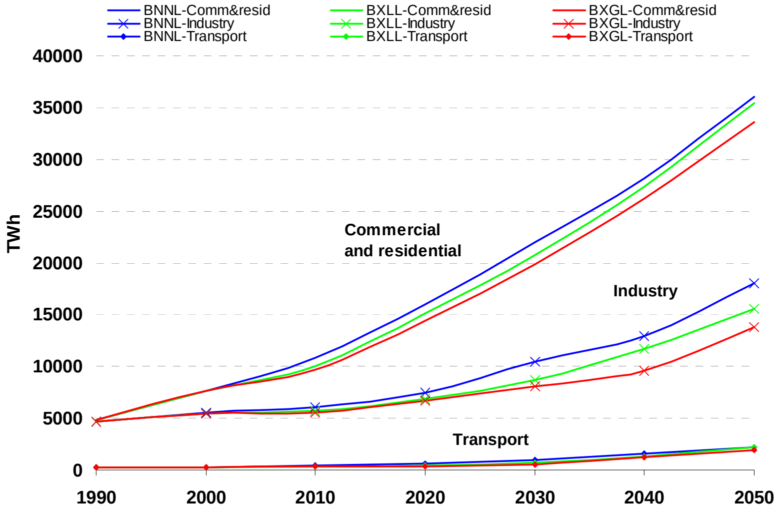

Fig. 12. Development in electricity consumption in the different demand sectors.

5.2 Environmental impacts

As described in Section 5.1.1, internalisation of external cost into the total production cost of electricity leads to fast penetration of cleaner, or less emitting technologies. This means a significant emission-reducing effect in both externality scenarios.

Figure 13 represents the relative change of global air emission over the reference case. For all considered emissions (CO_2, SO_2, NO_x), the most significant reduction occurs within the period 2000 to 2020. Until the year 2040, the emissions are partly stabilised. In the end of the time horizon, different development can be observed in CO_2 emissions and local pollutants. As the (learning) technologies with CO_2 removal start to penetrate the market between 2040-2050, total CO_2 emissions are reduced by 30% over the Baseline (BXGL case). On the other hand, SO_2 and NO_x emissions, although significantly dropped by 2040, start to grow again as the modern fossil systems (NGCC, coal advanced, IGCC) gain their share.

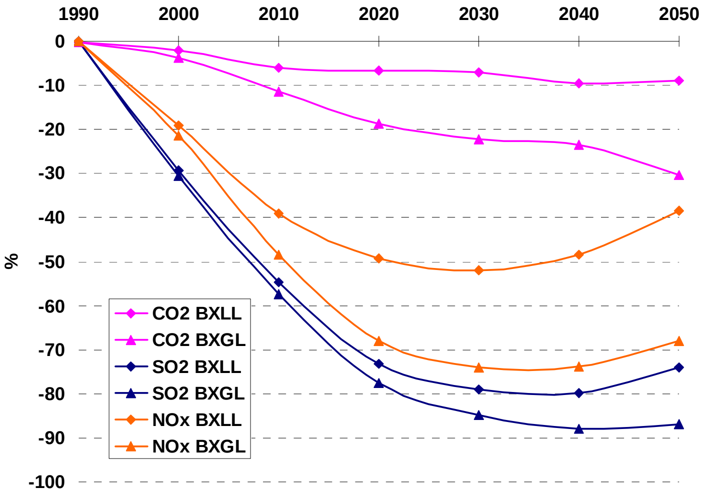

Fig. 13*:* Relative change in the global air emissions relative to the Baseline.

5.2.1 Emissions of local air pollutants (SO_2/ NO_x)

Figure 14 shows total SO_2 and NO_x emissions from the power production. To illustrate the effect of external cost towards the emission reduction, no local or regional pollution mitigation policies are considered in the world regions in the Baseline scenario. The SO_2 emissions culminate in the period 2020-2030 at the level of 80 Mt SO_2 per year in the Baseline. With lowered share of conventional coal plants the sulphur emissions drop significantly till 2050. Since the desulphurisation systems together with advanced coal and IGCC displace the conventional coal from the system in BXLL and BXGL, the reduction effect is rather dramatic. NO_x emissions increase in the Baseline until 2030 and then are stabilised at the annual level around 43 Mt NO_x. In the externality cases, there is no substantial increase in the NO_x emissions until 2040. Then in 2050 their level grows by 16% in BXLL and by 19% in BXGL case relative to 2040 due to increased penetration of new fossil-based technologies (see also Figure 6).

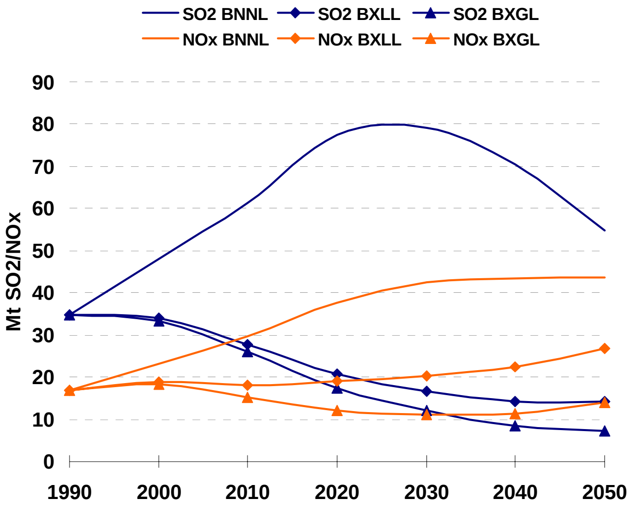

Fig. 14. Development of SO_2 and NO_x emissions from the power generation under the Baseline and externalities scenarios.

5.2.2 Global CO_2 emissions

Total global carbon emissions in the reference case rise during the whole modelled time horizon with annual rate of 1.6% and reaches a level of 13.7 Bt of carbon in 2050. In the BXLL case, total emission level is lowered by 9% in 2050, and the annual growth rate is reduced to 1.5%. In the BXGL case, the CO_2 emissions culminate around 2040 (i.e. at 10 Bt C per year) and then are reduced by 5% in 2050, when carbon-sequestration systems become competitive (see Figure 15).

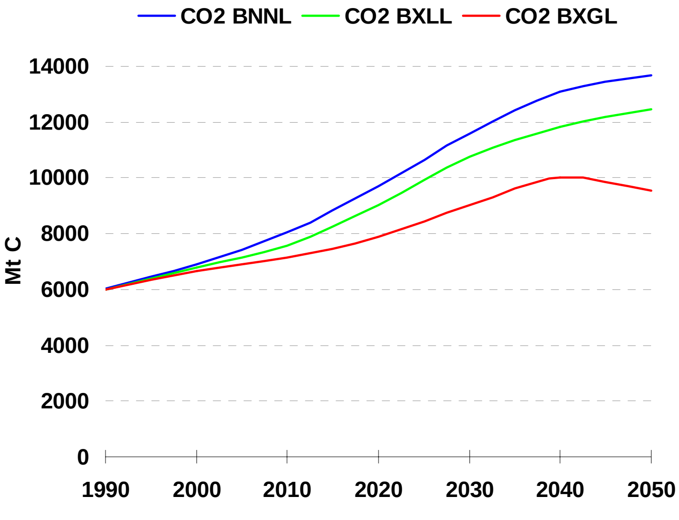

Fig. 15. Development of total global CO_2 emissions under the Baseline and externalities scenarios.

The decarbonisation effect of the policy comprising internalisation of external cost can be seemly demonstrated with the break down of the different CO_2 reduction components (Figures 16 and 17). Five carbon reducing components were considered: inter-fossil switching (i.e. from coal to natural gas), reduction of fossil fuel fraction due to increase in nuclear energy use, reduction of fossil fuel fraction in favour of renewables, and finally the reduction of end-use demand due to implementation of new policies (charging of external cost) [17]. In both scenarios, the inter-fossil switch plays dominant role in carbon mitigation (63% of CO_2 reduction in BXLL and 44% in BXGL case respectively). The important role of larger use of nuclear energy is reflected in the emissions reducing effect in the BXGL case, where in the time period 2010-2030 the nuclear energy contributes with some 30% to the total reduction. Carbon removal from fossil fuel combustion plays significant role in both externalities scenarios. Its share in overall CO_2 mitigation process in 2050 corresponds to 15% in BXLL case and 31.5% in BXGL case.

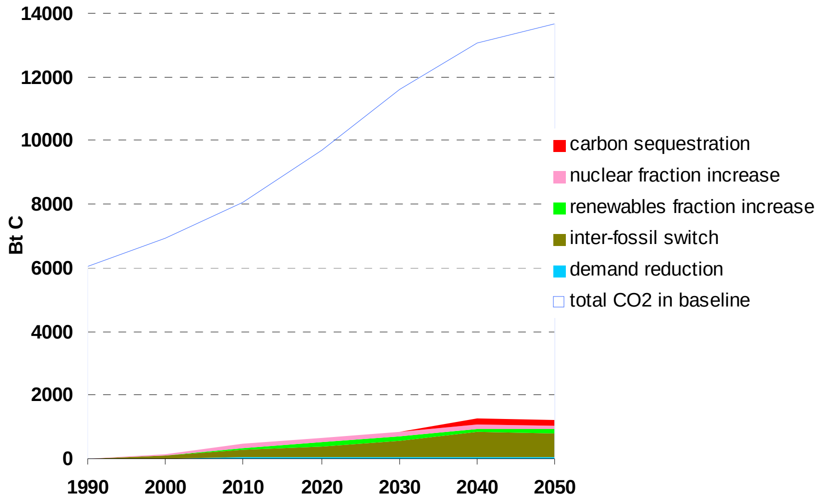

Fig. 16. Break-down of CO_2 reduction components under BXLL scenario.

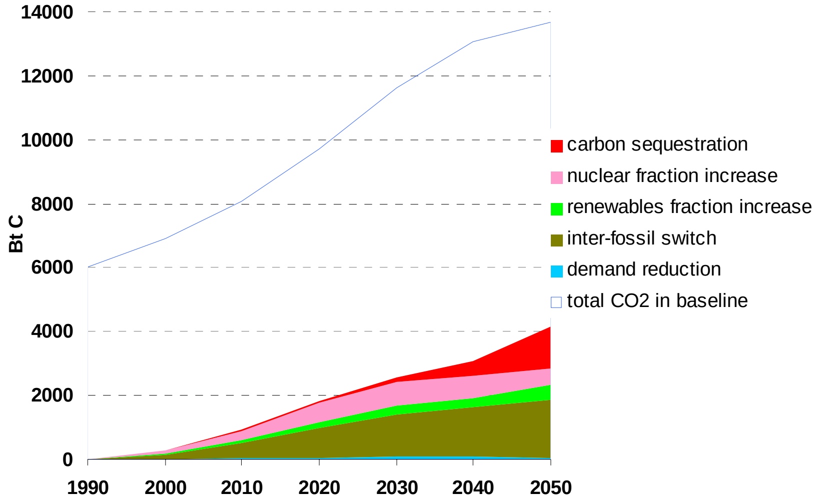

Fig. 17. Break-down of CO_2 reduction components under BXGL scenario.

5.2.3 Global indicators

A set of different indicators is used to analyse the behaviour of the reference energy system under scenarios with included external costs. First, the carbon intensity of the global reference energy system is illustrated presenting the amount of CO_2 emitted per EJ of primary energy consumption for the Baseline and externality cases (Figure 18). The carbon intensity in the Baseline scenario is slightly increasing until the year 2030, but then less emitting sources start to gain shares in the energy production. The same trend as in the reference case can be seen in the BXLL scenario, while the decarbonisation effects in the case with local and global external cost start from the beginning of the time horizon with annual declination rate of –0.9% (compared to –0.3% in BXLL case).

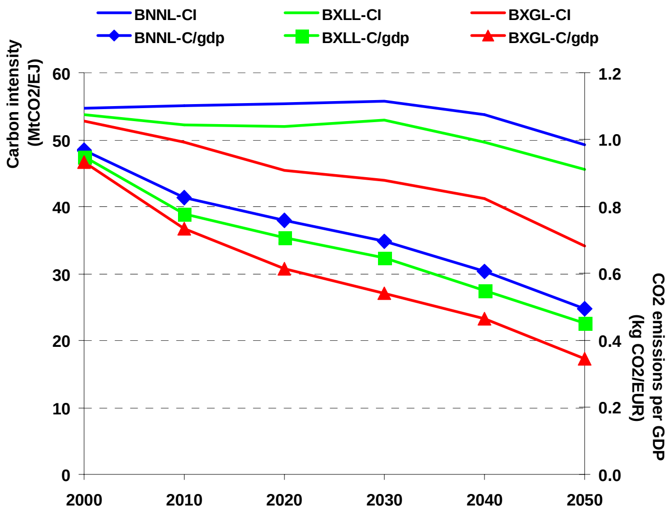

Fig. 18. Development in the carbon intensity and CO_2-per-GDP indicators under Base case and externality cases.

The decarbonisation trend of the energy sector is further portrayed when results are expressed per unit of economic activity, i.e. the global amount of CO_2 emissions per unit of gross domestic product. Figure 18 shows that there is a strong decrease in this indicator in all cases; while the decrease in the reference case relative to the year 2000 is 48%, in the externality cases reach values of 53% (BXLL) and 62% (BXGL). The annual declination rates between 2000-2050 for BNNL, BXLL and BXGL cases are of –1.3%, -1.5% and –2% respectively. Notice that the emissions per unit of GDP (Carbon/GDP) are the product of the carbon (Carbon/Primary Energy) and energy intensity (Primary energy/GDP).

5.3 Cost impacts

5.3.1 Electricity generation cost analysis

To evaluate competitiveness of different power generation technologies, a simplified calculation of electricity generation cost has been performed. The calculation allows assessing impacts of internalisation of different externality modes towards total production cost, and the effect of 'learning-by-doing' on the cost development over studied time period.

Total electricity generation cost (also referred to as levelized cost of energy or busbar cost) is calculated according this formula [adopted from 18]:

$$TGC = \frac{I * CRF}{Q} + \frac{FIXO\,\&\,M}{Q} + \frac{VARO\,\&\,M}{Q} + \frac{F}{Q} + \frac{E}{Q}$$

where:

I = Capital investment cost[1]
CRF = Capital recovery factor
Q = Annual plant output (kWhr)
$FIXO\&M$ = Fixed O&M cost
$VARO\&M$ = Variable O&M cost
F = Fuel cost
E = External cost

$$CRF = df * \frac{(1+df)^n}{(1+df)^n - 1}$$

where:
df = discounting factor
n = plant life time

Figure 19 summarizes results of the total generation cost calculation for the Baseline and externality cases for the present situation and cost projection for the year 2050. The region of ASIA is taken as an example for the analysis. The Base case results in 2000 indicate, that without external cost, IGCC, NGCC and pulverised coal are the cheapest alternatives at 3.0, 3.1 and 3.7 ¢/kWh, respectively. The projected generation cost in the Baseline reflect the change in fuel cost, the effect of ETL towards reduction of investment cost with accumulation of installed capacity by ‘learning’ technologies in 2050, and expected improvement in the conversion efficiency and a higher average load factor. The least cost systems are wind turbines, IGCC and NGCC with projected generating cost at the level of 2.0, 2.2 and 2.8 ¢/kWh, respectively.

If the external cost from the local pollution is added to the generation cost, the competitiveness of technology portfolio changes towards the end of the time horizon. The least cost options in this case in 2050 are the wind turbines, SPV and IGCC with total generation cost of 2.1, 2.8 and 3.0 ¢/kWh, respectively. In the case of internalised local and global externalities, the most competitive systems are again the wind turbines and SPV (2.1 and 2.6 ¢/kWh), followed by gas fuel cells and IGCC with CO_2 capturing (both at level 4.3 ¢/kWh).

It has to be stressed, that these results are indicative and bear all the uncertainties related to the fuel prices development and technological change. Another policy relevant

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[1] Specific investment cost for the learning technologies in 2050 has been calculated as follows [4]:

$$I_{2050} = I_0 * \left(\frac{CC_{2050}}{CC_0} \right)^{-b}$$

where
I_{2050} = Specific investment cost in 2050
I_0 = Specific investment cost at the starting point when technology is introduced into the system
CC_{2050} = Cumulative capacity of the technology in 2050
CC_0 = Cumulative capacity of the technology at the starting point
b = Learning index

$$-b = \frac{\ln pr}{\ln 2} \qquad = \qquad pr = 2^{-b}$$

where
pr is the progress ratio, the rate at which the cost declines each time the cumulative production doubles (e.g. a progress ratio of 80% implies that the costs are reduced to 80% of their previous value when the cumulative capacity is doubled).

comment to the presented values is, that the extent of extra charges due to emission of pollutants influences significantly the level of cumulative installed capacity of power plants. In other words, the technologies with high external cost are introduced into the system at a lower rate and their investment cost reduction is impaired.

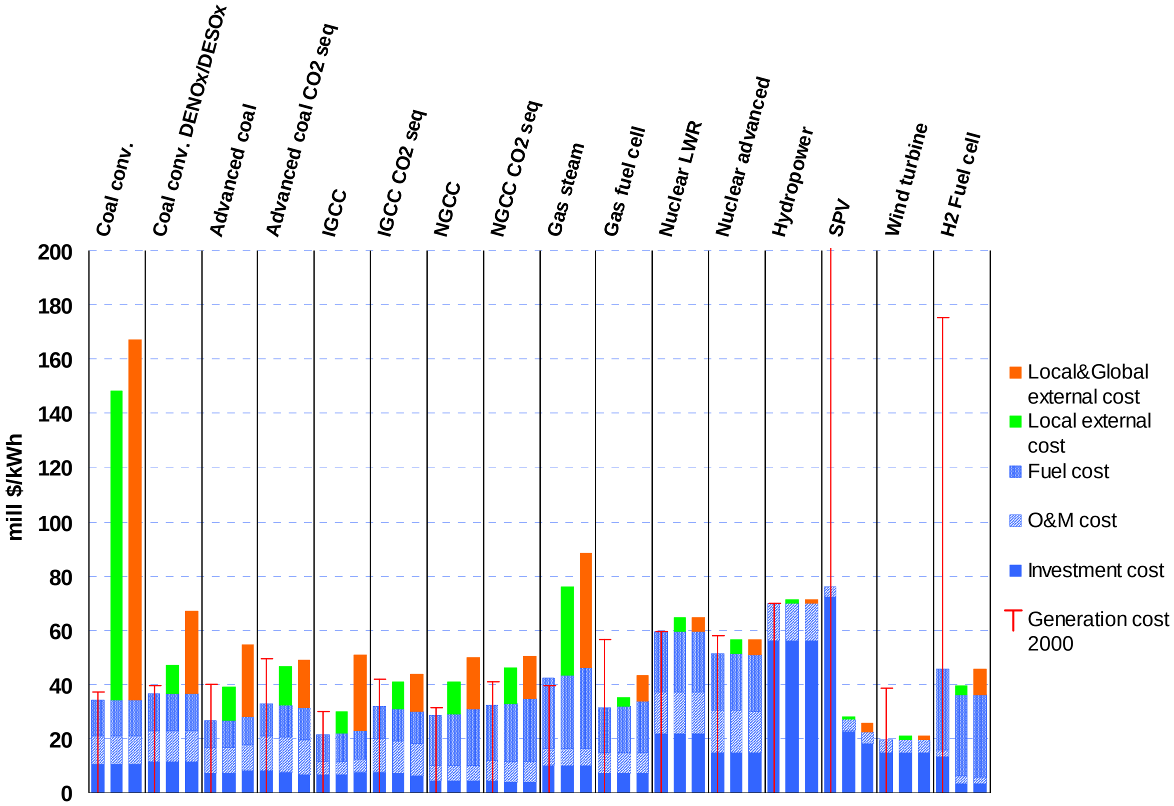

Fig. 19. Break-down of the cost components for power generation by scenarios in 2050 (example region ASIA). Bars from left to right represent BNNL, BXLL, BXGL cases.

5.3.2 Total system cost

The development of the annual total undiscounted system cost in all scenarios is presented in Figure 20. Relatively highest contribution of the extra charges to the total system cost appears in the first period after their introduction (2010). As the energy system tries to avoid paying the extra costs, new (investment intensive) systems are being installed and structural changes take place (e.g. fuel switch). This leads to significant increase in total system cost, especially at the end of the time horizon. The annual level of external charges is shrinking until 2030 as a result of the capability of the system to minimize the extra charges, but then it is growing again with the rise in the electricity demand, which has to be satisfied despite the charges.

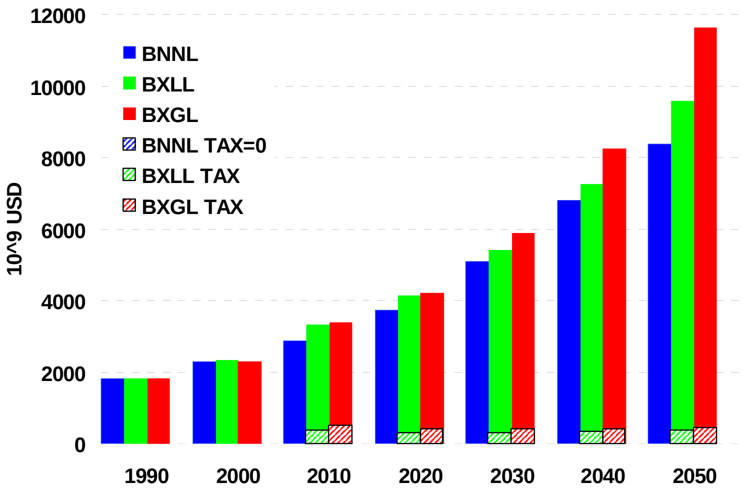

Fig. 20. Development of the total undiscounted system cost and the external cost fraction.

The GMM model runs indicate a high relative change in the cumulative total discounted system costs (or objective function) due to inclusion of the additional charges on the power generation (Figure 21). This increase over the reference development totals in local externalities and local plus global externalities cases 6.3% and 9.0%, respectively. The contribution of the external cost itself counts for 76% of the total increase in BXLL case, and 60% in the BXGL case. The rest is to be attributed to the structural changes occurring within the energy system.

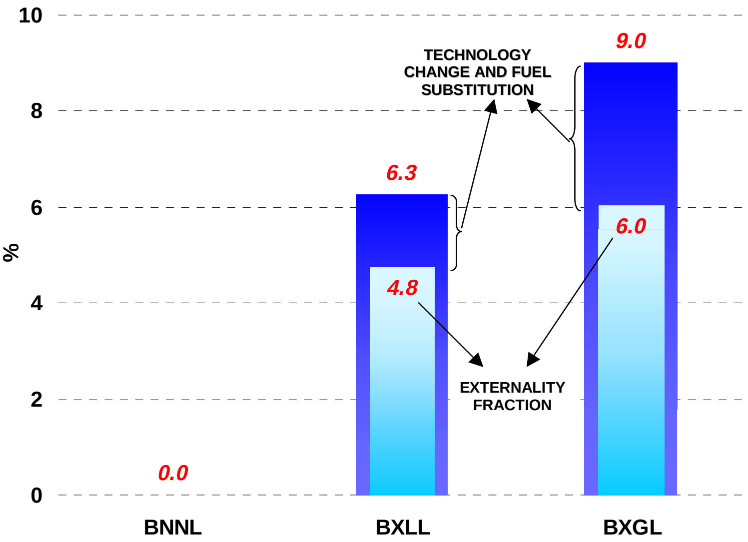

Fig. 21. Relative change in the cumulative discounted energy system cost including external cost fraction.

6. Conclusions

Internalisation of external cost in the power generation sector is an important policy instrument towards the sustainable development in the energy use. Modelling the impacts of such policies carries certain limitations and uncertainties, among which the most important are issues of valuating socio-political priorities of future energy sector developments, socio-political acceptance of technological options, discounting of the future damages to the present value, regional differences in valuating externalities, or the rate of technological change. Nevertheless, number of conclusions can be derived from attempt to model inclusion of externalities into the power generation system, which has been performed using Global Multi-regional MARKAL model with ETL and partial equilibrium.

Internalisation of externalities with and without climate change impacts fosters a fast introduction of emissions control systems and low-emitting power plants. Scenarios analysis reveals substantial changes in the electricity production system (i.e., diffusion of new technologies and fuel switching). In the case of the local externalities, the technologies as coal power plants with emission control, advanced coal power plants and IGCC replace the conventional coal systems. Natural gas combined cycles, and renewables increase their share in the power generation mix. Scenario with local and global externalities further accelerates the structural changes in the power production sector. Contribution of the coal-based generation is reduced to the production from the IGCC systems with carbon removal. Natural gas CC plays dominant role, there is significant increase in the nuclear energy production and renewable systems become to be highly competitive. GMM model runs indicate some efficiency loss due to the use of scrubbers (DeNO$_x$, DeSO$_x$, and C-capturing).

Externality charges on power generation increase the price of electricity for the end-users, therefore the reduction in final demand for electricity in industrial and residential & commercial sectors takes place; electricity consumption is substituted mainly by natural gas and oil.

Both types of external costs have positive global and local environmental impacts due to significant emissions reduction. SO$_2$ and NO$_x$ emissions drop by 50% to 90% in 2030 relative to the Baseline, then their elimination slows down with rising installation of new fossil-based systems (advanced coal, IGCC, NGCC). Charging the local and global externalities (BXGL case) leads to a strong decarbonisation effect. Breakdown of carbon emissions reduction components suggests the major contributions of the inter-fossil switch and increase in nuclear and renewable fraction in the primary energy use. Since the carbon sequestration technologies become competitive, they appear to be an attractive technological option in carbon abatement process.

Studying the impacts of external cost towards the growth in total system cost, it can be concluded, that structural changes and fuel substitutions contribute in BXLL and BXGL cases with 1.5% and 3.0%, respectively. On the other hand, ‘learning-by-doing’ is helping to moderate the level of external cost penalty.

In the future work the emphasis will have to be given to the sensitivity analysis of the total generating cost with different level of external charges, effects of discounting of future damages, and multi-criteria analysis considering different weight of social, economic and environmental/health aspects towards behaviour of the future energy system.

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8. List of abbreviations

Bt – Billion ton (10^9 ton)
CHP – Combined heat and power (cogeneration)
CNG – Compressed natural gas
CO$_2$ – Carbon dioxide
ETL – endogenous technological learning
FGD – Flue gas desulphurisation

GDP – Gross domestic product
GMM – Global multi-regional Markal model
H2FC – Hydrogen fuel cell
IGCC – Integrated coal gasification combined cycle
IPCC – Intergovernmental panel on climate change
LWR – Light water reactor
MARKAL – Market allocation model
Mt – Mega ton (10^6 ton)
NGCC – Natural gas combined cycle
NO_x – Nitrogen oxides
O&M Cost – Operation and maintenance cost
PFBC – Pressurised fluidised bed combustion
SO_2 – Sulphur dioxide
SPV– Solar photovoltaic system
SRES – Special report on emission scenarios
T&D – Transport and distribution

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