Low Carbon Economy, **2013, 4, 51-62**
http://dx.doi.org/10.4236/lce.2013.42006 Published Online June 2013 (http://www.scirp.org/journal/lce)

Producing a Double Dividend for the EU-27 and USA with the Macro-Economic E4M-GAIA Model: Meeting G8 80% Emissions Reduction Target Leads to Economic Growth

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Received January 13th, 2013; revised February 12th, 2013; accepted March 25th, 2013

ABSTRACT

The international negotiations concerning climate change, taken place during the UNFCCC conference in Durban at the end of year 2011, have failed to establish a new global agreement to reduce global emissions. Therefore, the G8 commitments on 80% reduction by 2050 seems to be the most realistic climate change mitigation framework for the time being, enhanced by the political will of the EU and USA administrations. For the needs of this paper, the G8 80% target is further extended to cover the whole EU-27 region, where the reduction commitments of the EU-27 member states are allocated based on the relevant allocation weights considered for the Kyoto Protocol obligations. This paper examines the implementation of the EU-27 and USA 80% emissions reduction target using a macro-economic hybrid model E4M-GAIA of the global economy, standing for Energy-Economy-Environment-Engineering Model of the Earth. The E4M-GAIA model, which adopts similar theoretical background with the "New Economics" school depicted mainly in the well-established Cambridge University' E3 models, is used to implement this target and to compare it with a reference scenario, where no reduction target is pursued. Both scenarios consider that impact of the financial crisis, with updated information to the end of 2010. This paper aims to provide evidence that the proper direction of a portfolio of policies including: regulation, behavioral shift, revenue recycling, energy investments, energy and carbon pricing, can lead to double dividend, namely meeting a deep reduction target and providing gains for the economy.

Keywords: G8 80%; Carbon Pathways; Post-Kyoto; Double Dividend

1. Introduction

The UNFCCC Conference that took place in Durban in December 2011 has postponed the agreement on a legally binding deal comprising all countries for the end of the current decade. Therefore it failed to meet the demand for urgent action, being supported by the latest evidence concerning the accelerating climate change. However there was some progress regarding the creation of a Green Climate Fund (GCF) for which a management framework was adopted. The fund is to distribute US$100 billion per year to help poor countries adapt to climate impacts The GCF can be considered a support in EU initiative in September of year 2009 to provide up to 15 billion euros per year to help developing countries fight climate change and adapt to its predicted devastating consequences. Considering the failure to meet an international agreement on climate change mitigation, the G8 commitment in June of year 2009 to reduce their emissions by 80% by 2050 and to work towards keeping temperature levels from rising 2 degrees Celsius, is standing as the most realistic framework for climate policies. Specific countries, such as the UK, passed new legislation in 2010 to reduce its emissions by 50% by 2025. In the USA, the Obama Administration expressed its commitment to a new climate policy through the adoption of a number of relevant legislation and the support of green companies and investments. The EU has been active the whole decade introducing a number of green policies, such as the Emission Trading System and a number of Directives, across its Member States. Moreover it works towards the integration of its energy markets by 2015 in electricity and gas, using and further strengthening the role of the well established regulatory (ACER) and operation organizations (ENTSOE, ENTSOG).

Considering the uncertainties produced by the financial and economic crisis, any projection for a binding global agreement seems to be stale. At the same time a number of crucial factors, such as the oil prices volatility, the nuclear debate following the Japan earthquake, energy security issues following the Arab turmoil, the energy technological improvements and the environmental concerns over climate change create a challenge of directing climate portfolios towards implementing double or even more merits, namely satisfying emission reduction targets, leading to economic boost, creating new jobs, addressing energy security and public health issues.

The economic crisis and climate change revealed some weaknesses for the neoclassical economic thought, mainly related to the general equilibrium and to the efficient use of resources. Those weaknesses have led a number of the dominant Computable General Equilibrium models to de-link deep emissions reduction targets from economic growth [1,2]. On the other side the economic crisis provided evidence to the existence of economic cycles, theory steadily being adopted by many more economists and policy makers. This has led to an extensive research on how the global economy can boost, which was interpreted by most governments as a need for a green growth. This paper aims at providing evidence that such green growth is possible, managing to produce a double dividend even for very deep reduction targets. The 80% emissions reduction target for EU-27 and USA, within the framework of the G8 80% reduction target, has been examined using the macro-econometric hybrid model E4M-GAIA of the global economy, in order to provide evidence that under a proper directed portfolio of policies including regulation, behavioral shift, revenue recycling, energy investments, energy and carbon pricing, a double dividend can be achieved.

2. Modeling Framework: E4M-GAIA Model Description

This section described the E4M-GAIA model, which stands for Energy-Economy-Environment Model of GAIA. Gaia term arriving from ancient Greek mythology represents the Earth system. Considering the Gaia hypothesis [3], where the Earth system should be considered as one entity, where the economic system should not be considered as closed system. The need for integrated modelling has been further enhanced by the two of the main challenges the human society is facing today, namely the climate change and the financial crisis, which revealed that the economic system should not be considered as a closed system, but it is crucial to examine its interaction with the energy system, the environment and the earth.

Towards this integrated approach, most economic models have been readjusted to incorporate the dimensions of energy, environment and engineering (E4 integrated approach), while a number of alternative theoretical frameworks (Post-Keynesian, “New Economics”, Economics of Climate Change, Economics of Gaia, Evolutionary economics, behavioral economics, complexity economics…) have been emerged as alternatives to the dominant neoclassical approach, in order to cover its inadequacies when facing those challenges. The E4M-GAIA model can be considered to adopt the “New Economics” theoretical background, which was introduced at the University of Cambridge, through the MDM-E3, E3ME and E3MG models [4,5], which have been evolved through time since the 1960s and the Cambridge Growth Project. Those models follow the same overall principles in their economics, construction and operation, namely: Post-Keynesian, structural, hybrid, macro-econometric and dynamic. Information on the “New Economics” theory that is adopted in the model can be found on several publications [6-8].

E4M-GAIA represents a novel approach to the modeling of technological change in the literature on the costs of climate stabilization. It is based upon a Post Keynesian economic view of the long-run. In other words, in modelling long-run economic growth and technological change, the “history” approach of cumulative causation and demand-led growth [9,10], focusing on gross investment [11] and trade [12], and incorporating technological progress in gross investment enhanced by R&D expenditures, has been pursued. Other Post Keynesian features of the model include: varying returns to scale (that are derived from estimation), non-equilibrium, not assuming full employment, varying degrees of competition, the feature that industries act as social groups and not as a group of individual firms (*i.e.* no optimisation is assumed but bounded rationality is implied), and the grouping of countries and regions has been based on political criteria. The exception to the Post Keynesian approach is that at the global level various markets are closed, e.g. total exports equal total imports at a sectoral level allowing for imbalances in the data. The model has been developed to include the bottom-up energy technology model, ETM [13], within the top-down highly disaggregated macroeconomic model, E4M-GAIA. Thus, like the studies [14,15] which are also based on the linkage of top-down and bottom-up models, this modelling approach avoids the typical optimistic bias often attributed to a bottom up engineering approach, and unduly pessimistic bias of typical macroeconomic approaches. The advantages of using this combined approach have been reviewed [16].

More details about the model can be found in a recent paper [17].

2.1. Mitigation and/or Policy Options and Instruments

The E4M-GAIA implements emissions reduction targets through the implementation of portfolio of policies. The model is capable of explaining how low-carbon technologies are adopted as the real cost of carbon rises in the system, with learning by doing reducing capital costs as the scale of adoption increases. The model includes the economic instruments of CO_2 emission allowances (auctioned or grandfathered), energy and carbon taxes, employment taxes, and other direct and indirect taxes. A rise in the costs of fossil fuels resulting from increases in CO_2 permit prices and carbon taxes thus induces extra investment in low-carbon technologies, and this is larger and earlier than the investment in conventional fossil technologies in the baseline. The carbon tax revenues and part of the permit revenues are assumed to be recycled in the form of lower indirect taxes. The outcome is that the extra investment and implied accelerated technological change in the stabilization scenarios leads to extra exports and investment more generally, and higher economic growth.

The policy instruments that are explicitly in the model to promote GHG abatement are:

- carbon and energy taxes;
- emission permit schemes are at regional and global levels by any mix of energy sectors;
- revenue recycling;
- R&D expenditures in total by sector and region;
- incentives;
- regulation.

2.2. Assumptions

For the purposes of this paper, a range of data updates and technical adjustments have been made.

2.2.1. Fossil Resource Costs

E4M-GAIA, as a demand driven model, does not have fossil resources supply curves. Considering recent projections of global fossil fuel prices [20], fossil resources costs for coal, oil and natural gas has been shifted upward. These reflect long-term drivers in rising energy demands and constrained supplies.

For the needs of this study base prices have been considered. To examine the uncertainty of those prices, the E4M-GAIA model has been run 1000 times for each scenario, where the fuel prices took a stochastic value under the following rule:

The stochastic (random value) could be up to ±15% of the base prices for the period 2010-2020 and up to ±30% of the base prices for the period 2030-2050.

The Base fuel prices, on which the above uncertainty flexibility percentages are applied, are shown in **Table 1**.

2.2.2. Electricity Technologies

E4M-GAIA has a sub-model for the treatment of the electric system expansion, as mentioned above. It includes 28 energy technologies. Each of them is represented by 21 technology characteristics. These technologies and their characteristics have been recently updated in order to represent new options. A comprehensive revision of economic and technical data on CCS, nuclear, wing, biomass and marine technologies has been undertaken [18]. CCS technologies are considered to account for capture efficiency (90%).

2.2.3. Transport Technologies

E4M-GAIA does not have a detailed representation of the transport system. It has three fuel options (petrol, diesel and electricity), with biofuels not being considered. Recent technical developments from the auto-manufacturers have been considered in the modelling by adopting a positive feedback approach. This means that once the electric vehicles start to penetrate in the market, the alternative options (e.g. hydrogen vehicles) have to become much more competitive than the electric vehicles to penetrate in the market. Considering that hybrid vehicles are already market available and plug-in vehicles will enter the market in the next decade, the transport sector is moving towards electrification. The penetration of new technologies e.g. electric vehicles is assumed to be made through regulation which forces auto producers to develop advanced plug-in electric vehicles. Moreover the penetration of electric vehicles is modeled to work in favour of certain renewables. Wind and tidal plants are considered to increase their capacity factor by up to 10%, depending on the penetration level of plug-in electric vehicles. It is assumed that the electrification of the transport sector will be accompanied with tariff policies

Table 1. Base fossil resource costs.

	Original units	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Crude Oil	2005$/bbl	31.38	50.62	57.50	55.00	55.00	57.50	60.00	65.00	70.00	70.00	70.00
Gas	2005$/MMBTU	4.77	7.46	6.75	6.75	7.00	7.32	7.64	8.27	8.91	8.91	8.91
Coal	2005$/tonne	35.89	60.48	55.00	55.00	57.04	59.63	62.22	67.41	72.59	72.59	72.59

that encourage cars to be charged during off peak times. This can lead to a further use of specific renewables, which have the capability to operate at their maximum output during off-peak times (e.g. night), but for technical reasons (the base plants can not be switched off), the renewables are otherwise underused.

2.2.4. Carbon Pricing

- EU-ETS

For the reference scenario the EU Emissions trading scheme is imposed with an EU-ETS price of €20/tCO2 from 2010 onwards in the electricity and industrial sectors-broadly on EU-ETS Phase 2 coverage. This price level and coverage is maintained through 2050. The carbon price is exogenous in the model. Carbon pricing is considered as one of the policies that are applied for helping financing energy investments. So, the carbon price can be considered as a price signal required, helping towards meeting deep emission reduction targets.

- CO_2 constraint curve

In contrast with most energy system or general equilibrium models, emission reduction targets are not implemented by imposing this target exogenously in the model. A number of policies (described in the next session and the discussion of the results) are implemented at different strengths and in different timing so as to meet the targets.

In order to examine the uncertainty of the carbon pricing, the 80% reduction target is being implemented with the base fuel prices, according to **Table 1**, targeting to meet this reduction target and also to provide a higher GDP output compared to the reference scenario. A similar work has been carried out recently with the E3MG model [19], which estimated that for this target it is needed a portfolio of policies including a carbon price to rise steadily at the levels of 200 $/tCO_2$ in 2000 year prices by 2050. It has to be mentioned, that as the E4M-GAIA is not an optimization model, any mitigation reduction scenario can have several solutions, leading to negative or positive cost compared to the reference scenario. This is in contradiction to the neoclassical approach where the reduction scenarios lead to positive cost, considering that the starting point of the scenarios accounts for the optimal energy efficient state. Therefore, for the E4M-GAIA model there might be solutions, e.g. different portfolio of policies or different extent and time those policies are implemented, that can lead in even more gains or significant cost, resulting from the non-linearity and nature of the model.

As, one of the aims of this paper is to provide evidence that such targets can be met with gains for the whole examined economies, a portfolio of policies (including the carbon pricing) has been selected to form the 80% reduction scenario. This portfolio includes the implementation of a specific evolution of the carbon pricing, which in case of the EU-27 and USA takes the values shown in **Figure 1**.

For the needs of this paper, and in order to examine the uncertainty of carbon pricing besides the uncertainty of fossil fuels pricing, we consider that the carbon price can take a stochastic value up to ±25% of the base carbon price for the period 2010-2020 and up to ±50% of the

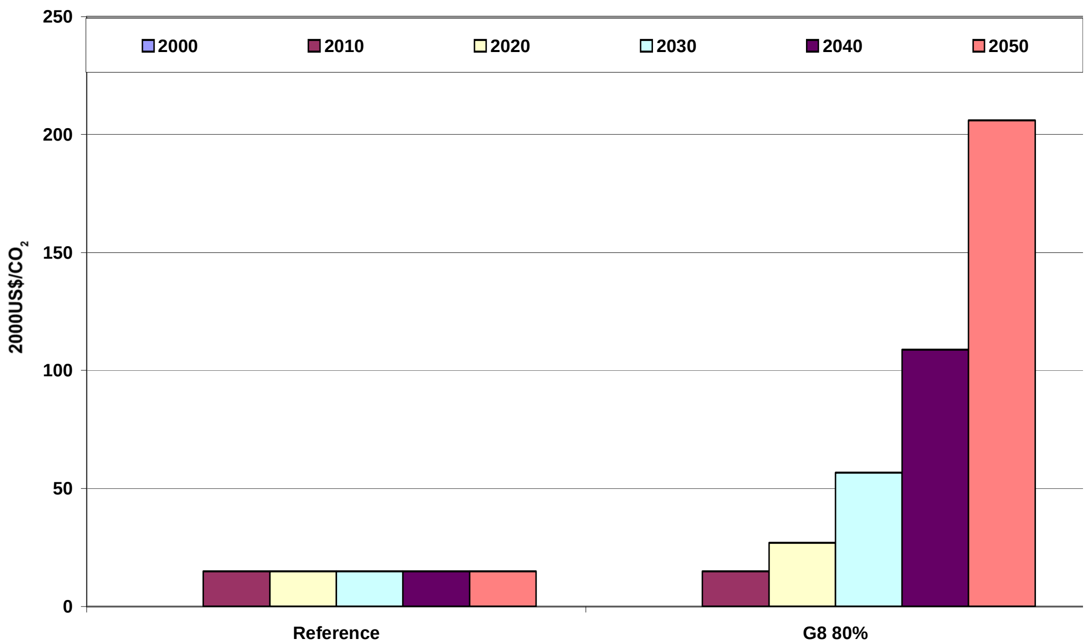


Figure 1. Base carbon pricing for the EU-27 and the USA in US$/tCO$_2$.

base carbon prices for the period 2030-2050.

2.2.5. Calibration

Base year 2000 CO_2, final energy, and primary energy calibration has been fine-tuned to exactly match with calibration sources [20].

3. Scenarios

The E4M-GAIA model is run for the 80% reduction target by 2050 compared to 1990 levels and for a reference case. An important advantage of the E4M-GAIA model is that it is an energy-economy-environment model of the global economy, allowing for the global reduction in costs of technologies if adopted by many countries. The cumulative investments on alternative technologies at global level, allow their faster penetration. Deep emission reduction targets, such as those examined at this paper, could be achievable at much lower costs when implemented internationally. CO_2 reduction targets are achieved through a portfolio of policies. This is in contrast with most energy system models or general/partial equilibrium models, where a reduction target is imposed exogenously and hence the models estimate the marginal abatement cost for meeting this target. The policies considered in E4M-GAIA are:

- Carbon price (either through Carbon trading for the Emission Trading System (ETS) sectors or Carbon Tax for the rest of the economy) is implemented. The revenues are recycled via the following policies.
- Incentives for electricity technologies through revenue recycling. These revenues are raised from the auctioning carbon permits. This subsidy is spread across new technologies, *i.e.* renewables and CCS (excluding nuclear and hydro).
- Accelerated diffusion of electric plug-in vehicles is assumed through technological agreements and behavioural shifts in transport demand.
- Revenues raised from carbon permits auctioning are recycled to energy-intensive industries in order to incentivize the conversion to low-carbon production methods.
- Carbon tax revenues from households are recycled via investments in energy efficiency by providing incentives for improving the energy efficiency of domestic dwellings and appliances and for introducing new ones such as low-emission dwellings and solar appliances.
- Accelerated carbon price increase at an earlier year e.g. 2020 (not applied at this paper).

It should be mentioned that energy efficiency policies for electricity consumption are considered as no-regret options [1], as they lead to reduction in electricity demand and so reduce the need for investment in new generation and infrastructure. Assumptions on the no-regret options have been based on a recent study [21], where as can be seen in **Figure 2** the energy efficiency policies have negative marginal abatement cost. These policies are implemented in the period 2010-2020. Based on the revenues from permit auctioning that are recycled via investments in energy efficiency at the consumption side, these measures can lead to significant demand reduction even in the medium term.

Moreover the rate at which plug-in vehicles replace conventional vehicles will affect the mix of electricity technologies in favour of some renewables, e.g. wind. This comes from the fact that it assumed that tariff policies are implemented that encourage plug-in vehicle users to charge their cars' batteries at night when the electric demand is at low levels. Such tariff policies com

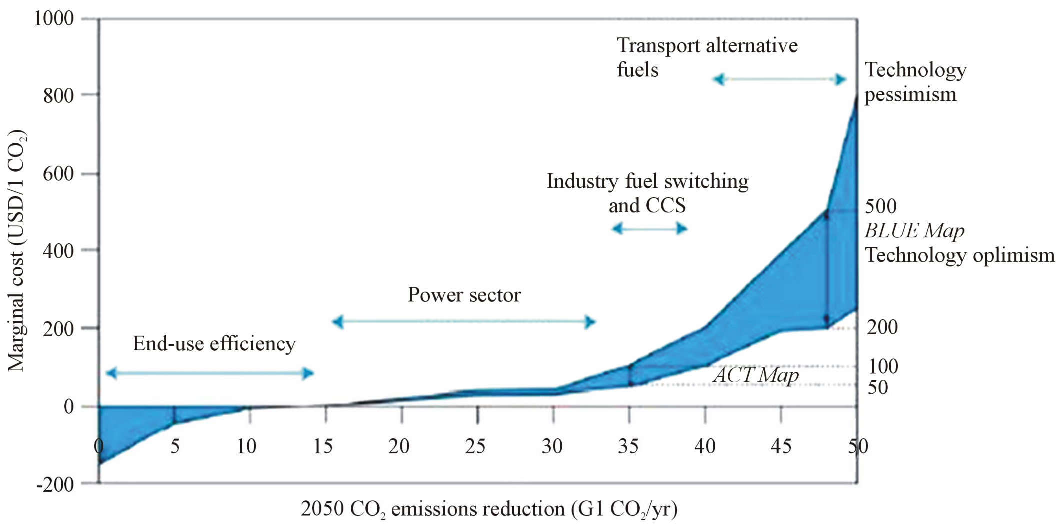


Figure 2. **Marginal abatement cost of different policies, source: [21].**

bined with control systems allow the user to select when their cars' batteries will be charged so as to allow a new peak before midnight and lead to a more balanced load curve. Such policies reduce the need for investment in new capacity, and raise the load factors of the existing equipment. This works in favour of stochastic generation, such as wind farms, which normally have to operate at low levels during the night, although they could operate at higher output due to higher wind speeds at that time.

The above scenarios are implemented under the following main modeling assumptions:

- The discount rate is required only in the energy technology sub-model (10%), for estimating the net present value of the different technologies.
- Penetration of technologies in electro-production is based on [22]: the theory combines the estimation of net present value and a probabilistic approach fro the diffusion of technologies compared to a marker technology.
- Reduction targets are implemented through a set of polices. These reduction targets are not set, but achieved via specially designed policy packages.
- International drivers are assumed.
- Macro effects are assumed e.g. in energy efficiency policies the direct plus macroeconomic rebound effect is considered.
- Economy is not treated as being in equilibrium.
- Full utilization of resources (e.g. no unemployment) is not assumed.

4. Results-Meeting the G8 Reduction Target

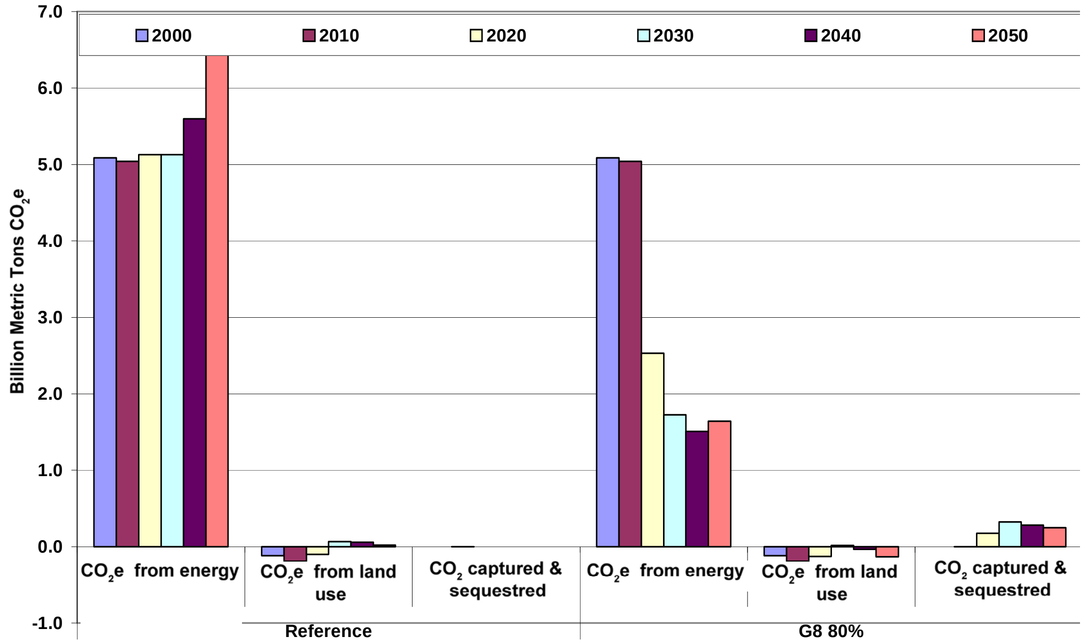
E4M-GAIA focuses on the implementation of policies rather than on the reduction targets. The different polices interact in a complex way, which can be analyzed through the non-linear nature of the E4M-GAIA model. Results for the USA and the EU-27 are presented. EU-27 constitutes of all major European countries (Germany, France, UK, Italy) as sole regions and other two regions (rest of EU-15 and the new 12 EU countries that have recently entered the European Union). Although the scenario concerns reduction efforts for the G8, similar assumptions for the other two sub-regions of the EU-27 have been made, as these countries are influenced by the decisions made at the European level.

4.1. CO_2 Emissions

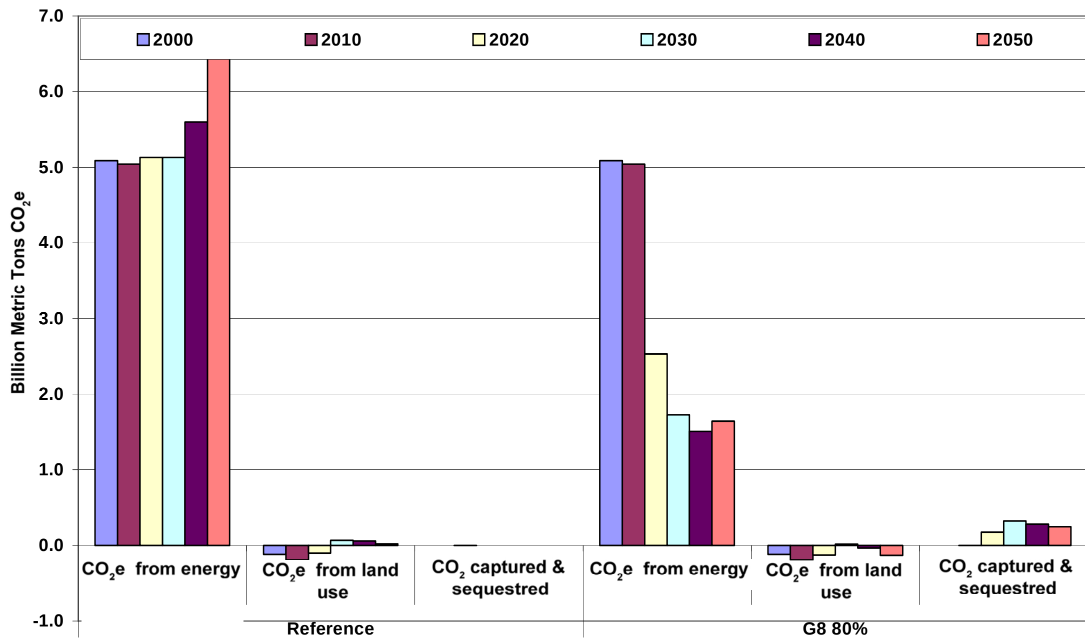
Figures 3(a) and **(b)** provide the CO_2 emission levels for the 2 scenarios over the projection period. CO_2 emissions for the reference scenario are estimated to have a small increase compared to 1990 levels for both presented regions. The increase is observed mainly in the last two decades 2030-2050, more obviously for the USA, and is attributed mainly to an increase in energy demand which is covered mainly from natural gas either for electric production or for heating purposes. The energy demand is estimated to fall in the period 2010-2020 due to current directed energy efficiency. Then the economic activity forces the energy demand to be increased, as the demand and the economic activity are positively correlated.

The energy demand and emissions level in the reference scenario is reduced in the medium term, resulting from the effect of the global recession. This scenario develops earlier and ongoing work [19] examining the financial crisis, which outlines some of the causes of the current crisis and suggests a global coordinated policy response focused on investment. The financial crisis affects the economic activity, the saving rates, the consumption, the access to the credit and so the investments leading to a lower economic growth for the medium term, after the recovery of the global economy. But in the long term (beyond 2020) the impact of the recession is partly offset from the policies that have been directed. The reference scenario considers all structural changes and investments directed until the mid- 2009, when the scenarios were constructed. The investments are treated as green energy investments that lead to tackling the climate change and also boosting the economy, [19]. However, the reference scenario does not consider additional long-term policies or the implementation of further energy investments, reported in several official publications in the medium term [20]. Such policies are considered in the CO_2reduction scenario.

At sectoral level, the consumption sectors (buildings, industry) decrease emissions in the first decade and later stabilize their emissions due to the implementation of energy efficiency measures, while the power sector is the first to reduce significantly its emissions up to 2035 even for the reference scenario. Alternative technologies prove to be competitive to the traditional ones and dominate almost the whole system in the carbon reduction scenarios. Crucial to the results is the emission reduction of the transport sector, due to the penetration of electric vehicles and behavioral shifts. As described above, the shift to electricity in the transport sector works in favor of some renewables, such as the wind, the availability of which is significant in the UK. The transport sector leads to an important reduction in overall emissions, resulting also from a behavioral shift that locks in the energy and emissions reduction resulting from the higher prices and the regulation. The rebound effect [23] *i.e*. the increase in energy use arising from the im- plicit reduction in costs of energy as a result of energy- efficiency improvements, is offset by the increase in en- ergy prices due to the emission trading scheme and the carbon tax. All the end-use sectors (transportation, resi- dential, services and industry) are covered by policies



(a)



(b)

Figure 3. (a) Emissions for the EU-27 in billion metric tons CO_2e; (b) Emissions for the USA in billion metric tons CO_2e.

that decrease their emissions sharply, especially for very strict targets such as the 80% reduction.

4.2. Energy Demand

The above described energy demand functions predict that the energy demand (**Figures 4(a)** and **(b)**) will remain almost stable in the period 2020-2030 and then be-increased up to 2050 for the reference scenario, affected mainly from the economic activity and from the fact that energy efficiency investments are considered for the first decade of the examined period. The emission reduction scenarios are implemented through increased investments in energy efficiency measures and also through behavioral shifts with neutral rebound effect. Such measures lead to a significant decrease in energy demand by about 50% - 60% for the G8 80% scenario compared to 1990

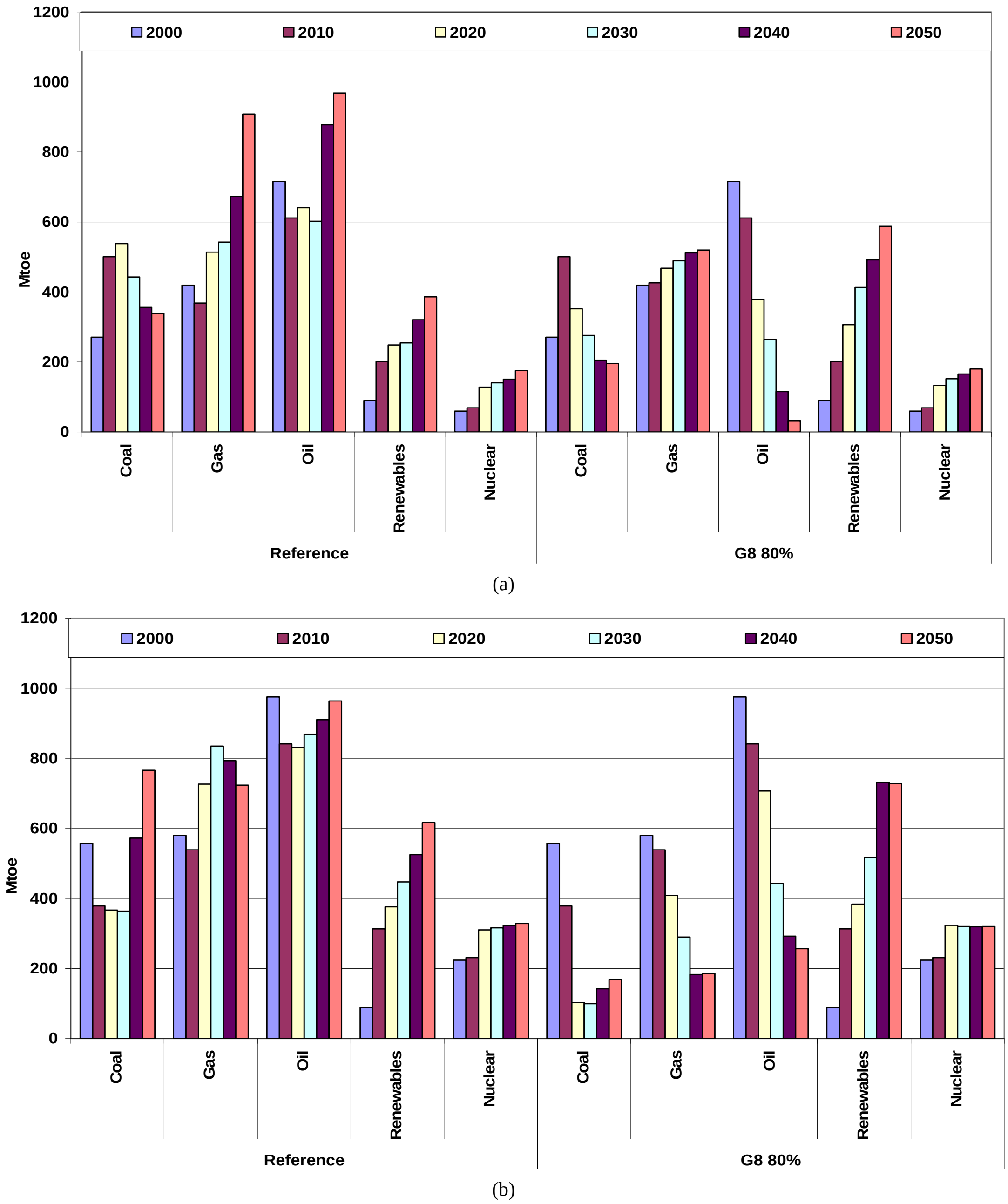


Figure 4. (a) Energy demand for the EU-27 in Mtoe; (b) Energy demand for the USA in Mtoe.

demand and even more compared to the reference demand in 2050. Demand for gas is increased for both scenarios, while the demand for oil remains almost stable for the reference scenario and decreased sharply for the reduction scenario. The penetration of renewables is impressive in case of the G8 80% reduction scenario, which is affected by the international effort-leading to lower costs-, to carbon pricing and other measures e.g. regulation-enhancing the related energy investments and to other factors e.g. electrification of transport. The demand for nuclear is considered to remain almost stable in both scenarios, as it is considered that there is a concern for energy safety issues, eliminating its potential to dominate the market, and a concern on energy security issues, allowing nuclear to keep a certain amount in the energy mix for diversification purposes. The demand for coal is decreased for the reference scenario, but for the emission reduction scenario, the political will of the European Union to support the Carbon and Capture Storage technology allows coal to keep an important part of the energy mix, by either new plants or retrofitting old units. This is not so obvious for the USA, where the coal demand is decreased even in the G8 80% reduction scenario, which is characterized by a higher share of renewables and nuclear in the energy mix.

The results show that the electric mix can be diverse which, considering the significant penetration of renewables, increases the energy security of the country. This diversity comes from the fact that the electric system expansion is not modeled as a classic cost optimization problem, where once one technology is slightly cheaper than the others is dominates the system. The different candidate technologies can penetrate into the system, by increasing their cost effectiveness through incentives, learning by doing and learning by R&D, based on a probabilistic approach [13]. This approach considers the market penetration of the different technologies in the history and estimates acceleration factors for them, allowing them to penetrate at a small or higher extent depending on their net present value.

Transport demand is decreased more compared to other sectors. This is attributed to behavioral changes and to a shift to electric vehicles through the implementation of relevant regulation. Electric vehicles are more efficient compared to conventional fuel vehicles and their penetration works in favor of renewables such as wind resources as they increase their capacity factor. The significant decrease in the transport demand is attributed to changes in citizens' behavior in two directions. The first is a positive feedback in the adoption of the new technologies by the consumers. This means that once the electric vehicle become the dominant technology, alternative options such as the hydrogen cars have to be cheaper enough and not just competitive, so as to gain percentage of the market. The second change is a behavioural shift of citizens to a different lifestyle by preferring cycling and public transport, which is considered as a policy with neutral rebound effect. But for the time being such policies are not modeled in great detail within the E4M-GAIA model.

4.3. Economic Results

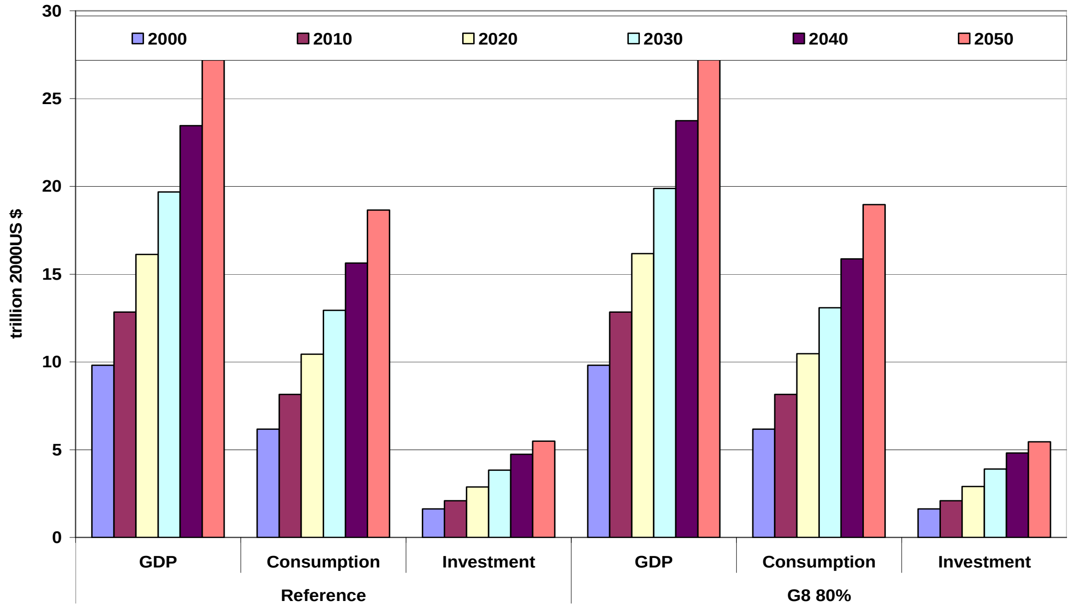
Carbon permit price (**Figure 1**) is increased steadily to a high price. The results show that the carbon price is not very high [1], when accompanied with several policies. As discussed above if the portfolio of policies were implemented with other priorities e.g. further electrification of the transport sector and further support on renewables, then the economic growth would be higher and the required carbon price lower. It has to be mentioned that in all scenarios, carbon price is implemented as a carbon tax or by auctioning emission permits, which both lead to gains for the government. These gains were recycled to energy sector investments.

Probably the most important conclusion arising from this paper is that there exist different pathways implementing deep reduction targets that also lead to an increase in economic growth (**Figures 5(a)** and **(b)**). But this requires that there exist policies to guarantee that the revenues from the energy sector or other policies e.g. green fiscal measures will be recycled to energy efficiency investments and low carbon technologies. Once this is ensured, it can be taken out that revenue recycling can lead to a rise in economic growth. **Figures 4(a)** and **(b)** show that consumers' expenditure and investment is slightly higher for all G8 80% reduction scenario compared to the reference scenario.

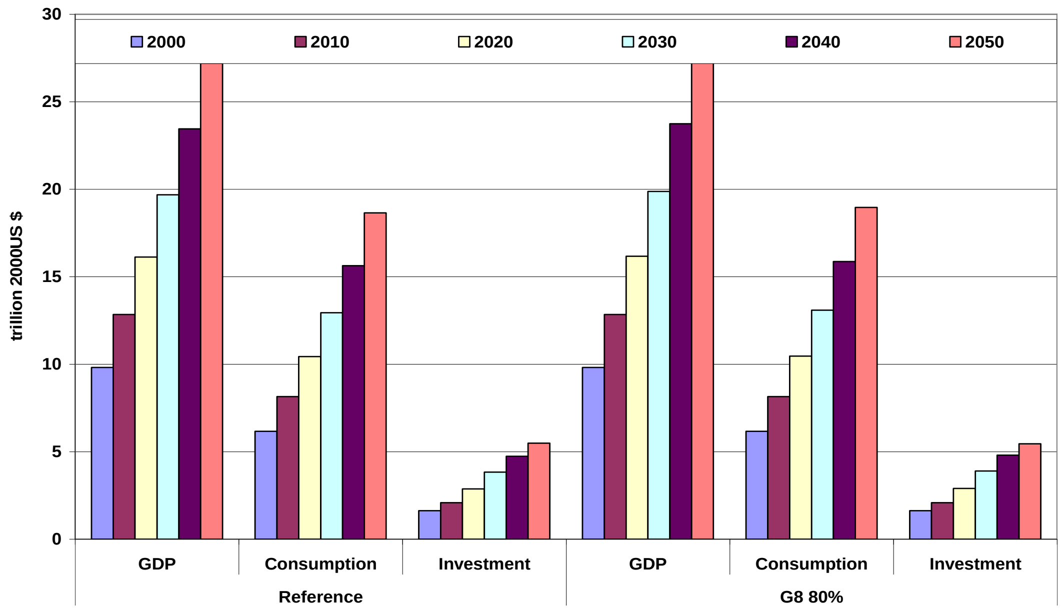
5. Conclusions

The E4M-GAIA model adopts a hybrid approach. The aggregate and disaggregate energy demand is estimated using econometric techniques, allowing for fuel switching for the 12 different fuel types and for the 19 fuel users, while the power sector is simulated using a probabilistic approach which considers the economic, technical, environmental characteristics of the power units but considers also the history. The electric system expansion is modeled by estimating parameters for the different technologies based on historical data, which allows new technologies to gain a share in the market even when their cost is higher than conventional technologies. Moreover the dispatch of the different technologies to meet the electric demand, although using the cost optimization approach comparing the penetration of the different technologies, takes historical data as its starting point. Both the energy demand system and the energy technology options are implemented so as to model market imperfections that exist in all markets and are not usually considered in the classical cost optimization techniques. These market imperfections, resulting either from socio-political factors or from the presence of oligopolies that speculate on the electricity price cause differentiation in the electricity mix across countries, and lead in many cases to significantly different profiles from those projected from models assuming perfect market conditions.

The G8 80% scenario (extended by its implementation at the whole EU-27) is implemented in this framework, allowing the cumulative investment at international level for alternative technologies so their faster penetration provides solutions with a more diverse electric mix. It is also important to mention that the emission reduction scenario is modeled not by imposing a reduction target and estimating the marginal abatement cost for meeting this target, but by applying different policies at different strengths and different timing, which is consistent with the theoretical background of the space-time economics adopted in the E4M-GAIA model. The reduction scenario has been implemented by applying in different strengths



(a)



(b)

Figure 5. (a) GDP, Consumption and Investment for the EU-27 in trillion US$; (b) GDP, Consumption and Investment for the USA in trillion US$.

and timing the policies of carbon pricing, direct investment and revenue recycling in the form of investments in the power sector, investments in the transport and other consumption sectors. The aim was all of them to have a positive effect, by reducing emissions whilst maintaining economic growth. This proves to be the most important conclusion of this paper, that there exist several portfolios of policies that can have large emissions reductions and also help the economy to grow. This finding is in contrast with those from many models predicting that energy investments will have an important negative effect on the economic growth, deriving from the assumptions in the neoclassical approach of full employment (so that there are no extra resources available to produce extra output) and of optimization of the baseline economy by a central planner (so that any shift away from the optimal solution will reduce GDP). But it is consistent with recent political decisions at EU, USA and Japan to invest on green technologies and infrastructure so as to boost their economies out of the global recession.

The power and the transport sector show the highest decrease in emissions and so constitute the most critical sectors for meeting deep reduction targets. The decarbonisation of the power sector happens in two directions: in the replacement of conventional units with gas, nuclear or CCS plants and in the further penetration of renewables. The extent and the timing of the incentives for these technologies are critical. Renewables penetrate at levels lower than 50%, based on the assumptions on technical restrictions. Recent research work under the IEA on the penetration rates of renewables suggests levels up to 40% [24] due to stability and power quality issues. But the electrification of the transport sector allows an increase of the capacity factor of stochastic renewables such as wind, if accompanied by the proper tariff policies. So their penetration level in the electricity production has been allowed up to 50%, generated mainly from wind farms and secondly from biomass, marine and solar plants. In all scenarios the model produces solutions with higher energy diversity than expected from a cost-optimization solution. In that way the model's probabilistic approach resolves the problem of energy security.

The decarbonisation of the electric and transport sectors leads to significant emission reductions and also maintains economic growth. But it has to be mentioned that very deep reduction targets such as the G8 80% target can only be achieved through stronger regulation, encouraging faster adoption of new carbon-reducing technologies and higher investment. This scenario implies a global technological revolution in favor of low-carbon products and processes, achieving lower costs through economies of specialization and scale. Decarbonizing the energy system is a space-time problem with the different portfolios of policies becoming preferable depending on the final and intermediate targets. Achieving the stringent 80% target for 2050 appears feasible, while maintaining economic growth, but implies adoption of a portfolio of policies including strong regulation and high emission permit prices.

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