Energy and Climate Policy Consideration Using the GCAM Model: Assessing Energy Sources and Technology Options

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Abstract- This paper aims at applying energy and climate policies with the Global Change Assessment Model (GCAM) model, towards assessing energy sources and technology options. Towards reducing emissions, the model is used to apply top-down climate policy, implementing the Representative Concentration Pathways (RCPs), as well as to apply bottom-up energy policies, implementing measures for the power and transport sector. The top-down climate policy enables the examination of ambitious emission reduction scenarios, such as the “RCP 2.0” and “RCP1.0” pathways, identifying that the energy mix shift towards environmentally friendly technologies is not adequate. The penetration of innovative technology options absorbing emissions is needed, especially beyond 2050, where major negative emissions are required to meet ambitious targets. Detailed energy balance flows, through the provision of Sankey diagrams, show the required changes from top-down perspective. The bottom-up energy policy perspective enables the formation of specific realistic scenarios in the different subsectors, such as the power and transport sectors, providing insights on the required policy changes on different energy sources and technology options, such as renewables and electric vehicles. Although our analysis does not provide a direct detailed comparison among the two approaches, both approaches provide clear signal on the penetration of electric vehicles, the renewables but as well the need for carbon capture technologies in the long-term.

Keywords Energy policy; Climate policy; GCAM; Power System; Transport Sector.

Acronyms and Abbreviations

AR	Assessment Report	BEV	Battery Electric Vehicles
CCS	Carbon capture and storage	CO_2	Carbon Dioxide
ETS	Emission Trading Scheme	EU	European Union
GCAM	Global Change Assessment Model	GDP	Gross domestic product
GHG	Greenhouse Gas	IAM	Integrated Assessment Models
IPCC	Intergovernmental Panel on Climate Change	IRENA	International Renewable Energy Agency
MTC	Million Carbon Tonnes	MJ	Mega Joule
NDC	National Development Contribution	PKT	Passenger Kilometre Travelled
RCP	Representative Concentration Pathways	SUV	Sport Utility Vehicles
UNFCCC	United Nations Framework Convention on Climate Change	USA	United States of America
US DOE	United States Department of Energy	VKT	Vehicle Kilometre Travelled

1. Introduction

The implementation of effective climate and energy policies is one of the first priorities from most governments and institutions. The acceleration of climate change leads to the needs for proper assessment and direction of such policies. There exist a number of different tools and methodologies used to apply climate and energy policies. Their result can be contradicting and/or can be misunderstood by decision makers. A crucial reason for this is the lack of capability on the modelling theoretical and numerical assumptions, as these drive the models. Moreover, another reason is the perspective of the application, namely top-down or bottom-up approach. Those perspectives might lead on different suggestions and concluding remarks, as usually they concern the application of different models, not allowing even an indirect comparison among them. There is space in the literature for the consideration of both perspectives especially with the same model.

This paper aims to implement energy and climate policies with the same modelling framework, aiming to present different perspectives on their application, namely top-down and bottom-up. Although our analysis does not provide a direct detailed comparison among the two approaches, it is useful on the identification of common signals towards low carbon economies. The paper uses the Global Change Assessment Model (GCAM) [1, 2], assessing different energy sources and technology options. The model is used to apply top-down climate policy, implementing the Representative Concentration Pathways (RCPs), as well as to apply bottom-up energy policies, implementing incentive measures for the power and transport sector. The application of top-down and bottom-up perspectives enables the comparison among the different perspectives, which stands an important debate in the energy system and climate change modelling community. However, in our analysis we do not provide detailed direct comparison among the two perspectives, but only at examining common trends in energy sources and technology options. This stands as a limitation of our work. However, we consider that our analysis contributes to the literature as we use a robust model through different perspectives, which leads to similar insights concerning the evolution of energy sources and of specific sectoral technologies. The top down perspective indicates the crucial sectors, sources and technologies for meeting deep reduction targets, while the bottom-up perspective indicates how those technologies and sources become realistic options.

RCPs [3] are possible climate futures, differentiated by how much greenhouse gases are emitted within this century [4]. They have been adopted by the Intergovernmental Panel on Climate Change (IPCC) [5] for its fifth Assessment Report (AR5) and are considered robust scenarios for decision making and research. The model is used to examine even more ambitious emission reduction scenarios, such as the RCP 2.0 and RCP1.0 pathways, aiming to identify that the energy mix shift is not adequate white the penetration of innovative technology options, especially beyond 2050, where major negative emissions are required to meet those targets for the ambitious scenarios [6]. Therefore, the assessment of different energy carriers and technology options on meeting those targets are essential. To do so, the model outcomes are extended to provide the detailed energy balance flows, through the provision of Sankey diagrams. Those diagrams provide a well-structured view on the evolution of the energy balance in each region over time, showing the flow of energy from its primary source to the end use sectors, through different transformation and technology options.

The bottom-up energy policy perspective enables the formation of specific realistic scenarios in the different subsectors, such as the power and transport sectors, providing insights on the required policy changes on different energy carriers and technology options, such as renewables and electric vehicles. There are several studies that focus on the contribution of specific technologies or energy carriers on how they could contribute to the implementation of the deep emission reduction targets. Foley et al. [7] provide a review of developments in technologies with a direct measurable impact on sustainability considering the Paris agreement on climate change. Dooley and Calvin [8] examine the temporal and spatial deployment of carbon dioxide capture and storage technologies, across the representative concentration pathways. Coope M. [9] examines the role of renewable and distributed resources in a low carbon future. We use the GCAM model to apply both climate and energy policy, assessing the energy carries and technology options from different perspectives. The model is applied for all its regions, however the results presented in this paper focus on the USA, although the President of US announced that United States would withdraw from the Agreement [10, 11]. All source code and results are offered in an open manner through the Harvard Dataverse Repository, at the persistent link https://doi.org/10.7910/DVN/A7JUMB [12]. Having mentioned the above, it is clearer that this study seeks to bridge the top-down and bottom-up climate policy. Top-down climate policy is analyzed through simulating the global condition of the energy system being constraint by maximum expected radiative forcing. The bottom-up approach parametrizes the performance of important technologies such as electric vehicles and investigates on which degree this affects carbon emissions.

2. GCAM Model

As mentioned in the previous section, one of the main aims of the paper is the implementation of energy and climate policies with the same modelling framework. This eliminates the discussion on the characteristics of the different models, but raising the importance of the applied perspective, namely top-down and bottom-up.

The Global Change Assessment Model (GCAM) enables the examination of different climate policies, such as the Representative Concentration Pathways (RCPs) [6], providing insights on the evolution of greenhouse gasses emissions and air pollutants in different regions, sectors, energy carriers and technology options, towards meeting those carbon pathways. The incorporation of an energy submodel system enables the examination of specific energy policies, focusing on the application of different measures are regional, sectoral and technology level. This bottom-up approach enables the understanding of potential impact of the future technology developments [14], or projecting the final use in different sectors, such as industrial, transportation [15], commercial or residential, but per different needs (cooling, heating, etc) and per specific fuel type.

Global Change Assessment Model [2] is a global integrated assessment model developed by the Pacific Northwest National Laboratory in Richland Washington, a U.S. Department of Energy (DOE) government research laboratory, to explore long-term energy and climate policy scenarios up to the end of 21st century by 5-years steps. It is an open source software, providing detailed data of energy resources, exploitation quantities by specific types of fuel, use in different sectors and subsectors of energy, agriculture and land use, economic information, as well as CO_2 emission, taxes, energy losses, price elasticity, but also trade of both, energy and carbon.

The GCAM model is a long-term equilibrium model, linking the economic, energy, land-use, and climate systems. Besides its neoclassical equilibrium nature, it adopts a novel approach in determining the market share of the different technologies, which is estimated based on a probabilistic approach and the considering of the substitution elasticity (σ) among the technologies.

Inputs in the GCAM model [13] includes numerous information and data such as fuel types, such as unconventional oil, crude oil, natural gas, coal, all types of renewable fuels, nuclear energy by fuel, etc. The model provides energy balance flows over the examined period, showing the evolution of the different forms of energy, from kits primary form the final end-use. In the case of end-use such as transportation, the data provided are even more detailed, for the specific type of vehicles and specific fuel, but also per passenger and distance.

3. Top-Down Climate Policy

The application of climate policy in GCAM can be done in different ways through: (i) the imposition of carbon taxation, where users can specify the price of carbon or Greenhouse Gases (GHGs) directly or setting (ii) the imposition of emissions constraints, where users can specify the total amount of emissions (CO_2 or GHG) and the model calculates the price of carbon needed to reach the constraint, iii) the imposition of climate constraints, where users can specify a climate variable (e.g., concentration or radiative forcing) target for a particular year, determining whether that target can be exceeded prior to the target year, while the model will adjust carbon prices in order to find the least cost path to reaching the target. However, the latter type of climate policy increases model run time significantly.

Imposing a climate policy affects the cost of energy production for carbon-intensive fuels. This induces a shift toward lower emitting technologies.

We use the GCAM model to apply four different Representative Concentration Pathways scenarios:

- RCP 4.5
- RCP 2.6
- “RCP2.0”
- “RCP1.0”

RCPs are possible climate futures, differentiated by how much greenhouse gases are emitted within this century, adopted by the Intergovernmental Panel on Climate Change [5] for its fifth Assessment Report (AR5). “RCP 1.0”, “RCP2.0”, RCP2.6, RCP4.5 pathways are named after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values, namely +1.0, +2.0, +2.6 and +4.5 W/m2, respectively. “RCP1.0” and “RCP2.0” are more ambitious scenarios (not used in AR5), developed by the authors for the needs of the paper towards assessing more ambitious targets.

The GCAM model is used to run RCP scenarios, aiming to provide a top-down pathway for meeting deep emission reduction targets, similar to the contributions provided by countries to the United Nations Framework Convention on Climate Change (UNFCCC) [16, 17]. Those emission pathways [18, 19] became formally part of the Paris Agreement, as all countries (Parties) are responsible to provide progress reports and submit them every five years. Through these obligatory actions, all Parties are obliged to cooperate and communicate among themselves and provide official long-term low GHG emissions development strategies. Currently, the biggest emitter of GHG in the world is China, while US has a significant contribution, as well as the EU. According to the global climate policy regime [20], all those countries had to plan and apply significant changes in their energy policies and strategies, both, short-term and long-term, but moreover, to develop and improve their energy sectors properly. All countries have proposed a variety of measures to meet the national goals, but also international aim for ecological progress.

Firstly, as the biggest emitter of greenhouse gasses in the world, China [21] started numerous changes in environment area, launching Emission Trading Scheme (ETS) in 2017 [22], [23] and proposing necessary developments in the near and distant future. China declared that country is rapidly moving to the low-carbon economy [24] providing budgetary supports, promoting renewable energy sources, development of nuclear power, strict control of the emissions in precisely marked industrial, agricultural, transportation and public sub-sectors, as well as the huge investments in energy efficiency such as highly-efficient electricity generation. J. Arrinda et al. [25] investigate the possibility of substantially increasing renewables penetration. China wants to achieve carbon reduction of 60-65% per GDP unit by 2030 [26] in comparison to 2005 level. USA, the second largest energy producer in the world, and at the same time, the second largest consumer has main goals to reduce greenhouse gases emissions by 28% in 2025. Following the global reaction, USA made some steps in the energy field. USA has target of reducing GHG emissions by 17% below 2005 level by 2020 and by 26-28% below 2005 level by 2025. The targets that the USA composed have to be achieved through measures such as The Clean Power Plan [27] and fuel efficiency standards. On the other hand, all 28 members of European Union [28] have agreed to turn to the green developments as an important component of the global environment safety and speak with one voice on this issue. Targets that EU clearly proposed are to achieve at least 40% domestic reduction in GHG emissions by 2030 compared to 1990 through the variety of actions - finance, legal, promotion, education.

Our different scenarios that we run in GCAM for the different regions, provided us numerous outputs. Figure 1 provides the emissions in million carbon tons per RCP, for USA (the model estimates emissions for all 32 regions, but for comparison reasons we provide results for USA).

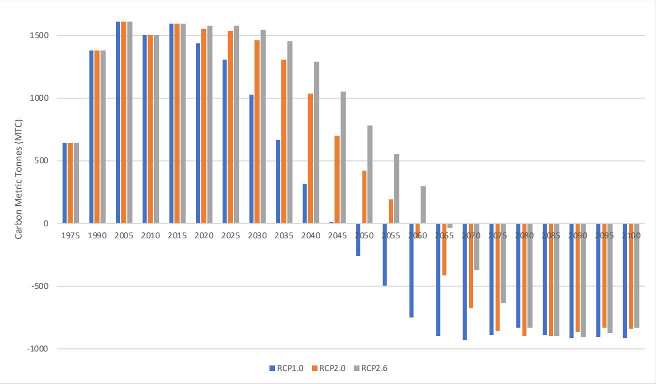

Fig. 1. USA emissions in million carbon tons per Representative Concentration Pathway (RCP)

As mentioned above, the results and the discussion focus more on USA considering that the following section of energy policies that has to be more specific concerns policies for USA, but for comparison reasons we provide in this section some indicative comments for the other two big emitters, China and EU. According to "RCP 1.0", negative carbon emissions are noticed at 2050 for China and US, while in the case of EU, negative emissions will begin later, in 2075. The situations in the case of "RCP 2.0" and 2.6 look similar as the "RCP 1.0". More precisely, China and US will again achieve negative emissions much before EU will, for "RCP 2.0" in 2060 both, while for RCP 2.6 in 2065 US and five years later China, in 2070. On the other hand, EU will experience negative carbon emissions in 2085 and 2095 for "RCPs 2.0" and 2.6. Finally, RCP 4.5 predicts late negative carbon emissions for all analysed countries, at 2090, but it also showed positive emissions again in 2100, while EU positive emissions are expected even earlier, in 2095.

Besides, the evolution of emissions at the aggregate level, the paper focuses at the evolution of the energy balances, aiming to identify the role of the energy carriers and technologies on meeting the emission reduction targets. Figures 2-4 provide Sankey diagrams, for the USA on years 2010, 2030 and 2100 respectively, for the "RCP1.0" scenario, which is the most ambitious. Sankey diagrams are a specific type of flow diagram, visualizing the flows from primary energy to the final end use consumers. Sankey diagrams are used by international institutions, such the International Energy Agency, to represent the whole chain of the energy sector in one figure. From those Figures, it can be derived that the penetration of renewables is vital for meeting emission reduction target, however this penetration is relevant limited compared to the full decarbonization of the energy sector by the end of the century. Similarly, the potential of electric vehicles, is not depicted in the year 2030, as the market uptake require considerable number of years for radically changes the vehicles stock types. Similarly, the graph shows that the role of fossil fuels, oil, gas and nuclear carriers, remain considerable in year 2030. Concerning the other regions, the penetration of renewables is faster for year 2030, however the generic results are similar, namely the transformation of the energy sector is not radical. Those results indicate that, although the accelerating global climate change, the relevant agreements such as the Paris Agreement, are not ambitious enough for short and medium-term transformation of the energy sector.

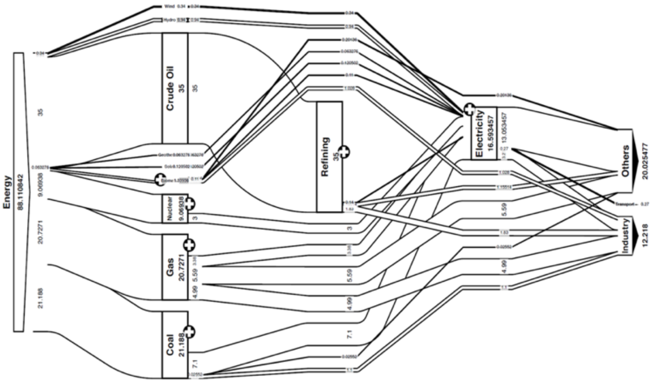

Fig. 2. USA Sankey diagram for "RCP1.0" scenario in year 2010

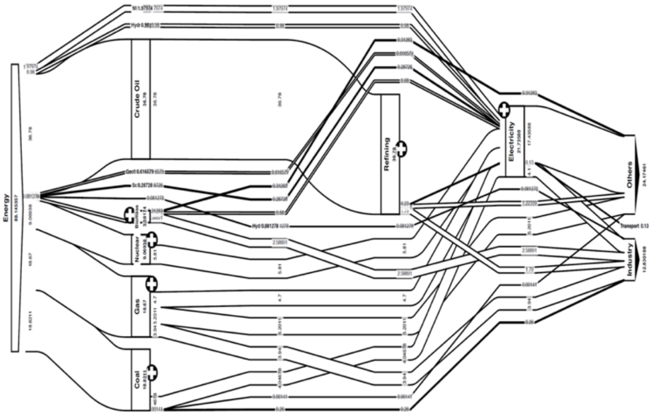

Fig. 3. USA Sankey diagram for "RCP1.0" scenario in year 2030

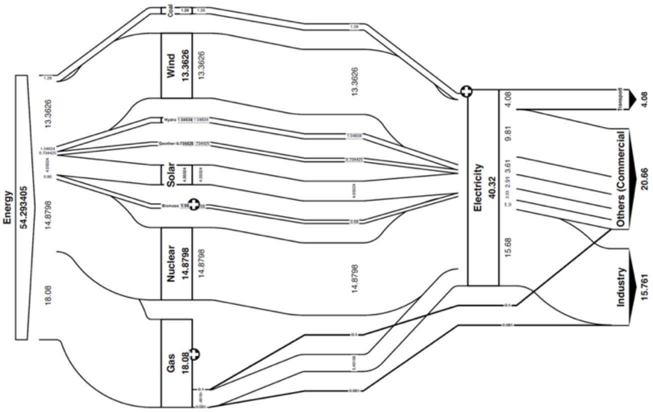

Fig. 4. USA Sankey diagram for "RCP1.0" scenario in year 2010

The Sankey diagrams show that according to the "RCP 1.0", in 2030 there will be numerous changes in energy balance flow of USA compared to 2010. Firstly, as it is presented on diagram, it is expected that in 2030 demand for commercial and residential sector will increase, as well as energy needs in industry. On the other hand, total primary energy will stay on the quite same level, making several differences in energy balance flow, such as significant transformation from fossil fuels to the renewable energy. The energy production is expected to move from coal and natural gas that will experience decrease in 2030, to the biomass and solar energy, but also to the development of the wind energy, whose production will increase almost six times compared to the 2010 level.

In the USA energy balance flow in 2030, there is an innovation - hydrogen will become new type of energy produced in order to cover some of the industry energy demand. When it comes to the electricity generation, its needs will rise, according to the increase of electricity demand in both, residential and commercial sector for around 25% per each. As the model showed, electricity generation will still continue to be secured from all types of fuel, but in 2030 biomass and wind will take more important place in energy mix, while nuclear power and solar energy will also have significant increase. On the opposite side, coal demand for electricity generation is expected to reduce, while hydrocarbons will still present fuel of high importance with slight increase in the need for natural gas and refined liquids.

To summarize, the top-down perspective provides clear signals towards the decarbonization of the power sector and the electrification of the transport sector. Those insights are examined in the next section from a bottom up perspective, by applying energy policies at sectoral level, aiming to capture if those options and sources stand as a realistic solution.

4. Bottom-Up Energy Policy

The implementation of energy policy in GCAM can be done in different ways, through (i) the imposition by users of constraints (lower & upper bounds) on energy consumption, where the model will solve for the tax (upper bound) or subsidy (lower bound) required to reach the given constraint. Within an individual sector, these constraints can be share constraints (e.g., fraction of electricity that comes from solar power), which allows to model renewable portfolio standards and biofuels standards. (ii) the implementation of energy policy at technology/sectoral level, through the application of incentives (subsidies) on technologies, tax policies, registration fee exemptions, technology or sectoral specific policies.

4.1. Energy policy in the transport sector

In order to understand the energy policy in transport sector, it is important to describe GCAM's transport sub-system [1, 2]. Demand for passenger transport (in passenger kilometers) in GCAM is a factor of a base year calibration parameter, an index for income in the form of per-capita GDP (defined on a purchasing power parity basis), an index of price of transportation (or generalized user cost) aggregated across all modes, size classes, and technologies and the population in each region and time period. Crucial factors are the income and price elasticities with respect to per capita passenger demand.

As described at the relevant report [29], the evolution of each technology depends on its costs (in $/passenger kilometres), which depends on the fuel price ($/MJ), the vehicle energy or fuel intensity (MJ/VKT), the non-fuel price of transportation for the given mode, and the load factor defined either as passengers per vehicle or tones per vehicle. Fuel prices are endogenous and include any carbon emissions costs. The non-fuel price for private modes, like cars and two wheelers consider, the purchase cost of vehicles (including taxes and registration fees) as well as variable and fixed annual operating costs. These costs are then "levelized" to $/VKT and $/PKT based on annual VKT per vehicle and load factors.

As mentioned above, market share considers a probabilistic approach in all sub-sectors, including the power and the transport sector. Determining market shares of each mode for each region and time period (or size class), technology is endogenous, and determined using a calibrated logit formulation [29]:

$$\boxed{S^{i,r,t} = \frac{(SW^{i,r})*(P^{i,r,t})^{\lambda_i}}{\sum_i (SW^{i,r})*(P^{i,r,t})^{\lambda_i}}} \qquad (1)$$

Where:

S is the market share,

SW is the share weight,

Pi is the cost of transport service for a mode i,

λ is the logit exponent.

The share weight is a calibration parameter, and the logit exponent regulates the degree to which future price changes will be reflected in modal shifts. This methodology is used to determine market shares of (i) various technologies within a size class, (ii) various size classes within a given mode, (iii) various modes.

For the needs of our paper, we apply an energy policy in the power and in the transport sector with GCAM for the case of USA. As a transport policy, we examine the penetration of electric vehicles in the passenger cars in the transportation sector, on the baseline RCP4.5 scenario, focusing on the USA region. The costs as well as the penetration potential of electric vehicles has been examined thoroughly in the literature, using different approaches. Hagman et. al. [30] examined the cost of ownership and its potential implications for battery electric vehicle diffusion, while Hao et. al. [31] focused on levelized costs of conventional and battery electric vehicles in China. Brenna M et al [32] studied the deployment of charging stations. L. Mingrone et al [33] investigated the possibility of creating an urban transport system based on electric vehicles. M. Brenna et al [34] provided an analysis for utilising renewables for EVs charging. Belzowski [35] examined the cost of car ownership, providing a diesel versus gasoline comparison, while Levay et al. [36] examined the effects of fiscal incentives on market penetration of electric vehicles. Kochha and Hörner [37] focused on the costs and the willingness-to-pay for the electric vehicles. Newbery and Strbac [38] provided analysis on what are needed for battery electric vehicles to become socially cost competitive. Longo, M. et al [39] analysed the potential of updating the vehicle fleet with EVs using sustainable solar energy. Lebeau et al. [40] provided a total cost of ownership analysis for electric vehicles, while Becker et al. [40], provided forecasts for the penetration of electric vehicles in the US. Jiang et al. [42] provided a financial analysis as well as a comparison among compact electric and gasoline cars, while Wietschel et al. [43] examined different scenarios for their market penetration. Hardman et al. [44] focused on the effectiveness of financial purchase incentives for battery electric vehicles, while Sivak and Schoettle [45] examined the relative costs of driving electric and gasoline vehicles in the USA. For our analysis we used data from the Bureau of Transportation Statistics [46]. We apply exemption in the registration fees and incentives in buying electric vehicles, which lead electric vehicles to become competitive to conventional ones by 2025. We apply this policy in the following categories:

- Large cars,
- Light Truck & Sport Utility Vehicles (SUVs)
- Compact cars, Mid-size cars and Motorcycles
- In all above categories together

Towards, implementing an energy policy for the transport sector, we had to analyse the cost of owning battery electric vehicles (BEV) and conventional vehicle types, so as compare their capital expenditure and operational costs. The capital cost includes the purchasing price of the vehicle and the sales tax, while the annual operating costs are consisted out of the maintenance and repair costs, fuel costs for the average travelled distance yearly, annual registration tax including the road taxes, and finally tires replacement. The analysis is based on the average annual distance travelled by the car in USA is 12,000 miles per vehicle. Concerning the capital costs, the purchase price for both vehicles is given in Table 1. Currently, the US regulations do not require sales tax on the electric vehicle after the purchase of the new car, while this capital expenditure is required for the conventional cars. The beneficial opportunity for the potential owners of the Battery Electric Vehicles (BEV) is that the USA offers federal tax refund option for those citizens that fulfil specific requirements. It is obvious that total capital costs for the vehicles are more competitive for the purchase of the conventional cars. However, the capital cost of electric vehicles has a decreasing trend, affected by incentives, learning by doing and learning by research.

Table 1. USA Sankey diagram for "RCP1.0" scenario in year 2100

	Price of vehicle	Sales tax
BEV	35,000	/
Conventional car	25,000	2000

Considering the decreasing trend in capital costs, as well as the operating costs, we estimate that the levelized cost of large cars is steadily decreasing at the level of 0.153 $/VKT.

Based on this analysis, we impose the assumptions on the GCAM model, leading an evolution of the levelized costs of alternative technologies for large cars category as shown in Figures 5-6, after the implementation of the energy policy for electric vehicles in the Large Cars and the Light Truck & SUVs categories respectively. Figures 7-8 provide the technology share for the Large Cars and the Light Truck & SUVs categories respectively.

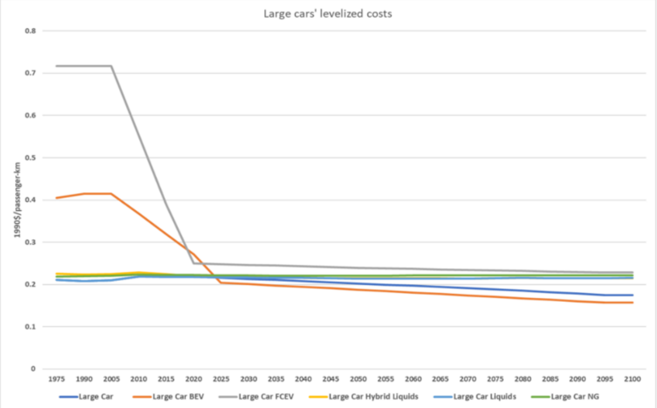

Fig. 5. Levelized costs of alternative technologies for large cars category

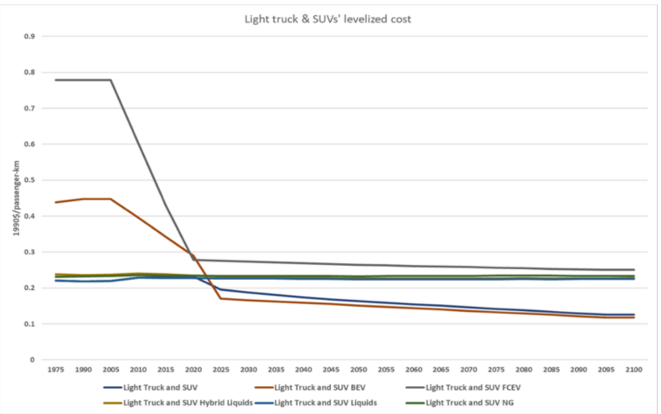

Fig. 6. Levelized costs of alternative technologies for Light truck & SUVs

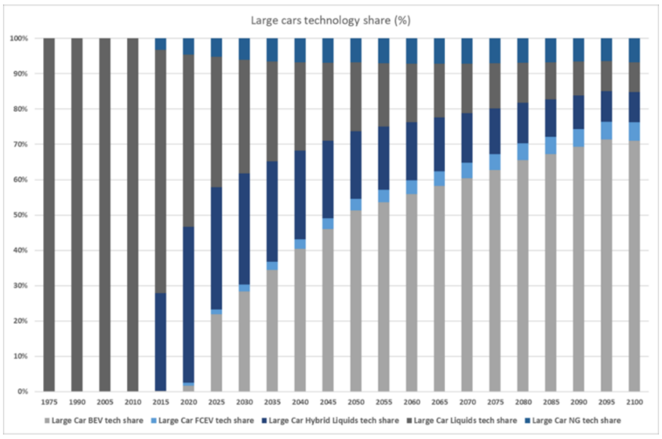

Fig. 7. Evolution of technology share for the Large cars' category

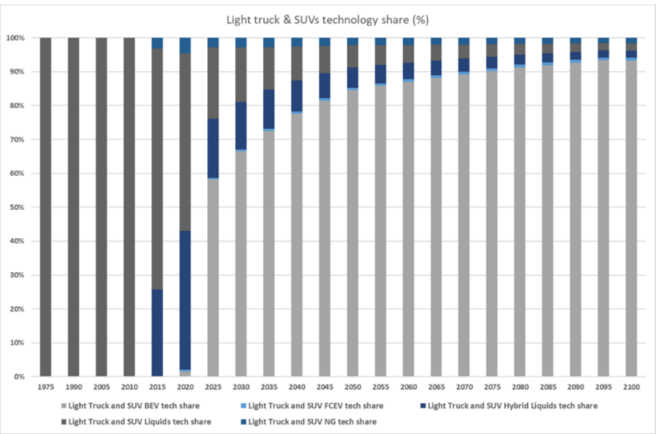

Fig. 8. Evolution of technology share for the Light truck & SUVs category

4.2. Energy policy in the power sector

Current state-of-the-art in emerging applied technologies is able to show energy system situation in the following decades. International organizations, national laboratories and other renowned institutions are describing current and expected situation of the power system. Special attention is given to energy production from renewable sources, hence wind, solar, biomass and the technology of Carbon Capture and Storage (CCS).

In this analysis, the work of National Renewable Energy Lab [47] is taken into account to specify the situation for large scale and residential (rooftops) photovoltaics (PV). Large photovoltaic installations are expected not to exceed the price tag of 1000$/kW in 2020. Residential PVs are excepted to cost 2000$/kW in 2020, declining at 1500 and 1200$/kW in 2025 and 2030 respectively. International Renewable Energy Agency (IRENA) [48] proposes for wind power a cost for wind at 1600$/kw in 2020 and at 1200 in 2030. For biomass the default costs of GCAM [49] are applied and a 30% reduction for all Carbon capture and storage (CCS) technologies in the period 2030-2040 and a reduction in geothermal energy at 4000$/kW in 2035 are used. These costs are translated in value per EJ produced for the USA in Figure 9.

Therefore, as an energy policy in the power sector, we have incorporated the assumptions from the above-mentioned studies. To simulate the above situation, the authors have described these assumptions to an additional GCAM file, which is added to the configuration files at the beginning of the simulation cycle. Considering that there is no ambitious reduction target, the emissions are stabilized at high levels, as shown in Figure 10. It appears that coal remains an important electroproduction contributor in the USA (Figure 11) when no ambitious target exists, which is also linked to the fact that CCS technologies start to penetrate in the power system as shown in Figure 12) for modest emission targets. The low carbon technologies, and especially wind and solar penetrate also in the power system, however although being competitive as shown in Figure 9, they do not become by the dominant technologies. This is attributed to the assumptions, that their levelized cost will not decreased further, as well as the nature of model, providing cost optimum solutions, under environmental constraints. The incorporation of probabilistic approach in the market share, alleviates the provision of solutions monopolizing the energy mix, which is a usual drawback of long-term planning with neoclassical equilibrium models. Therefore, assuming several technologies with comparable costs and not ambitious emission reduction targets, lead to a diverse energy mix, as shown in the following figures. In case of technology developments, incentives in specific technologies and/or emission targets, the evolution of low carbon technologies becomes considerably higher. However, as also noticed in the Climate Policy section, the evolution of CCS technologies is inevitable, even in the RCP4.6 scenario, which is the reason we have chosen to show the results for this scenario in this Energy Policy section.

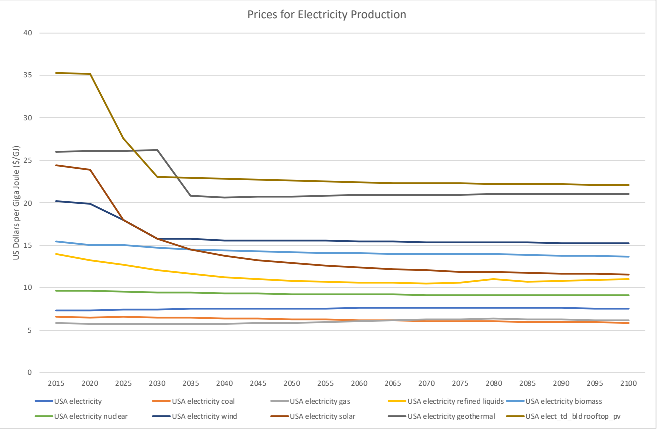

Fig. 9. Evolution of electroproduction from different technologies ($/GJ)

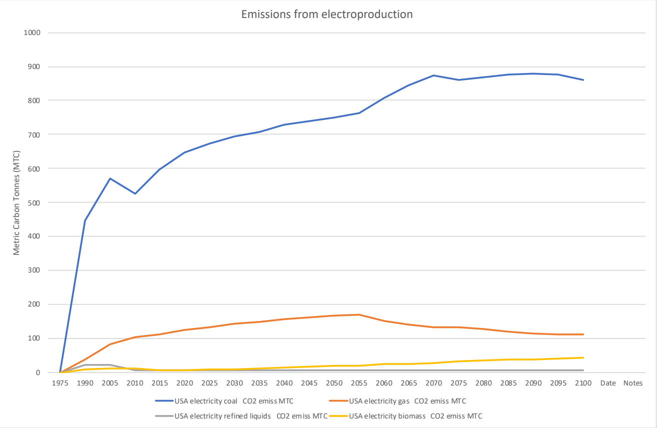

Fig. 10. Evolution of carbon emissions at the electricity sector of the USA (Million Tones carbon)

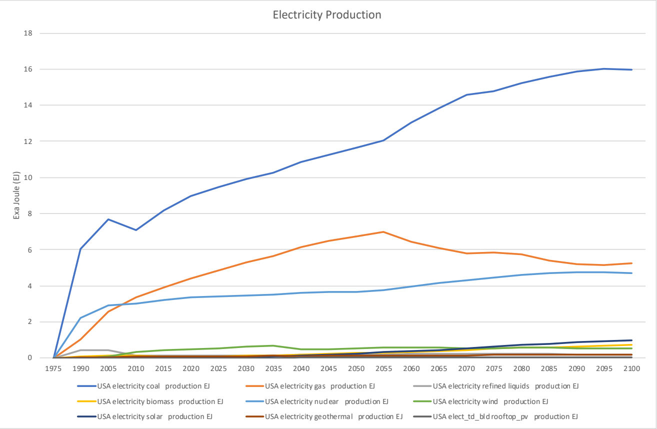

Fig. 11. Evolution of electroproduction from different technologies in the USA (GJ)

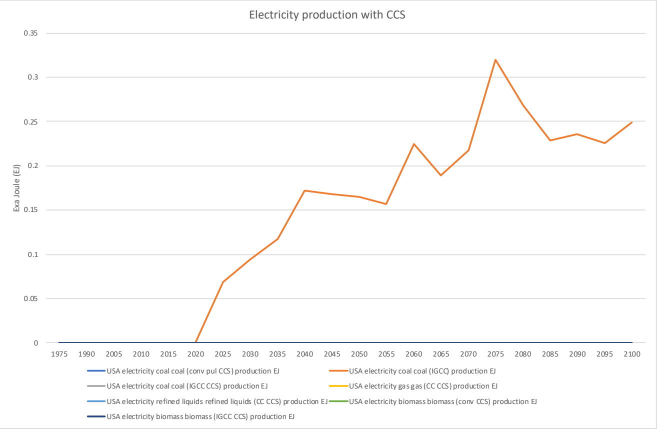

Fig. 12. Evolution of electricity production for technologies with CCS in the USA (EJ)

5. Conclusions

This paper aims to implement energy and climate policies with the same modelling framework, aiming to present different perspectives on their application, namely top-down and bottom-up. This paper applies energy and climate policies with the Global Change Assessment Model (GCAM) model, towards assessing energy sources and technology options with both perspectives. We apply top-down climate policy, through the application the Representative Concentration Pathways (RCPs), which affects the cost of energy production for carbon-intensive fuels, towards lower emitting technologies. It provides a clear message that negative emissions are required for deep emission reduction targets. The provision of detailed Sankey diagrams shows the evolution of different technologies and energy sources, depicting the role of low carbon technologies but as well of carbon capture technologies. We also apply bottom-up energy policies, implementing incentive measures for the power and transport sector. We apply bottom-up technology specific policy, examining the penetration of electric vehicles in different passenger transport categories (large cars, compact cars, mid-size cars, light truck & SUVs, motorcycles). The levelized cost of technology is changed through exemption of registration fees and capital cost decrease though incentives, learning by doing and research. We provide the technology shares evolution, as well as the evolution of sectoral energy demand and transport demand.

The application of top-down and bottom-up perspectives enable the generic comparison among the different perspectives, which stands an important debate in the energy system and climate change modelling community. The top-down climate policy enables the examination of ambitious emission reduction scenarios, such as the “RCP 2.0” and “RCP1.0” pathways, identifying that the energy mix shift towards environmentally friendly technologies is not adequate. The penetration of innovative technology options absorbing emissions is needed, especially beyond 2050, where major negative emissions are required to meet ambitious targets. The bottom-up energy policy perspective enables the formation of specific realistic scenarios in the different subsectors, such as the power and transport sectors, providing insights on the required policy changes on different energy carriers and technology options, such as renewables and electric vehicles. The incorporation of probabilistic approach in the market share, alleviates the provision of solutions monopolizing the energy mix, which is a usual drawback of long-term planning with neoclassical equilibrium models. Therefore, assuming several technologies with comparable costs and not ambitious emission reduction targets, lead to a diverse energy mix. In case of technology developments, incentives in specific technologies and/or emission targets, the evolution of low carbon technologies becomes considerably higher. However, as also noticed in the top-down climate policy, the evolution of CCS technologies is inevitable.

All data and source code are openly available through Harvard Dataverse. This enables other researchers who wish to build upon these finding as well as the policy makers who plan to apply the above-mentioned top-down and bottom-up policies with the GCAM model. A major disadvantage of our analysis stands the fact there is no direct comparison among the two perspectives. The examination of a specific target i.e. emission reduction target, through top-down and bottom-up approaches would contribute invaluable to the literature. Our intention aimed to explore such analysis, however we faced problems in the formation of bottom up policies, as well as need for comprehensive effort. Meeting a top-down target with bottom-up policies in fact is transformed as a sensitivity analysis on numerous sectoral policies. Those policies might differentiate not only on the sector they are applied, but also on the timing and magnitude of the applied policy. This leads to a comprehensive number of potential combinations of bottom-up policies. This stands as the main problem in the formation of National Development Contributions (NDCs). This fact has led us on examination of specific sectoral policies, based on signals from the top-down analysis. This improved our capability of linking at some extend the two perspectives, by providing clear signals from both approaches. Moreover, we provide insights on the realism of bottom-up assumptions/policies. To sum-up, a comprehensive analysis on the bottom-up side could strengthen considerably our analysis and contribute in the literature. This stands as one of our priorities for future research. . Moreover, future research could also benchmark the results, compared to the outcomes from other Integrated Assessment Models (IAMs), enabling a comparison not only on the applied perspective, but also on the applied model with similar methodological characteristics.

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