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Global transportation scenarios in the multi-regional EFDA-TIMES energy model

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ABSTRACT

The aim of this study is to assess the potential impact of the transportation sector on the role of fusion power in the energy system of the 21st century. Key indicators in this context are global passenger and freight transportation activities, consumption levels of fuels used for transportation purposes, the electricity generation mix and greenhouse gas emissions. These quantities are calculated by means of the global multi-regional EFDA-TIMES energy system model. For the present study a new transportation module has been linked to the EFDA-TIMES framework in order to arrive at a consistent projection of future transportation demands. Results are discussed implying various global energy scenarios including assumed crossovers of road transportation activities towards hydrogen or electricity infrastructures and atmospheric CO_2 concentration stabilization levels at 550 ppm and 450 ppm. Our results show that the penetration of fusion power plants is only slightly sensitive to transportation fuel choices but depends strongly on assumed climate policies. In the most stringent case considered here the contribution of electricity produced by fusion power plants can become as large as about 50% at the end of the 21st century. This statement, however, is still of preliminary nature as the EFDA-TIMES project has not yet reached a final status.

1. Introduction

Fusion power is inherently safe, has a large resource base and low environmental impact. Due to these arguments fusion power may be able to gain large market shares as soon as this technology becomes available for commercial use. On the other hand it is a nuclear technology (which undermines public acceptance), it is technically extremely challenging and investment costs can be expected to be very high. However, the actual role of fusion power in the energy system of the future will primarily be determined by the economics of fusion power plants and future energy prices. In order to assess the role of fusion power within the complexity of the world's energy system the EFDA-TIMES project has been brought under way. The EFDA-TIMES model is a global multi-regional energy system model developed under the framework of the Socio-Economic Research on Fusion (SERF) program of the European Fusion Development Agreement (EFDA) using the energy system modeling framework TIMES [1]. TIMES is developed within the Energy Technology System Analysis Program (ETSAP) of the International Energy Agency (IEA). The EFDA-TIMES model represents an ideal tool to explore the conditions under which fusion can become a successful contributor to the future energy market.

Future energy prices and availability are not only determined by future levels of electricity demand but are coupled to the entire system of energy supply, conversions, distribution and consumption. This applies also to the sector of passenger and freight transportation which, with its high dependency on carbon fuels, plays a crucial role for fossil fuel availability. Over the last 30 years the demand for motorized mobility has grown significantly in all industrialized countries. Moreover, the transportation sector is expected to account for a significant share of future greenhouse gas emissions. As about 70% of the world population lives in developing countries, where per capita travel demand is currently low, future trends in mobility will be of critical importance to the world's fuel supply and carbon dioxide emissions throughout the 21st century. It is the aim of the work initiated here to improve on the implementation of the transportation sector within the EFDA-TIMES model and to study the implications for the future role of fusion power within the projected energy system of the future.

2. EFDA-TIMES

EFDA-TIMES is a global multi-regional technology explicit partial equilibrium energy model which uses the The Integrated MARKAL-EFOM System (TIMES) developed by IEA-ETSAP [1]. TIMES is a bottom-up energy model generator which maximizes the total economic surplus. In its simplest variant, this can be expressed via

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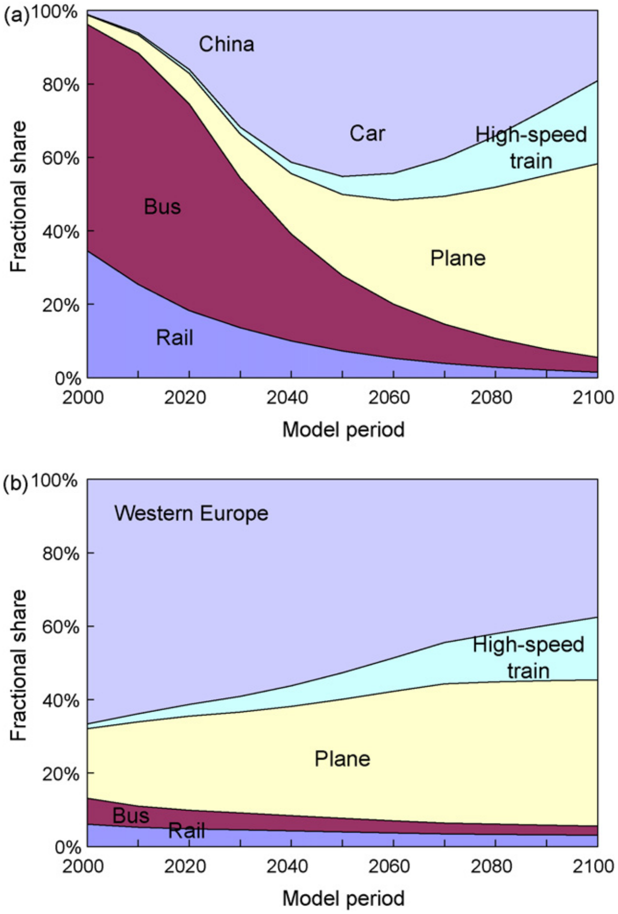

Fig. 1. Modal split in two world regions.

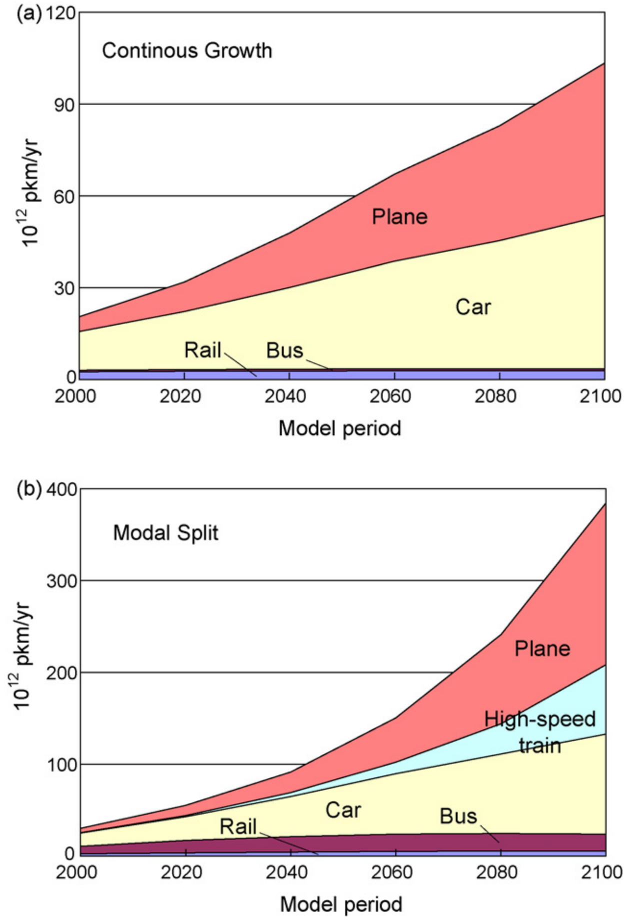

Fig. 2. Global personal transportation activity in both demand scenarios. For the *Continuous Growth* case the transportation activity has been converted to person kilometers per year by assuming an average load factor of 1.7 passengers per car and 25 passengers per bus. For planes and rail we have used energy intensities of 2.1 MJ/pkm and 0.48 MJ/pkm, respectively.

the objective function $\hat{Z}$

$$\hat{Z}(b) = \sum_r \left\{ \sum_y \zeta(r,y,b)\left[C^r_{\mathrm{inv}}(y)+C^r_{\mathrm{itax}}(y)+C^r_{\mathrm{dec}}(y)+C^r_{\mathrm{fix}}(y) + C^r_{\mathrm{ftax}}(y)+C^r_{\mathrm{var}}(y)+C^r_{\mathrm{elast}}(y)-C^r_{\mathrm{rev}}(y)\right] - C^r_{\mathrm{sal}}(b)\right\} \tag{1}$$

which is given as the sum over all model regions r, years y and cost components C^r_i including investment costs, investment taxes and subsidies, decommissioning costs, fixed costs, variable costs, demand loss costs, revenues and salvage values. ζ is a discounting factor discounting all cost components to the base year b. The mathematical rationale of TIMES is to globally minimize the objective function under certain constraints (energy conservation at each step of the energy system, fossil energy resources, renewable energy potentials, growth constraints, etc.) using linear programming techniques.

The EFDA model is a global model spatially subdivided into 15 world regions. It covers a time horizon from 2000 to 2100. The model structure is characterized by four basic components: the supply, demand, technology and policy scenario. The technological data is given for distinct energy sectors: upstream, electricity, transport, industry, residential, commercial and agriculture. The latter five define the energy service demand sectors. The EFDA-TIMES demand scenario is given by a set of demand driver projections obtained from the GEM-E3 general equilibrium model [2]. The supply scenario is represented by a database of costs and bounds on the availability of energy resources. The technology scenario consists of a rich basis of energy conversion technologies characterized by specific efficiencies, availabilities and costs. In the base case the policy scenario of the EFDA-TIMES model is empty but can be used to study the impact of fuel taxes, emission taxes, emission permit trading and so on. Additional information on a very similar model, ETSAP-TIAM, can be found at [3].

3. Transportation sector

In this study we compare two different approaches of modeling the passenger transportation demand scenario. Both recipes will be described briefly below. For the freight transportation sector, however, we use one common approach, introduced briefly thereafter.

3.1. *"Continuous Growth"*

In this sub-model variant, passenger transportation is subdivided into 7 different modes of transportation, which in the case of the road transportation segments are measured by vehicle kilometers per year and by their final energy consumption for the off-road segments. Future projections for the transportation demands in each of these segments are obtained by relating the individual energy service demands $E(y)$ in the year y to one of the demand drivers $D(y)$, such as GDP (light trucks, planes), GDP per capita (cars) or population (buses, two and three wheels, trains) through the formula

$$\frac{E(y)}{E(y_0)} = \left[\frac{D(y)}{D(y_0)}\right]^{\lambda_E}, \tag{2}$$

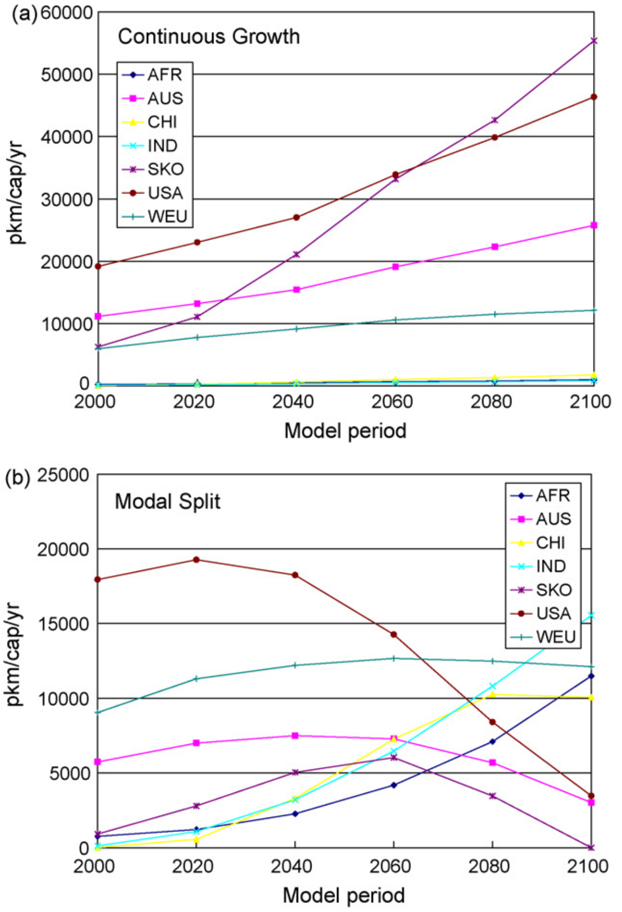

Fig. 3. Global per capita car travel activities in various world regions for both demand scenarios.

where λ_E is the elasticity of each energy service demand to its driver. This rationale leads to ongoing growth over the entire 21st century in almost all passenger transportation segments.

3.2. *"Modal Split"*

The *Modal Split* sub-model variant is based upon a model developed by Schafer and Victor [4]. The model parameterization is derived from an analysis of transportation data for eleven world regions over the time period from 1960 to 1990. A minor extension of the model was invented in [5,6]. Passenger transportation is separated in 5 distinct demand segments: cars, buses, trains, high-speed trains and planes. The travel volume is for all cases measured by person kilometers per year. The transportation activities in each of these five segments are obtained by means of five constraints deduced from the analysis of historical transportation data:

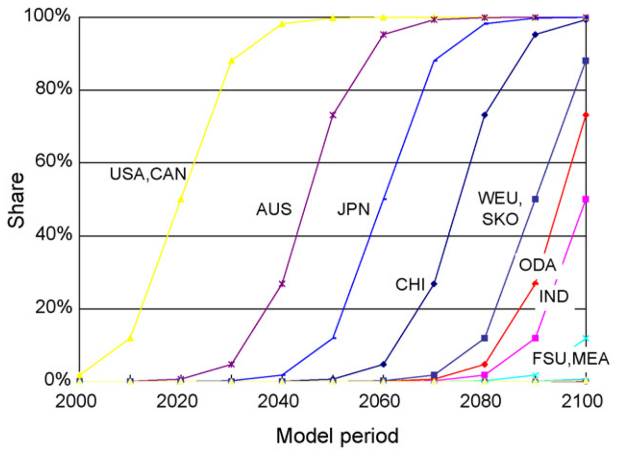

Fig. 4. Forced shares of hydrogen use for the road transportation segments in the *Hydro* scenario. For some regions (AFR, CSA, EEU, MEX) the transition takes place several years after the end of the model time horizon and, thus, its onset is hardly visible in the figure.

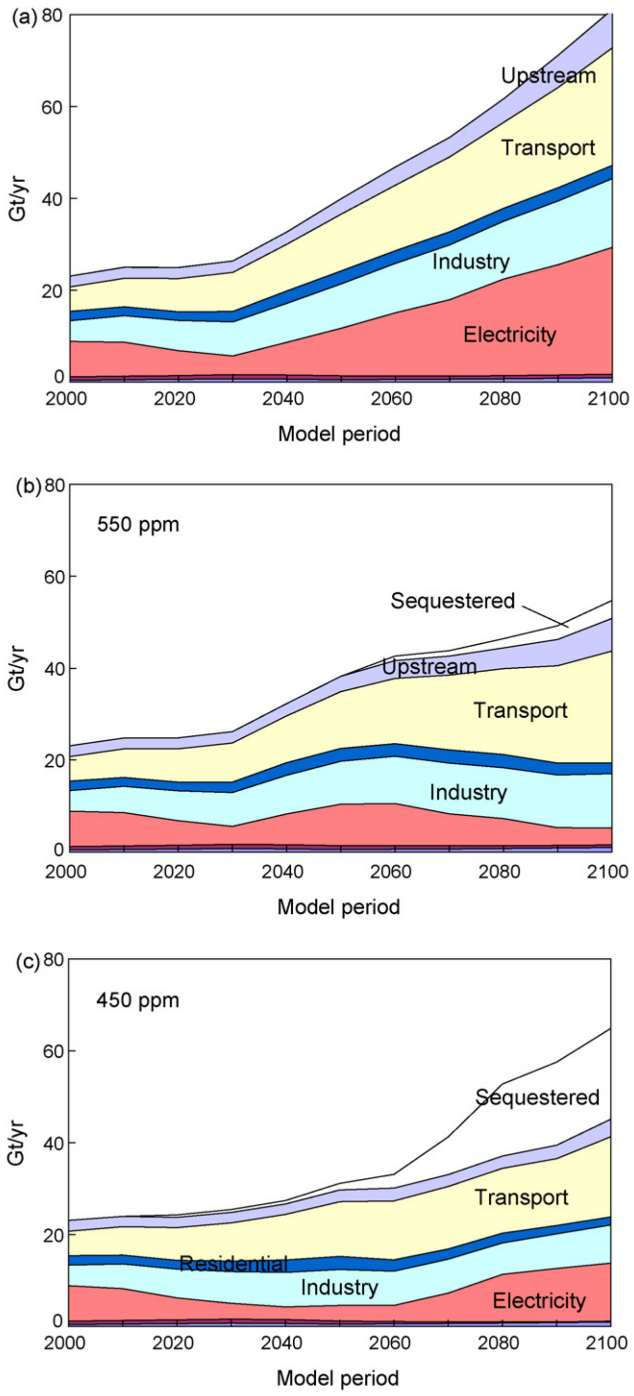

Fig. 5. Global CO_2 emissions for various climate scenarios.

1. Total transportation activity per capita grows linearly with GDP_{PPP} per capita.
2. The average citizen in each society spends about 1.1 h a day traveling.

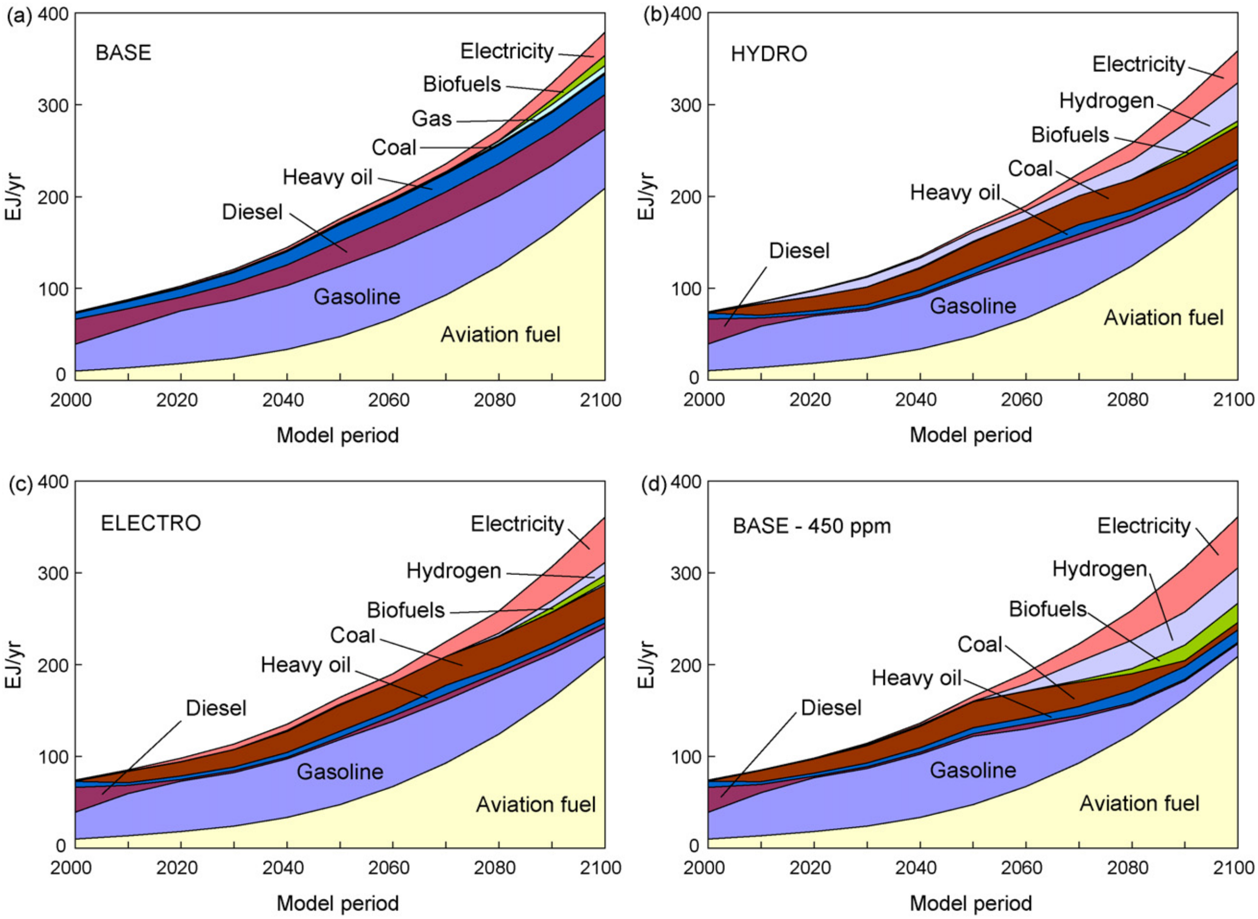

Fig. 6. World use of transportation fuels for various transportation/climate scenarios.

3. Conventional rail transport shares decrease slowly in all regions.
4. The decreasing share of low-speed transport modes (bus and rail) in less industrialized regions with high population density follow the historical development of Japan and regions with medium density follow the development of Western Europe.
5. Among high-speed modes (planes and high-speed trains), train shares increase from 4% in 1990 to 30% in 2100.

With growing GDP per capita the first two assumptions drive a change in the modal split towards ever faster modes of transportation. This is illustrated for two world regions in Fig. 1. In Western Europe we find a relative decline of car travel activities in favor of higher speed modes (plane, high-speed train). In China this transition only occurs in the second half of the century as here passenger transportation is dominated today by low speed public transport modes (bus, rail).

3.3. Discussion

Both passenger transport demand scenarios lead to high growth rates of transportation activities over the 21st century. This is illustrated in Fig. 2. In the *Modal Split* scenario we find a much stronger increase of travel volumes towards the end of the model horizon. This comes because of the higher speeds which are possible due to the shift away from low to high-speed transport modes. With the population and GDP projections from GEM-E3 the *Modal Split* scenario predicts a total per capita travel volume of roughly 37,000 km per year, of which 17,000 km are traveled by plane. For comparison, currently the average EU citizen travels 1500 km by plane in each year. The world average car travel activity will roughly reach the current EU level at the end of the 21st century. Most pronounced growth rates, however, can be observed for high-speed trains.

Ongoing growth in all segments and regions can eventually lead to rather extreme values in already developed countries. This is illustrated for the case of car travel for some selected world regions in Fig. 3. The high levels in the USA and South Korea at the end of the time horizon for the *Continuous Growth* case appear rather unrealistic realizing that the average citizen would have to spend almost 4 h each day in his car. Such high transportation demand levels will eventually drive people to use higher speed transportation modes which is realized in the *Modal Split* scenario. As can be observed in the other panel of Fig. 3 a decline of car travel launches from certain activity levels on. This leads to more realistic estimates of passenger transportation activities over the entire time horizon.

3.4. Freight transport

The freight transportation sector covers 6 transport modes: commercial trucks, medium sized trucks, heavy trucks, freight trains and domestic and international navigation. Transportation volumes are again measured as vehicle kilometers per year for the road segments and by the final energy energy consumption for the off-road cases. The demand projection is in all cases obtained by linking the individual demands with GDP using Eq. (2) which is a reasonable recipe recalling that GDP is mainly determined by the total volume of goods produced whose distribution in turn induces freight transportation activity.

4. Scenario results

We have evaluated our model assuming the following set of energy scenarios:

4.1. Demand scenario

We have considered both the transportation demand scenarios *Continuous Growth* and *Modal Split*. Both have been discussed in the previous section.

4.2. Technological scenario

We consider two distinct technological transportation scenarios, the *Hydro* and the *Electro* scenario. In both cases we assume a transition from the dominant use of fossil energy carriers towards a hydrogen or electricity dominated infrastructure, respectively. We suppose this technological change to be closely related to GDP per capita. Starting in the region with the highest present value of GDP we impose the transition towards an alternative infrastructure to happen in all world regions at similar levels of GDP. This characteristic is close to actual observations in various segments of economic development. The functional behavior of the transition we suppose to follow a logistic curve and is shown in Fig. 4. For the *Electro* case, however, we eventually impose only a 50% share of the road traffic volume since this technology might also in the future not be suited to satisfy the demand for individual long distance travel.

4.3. Policy scenario

In addition to the base case (not including any policies) we consider two climate scenarios, namely the stabilization of the global atmospheric CO_2 concentration at levels of 550 ppm and 450 ppm, respectively. More stringent scenarios suggested by the IPCC [7] will be analyzed in the near future.

4.4. Discussion

Fig. 5 shows the annual levels of CO_2 emissions for all policy scenarios. Both in the 550 ppm and 450 ppm cases a substantial reduction of the net emissions towards the end of the time horizon can be observed. As can be seen in the 550 ppm case, this reduction has the largest effect in the electricity sector where a great amount of cost effective alternatives exists. In particular the sequestration technique, which becomes sizable in the 450 ppm case, can be applied most effectively in connection to electricity generating plants. The transportation sector turns out to be most rigid against any greenhouse gas emission reduction. Only in the 450 ppm case a decrease of the emission level in the last third of the century can be observed.

A key indicator for any transportation scenario and its potential impact on the residual energy system is the specific transportation fuel consumption pattern. For the case of the transportation and policy scenarios considered here this is shown in Fig. 6. In the base case an ongoing dependency on liquid fossil fuels can be observed in spite of the depleting resource base. In Fig. 7 we show that this situation nonetheless is consistent with todays estimates of fossil fuel availability. As expected both in the *Hydro* and *Electro* cases higher consumption levels of hydrogen and electricity for transportation purposes can be observed. At the same time the consumption of gasoline and in particular diesel declines. This is also the case in the 450 ppm scenario, however, not implying any specific transition away from fossil energy carriers. The levels of hydrogen and electricity use in the 450 ppm case is even slightly higher than in the *Hydro* and *Electro* scenarios, implying an even faster transition towards alternative fuel vehicles as anticipated in the transportation scenarios. Consequently, also the sector of electricity generation will be affected more rigorously by the climate constraints.

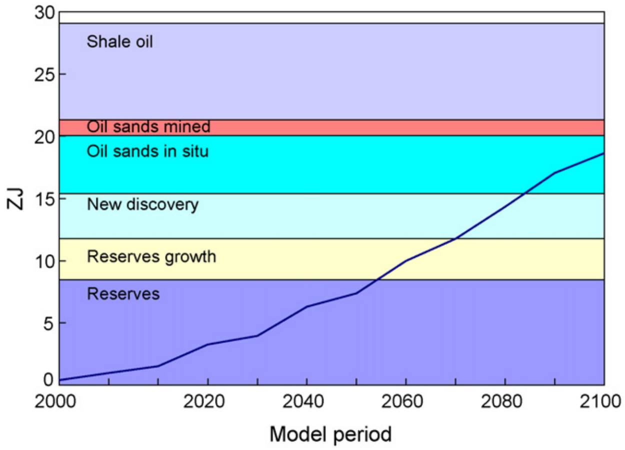

Fig. 7. Global crude oil resources disaggregated into various production steps and global cumulative crude oil consumption. The summed crude oil resource base corresponds to 29.06 ZJ or 693.88 Gtoe.

The levels of electricity generation for both climate scenarios is shown in Fig. 8 together with the contribution of fusion power plants. Obviously the decarbonization of the electricity mix substantially helps to create a market for fusion power. This, however, is sensitive to the assumptions on the economics of future

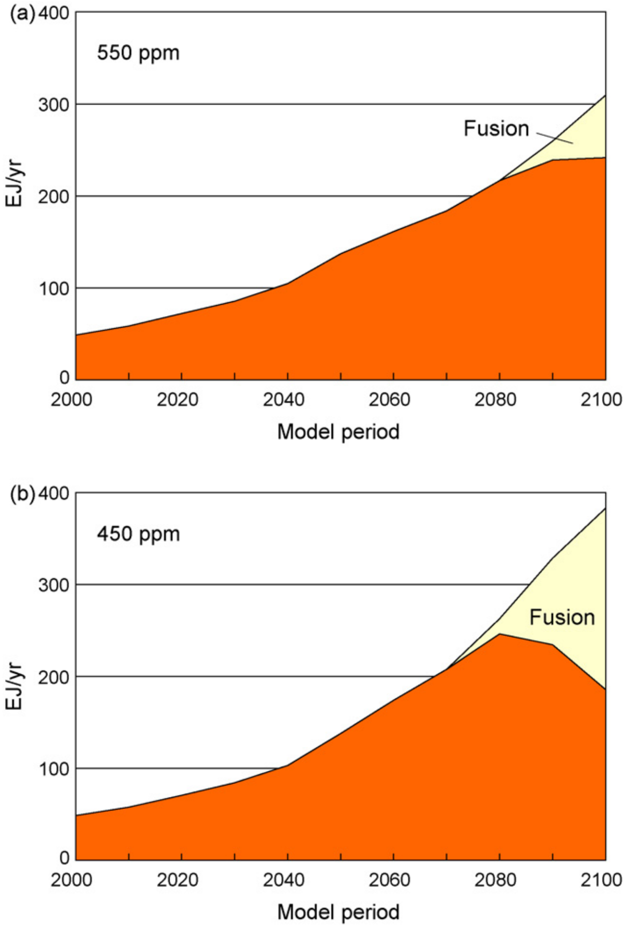

Fig. 8. Total electricity production for the 550 ppm and 450 ppm cases highlighting the contribution of fusion power.

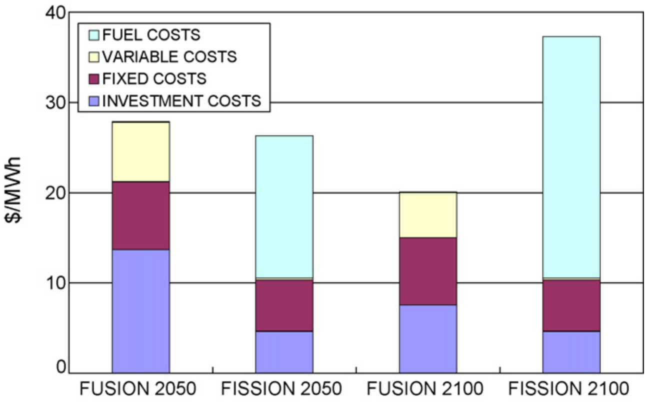

Fig. 9. Undiscounted cost components to the TIMES objective function from fusion and fission power plants for two distinct model years in one model region (USA). Fuel costs for fusion plants are not visible on this scale.

fusion power plants. This issue is discussed elsewhere [8]. With the present parameters, implying a 450 ppm CO_2 concentration target, the contribution of fusion power to the total electricity generation level can become as large as 50% at the end of the 21st century. This would materialize in the long term because of the steeper investment learing curves to be expected for the emerging fusion technologies as compared to the mature fission technologies, the limitations on fossil energy use due to the carbon dioxide constraint, and the increasing nuclear fuel price due to the growing scarcity of uranium towards the end of the 21st century. As an example, the cost components to the TIMES objective function from both fission and fusion power plants are shown in Fig. 9 for two model years implying full load operation. Still, this is only a preliminary result since the recent revision of the EFDA-TIMES model has not yet been completed.

The views and opinions expressed herein do not necessarily reflect those of the European Commission. This work was carried out within the framework of the European Fusion Development Agreement.

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