Including road transport in the EU ETS (European Emissions Trading System): A model-based analysis of the German electricity and transport sector

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A B S T R A C T

The EU ETS (European Emissions Trading System) is being enlarged stepwise to cover an increasing amount of overall European CO_2 emissions. However, one of the largest and still growing CO_2 emitting sector, the transport sector, and particularly road transport, has not yet been included in the EU ETS. Against this background, the question arises whether integrating the road transport sector in the EU ETS represents a cost efficient CO_2 reduction strategy. For this reason, the consequences of this integration are analysed with a focus on Germany. To do so we utilise a model based approach. In order to account for both sectors simultaneously, we couple an electricity system model, *PERSEUS EU* (Package for Emission Reduction Strategies in Energy Use and Supply in Europe), with a road transport model, *COMIT* (CO_2 emission Mitigation in the Transport sector). The time horizon we consider ranges from 2010 to 2030. In our analysis, we differentiate our scenarios according to commodity prices, share of renewable energies in electricity generation and share of electric vehicles. The results show that the enlargement of the EU ETS to include road transport leads to a reduction of overall CO_2 emissions, but equally reduces the mitigation efforts in the road transport sector. Simultaneously, the German electricity sector is mainly influenced according to the certificate demand or supply of the road transport sector.

Keywords:
CO_2 emissions trading
Electricity sector
Road transport

1. Introduction

In order to reach the Kyoto targets, the EU ETS (European Emission Trading System) was established in 2005 according to EU directive 2003/87/EC and already covers 30 countries (the 27 EU Member States in 2010 plus Norway, Iceland, and Liechtenstein) [1]. Until now it has been structured into four periods up to 2028 with varying restrictions. Whereas so far national caps have been allo cated, in the third phase of the EU ETS (2013–2020) only one single Europe wide cap is applied. Furthermore, the European Union has standardised the installations affected by the EU ETS as well as the allocation and auctioning of CO_2 allowances. In this way, CO_2 emissions are to be reduced where it is most cost efficient.

Two major CO_2 emitting sectors are excluded from the EU ETS. These are the residential sector with a share of 9.9% of overall CO_2 emissions in the European Union (EU27) in 2007 and transport, which is the only sector without emission reductions so far. In 2007, CO_2 emissions from transport increased by 25% compared to 1990 and had a share of 23.1% in the EU27 CO_2 emissions [2]. More than 71% of these emissions in 2007 originated from road transport [3].

From an economic point of view, these framework conditions are inefficient: some sectors in the EU ETS struggle to reduce their emissions, while others are not affected by the limitations (i.e. transport sector). The latter increases the pressure on those already "suffering" from the EU ETS. These inefficiencies are most apparent in the transport sector, as its emissions are still growing and will continue to increase on a European scale and are going to double on the global scale up to 2050 [4]. This development strongly conflicts with the long term CO_2 emission targets of industrialised nations, such as Germany, which is striving to reduce CO_2 emissions by 30–40% by 2030 compared to 1990 and by about 80% by 2050 [5,6]. Another policy instrument in this issue is the European Directive 443/2009, which forces vehicle manufacturers to meet the vehicle specific CO_2 emissions of 95 g per km by 2020 for new passenger

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Abbreviations

BEV	battery electric vehicle
CDM	Clean Development Mechanisms
CO_2	carbon dioxide
COMIT	**CO_2** emission **Mi**tigation in the **T**ransport sector (multi agent based model)
EU	European Union
EU27	the 27 countries of the EU in 2010
EU ETS	European Emissions Trading System
EV	electric vehicles
GMP	German Mobility Panel
ILUTE	integrated land use, transportation, environment
JI	Joint Implementations
MAS	multi agent (based) simulation
MATSim	Multi Agent Transport Simulation
N_2O	nitrous oxide
NREAP	National Renewable Energy Action Plans
PFC	perfluorocarbon
PERSEUS EU	Program **P**ackage for **E**mission **R**eduction **S**trategies in **E**nergy **U**se and **S**upply in **Eu**rope (energy system model)
RES	renewable energy sources
VMT	vehicle miles travelled

cars. Unfortunately, this instrument focuses on the efficiency of the vehicles and therefore neglects the rebound effect. This means that more efficient cars lead to lower operating costs and therefore stimulate a higher mileage [7]. Even though the German transport sector is one of the few worldwide with decreasing CO_2 emissions, most experts agree that technical measures of conventional passenger cars alone will not enable vehicle manufacturers to meet the European reduction target [8,9]. This is mainly determined by the high technical CO_2 emission abatement costs. On the other hand, these high costs could also be interpreted as a great willingness to pay for luxury passenger cars.

A first step towards including the transport sector in the EU ETS was taken in 2012, with all flights arriving at and/or departing from EU airports being included (European Directive 2008/101). The idea of integrating road transport in cap and trade and other approaches has been discussed extensively for several years (e.g. Refs. [10,11]). Due to the low price elasticity for fuel in road transport (e.g. Refs. [12,13]) and comparatively low marginal CO_2 abatement costs in the energy sector, such an integration into the EU ETS leads to monetary flows from the transport sector to the other EU ETS sectors rather than to real emission reductions within the road transport sector. An efficient reduction of overall emission is, however, assured [14].

Today, significant emissions reductions within the European transport sector without the EU ETS seem to be unlikely. The historic CO_2 emissions development in the European transport sector shows that a reduction is impossible without a substantial change in the traffic participant's attitude, a technical breakthrough or a faster increase of transport cost in comparison to income gains. On the one hand, inclusion in the EU ETS would lead to a marginal increase in transport costs in road transport (which might be higher if stronger emission targets are imposed) and on the other hand it leads to an increased allowance demand in the EU ETS market, where the energy industries have a major market share. Hence, the main impacts of such an implementation could be a change in the price of allowances in the EU ETS and due to this in electricity generation as well as in mileage performance and vehicle fleet composition. Therefore, these impacts will be analysed in considering feedback to road transport itself and the mitigation potentials from energy industries. The interactions between these two sectors actually increase through the market penetration of EV (electric vehicles) – which seems to be relevant for the coming decades [15,16]. Hence, a model based approach is chosen for this analysis to cope with the high system complexity in a systematic way. This model approach has to adequately cover both sectors.

In the energy industry, mainly investment and production planning are affected by the EU ETS. Optimising energy system models enables an adequate analysis of the long term energy system developments to be made for investment planning for power plants [17–26]. In the EU ETS, the development of the CO_2 allowance price depends mainly on the marginal CO_2 abatement costs of European power plants and the CO_2 reduction target. We therefore use an optimising energy system model (*PERSEUS EU* (Package for Emission Reduction Strategies in Energy Use and Supply in Europe)[1]), which includes emissions trading and assumes optimising agents in the energy industry [27,28]. The road transport sector, by contrast, is characterised by individual purchase decisions (especially in passenger transport) of multiple actors with heterogeneous preferences and decision patterns. Here we apply the *COMIT* (CO_2 emission Mitigation in the Transport sector)[2] model, which is a MAS (multi agent based simulation) model, which is widely accepted as being able to cope with these (sometimes irrational) inhomogeneities [14]. As already stated, this combination of sophisticated models of both sectors is necessary in order to achieve sound results for our research question.

So far the two models have only been used separately and therefore contain only a reduced representation of the other sector. The corresponding results have thus never considered all the necessary aspects of the impact of road transport being included in the EU ETS. In the following, the results are harmonised and allow for the first time a consistent interpretation, insofar as both models use the same relevant parameter values (e.g. oil prices) and exchange their values for the demand and price of CO_2 emission allowances.

The paper is structured as follows: After an outline of the two models applied, *COMIT* and *PERSEUS EU*, their data exchange and underlying scenarios are described. Subsequently, the model results are presented and their sectoral impacts are discussed. The paper concludes with a discussion of the impacts of an extended EU ETS on the German road transport and (European) electricity sectors.

2. Modelling the German road transport sector by the *COMIT* model

Multi agent simulation is a fairly new modelling approach in transport economics. The first MAS models focused more on network based approaches (e.g. MATSim (Multi Agent Transport Simulation) [29] and ILUTE (integrated land use, transportation, environment) [30]). As CO_2 emission reductions of optimised routing and navigation seem lower than reductions from car fleet technology and mileage, we neglect the underlying road network for the following analysis [14]. The *COMIT* model used here focuses on mode shift, mileage reduction, and vehicle purchase decision for private households and freight forwarders.

2.1. Model structure

The *COMIT* model includes 700 different households and more than 600 different road freight transport actors, which represent

[1] Program **P**ackage for **E**mission **R**eduction **S**trategies in **E**nergy **U**se and **S**upply in **EU**rope.

[2] **CO_2** emission **Mi**tigation in the **T**ransport sector.

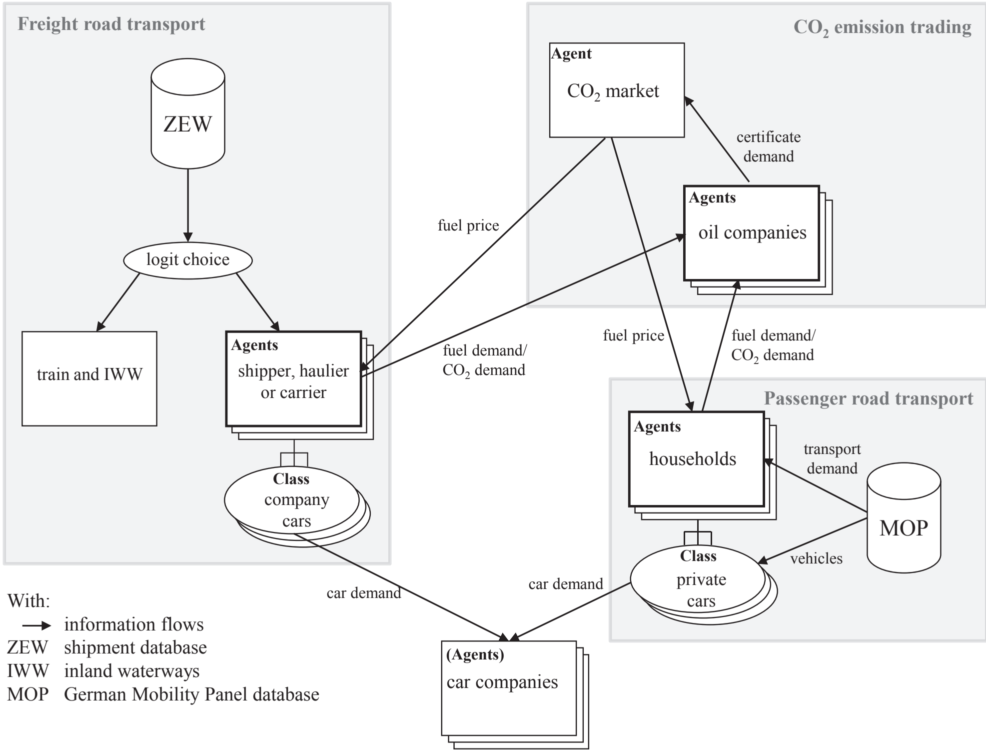

Fig. 1. Class diagram of the meso-economic model [14].

the German traffic participants. The model was developed to analyse the impact of an extension of the EU ETS to German road transport [14]. In the model, the main agents are private households (demanding fuel and new passenger cars), freight forwarders (demanding diesel and new freight vehicles), vehicle manufacturers (providing new cars), and oil companies (importing/refining and selling fuel) (Fig. 1). The latter actors are affected by the EU ETS and, hence, trade the allowances. Modelling of households and freight forwarders is based on empirical data [31,32]. A CO_2 reduction path (number of allowances allocated to the oil companies) is adapted to the German policy targets of 25% between 2010 and 2030 (derived from the objective for 2050 by Ref. [33]). The CO_2 emission reduction in transport implies a continuous reduction of allowances during the simulation period for the obliged party (i.e. oil companies). As it is an open emissions trading system, this reduction of allowances does not necessarily imply a real reduction of CO_2 emissions within the transport sector. If traffic participants ask for more fuel, the oil companies are forced to buy allowances on the residual EU ETS market. Hence, the reduction of emissions takes place in other sectors — but with a resulting increase in the corresponding CO_2 allowance prices, which will be marked up to the fuel price of the following day.

The core of the model consists of a loop, which represents an average exchange market day and which is repeated 264 times a year (Fig. 1). On each day represented, the traffic participants may adjust their VMT (vehicle miles travelled) according to current fuel prices (eq. (1)). Furthermore, the household agents decide once a year whether to buy a new (or used) car or continue to drive their old one. Simultaneously, freight forwarders randomly receive transport orders from the database [14] every day and execute these orders using trucks or combined means of transport (truck—train—truck) according to the underlying logit model [31] (eq. (5)). If the fuel price increases, freight forwarders can avoid additional costs by using combined means of transport instead of trucks. Oil companies decide every evening whether to buy or to sell allowances on the EU ETS market or not to trade allowances at all, based on their shortage of allowances.[3] The additional demand for allowances is transferred to the *PERSEUS EU* model and the resulting price for CO_2 allowances is incorporated into the fuel price for the next day.

The reaction functions of households are generally difficult to estimate because individuals react differently to political instruments and the many influencing factors can hardly be measured [34—38]. Moreover, there has been no significant (real) fuel price increase in the last few decades in Germany (except in the late 70s and 80s),[4] which could be used to calibrate the model. A widely applied approach is to cluster some reaction functions according to different types of households, regions or attitudes or to take social networks into consideration. The *COMIT* model simplifies these influences and uses statistically estimated individual reaction functions based on empirical panel data [14].

2.2. Main agents

The 700 private households in the model, representing the 40 million German households, are defined by the following attributes: monthly VMT ($mileage_{n,i,k}$), fuel efficiency ($fuelCombustion_{n,i,k}$), car age ($carAge_{n,i,k}$), fuel type (diesel or not) ($diesel_{i,k}$) of their vehicles, luxury car or not ($premium_{i,k}$), paid fuel prices ($fuelPrice_{i,t}$), household size ($hhSize_i$), number of household members with a high school diploma ($nHSD_i$), number of employed household members (nEP_i), children under 10 years old living in the household ($kidD_i$), and holiday trip ($holiday_i$) during the survey.

[3] In the model, their strategy is simplified to a daily balance of their allowance account.

[4] Whereas in the 70s and 80s the nominal fuel price change was about 20% p.a. on three occasions, there was no price change above the 10% corridor except in 2000 and 2010 within the last 15 years [38].

Model inputs are transport panel data from a mobility survey, GMP (German Mobility Panel) [39], which include characteristics of more than 20,000 German traffic participants. To determine the reaction function of households to fuel price changes (eq. (1)), the *COMIT* model is based on a fixed effects panel regression model by Ref. [40]. The results are based on 1409 observations and are taken from [14:126ff].

$$\begin{aligned}\ln(\text{mileage}_{n,i,k}) &= 7.66 + 0.539\cdot\ln(\text{fuelCombustion}_{n,i,k}/100) \\ &- 0.545\cdot\ln(\text{fuelPrice}_{i,t}) - 0.02\cdot(\text{carAge}_{n,i,k}) \\ &+ 0.21\cdot\text{diesel}_{i,k} + 0.24\cdot\text{premium}_{i,k} + 0.07\cdot n\text{HSD}_i - 0.10\cdot n\text{EP}_i \\ &+ 0.27\cdot\text{holiday}_i + 0.11\cdot\text{kidD}_i - 0.0001\cdot\ln(\text{CO}_2\text{Price}_{i,t})^2 \end{aligned} \quad (1)$$

Here, $\ln(\text{mileage}_{n,i,k})$ is the log of the monthly VMT of households $i\in\{1-I\}$ with car $k\in\{1-K\}$ in the year $n\in\{1-20\}$. It is influenced positively by the fuel efficiency of the car, the diesel and the premium variable, the proxy of the education level of the household, the number of employed people in the household, as well as by the holiday and children variable. Negative influences are the fuel price, the car age, and the additionally included CO_2 price variable (by adding the squared log). This price reaction of households is determined every day $t\in\{1-264\}$ to adapt their VMT to the current fuel prices (which include the CO_2 prices).

As depicted above, the second possibility of reacting to higher fuel prices is to buy a new car. The decision is based on a two-stage approach (cf. [40] or [41]) and considers different car segments and drive chain technologies such as gasoline, diesel, compressed natural gas, liquefied petroleum gas and EV. In stage I, the household assesses once a year whether to buy a new (or used) vehicle. The underlying decision is based on a logistic function for each car ($U_{n,i,k}$) composed of econometrically estimated parameters (eqs. (2) and (3)). For the model estimation $U_{n,i,k}$ equals one, if the empirical household bought a new car, if not $U_{n,i,k}$ is defined as zero. Dependent variables are the vehicle age of the current vehicle ($\text{carAge}_{n,i,k}$), its annual mileage and the household type (hhtype_i).[5] Within the *COMIT* model, the logistic error term is transformed into a uniformly distributed error term ($\varepsilon_{n,i,k}$) between −0.1 and +0.1.

$$\begin{aligned}U_{n,i,k} &= 2.476 + 0.368\cdot\ln\left(\text{carAge}_{n,i,k}\right) \\ &+ 0.263\cdot\ln\left(\text{mileage}_{n,i,k}\right) - \text{hhtypeConst}_i + \varepsilon_{n,i,k}\end{aligned} \quad (2)$$

$$\text{With hhtypeConst}_i = \begin{cases} 0.476, & \text{if} \quad \text{hhtype}_i = 1 \\ 0.702, & \text{if} \quad \text{hhtype}_i = 2 \\ 0, & \text{else} \end{cases}$$

From this estimated utility $U_{n,i,k}$ per vehicle, the probability of buying a car can be expressed by eq. (3).

$$P_{n,i,k} = \frac{e^{U_{n,i,k}}}{1+e^{U_{n,i,k}}} \quad (3)$$

If the probability of buying a vehicle $P_{n,i,k}$ is below a household-specific uniformly distributed threshold between 0 and 1, the household rejects the decision to buy a car, it continues to drive its old vehicle and the household is excluded from the car purchase decision module in the current year of simulation. Otherwise, it decides to buy a car and within the next step of stage I, the car age of the new vehicle is defined by an econometrically estimated function by Ref. [14]. This depends on the age of the current vehicle and the household type.

In stage II of the decision, the car segment is chosen according to the previous vehicle segment with a certain transition probability to the neighbouring segments (cf. [42]). Within this car segment, a representative vehicle for each drive chain technology (gasoline, diesel, gas, BEV (battery electric vehicle), and PHEV (plug-in hybrid electric vehicle)) is taken from the *COMIT* vehicle database. In a next step, some alternatives are rejected due to the individual perception of the number of fuelling infrastructures, vehicle range or individual innovation friendliness [43].

The resulting reduced sample of cars within the segment is then transferred into stage III, where a utility value ($U_{n,i,k}$) is calculated for each vehicle. The underlying utility function (eq. (4)) contains a techno-economic weighted TCO (total cost of ownership) approach and a socio-economic technology choice function based on a stated preference analysis by Ref. [44]. Both components are empirically acknowledged for the car purchase decision. Their weighting, however, is vague and person-specific (cf. [45]). Nevertheless, many studies highlight the significance of the TCO approach [40,41,46]. Therefore, we choose a constant weighting of the two components with $\alpha = 0.7$ and $\beta = 0.3$ for the following calculations. This meets the current market situation satisfactorily.

In order to have comparable scales for both utility components, both are correspondingly transferred into the probability for choosing the considered vehicle. For the TCO component, the LUCE model [47] is used for the transformation, assuming the IIA condition for the vehicle sample. The LUCE model allows the use of a household-specific weighting factor γ_i, indicating the involvement of the decision maker. In the current scenario it is set to 3, which fits well with current market observations. For the second component of the utility function, the logit-specific transformation (odds ratio) is used.

$$U_{n,i,k} = \alpha\cdot\frac{\left(U^{\text{TCO}}_{n,i,k}\right)^{\gamma_i}}{\sum\limits_{k\in K}\left(U^{\text{TCO}}_{n,i,k}\right)^{\gamma_i}} + \beta\cdot\frac{e^{U^{\text{SOC}}_{n,i,k}}}{\sum\limits_{k\in K} e^{U^{\text{SOC}}_{n,i,k}}} \quad (4)$$

Finally, the household calculates the utility $U_{n,i,k}$ for each considered vehicle and chooses the vehicle with the highest utility. Then, the vehicle fleet in the *COMIT* model is updated correspondingly. A detailed description is given in Ref. [43]. The *COMIT* model considers rebound effects of these technologies.

Within the *COMIT* model, agents in road freight transport (shippers, freight forwarders, and carriers) choose their mode of combined transport (i.e. truck–rail–truck) according to a statistically estimated nested logit model for German road transport by Ref. [31]. All orders of the shipping database from 500 (out of 3000) telephone interviews with German forwarders [31] are given with more than 30 variables. Most of them [26] are integrated in the logit model (eq. (5)). Therefore, the mode decision of forwarders depends among other things on the number of employees of the forwarder, transport volumes on the considered relation, available time for scheduling, number of similar transports, duration of transport in combined transport and truck alone, costs of the two alternatives, etc.). The cost of transport depends on the fuel (and electricity) prices and is therefore the decisive variable here. All variables depend on the day t, forwarder $q\in\{1-600\}$ and shipment $o\in\{1-O\}$. Shipments with a mileage below 50 km are directly performed by truck alone.

$$\text{CTTruck}_{t,q,o} = \begin{cases} \beta\cdot X_{t,q,o}, & \text{for truckKm} > 50\text{km} \\ 1, & \text{for truckKm} \le 50\text{km} \end{cases} \quad (5)$$

The freight forwarder's fleet is simplified in the model and is represented by a pool of identical trucks, of which the efficiency is

[5] The German Mobility Panel distinguishes between four households types: (1) 1–2 person households with employed person(s), (2) 1–2 person households without employed persons (in particular pensioners), (3) households with children under the age of 18, and (4) households without children and more than two adults (in particular shared accommodation).

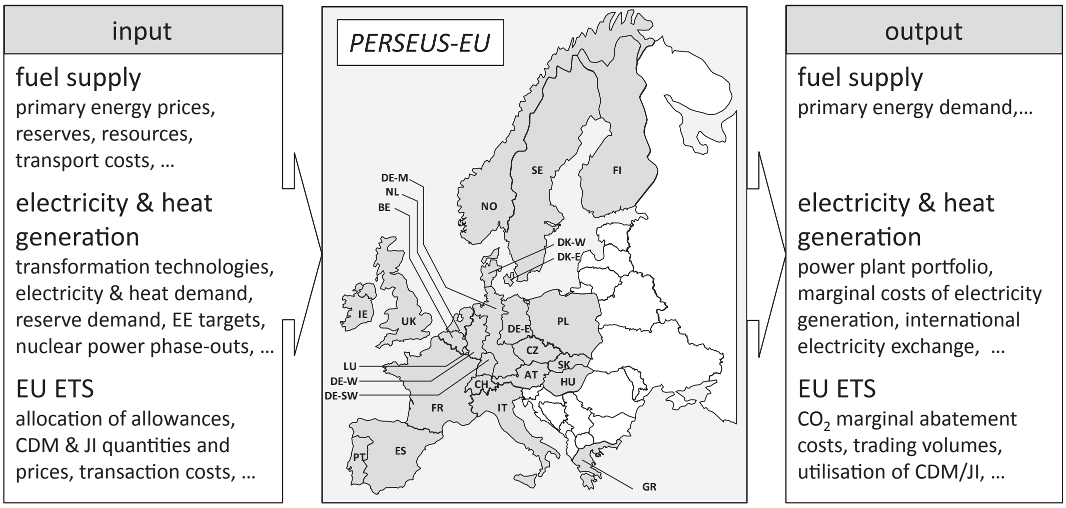

Fig. 2. Regional scope and main inputs/outputs of *PERSEUS-EU*.

upgraded by 0.2 L per 100 km every year (gain in efficiency less than 1%). 600 freight road forwarders are implemented in the *COMIT* model, which represents the German freight road sector. In the *COMIT* model, it is assumed that the freight volumes increase by 1.6% per year [48] independently of the fuel costs.

2.3. CO_2 emission trading in the COMIT model

As depicted above, the up stream emission trading system in the *COMIT* model affects the oil companies which have to have the right amount of allowances at the end of each trading period. This is achieved when the allocated allowances (CO_2Supply) plus the additionally bought allowances (cerDemand) correspond to the amount of CO_2 emissions produced by the fuel sold in this trading period (CO_2Demand), which is defined as follows (eq. (6)).

$$CO_2Demand_t = \sum_{i=1}^{I}\sum_{k=1}^{K} mileage_{t,n,i,k}\cdot\frac{fuelCombustion_{t,n,i,k}}{100}\cdot CO_2Factor_j + \sum_{q=1}^{600} mileage_{t,q}\cdot\frac{fuelCombustion_{t,n,q}}{100}\cdot CO_2Factor_{diesel} \quad (6)$$

Therefore the daily CO_2 demand of road transport participants ($CO_2Demand_t$) depends on the individual mileage of households or trucks ($mileage_{t,n,i,k}$ and $mileage_{t,q}$), fuel efficiency per kilometre ($fuelCombustion_{t,n,i,k}$ and $fuelCombustion_{t,n,q}$) and the corresponding emission factor of fuel ($CO_2Factor_{j,diesel}$), where j indicates the fuel types (diesel, gasoline or premium gasoline). The sum of the daily CO_2 demand of one year has to equal the amount of allowances held by the oil company. CO_2 demand from the traffic participants minus the allowances allocated to the oil companies equals the additional allowance demand on the existing EU ETS modelled in *PERSEUS EU*.

3. Modelling the German electricity sector by the *PERSEUS-EU* model

The development of the CO_2 allowance price in the EU ETS depends mainly on the CO_2 reduction target and the marginal CO_2 abatement costs of the European power plants, which represent the predominant EU ETS sector. In turn, the electricity sector is significantly influenced by the CO_2 allowance price. Due to this interdependency, an integrated approach regarding the development of the European power plant portfolio as well as the corresponding CO_2 allowance price is needed.

To adequately consider CO_2 emissions trading in an optimising energy system it is necessary to take the model costs and restrictions associated with the EU ETS into account. These include costs and restrictions of the CO_2 abatement technologies as well as those associated with allowance and credit trading itself, and prices and quantities of JI (Joint Implementations) and CDM (Clean Development Mechanisms) credits. Additionally, the regional scope has to cover the main participating countries of the EU ETS as well as their cross national electricity exchanges.

The optimising energy system model *PERSEUS EU* is part of a model family widely used for different analyses of long term developments in the European energy system (see e.g. Refs. [28,49,50]). It is based on an inter regional electricity balance throughout Europe and encompasses the electricity systems of 22 countries (Fig. 2) on a technologically highly detailed level, with nearly 3000 unit classes, each of which has even more processes.[6] While the EU ETS covers even more countries, for the scope of this paper it is sufficient to consider only those countries that emit the major part of the CO_2 emissions covered by the EU ETS.

The construction and operation of power plants are subject to several (technology specific) techno economic restrictions in the model. These include among others the availability of installed power plant capacities, ramp rates, minimum or maximum full load hours, and (de)commissioning constraints. These restrictions allow an adequate description of the existing and future energy system in Europe, including power plant operation and future capacity development (for more details see Ref. [28]). The driver for the expansion and operation of power plants in the model is the exogenously given demand for electricity. Its time

[6] Such models are also called bottom-up models.

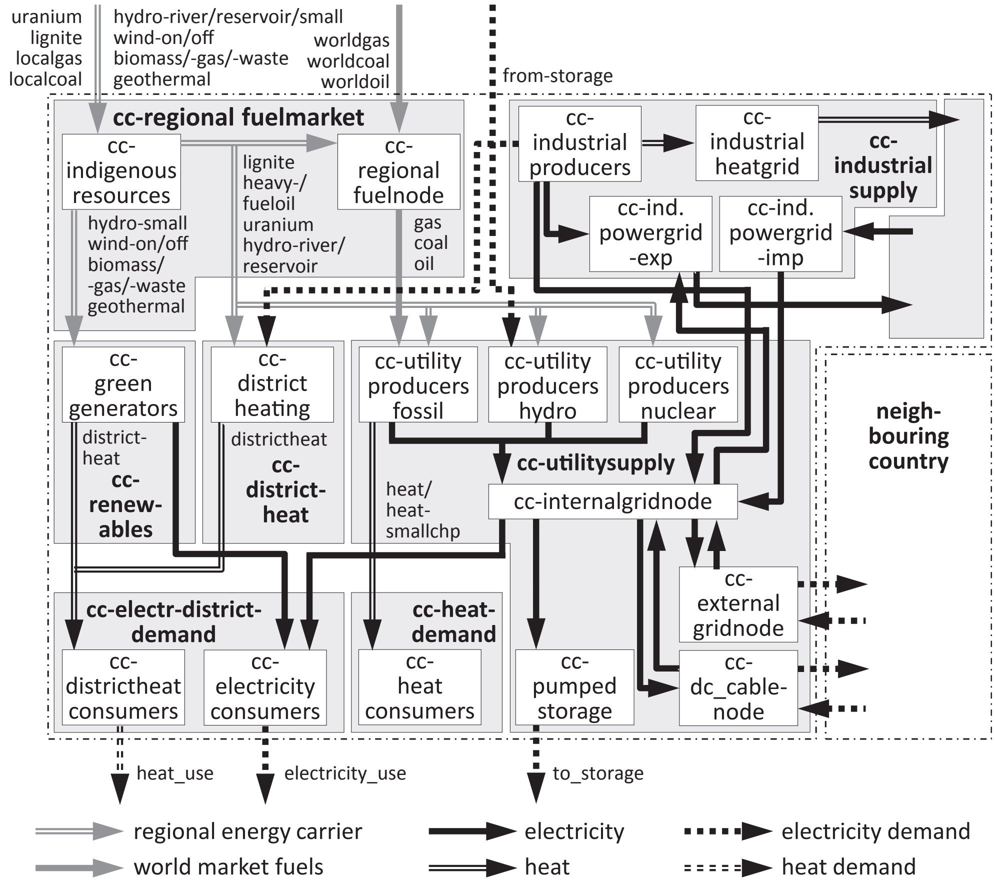

Fig. 3. Model structure of *PERSEUS-EU* [28].

differentiated demand profile of one year is represented by 44 time slices, which are structured in four seasons with 2 type days [18]. The complete time horizon covered in this analysis extends up to 2030.

The model structure is presented to give an overview of the system boundaries and coverage. Additionally the objective func tion of *PERSEUS EU* is introduced, constituting the decision crite rion of the model. After this short overview of *PERSEUS EU*, the modelling of the EU ETS is explained in more detail.

3.1. Model structure

In the *PERSEUS EU* model, each cc (country considered) is modelled separately and shows the same model structure (Fig. 3). This structure consists of several sectors which can be grouped into fuel supply, electricity, and heat generation as well as final energy demand for electricity and heat. While the model focuses on the electricity sector, also heat generation, transport, and de mand have to be taken into account in order to consider the in terdependencies between the two energy forms (i.e. in combined heat and power generation). The fuel supply sector includes indigenous resources and supplies from outside the country. This sector provides the input energy carriers for the energy conversion sector, which contains the public and industrial electricity and heat production. Additionally, energy conversion based on RES (renewable energy sources) and the generation of district heat are treated separately in this sector in order to consider their specific characteristics (i.e. district heat pipeline transport). The electricity is fed into a transmission grid node, while heat is provided either directly to the final heat consumers or to the end user via onsite industrial heat grids. The electricity transmission grid node transports electricity to the final energy demand sector as well as to the pumped storage power plants. Furthermore, this node is connected to the interconnections between the European coun tries (overhead power transmission lines and underground direct current transmission lines).

3.2. Objective function

The linear objective function of *PERSEUS EU* (eq. (7)) is based on a minimisation of all decision relevant system expenditures discounted to the base year of 2007 (α: discount factor). It in cludes all expenditures related to energy flows ($FL_{ec,t}$), to power plant operation ($PL_{proc,t}$) and power plant capacities ($Cap_{unit,t}$ and $NewCap_{unit,t}$) as well as to the EU ETS. For the energy flows of each ec (energy carrier), in each period (t) between two pro ducers (prod and prod′ or imp, exp) fuel costs ($Cfuel_{ec,t}$), trans mission fees ($Cfee_{ec,t}$), and other expenditures ($Cvar_{ec,t}$) (i.e. financial incentives for renewable energies) are taken into ac count. Considering variable costs ($Cvar_{proc,t}$), fixed operational costs ($Cfix_{unit,t}$), investments ($Cinv_{unit,t}$), and load change costs ($Cload_{unit,t}$) allows us to consider the operation and capacity development of new and existing power plants and their load variations ($LVup_{unit,seas\text{-}1,seas,t}$ and $LVdown_{unit,seas\text{-}1,seas,t}$). The last two elements of the objective function include costs related to the EU ETS, such as transaction costs ($Ctrans_{CO_2,t}$) and penalties for violating emission caps ($Cpen_{CO_2,t}$) as well as expenditures for credits from CDM and JI projects ($Ckyo_{kyoID,t}$). Hence, the modelling approach covers three optimisation problems, namely, system expansion planning, capacity production planning, and CO_2 emission trading.

and the emission allowances ($\mathrm{EmissRights}_{\mathrm{sec},CO_2,t}$). The emissions trading balance (eq. (9)) is complemented by two supplementary elements: additional emissions which are subject to a mostly

$$\min \sum_{t\in T} \alpha_t \cdot \left(\begin{array}{l} \left(\begin{array}{l} \sum\limits_{\mathrm{imp}\in \mathrm{IMP}} \sum\limits_{\mathrm{ec}\in \mathrm{EC}} \sum\limits_{\mathrm{prod}'\in PROD'_{\mathrm{imp,ec}}} \left(\mathrm{FL}_{\mathrm{imp,prod',ec},t} \cdot \mathrm{Cfuel}_{\mathrm{imp,prod',ec},t}\right) \\ + \sum\limits_{\mathrm{prod}\in \mathrm{PROD}} \sum\limits_{\mathrm{ec}\in \mathrm{EC}} \sum\limits_{\mathrm{prod}'\in \mathrm{PROD}'_{\mathrm{prod,ec}}} \left(\mathrm{FL}_{\mathrm{prod,prod',ec},t} \cdot \left(\mathrm{Cvar}_{\mathrm{prod,prod',ec},t} + \mathrm{Cfee}_{\mathrm{prod,prod',ec},t}\right)\right) \\ + \sum\limits_{\mathrm{exp}\in \mathrm{EXP}} \sum\limits_{\mathrm{ec}\in \mathrm{EC}} \sum\limits_{\mathrm{prod}\in \mathrm{PROD}_{\mathrm{exp,ec}}} \left(\mathrm{FL}_{\mathrm{prod,exp,ec},t} \cdot \mathrm{Cvar}_{\mathrm{prod,exp,ec},t}\right) \end{array} \right) \\ + \sum\limits_{\mathrm{proc}\in \mathrm{PROCGEN}} \left(\mathrm{PL}_{\mathrm{proc},t} \cdot \mathrm{Cvar}_{\mathrm{proc},t}\right) \\ + \sum\limits_{\mathrm{unit}\in \mathrm{UNIT}} \left(\begin{array}{l} \left(\mathrm{Cap}_{\mathrm{unit},t} \cdot \mathrm{Cfix}_{\mathrm{unit},t}\right) \\ + \left(\mathrm{NewCap}_{\mathrm{unit},t} \cdot \mathrm{Cinv}_{\mathrm{unit},t}\right) \\ + \sum\limits_{\mathrm{seas}\in \mathrm{SEAS}} \left(\mathrm{LVup}_{\mathrm{unit,seas}-1,\mathrm{seas},t} + \mathrm{LVdown}_{\mathrm{unit,seas}-1,\mathrm{seas},t}\right) \cdot \mathrm{Cload}_{\mathrm{unit},t} \end{array} \right) \\ + \sum\limits_{\mathrm{sec}\in \mathrm{TRADESEC}} \left(\begin{array}{l} \left(\left(\mathrm{Emissaux}^{+}_{\mathrm{sec},CO_2,t} + \mathrm{Emissaux}^{-}_{\mathrm{sec},CO_2,t}\right) \cdot \dfrac{\mathrm{Ctrans}_{CO_2,t}}{2} \right) \\ + \left(\mathrm{EmissPen}_{\mathrm{sec},CO_2,t} \cdot \mathrm{Cpen}_{CO_2,t}\right) \end{array} \right) + \sum\limits_{\mathrm{kyoID}\in \mathrm{KYOID}} \left(\mathrm{KyoCert}_{\mathrm{kyoID},t} \cdot \mathrm{Ckyo}_{\mathrm{kyoID},t}\right) \end{array} \right) \tag{7}$$

3.3. CO_2 emissions trading

In the *PERSEUS EU* model, a quantity based approach is used to integrate the EU ETS. The formerly free commodity CO_2 is now linked to emission allowances. In reality, the obliged agents are individual companies, but in order to reach a compromise between model size and level of detail, sectors are used as market agents. These market agents are connected via transmission lines and the emissions trading system. Hence, electricity production is allocated within the framework of transmission line capacities and the EU ETS trading restrictions in the model until the decision relevant system expenditures are minimised.

This quantity based approach in *PERSEUS EU* covers the following equations. First, the CO_2 emission volume ($\mathrm{EmissVol}_{\mathrm{sec},CO_2,t}$) of each sector (sec) in period (t) is calculated as the product of the utility level of each process ($\mathrm{PL}_{\mathrm{proc},t}$) in the affected sectors and the specific CO_2 emission factors ($\mathrm{EmissProc}_{CO_2,\mathrm{proc},t}$) (eq. (8)). To take emissions in the supply chain into account, emissions of the energy flows ($\mathrm{EmissFlow}_{CO_2,\mathrm{prod,prod',ec},t}$) can be included in the model.

$$\mathrm{EmissVol}_{\mathrm{sec},CO_2,t} \quad \sum_{\mathrm{proc}\in \mathrm{PROC}_{\mathrm{sec}}} \mathrm{PL}_{\mathrm{proc},t} \cdot \mathrm{EmissProc}_{CO_2,\mathrm{proc},t} + \sum_{\mathrm{proc}\in \mathrm{PROC}'_{\mathrm{sec}}} \sum_{\mathrm{ec}\in \mathrm{EC}} \sum_{\mathrm{prod}\in \mathrm{PROD}_{\mathrm{prod',ec}}} \mathrm{FL}_{\mathrm{prod,prod',ec},t} \cdot \mathrm{EmissFlow}_{CO_2,\mathrm{prod,prod',ec},t} \tag{8}$$

$\forall t\in T;\ \forall \mathrm{sec}\in \mathrm{SEC}$

Second, the sectoral CO_2 emissions trading volume results from the difference between the CO_2 emission volume ($\mathrm{EmissVol}_{\mathrm{sec},CO_2,t}$)

prohibitive penalty ($\mathrm{EmissPen}_{\mathrm{sec},CO_2,t}$), and excess emission rights which are not tradable due to exogenously given restrictions ($\mathrm{EmissLoss}_{\mathrm{sec},CO_2,t}$). In the case of using penalised emissions ($\mathrm{EmissPen}_{\mathrm{sec},CO_2,t}$), the emission rights of the next period ($\mathrm{EmissRights}_{\mathrm{sec},CO_2,t+1}$) will be reduced by the amount of these penalised emissions from the previous period.

$$\Delta\mathrm{Emiss}_{\mathrm{sec},CO_2,t} \quad \mathrm{EmissVol}_{\mathrm{sec},CO_2,t} \quad \mathrm{EmissRights}_{\mathrm{sec},CO_2,t} + \mathrm{EmissLoss}_{\mathrm{sec},CO_2,t} \quad \mathrm{EmissPen}_{\mathrm{sec},CO_2,t} \tag{9}$$

$\forall t\in T;\ \forall \mathrm{sec}\in \mathrm{TRADESEC}$

Third, at the end of each trading period the amount of CO_2 emissions in the EU ETS sectors has to equal the sum of emission allowances and permitted Kyoto credits from JI or CDM projects. The available amount and the corresponding costs of these credits are modelled as cost potential steps [28]. The banking option and further optional trading restrictions are also implemented. Addi tionally, costs incurred by the trading of allowances and credits ($\mathrm{Ctrans}_{CO_2,t}$) are considered in the objective function.

Due to the coupling of CO_2 emissions trading with the capacity expansion planning of the European countries, this approach al lows us to analyse the interdependencies between and impacts on both sectors in an integrated and consistent way.

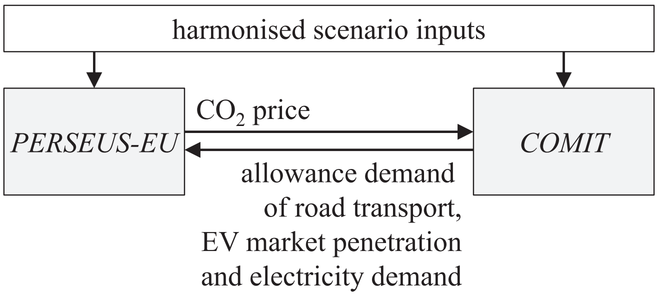

Fig. 4. Model coupling scheme.

4. Model coupling, scenario definition, and critical appraisal

In this section, we first explain the model coupling. Subse quently, we define the four main scenarios in our analysis. Further scenario variations are subsequently discussed. The section con cludes with a critical appraisal of the chosen models and the overall approach.

4.1. Model coupling

The coupling of the two models (Fig. 4) starts with a model run of *PERSEUS EU*, which provides the initial development of CO_2 emission allowance prices as an input for the *COMIT* model. *COMIT*, in turn, uses this input information to calculate the need for CO_2 emission allowances for the road transport sector. With this addi tional demand, the German overall CO_2 emission cap in *PERSEUS EU* is adjusted and a new model run is started. This model loop is continued until no further change of the CO_2 emission cap is needed. Sufficient result convergence is usually reached after only two to five model runs.

In scenarios including electric mobility, additional parameters have to be exchanged between the models. Namely, *COMIT* calcu lates the German market penetration of EV. In order to account for the additional electricity demand by EV on the European level — which seems necessary to account for the pan European EU ETS — the German market penetration is then multiplied by the German market share within the European passenger car fleet. This factor will be around 7 until 2030 if the current European fleet develop ment is considered [51].[7] These data are transformed into a suitable format (load curve and electricity demand) and transferred to *PERSEUS EU* as exogenous parameters.

Ultimately, a balance between CO_2 emission mitigation options in the electricity and road transport sectors is obtained, and the influence on CO_2 allowance prices of an extension of the EU ETS to the German road transport sector can be analysed.

4.2. Scenario definition

In addition to the exchange of parameter values, our analysis comprises two main scenario paths. These scenarios are based on the CP (*Current Policy*) and NP (*New Policy*) scenarios from the World Energy Outlook [52] (Table 1). They represent two com modity price development paths to analyse the impact of different fuel prices. In the *Current Policy* scenario, the crude oil price in creases from US$ 63 per barrel in 2010 to US$ 125 per barrel in 2030. In the *New Policy* scenario, the price rises to US$ 106 per barrel.

In order to estimate the impact of EV on these scenarios, both scenarios are calculated with and without the option of buying EV. The parameter set ‘electric mobility’ was chosen as an additional scenario variation, because the electricity and road transport sec tors interact strongly, especially regarding CO_2 mitigation strate gies. This results in a total of four main scenarios. In order to show the impact of a very high market penetration of EV, we also calculated a scenario (*High EV*), where all the parameters within the purchase decision for EV are changed to unrealistically positive values. This includes complete availability of charging stations at home and at the workplace, a change of doubts about EV to a preference for EV, a stronger weight of vehicle operating costs, a rapidly decreasing battery price, and we assume a permanently available second car for all households (e.g. car sharing).

In addition, the scenarios contain different goals for electricity from renewable energy sources (RES) after 2020. The RES targets of the two scenarios *Current Policy* (with and without EV) are extrapolated to 2030 with half of the average increase of the period from 2010 to 2020. In the other two scenarios, the RES targets from 2021 onward are assumed to have the same average increase of the prior period. As the goals for renewable energies are calculated as a percentage of gross final electricity demand as outlined in the NREAP (National Renewable Energy Action Plans) of each European country [53], the absolute amount of renewable electricity pro duced is higher in scenarios with EV due to the overall higher electricity demand (s. Table 2). In order to analyse the impact of even higher RES targets on the enlargement of the EU ETS, we additionally examine scenarios up to twice the RES amount in 2030 compared to the *New Policy* scenarios. However, these results show only a minor impact on our analysis focus. Therefore we do not discuss them in more detail in the results section.

Concerning the EU ETS cap, all scenarios are based on the NAPs and assume a Europe wide cap decrease of 1.74% per year up to

Table 1
Main scenario assumptions.

Scenario	Parameter	Assumed development
Current Policy	Crude oil price	Increase to 125 US$/bbl in 2030 (equals gasoline priced from € 1.45 to € 1.98 up to 2030 for Germany)
	RES targets	Up to 2020 according to the NREAPs; since 2021 half of average yearly increase of 2010 2020
New Policy	Crude oil price	Increase to 106 US$/bbl in 2030 (equals gasoline priced from € 1.45 to € 1.82 up to 2030 for Germany)
	RES targets	Up to 2020 according to the NREAPs; since 2021 average yearly increase of 2010 2020

[7] Due to the great uncertainty of this market share, we also considered the factors 5 and 10 as sensitivities. Our results, however, confirm only a very marginal impact on the installed capacity (<1%) and CO_2 emissions (<€ 1 per tonne in 2030).

Table 2
Assumed total electricity demand of Germany ([18,54] and own calculations).

Electricity demand [TWh]	2010	2020	2030
Without EV	522.5	507	495
With 6% EV	522.5	510	507
With 50% EV	522.5	517.5	537

2013. In the transport sector, a (so far non binding) reduction target for the CO_2 emissions of road transport by the German Federal Government is 10% (40%) by 2020 (2050) compared to the 2005 emission levels [32]. Based on these targets, we assume a reduction target of 25% in 2030 compared to 2010 for all scenarios in the *COMIT* model. This equals an average CO_2 emission reduction of about 1.1% per annum for road transport.

4.3. *Critical appraisal*

With respect to the modelled road transport market, it has to be pointed out that the car purchase decision by households is a rather complex process. There are numerous models for representing this decision and the results are diverse [55]. For this reason and due to its minor impact on our analysis here, it is strongly simplified in the *COMIT* model [14]. Furthermore, the assumption of equal market shares of EV in all European countries states only a rough estimation.

It has to be emphasised that *PERSEUS EU* focuses on the long term development of the European power plant portfolio only. For such an analysis, scope optimising energy system models are widely used as documented in the model description. However, this means that no statements regarding developments in the short term (i.e. daily change of CO_2 prices) are possible. Additionally, volatile feed in of renewable energies has to be considered in a simplified manner using side constraints for power and energy reserve requirements as well as for operation of peak load power plants (i.e. gas turbines). These limitations of the applied model only influence the results of this paper to a small extent, because the long term effects dominate the analysis findings.

As both models are coupled via a soft link, the convergence of the results cannot be guaranteed. Furthermore, the electricity price is not exchanged iteratively between the two models as it does not have a significant influence on the total costs of ownership during the EV lifetime [56] – especially for the small price changes of our analysis. Hence, marginal changes in the electricity price do not directly affect the EV market penetration.

5. Model results of the transport sector

Due to a considerable increase in trade volumes within the EU [57], which cannot be compensated by the technical efficiency gains of the truck fleet, a slightly increasing amount of CO_2 emis sions of road freight transport can be observed. This leads to a convergence of the CO_2 emission shares of households and carriers in the *COMIT* model – even though passenger transport still con tributes more than two thirds in 2030. Hence, the emission reduction of 1.1% p.a. is more precisely an emission reduction of about 2% p.a. for passenger road transport and a slight increase of CO_2 emissions by freight road transport. This is due to the fact that the reduction efforts of car manufacturers will increase consider ably due to EU Regulation 443/2009, which targets a specific limit of CO_2 emissions per km and light duty vehicle of 120 g in 2015 and 95 g in 2020 for the average light duty vehicle fleet sold. For the new vehicle fleet, this means a significant increase in the historic emission reduction path of 1.1% p.a. to about 3% p.a. up to 2015 and to about 6% p.a. up to 2020. This development, together with an electrification of the drive train, leads to decreasing operating costs and therefore to a rebound effect and increasing mileage. An appropriately designed ETS can better cope with this rebound ef fect, at least for CO_2 emissions, as it focuses on total emissions. The rebound effect might however lead to increasing air pollutants and other negative effects which are neglected here. The *COMIT* model results show that traffic participants in Germany do not respond to the shortage in allowances and increased fuel prices in all scenarios, but continue to drive a relatively stable mileage corresponding to the level of recent years. This is not surprising as an allowance price of about 50 euros per ton of CO_2 only leads to a fuel price increase of 7% in 20 years (i.e. 10 cents per litre) (Fig. 5). The corresponding fuel prices based on the crude oil price of the corresponding scenario and the allowance price of the EU ETS increase by less than 2% p.a. on average, which is comparable to the historical German fuel price

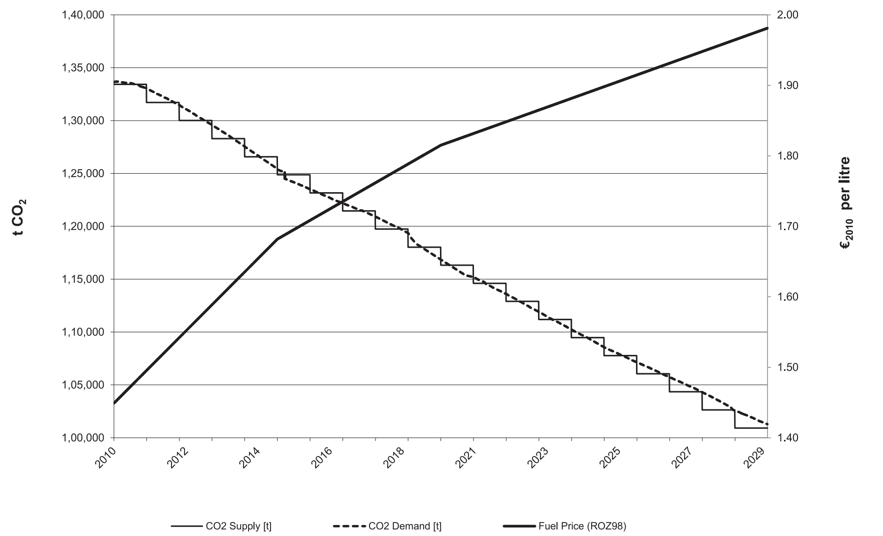

Fig. 5. Simulation results for CO_2 supply and demand as well as real fuel prices in German road transport for the CP scenario with 6% market share of EV.

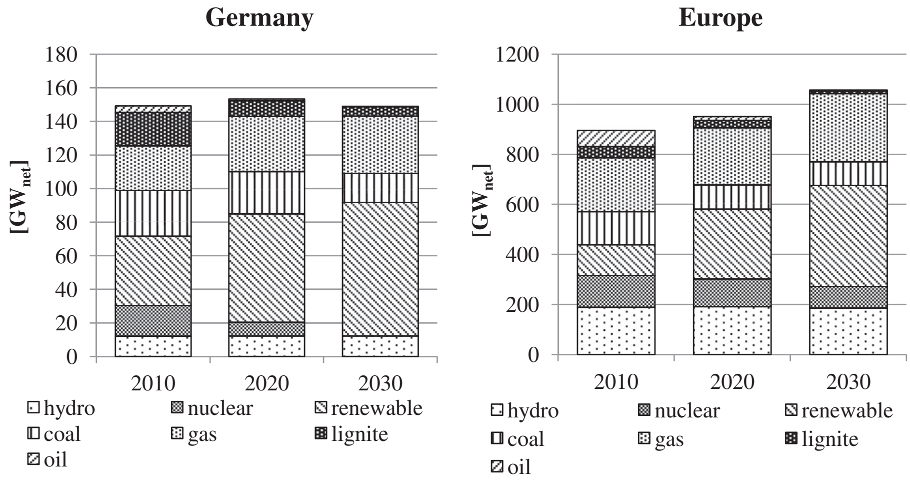

Fig. 6. Development of power plant net capacity (*Current Policy* without EV scenario).

development [58]. Thus, the impact on the households' decisions on transport is small. Hence, we might argue that the emissions trading system will only make the transport sector pay for its emissions and not really contribute to emission reductions in road transport. Nevertheless, the impact on car dependent households (especially in the countryside) could be significant in terms of their additional expenditures. An increasing fuel price of 10% equals an additional expenditure of about 15 euros per month. In forcing the road transport sector to decrease its emissions, the costs for society seem to be higher. The ETS guarantees the efficient achievement of the overall CO_2 reduction target, but does not (necessarily) decrease CO_2 emissions in the transport sector.

The impact on freight transport is equally low. Fierce competition on the European freight transport market, however, may react sensitively to these price changes. Especially long distance shipments are affected. A redistribution of revenues or a lowering of other fuel taxes might, however, lower the additional burdens of the road transport actors.

With respect to the shares of EV, only minor effects were identified for the scenarios with different EV shares. The estimated market share of EV in 2030 amounts to 10–11% – with about 70% BEV. The penetration rate is only 0.6% higher in the *Current Policy* scenario than in the *New Policy* scenario. Only for the *High EV* scenario is there a market share of 44% due to very optimistic EV assumptions (Section 4.2) In order to measure the impact on the European scale, we included similar EV market penetration rates based on [18] for all other Member States. Apparently, this low market penetration leads to minimal reduction of CO_2 emissions within road transport by less than 6% for the *Current Policy* and *New Policy* scenario but to about 20% within the *High EV* scenario.

The results confirm that the enlargement of the EU ETS leads to an economically efficient mitigation of CO_2 emissions in the economy, as the marginal abatement costs are significantly lower than the technical measures, which correspond to certificate prices of far more than € 100 per tonne of CO_2 [59,60]. With respect to CO_2 mitigation in passenger road transport alone, EU regulation 443/2009 seems to be more effective.

6. Model results of the electricity sector

In all scenarios considered, the exogenously stipulated expansion of RES is accompanied by a significant increase of gas power plant capacities in Europe and Germany up to 2030 of between 19 and 37% compared to 2010 (Fig. 6). In contrast to gas fired power plants, the share of lignite use decreases considerably (Germany 13.4% to 5.7[8]–3.4%, EU 5% to approx. 1%) as does the Europe wide share of nuclear power plants (14.2% to 8–4.3[9]%). Oil fired power plants play a diminishing role up to 2030. However, the development of coal fired power plants varies between the scenarios. In the *Current Policy* scenarios, coal use initially declines, but increases slightly in later periods with increasing EV shares. In the *New Policy* scenarios, the corresponding increase of coal use does not appear. One reason is the exogenously given higher amount of renewable energies in the *New Policy* compared to the *Current Policy* scenarios. Due to the higher share of volatile RES supply, a further increase in flexible power plants, e.g. gas turbines, is required. In turn, the full load hours of coal fired power plants are reduced significantly. Additionally, renewable energies expand more strongly in scenarios with electric mobility, because EV increase final electricity consumption. Thus, since the percentage of RES in gross final electricity demand is fixed, the total amount of RES grows. Depending on the EV share and therefore on the total electricity demand, the overall power plant capacity in Europe grows between 18 and 34% from 2010 to 2030, while the growth in Germany is rather small and ranges up to 8%. This small growth is caused by currently existing overcapacities. The biggest growth occurs in those scenarios which possess high RES shares and high EV shares. The reasons therefore are the comparatively small full load hours of RES and the additional final electricity demand of EV compared to the other scenarios.

Besides these basic developments, several impacts on the electricity sector due to the enlargement of the EU ETS can be identified. In scenarios with an additional allowances demand due to the enlargement of the EU ETS, more nuclear and gas power plants are utilised compared to scenarios without EU ETS enlargement. In contrast, in scenarios with an additional allowances supply and electricity demand due to EV, mainly the share of coal and in part of lignite power plants increases. Independently of a demand or supply of allowances from *COMIT*, different RES shares do not change the impact on the electricity sector, which occur, if the EU

[8] Only in the *High EV* scenarios is this slightly higher share of lignite power plants found. With higher RES shares this effect vanishes.

[9] Only in scenarios with the highest RES shares does the share of nuclear power plants reach this lower value.

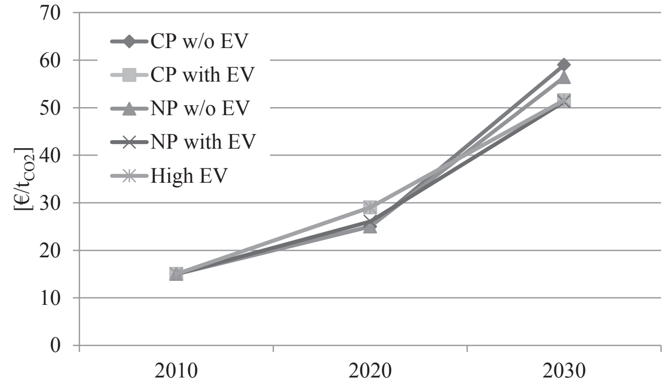

Fig. 7. Development of marginal CO_2 abatement costs.

ETS is extended to the road transport sector. Therefore we do not discuss different RES shares in more detail.

Different EV ratios show only marginal impacts on the German power plant fleet, because the carbon reduction in the transport sector caused by the replacement of ICEV (internal combustion engine vehicle) by EV approximately equals the additional CO_2 emissions in the energy sector caused by the specific emissions of electricity for EV. On the European scale, this effect is less ambiguous. A higher share of EV leads for our enlarged EU ETS system to a higher availability of certificates and therefore to a slight increase of fossil fuels in the energy sector. Nonetheless, extending the EU ETS to road transport affects the electricity sector much less than RES targets or existing CO_2 reduction targets. This also holds true for electricity generation in Germany and Europe.

The marginal CO_2 abatement costs nearly quadruple up to 2030, but only diverge after 2020 (Fig. 7). This strong rise results mainly from continued CO_2 cap reduction, which leads to the necessity of using more and more expensive mitigation options. The extension of the EU ETS to the road transport sector influences the development of the marginal CO_2 abatement costs at maximum from 8€/t_{CO_2} (*COMIT* supply: *Current Policy* with 50%) to +5.5€/t_{CO_2} (*COMIT* demand: *New Policy* w/o EV) in 2030. The differences in CO_2 abatement costs due to the additional CO_2 demand from *COMIT* and due to the additional electricity demand of EV are in the same order of magnitude.

The differences in CO_2 emissions of the German electricity sector in the scenarios depend on diverse aspects, particularly on the investment decision in *PERSEUS EU*, which is based on a perfect foresight approach and the additional demand or supply of CO_2 allowances from *COMIT*. Therefore, and due to the fact, that only small differences in CO_2 emissions occur with an EU ETS enlargement, a general conclusion is hardly possible and mainly depends on *COMIT* results regarding the EU ETS enlargement.

7. Conclusions and outlook

If the anthropogenic impact on climate change by greenhouse gases and the alarming rate of global warming is accepted, a comprehensive reduction of greenhouse gases, i.e. in particular CO_2, is essential. In the European context, all sectors contribute to emission reductions except for the transport sector. This is inefficient from an economic point of view (cf. [61]). On the global scale, the predicted strongly increasing passenger vehicle fleet and freight transport volumes are precursors of a considerable increase in future CO_2 emissions up to 2050. This development requires strong political commitments on the global level.

A political instrument discussed for reducing CO_2 emissions in the transport sector is including road transport in the EU ETS by an upstream scheme. Oil companies would have to trade allowances for the carbon content of their fuel sold. This concept would lead to a decreasing amount of overall CO_2 emissions, but will not guarantee that the sector specific reduction targets are reached. Since the marginal abatement costs differ in the sectors, the EU ETS leads to an efficient abatement of emissions.

An analysis of the impact of this emissions trading concept has to consider the road transport and the energy sector in parallel. Therefore, we applied two models: a model for road transport, *COMIT* [14], and the electricity system model *PERSEUS EU*. Furthermore, both models are extended by considering EV in order to analyse these additional effects on the EU ETS and the electricity sector.

The result of the simulation is that traffic participants do not react significantly to increased allowance prices. This is not surprising, as a price increase of allowance prices of € 10 leads to an increase in fuel prices of only € 0.02 (about 1%). Only the technological improvements of vehicles lead to a slightly decreasing amount of CO_2 emissions within road transport. This effect is, however, somewhat reduced by the rebound effect. Due to the decreasing number of allowances in the road transport sector, this leads to an increased allowance demand by oil companies in the EU ETS. However, this is not sufficient to raise the overall market price for CO_2 allowances in the EU ETS significantly from the transport sector's point of view, because the share is too small and the electricity sector has further emission reduction potentials at comparably low marginal abatement costs. Hence, the price impact on the EU ETS through an integration of road transport is limited. Even if the costs are passed on to the final consumer (vehicle user), the development of CO_2 emissions in road transport remains almost unaffected. This leads to an economically efficient situation where the transport sector (the vehicle user) pays for emission reductions in the electricity sector. Hence, the only possibility of reducing CO_2 emissions in passenger transport seems to be a change in user behaviour, e.g. an accelerated trend towards more fuel efficient cars (e.g. EV). As shown by our model results, the impact of the assumed shares of EV on the power plant portfolio and EU ETS market is rather marginal. On the European level, a higher share of EV decreases the pressure to reduce CO_2 emissions somewhat compared to a situation without EV. Therefore, the results recommend including road transport into a future phase of the EU ETS in order to reduce national CO_2 emissions.

All *COMIT* model results presented are limited to Germany, and the results of *PERSEUS EU* are limited to the EU. With respect to the global scale, a stronger increase in vehicle fleet and freight transport volumes should be considered – especially in emerging markets. Furthermore, the development of the national power plant portfolio and the charging strategy of EV have an effect on the results (cf. [62–64]). The general trend of the results, however, remains the same.

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