Modeling Interconnected National Energy Systems Using an Energy Hub Approach

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***Abstract*—This paper describes an approach to model interconnected national energy systems using the concept of energy hubs. Each country is modeled as an energy hub, characterized by the national generation infrastructures for heat and electricity, the demand for heat and electricity as well as properties detailing mobility demand. Countries are interconnected via electricity and gas networks, i.e. it is possible to import or export electricity and/or gas. The paper gives a short introduction to the concept of energy hubs and describes the extensions of the concept to account for national multi-carrier energy systems. In a subsequent part the network model is introduced. The different constituents (generation, demand, transmission infrastructures) form an optimization problem, where a numerical solution approach is combined with particle swarm optimization. Furthermore, it is described how the relevant data concerning demand, generation and network infrastructures was obtained. The paper is concluded with three case studies demonstrating the applicability of the proposed approach.**

***Index Terms*—Multi-Energy Carrier Systems, Energy Hubs, Power System Economics, European Transmission Networks**

I. INTRODUCTION

One major goal of European energy policy is the establishment of a pan-European market. In regulation 1228/2003 of the European parliament and the council [1] it is stated that: "The creation of a real internal electricity market should be promoted through an intensification of trade in electricity, which is currently underdeveloped compared with other sectors of the economy." Such a reinforcement of trade is not only an objective in the electricity sector. Similar reasoning exists for natural gas markets and related infrastructures. Hence, the priority projects for Trans-European Energy Networks (TEN-E) include both: recommendations in terms of investments in cross-border electricity and natural gas interconnections. Legislation regarding markets as well the stimulation of investment projects may be seen as two major measures to further intensify trade. However, the success of these strategies seems to be closely linked to the overall developments in terms of technological progress in energy generation and transmission, depletion of fossil resources and related price changes for primary energy carriers, national policies in terms of renewable integration, energy efficiency, etc.

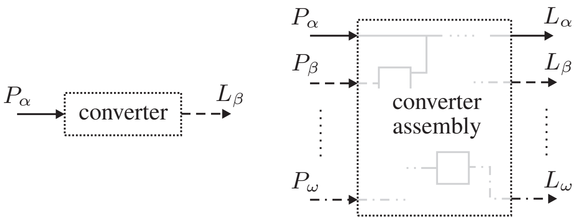
The contribution of this paper is the conceptual and mathematical formulation of a modeling framework capable of representing interconnected national energy systems, taking into account the three major pillars of final energy-related demand being electricity, heat and mobility. Countries may cover their demand relying on national generation infrastructures for electricity and heat but they are also interconnected via electricity and gas networks, and thus, may trade with each other. The model takes the dependency of the different energy carriers (e.g. gas and electricity) explicitly into account relying on a multi-carrier optimal power flow.

Related work targeting the integrated planning and operation of natural gas and electricity infrastructures has been for instance reported in [2], [3], [4], [5]. The work described in this paper presents above all extensions in terms of the generalized description of national energy systems as energy hubs, the inclusion of mobility demand and the inclusion of effects related to CO_2 pricing.

The remainder of the paper is organized as follows: Section II gives a brief introduction to the concept of energy hubs as reported in [6]. Section III describes the extensions and adoptions of the original energy hub concept to capture the characteristics of national energy systems. Furthermore, the modeling of the network infrastructures is described. In Section IV the optimization problem is formulated. The following Section V details the various data sources used for the case studies (Section VI). Section VII concludes the paper, discusses the results and provides a further outlook.

II. A BRIEF INTRODUCTION TO ENERGY HUBS

The concept of energy hubs has been developed within the scope of the Vision of Future Energy Networks (VoFEN) project [7]. "An energy hub generally represents an interface between energy producers, consumers, and the transportation infrastructure. From a system point of view, an energy hub provides the functions of in- and output, conversion and storage of multiple energy carriers."[8] Figure 1 presents a schematic of an energy hub as developed in [6], [9].



(a) Converter with single in-/output.

(b) Converter arrangement with multiple in-/outputs.

Fig. 1. Model of power converters with inputs $P_\alpha, P_\beta, \dots, P_\omega$ and outputs (loads) $L_\alpha, L_\beta, \dots, L_\omega$. [9]

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The hub is characterized by a set of energy carriers $\alpha, \beta, \ldots \in \mathcal{E} = \{electricity,\ natural\ gas,\ heat,\ \ldots\}$ where each energy carrier may be a hub input and/or a hub output. The set of input powers (output powers) is defined by $P_\alpha, P_\beta, \ldots, P_\omega$ $(L_\alpha, L_\beta, \ldots, L_\omega)$. Specific technologies inside the hub allow for the conversion of energy carriers. Accordingly, an energy hub can be modeled as a combination of different converters covering multiple in- and outputs. Equation 1 provides the mathematical description of the energy hub.

$$\underbrace{\begin{bmatrix} L_\alpha \\ L_\beta \\ \vdots \\ L_\omega \end{bmatrix}}_{\mathbf{L}} = \underbrace{\begin{bmatrix} c_{\alpha,\alpha} & c_{\beta,\alpha} & \cdots & c_{\omega,\alpha} \\ c_{\alpha,\beta} & c_{\beta,\beta} & \cdots & c_{\omega,\beta} \\ \vdots & \vdots & \ddots & \vdots \\ c_{\alpha,\omega} & c_{\beta,\omega} & \cdots & c_{\omega,\omega} \end{bmatrix}}_{\mathbf{C}} \underbrace{\begin{bmatrix} P_\alpha \\ P_\beta \\ \vdots \\ P_\omega \end{bmatrix}}_{\mathbf{P}} \tag{1}$$

The entries of the coupling matrix $\mathbf{C}$ are the converter coupling factors. Each coupling factor relates one particular input to a certain output incorporating the specific conversion efficiencies [9], [6].[1]

III. A Model of Interconnected National Multi-Carrier Energy Systems

A. National Energy Systems as Energy Hubs

In previous publications [8], [9], [6] it has been emphasized that the energy hub concept can be applied to model diverse energy infrastructures. Examples include big building complexes, factories, hospitals etc. In the following we propose to extend the energy hub concept to account for national energy systems. The idea is to describe a country as individual entity characterized by a certain resource in-feed, an energy demand and a number of conversion devices representing the technological possibilities to cover energy-related final demand. Typically, the latter comprises three main constituents being electricity, heat and mobility. The following paragraphs briefly sketch the modeling approach for each.

1) Modeling of Electricity Generation Technologies and Electricity Demand

For each country, power plants of the same fuel type are aggregated into one "combined" plant with a maximum output that is equal to the sum of the individual generators' limits. Each aggregated plant is then modeled as an energy conversion device with specific parameters. (See Table I.) Concerning the generators' cost functions $C(P)$ we rely on the well-known second order polynomial approximation $C(P) = a + bP + cP^2$. The cost functions for the individual technologies were compiled from the European project *"Cost Assessment for Sustainable Energy Systems"*.[11] The electricity load is assumed to be fix. Table I presents an overview of the major generation technologies considered and related parameters.

Generation Type	**Input Energy Carrier**	**Parameters**
Electric power plant	coal, natural gas, uranium, oil, water, wind, solar, biomass etc.	P^{min}, P^{max}, Q^{min}, Q^{max}, η_{elec}, $C(P)$
Combined heat and power (CHP) plant	natural gas, coal, biomass etc.	P^{min}, P^{max}, Q^{min}, Q^{max}, η_{elec}, η_{heat}, $C(P)$

TABLE I
Properties of Generation Technologies. P^{min} and P^{max} refer to the active power generation limits. Q^{min} and Q^{max} give the reactive power limits. $\eta_{elec}, (\eta_{heat})$ is the electrical (thermal) efficiency. $C(P)$ defines the cost function.

2) Modeling of Heating Technologies and Heat Demand

Heating technologies are modeled in a similar manner with aggregated heating technologies based on fuel types and quadratic cost functions. However, for the heat load we distinguish between residential and industrial heat (approx. 20 % of total heat load) as residential technologies cannot supply industrial heat. Exemplary heating systems considered in the model are displayed in Table II.

Heating Device Type	**Input Energy Carrier**	**Parameters**
"Standard" heating device	coal, oil, gas, gasoline etc.	H^{min}, H^{max}, η_{heat}, $C(P)$
Combined heat and power (CHP) device	natural gas, coal, biomass etc.	H^{min}, H^{max}, η_{elec}, η_{heat}, $C(P)$
Heat pump	electricity	Coefficient of Performance (COP)

TABLE II
Properties of Heating Technologies. H^{min} and H^{max} refer to the maximum heating output. $\eta_{elec}, (\eta_{heat})$ is the electrical (thermal) efficiency. $C(P)$ defines the cost function.

3) Modeling of Transport Modes and Mobility Demand

To include mobility in the energy hub concept transport efficiencies for different transportation technologies (e.g. combustion engines, electrical drives or hybrid drives) are defined. As mobility demand is often given as person-kilometers, the technology-related transport efficiency can be defined in terms of how much energy input is needed to travel one person-kilometer. Equation 2 gives an example. For a four passenger car with an average fuel consumption of ten liters of gasoline per 100 kilometers the transportation efficiency η_{mob_fuel} in person-kilometers (pkm) per Megajoule (MJ) can be calculated as follows[2]:

$$\eta_{mob\_fuel} = \frac{100 \text{ kilometers } \times 4 \text{ persons}}{32 \text{ MJ/liter} \times 10 \text{ liters}} = 1.25 \frac{\text{pkm}}{\text{MJ}} \tag{2}$$

In a similar way η_{mob_elec} can be calculated for electric drives. In compliance with the previous sections on heat and electricity, aggregated technology representations have been formulated. The model considers private cars, trains and buses as transport modes, where the mobility load was derived from the daily average person kilometers (37 km in Europe). The shares of individual transport modes where determined to match the available country data. (See Section V.) Table III presents the different transportation technologies considered.

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[1] A coupling matrix C as shown in Eqn. 1. represents the "plainest" case. Depending on the conversion technologies inside the hub one energy carrier may serve as input to more than one converter. Such a constellation makes the use of internal dispatch factors necessary. The underlying theory is not presented in the scope of this paper. The reader is referred to [10] for details.

[2] The energy content of 1 liter of gasoline is app. 32 Megajoule.[12]

Transportation Technology	**Input Energy Carrier**	**Parameters**
Internal Combustion Engine (ICE)	Gasoline	M^{max}, η_{mob_fuel}, fuel cost
Electric motor	Electricity	M^{max}, η_{mob_elec}
Hybrid Electric Vehicle	Electricity, gasoline	M^{max}, η_{mob_elec}, η_{mob_fuel}, fuel cost

TABLE III
PROPERTIES OF TRANSPORTATION TECHNOLOGIES. M^{max} REFERS TO THE MAXIMUM MOBILITY OUTPUT (PKM). η_{mob_elec}, (η_{mob_fuel}) IS THE MOBILITY EFFICIENCY FOR TECHNOLOGIES BASED ON ELECTRICITY INPUT (GASOLINE INPUT) .

Figure 2 shows a schematic of a country modeled as energy hub. Regarding input energy carriers, "networked" carriers, such as electricity P_{el} and gas P_{gas} are distinguished from "local" resources P_{local} such as coal, uranium, oil etc. "Local" resource does not necessarily mean that a specific energy carrier is a natural resource of the country. The term local refers to the system boundary as we do not look into the transportation of coal, uranium or biomass. This also applies to natural renewable resources, e.g. wind, solar radiation etc. which are taken for granted.

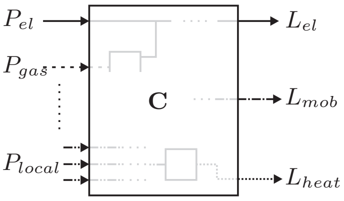

Fig. 2. Representation of a country as an energy hub with electricity, natural gas and local energy resources as input powers and electricity, mobility and heat loads as output powers.

B. A Hub-Based Network of National Energy Systems

Figure 3 shows a system of four hubs (countries). The hubs are connected by an electricity and a natural gas network. From the figure it becomes obvious that congestions inside countries are neglected. Only the interconnection capacities between countries are taken into account. We refrain from presenting the flow equations as this exceeds the scope of this paper. In [9] the flow modeling of electricity and gas networks is described comprehensively.

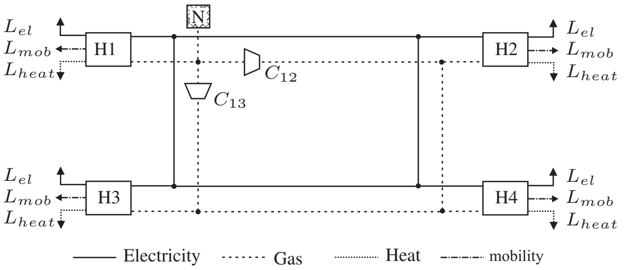

Fig. 3. Example of a system with four energy hubs (countries) which are interconnected by a natural gas and electricity system. Figure adapted from [13].

IV. OPTIMIZATION FRAMEWORK

The previous sections described the modeling of individual countries as energy hubs as well as the construction of an interconnected model of countries (hubs). In a next step a multi-carrier optimal power flow is formulated in order to optimize the whole system. With the various loads (electricity, heat, mobility) being fixed the objective is to minimize the generation cost while satisfying the constraints regarding generation and transmission.[3] The optimal power flow delivers marginal prices for heat and electricity in each country as well as information on congested interconnections. From an economic point of view the chosen approach corresponds to the assumption of perfectly competitive markets with inelastic demand, where market participants are price takers. Hence, we do not model the possibility of strategic behavior (strategic bidding) on the generation side. Prices can not rise above competitive levels or in other words: prices reflect marginal costs in compliance with the theory of perfectly competitive markets.

A. Formulation of the Multi-Carrier Optimal Power Flow

The formulation of the multi-energy carrier optimal power flow (OPF) requires an additional set of variables defining the hub numbers $\mathcal{H}$: $i, j, \ldots \in \mathcal{H} = \{1, 2, \ldots, N_H\}$. Each hub (country) i is then defined by a coupling matrix C_i, by the power inputs P_i and the hub loads L_i. The network power flows are denoted by $\mathbf{F}_\alpha$. The term $\mathbf{G}_\alpha(\mathbf{P}_i)$ refers to the set of power flow equations of the hubs and the different networks (e.g. electricity and gas). The hub input power is constrained by lower limits $\underline{\mathbf{P}}_i$ and/or upper limits $\bar{\mathbf{P}}_i$. Networks flows are subject to lower flow limits $\underline{\mathbf{F}}_\alpha$ and upper flow limits $\bar{\mathbf{F}}_\alpha$. The optimization problem can subsequently be formulated as follows:
Minimize

$$f(\mathbf{P}_i, \mathbf{F}_\alpha) \tag{3}$$

subject to

$$\mathbf{L}_i - \mathbf{C}_i\mathbf{P}_i = 0, \ \ \forall i \in \mathcal{H} \tag{4a}$$

$$\mathbf{G}_\alpha(\mathbf{P}_i) = 0, \ \ \forall \alpha \in \mathcal{E} \tag{4b}$$

and

$$\underline{\mathbf{P}}_i \leq \mathbf{P}_i \leq \bar{\mathbf{P}}_i, \ \ \forall i \in \mathcal{H} \tag{5a}$$

$$\underline{\mathbf{F}}_\alpha \leq \mathbf{F}_\alpha \leq \bar{\mathbf{F}}_\alpha, \ \ \forall \alpha \in \mathcal{E} \tag{5b}$$

In the objective function $f(\mathbf{P}_i, \mathbf{F}_\alpha)$ also the CO_2 intensity of electricity and heat generation and the provision of mobility is taken into account. For this purpose each technology is characterized by the emissions caused by the production of a certain amount of electricity, heat or person-kilometers. In conjunction with a price for e.g. one ton of CO_2, the effect of emissions is directly incorporated.

B. Using Particle Swarm Optimization to Improve Optimization Performance

As the optimization problems related to the optimal dispatch of the hubs (countries) and the optimal power flow problem are very likely to be non-convex [9] the determination of

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[3] The problem is formulated in a deterministic way not taking uncertainties into account. This choice was made because of complexity reasons. A probabilistic approach appeared mathematical infeasible in the multi-energy carrier framework.

a global optimum cannot be guaranteed. To improve optimization performance, a particle swarm optimization (PSO) is deployed in order to find an appropriate starting vector resp. to avoid a start of the optimization routine with only guessed values. A further feature used in conjunction with the PSO algorithm is the distinction between control and state variables. The former are "optimizable" variables, where the latter describe only the system state determined by the values of the control variables. In our example control variables include e.g. the active power produced by the generators, the heat produced by each generator / heating system as well as the mobility output for each transport mode. State variables are the voltage angles, gas pressures, line flows in transmission or gas pipelines etc. Figure 4 presents a schematic of the optimization procedures, where the following paragraphs briefly describe the three individual stages.

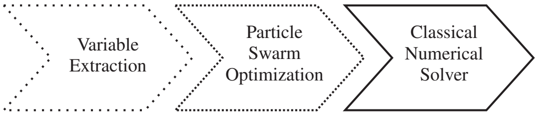


Fig. 4. Optimization Procedure

1) Extraction of Variables

As mentioned before the performance of the PSO algorithm could be improved by separating control and state variables. In a first step, the PSO algorithm (see the next paragraph) only takes into account the control variables for an iterative solution of the problem. In a second step it is checked whether a possible solution violates the constraints or if it is feasible. Such a "split" of variables reduces the mathematical complexity of the PSO problem and leads to faster "convergence".

2) Particle Swarm Optimization

Particle Swarm Optimization is a metaheuristic method designed to iteratively optimize a given problem by interactions in a population of particles. The algorithm "generates" such a population of particles and evolves the population in terms of "fitness" for a specified number of iterations until the fittest member is found. Fitness in our context means lowest generation and emission cost (obeying also generation and network constraints). We refrain from presenting a detailed mathematical formulation as PSO algorithms our widely known. An application example for a security constrained dispatch problem can for instance be found in [14].

3) Classical Numerical Solver

The last step of the optimization procedure involves a "classical" numerical solution of the optimization problem introduced in Equations (3) - (5b). The optimization routine was implemented in MATLAB using the function *"fmincon"*. Instead of initializing the optimization with a flat start or guessed values the starting vector obtained from the PSO algorithm was used. In doing so, convergence could significantly be improved. However, the overall solution of the problem required several hours of computing time, typically in the range from 6 to 10 hours.

V. DATA REQUIREMENTS AND DATA SOURCES

The previous sections outlined the chosen modeling approach being a multi-carrier optimal power flow with energy hubs representing individual countries. Such an OPF framework requires several data inputs regarding generation and consumption of heat and electricity, mobility demand and the transmission networks for gas and electricity. In the following an overview on data sources is given together with brief explanations how the data was "adopted" to suit the model's needs.

A. Data on Electricity and Gas Networks

To the best knowledge of the authors reliable data sources describing the physical transmission limits of gas pipelines in Europe as well as flow rates etc. is publicly not available. Although, the modeling framework is capable of simulating a combined gas and electricity optimal power flow, we chose not to include the gas network in the following case studies. Without gas transmission limits the impact of gas flows on electricity and gas prices is negligible (only driven through losses). Thus, we opted to treat gas as so-called "local" resource without considering its transport. This simplification proved to have no significant impact on the final results.

Concerning the electricity network we relied on the data published by the European Network of Transmission System Operators for Electricity (ENTSO-E). Specifically, we used the Net Transfer Capacity (NTC) values available from [15]. Such an approach is possible as each hub represents a country as a whole not taking into account internal congestions.

B. Data on Electricity Generation and Demand

Section III-A described the considered generation technologies together with the relevant parameters, such as active and reactive power limits, generators' cost functions etc. Information to compile such generation and demand data was taken from various sources as follows:

- Data related to the costs of production: [11]
- Data concerning fuel types, maximum power outputs, production shares for individual countries etc.: [16], [17], [18]
- Demand data was compiled from: [16].

C. Data on Heat Generation and Demand

Concerning heat, the model distinguishes between the industrial sector and residential heating demand. Data for the industrial sector can be found in [16]. Information for residential heating technologies and individual country shares was taken from [19], where three heating categories are defined: water heating, space heating and cooking. In a further step the heating load of a country was estimated by population size and typical demand values. In [12] the following values are given: for water heating 12 kWh per person per day, for space heating 24 kWh per person per day, for cooking 5 kWh per person per day. Together with the population size, heating demand per category can be further converted into power values to reflect the total heating load of a country.

D. Data on Mobility Provision and Demand

As outlined in Section III-A four “mobility providers” have been incorporated in the model, namely private cars and public buses (with internal combustion engines), trains (with electric motors) and hybrid electric vehicles (with an internal combustion engine and an electric motor). These four categories are shortly described below:

Private Cars: According to [12] it is assumed that private cars have a fuel efficiency of 10 liters per 100 kilometers with a fuel energy content of 32 Megajoule/Liter. As privately owned cars only carry one passenger in 75 % of the time, we make the worst-case assumption that a private car provides mobility only for one person, resulting in a transportation efficiency (η_{mob_fuel}) of 0.3125 pkm per MJ.

Trains: In compliance with [12] we assume a transportation efficiency (η_{mob_elec}) of 4.63 pkm per MJ for trains.

Buses: A transportation efficiency (η_{mob_fuel}) of 0.3125 pkm per MJ is assumed for busses.[12]

Hybrid Electric Vehicles: As a hybrid vehicle has two drives, we assume transportation efficiencies of $\eta_{mob\_fuel} = 0.3125$ pkm per MJ (internal combustion engine) and $\eta_{mob\_elec} = 2.13$ pkm per MJ (electric motor).

The mobility load of the individual countries was estimated using the population size (over the age of 10) and the average number of traveled kilometers per person per day, which amounts to 37 km in Europe. The proportional shares of the different transport modes were taken from the national statistical yearbooks [20], [21], [22], [23], [24], [25], [26]. When country data was not available an “educated guess” was made.

VI. CASE STUDIES

In the following three different case studies will be provided to demonstrate the applicability of the model. At first a baseline scenario of four countries is presented (Switzerland, Germany, Italy, France). Then we will study the effects of pricing carbon emissions. In a last scenario we evaluate the currently proposed Trans-European Energy Networks (TEN-E) Projects for electricity.

A. Baseline Scenario

In the baseline scenario we use an average winter day. The model comprises Switzerland, France, Italy and Germany. We analyze an operational snapshot of one hour. The objective is to minimize generation costs while satisfying heat, electricity and mobility loads as well as obeying the electricity network constraints. Fuel costs are not differentiated per country. Also CO_2 emissions are not taken into account here. Figure 5 provides a comparison of locational marginal prices obtained from simulation and average yearly spot prices according to [27]. Note that the figure also includes information on five additional countries (Austria, Belgium, The Netherlands, Spain, Portugal) studied in the third case study in relation with the TEN-E projects. The values have been normalized as the proposed marginal cost approach does not appear sufficient to reproduce absolute values but can provide an indication of overall price levels.

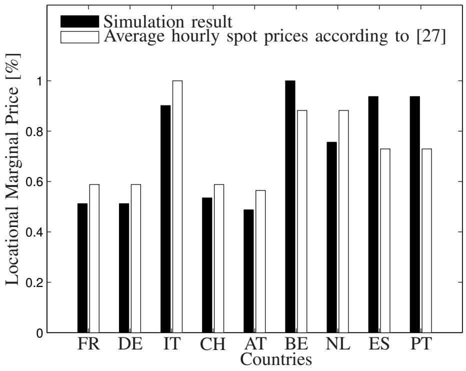
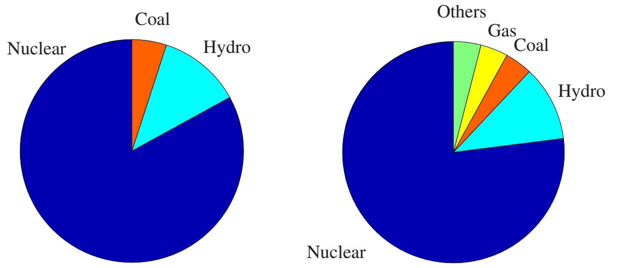


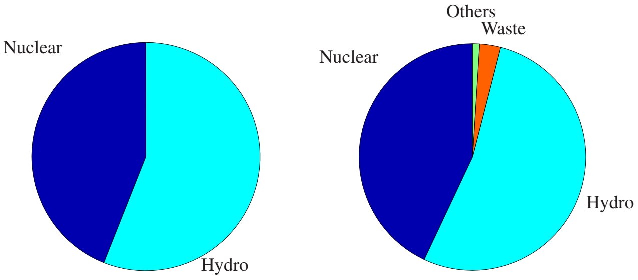
Fig. 5. Comparison of locational marginal prices obtained from simulation and average yearly spot prices according to [27].

Figures 6 and 7 show comparisons of the simulated generation mix and the actual generation mix for France and Switzerland. Similar to the overall price levels the simulation results match the actual generation mixes reasonably. The deviations observed may be caused by the fact that the statistical material of the IEA covers the average generation mix over one year. In doing so, also peak days are considered. However, our simulation is based on an average winter day, where peak generation is not dispatched.



(a) Simulated Generation Mix France (b) Actual Generation Mix France

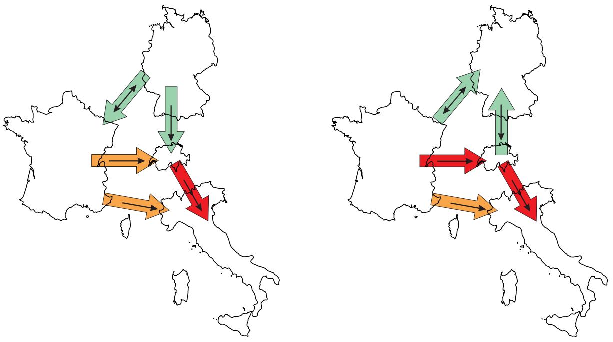
Fig. 6. Comparison of the generation mix obtained from simulation and the actual generation mix for France [16].



(a) Simulated Generation Mix Switzerland (b) Actual Generation Mix Switzerland

Fig. 7. Comparison of the generation mix obtained from simulation and the actual generation mix for Switzerland [16].

Figure 8(a) displays the flow patterns obtained from simulation in comparison with the typical flow patterns as documented on the ENTSO-E website [15]. Red arrows indicate congestion. Orange arrows represent a line loading of more than 75 %. Green arrows illustrate a line loading of less than 75 %. The thin black arrows inside the colored arrows show the reference flow direction as obtained from [15]. Note that the cross-border flow between France and Germany changes direction depending on the season and the time of the day (indicated with two arrowheads in both directions).



(a) Cross-Border Flows Base Case

(b) Cross-Border Flows with Emission Pricing

Fig. 8. Comparison of cross-border flow patterns without (a) and with (b) taking CO_2 emissions into account in the objective function. Red arrows indicate congestion. Orange arrows represent a line loading of more than 75 %. Green arrows illustrate a line loading of less than 75 %. The thin black arrows inside the colored arrows show the reference flow direction as obtained from [15].

Generally, the baseline scenario showed that the proposed approach captures the actual system properties well. Thus, it served as a good calibration indicator for additional case studies as reported in the next two sections.

B. Effect of Pricing Carbon Emissions

Relying on the four country model as described above we now include CO_2 emissions in the objective function. Thus, not only generation costs have to be mimized but also emission costs. For illustration purposes we assume a rather high CO_2 price of 50 Euros per emitted ton. Figure 9 shows the increase in heat or electricity prices in percent for each country. As heat generation is to a much stronger extend based on fossil fuels, the increase in heat prices is generally higher than for electricity. Note that we have assumed equal prices for natural resources in each country, thus, heat prices are equal in the whole system. The difference in electricity prices originates from congestion in the system. At first sight it might appear counter-intuitive that France and Switzerland with high shares of nuclear and hydro generation face a stronger increase in electricity prices through CO_2 pricing. This effect is caused by the difference in national generation portfolios. As we perform an optimization of the overall system, Germany and Italy shut down all generation based on coal. Additionally, Figure 8(b) shows that Germany in comparison with the baseline scenario relies to a larger on imports. Hence, exporting (producing) countries are penalized stronger than importing countries. The price increase in Switzerland is on the other hand caused by the changing flow pattern as we now face also congestion between France and Switzerland driving the locational marginal price in Switzerland trough congestion effects. It is obvious that pricing carbon emissions significantly influences network flows. This case study may serve as a first indication of the complex effects introduced in the technical system by regulatory changes.

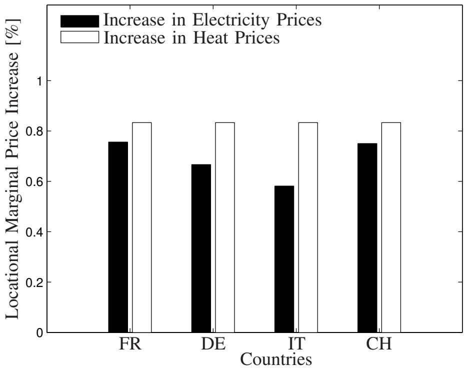


Fig. 9. Comparison of electricity and heat price increases compared with the baseline scenario (see Figure 5).

C. Trans-European Energy Networks (TEN-E) Projects

For the last case study we extend our model to include the following nine European countries: Austria, Belgium, France, Germany, Italy, The Netherlands, Portugal, Spain, Switzerland. In line with the previous case studies, the scenario analyzes an operational snapshot of one hour for all countries. The objective is to minimize generation and emissions costs while satisfying heat, electricity and mobility loads as well as obeying network constraints for gas and electricity grids. Fuel costs are not differentiated per country. The price of carbon emissions was set to 9.5 Euros per ton of emitted CO_2. Figure 5 provides a comparison of locational marginal prices in each country obtained from simulation and average yearly spot prices according to [27].

Figure 10 displays the electricity cross-border flows between the countries. Red arrows indicate a line loading of one hundred percent, and thus, congestion. The “flashes” indicate proposed transmission expansion projects as defined in the scope of the Trans-European Energy Networks (TEN-E). It can be seen that bottlenecks identified through simulation coincide with the projects. The results prove on the one hand the applicability of the model, on the other hand they emphasize the importance of the identifed TEN-E projects.

VII. CONCLUSION AND DISCUSSION

In the paper a modeling framework for national energy systems was described, where countries are represented as a system of energy hubs interconnected via electricity and gas networks. The model accounts for the interdependency of different energy carriers (e.g. coal, gas, electricity, petroleum etc.). It allows to study different measures to facilitate energy trade in Europe, e.g. specific network investment projects,

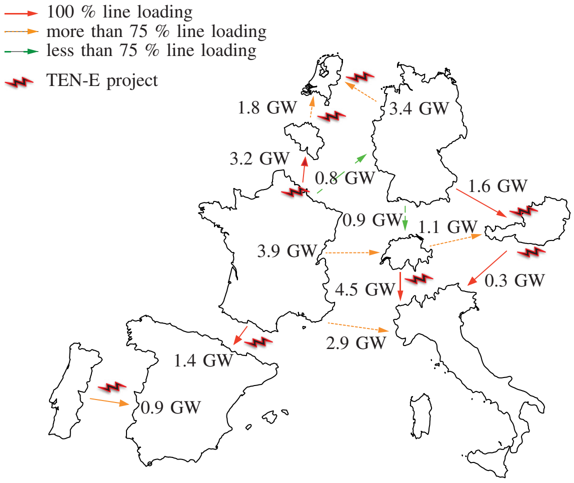


Fig. 10. Cross-border flows in the nine-country model. “Flashes” indicate a Trans-European Energy Networks (TEN-E) Project.

changes in national generation portfolios or national demand, effects related to the taxation of CO_2-emissions etc. The model is capable of reflecting the three main pillars of energy-related demand being electricity, heat and mobility. In the paper the related optimization problem was formulated. The applicability of the proposed framework was demonstrated using three case studies, one of them an evaluation of the proposed TEN-E projects.

The case studies presented in this paper were focussed mainly on electricity networks and electricity generation infrastructures. Further work will target scenarios related to developments concerning heat and mobility demand to make full use of the multi-energy carrier framework.

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