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Optimal Electric Power Transmission Planning Taking Environmental Constraints into Account

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Abstract

As environmental criteria become more and more important for the energy systems operation and planning, this paper proposes a method that can support the decision makers in future electricity systems planning. The evaluation of future electric power transmission investment plans is based on a social welfare analysis when the external costs of production are internalized. The social benefit can be further used to compensate the investments required for market enhancement and sustainable development.

1 Overview

1.1 Introduction

The worldwide reconstruction of the electric power systems is taking place under increasing end-user energy demand, environmental changes and active trading markets. The realization of a common market in Europe as well as power supply improvements are not possible without investments in the transmission sector. These investments can be either in new transmission lines or in line capability upgrades using new technologies, e.g. FACTS devices. This means that the transmission planning and analysis of electric power systems cannot remain the same as it was 10 or 20 years ago.

The generation sector and the energy balance is an important part of the electric power systems planning, but the present requirements in Europe and other places in the world call for new methods and tools to analyze the development of the electricity system, including the transmission and distribution systems [1]. The topic is sensitive due to the fact that transmission investments create winners and losers [2].

The following analysis is based on social welfare, i.e. consumer benefits minus producer costs. The considered requirements are the environmental impact of energy consumption and accordingly production, the impact of the transmission capacity increment on the market, as well as the benefit or the deficit in social welfare.

The energy production is commonly associated with negative effects. Fossil fuel power plants are much cheaper and competitive than other types of power plants but not sustainable. They are the main sources of CO₂, NO_x, SO₂ and fine particles. Hence, a number of negative effects are arising, the costs of which are not represented in the electricity prices and correspond to market insufficiencies. These are known as external costs. They refer to environmental damages, health impacts and climate change respectively. The discussion how and whether it is possible to estimate the monetary values of external costs is not the subject of this paper, but how it is possible to consider them in the electric power transmission planning and operation. This paper, accordingly, emphasizes the compensation of transmission investments from the social benefit that arises from the internalization of external costs.

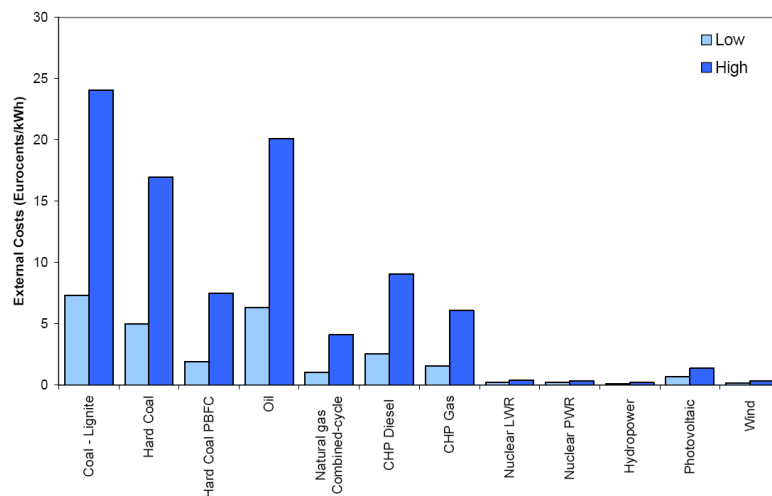
1.2 External costs of electricity production

In the power production sector the most considerable external effects are negative effects, the worst being health disorders and deterioration of the environment, basically due to the usage of fossil fuels in energy production. Fossil fuels power plants produce dangerous and harmful gases (CO₂, SO₂, NO_x, etc.) which have negative impact on the environment and on the human health. Secondary effects emerge also from the extremely high risk of environmental impact in case of an accident in a nuclear power plant, or the ecologic and aesthetic disturbance of windmills in farm fields, or even of overhead transmission lines.

According to the monetary valuation each generation technology except for its public advantages is characterized by a value of damage. Many projects supported by the European Commission like ExternE, NEEDS, CAFE, CASES have tried to estimate this imposed damage and to present it as a monetary value in order to internalize the additional social costs in the market operation. Top-down models have been used as first approach to the problem but for higher accuracy of the resulted values of the external costs the bottom-up models are more suitable as they are more detailed and focused on the available technologies. Therefore the ExternE methodology has been highly approved as the most appropriate method for the estimation of the external costs [3].

According to the drivers that define the values of each production technology, the external costs have been estimated and presented in fig. 1.

Among the other fossil fuels lignite holds the first place in the rank of



Data source: ExternE-Pol, 2005 ; CAFE, 2005 ; European Environment Agency/ETC.

Figure 1: Low/High estimation of external costs

hazardous production technologies and then follows oil and hard coal. In fact, if one looks closer at the emitted contaminants for the same produced quantity using different fuels, lignite emits the most in the whole life cycle. As shown in figure 2, SO₂, CO₂ and particulate matter PM₁₀ are the main emitters in case of lignite, resulted from an internal study. Moreover SO₂ and PM₁₀ are the most harmful for the human health and thus they strongly affect the external costs.

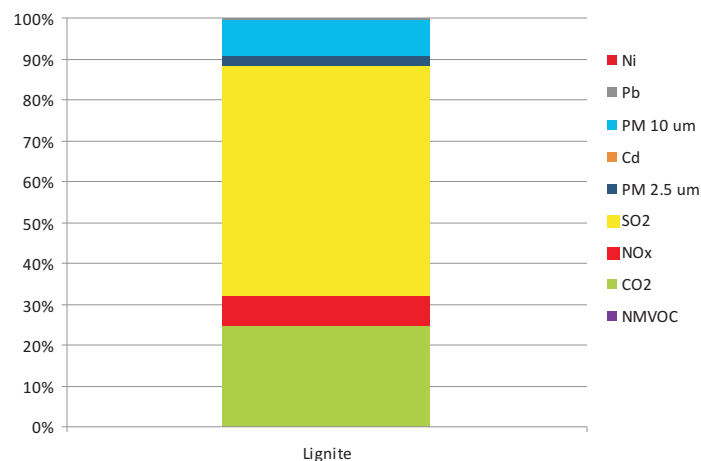


Figure 2: Emitted contaminants of lignite

2 Methods

2.1 Direct Current - Optimal Power Flow (DCOPF)

The analysis is based on Optimal Power Flow (OPF). An OPF is a static optimization method that solves the problem of power flow when different criteria are to be satisfied subject to equality and inequality constraints. In the simplest case, an OPF can be viewed as a method that solves the problem of minimizing an objective function, e.g. the total cost, satisfying the power flow equations [4].

The OPF problem can be formulated as [5]:

$$\begin{aligned} & \text{minimize } f(u,x) \\ & \text{s.t. } g(u,x) = 0 \\ & \quad h(u,x) \leq 0 \end{aligned}$$

where $f(u,x)$ is the objective function, $g(u,x)$ and $h(u,x)$ represent the power flow equations and inequality constraints respectively, u corresponds to the decision variables and x to the states that minimize the objective function.

As described in [6] the OPF is capable to represent the characteristics of the modern liberalized electricity market and to support the market-based system analysis [7], [8], as well as to solve the problem of multiple energy carriers [9]. Furthermore, the OPF is able to combine conflicting and independent variables to the overall optimum.

In this paper a DCOPF without losses consideration has been used in order to maximize the social welfare, to calculate the nodal prices and determine the production levels of the generators. Transmission and generation limits as well as external costs are considered in the optimization formulated below:

$$\text{minimize}\{-SW\} = \text{maximize}\{CB - PC\} \quad (1)$$

	equalities	inequalities
s.t.	$G_i - L_i = 0$ $L_i = a_i + b_i D_i$ $b_i = \frac{\Pi_{0_i}}{\varepsilon G_{0_i}}$ $a_i = \Pi_{0_i} - b_i G_{0_i}$	$G_i, L_i > 0$ $G_{i_{min}} < G_i < G_{i_{max}}$ $-TCL \leq Pf_{ij} \leq TCL$

where

Π_{0_i}, G_{0_i} the initial values for inelastic demand

ε the mid-term price elasticity

TCL the transmission capacity limit

CB the consumer's benefit

PC the producer's cost

2.2 Internalization of external costs

In the following analysis the role of internalization of external costs has been thought to be a tool for providing right price signals during the transmission planning avoiding market failures. Additionally it could be used as policy strategy to finance the required transmission plans enhancing the market and promoting the integration of green technologies towards a sustainable future.

Under market conditions there are different economic tools for internalizing the external costs in the power systems operation. Namely one could use either taxes expecting that the utilization of emitting technologies will decline, or to subsidize the green cleaner technologies in order to become more competitive against the traditional, or even to combine both methods for aggregating the advantages. The best solution might be to use one of these methods but on the other side to promote the R&D sector together with a load management concept. Of course there are also other mechanisms that can influence the behavior of consumers and producers like communication or normative mechanisms [10].

Focusing on economic tools a policy of internalization of external costs leads to a cost supplement either for the government or for the industry. The internalization of external costs means that the price for the same quantity of produced energy will be higher in case of taxes or lower in case of subsidy. According to that the produced quantity of more expensive power plants is going to increase, while on the other hand the production of cheaper power plants will decrease. Figure 3 describes the situation after the internalization representing the marginal costs of a relative cheap power plant i.e. coal power plant and the demand as linear functions. The surface A-B-C represents the social welfare loss in that case.

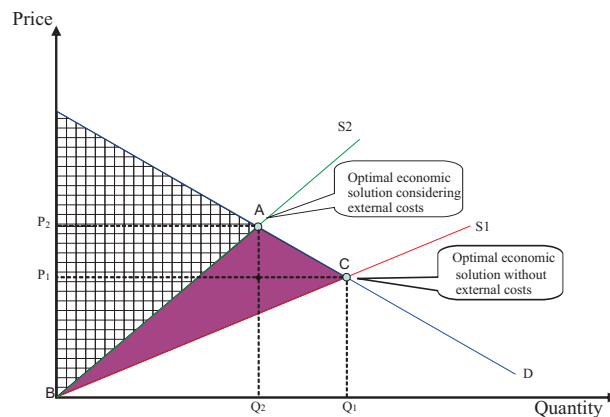


Figure 3: Internalization of external costs in a linear supply function, loss of social welfare $\Delta A-B-C$

\mathbf{EC}_i the externality cost

\mathbf{Vd}_j the value of damage for several emitters

\mathbf{G}_j the emitted quantity produced

After the internalization the production cost function is:

$$\Pi_i = m_i Q_i + EC_i \Rightarrow \Pi_i = e_i Q_i \quad (4)$$

where

$$e_i = m_i + \sum_j Vd_j \quad (5)$$

The following example will allow a better understanding of the internalization effects in a very simple network of 4 nodes. The network consists of 3 generators, one load and 8 transmission lines. It is assumed that a coal fired power plant, a nuclear station and a hybrid distributed generation system corresponds to each of the generators respectively. The marginal costs of the generators are given considering the nuclear as the cheapest technology and the distributed generation system as the most expensive. According to the estimated values for the external costs, the internalization entails higher production prices using lignite instead of hybrid distributed generation, for the same quantity produced. Thus, the feeding of each generator into the system changes as well, as shown in figure 5.

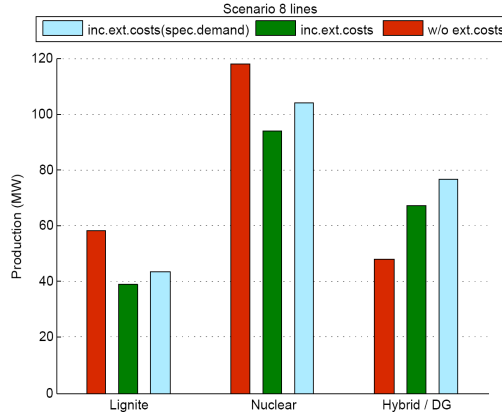


Figure 5: Production mix change for several cases: w/o ext. costs on the left (red), considering ext. costs in the middle (green), considering ext. costs and inelastic demand on the right side (blue)

The case of specific demand refers to inelastic demand which brings the equilibrium closer to the initial state but gives a more expensive solution as it is non-optimal. In general one can imagine that the new green technologies

become more competitive and more advantageous in comparison with the old common production technologies. Furthermore, it appears a reallocation of congestion as depending on the infeed location.

Eventually, a loss of social welfare is been expected due to the fact that the nodal prices get higher. However as already commented the deficit is not larger than the aggregated profits. The social benefits from the internalization through the reduction of negative effects, are able to compensate this loss.

The social benefit for a power plant is calculated as:

$$SB_i = \Delta G_i * EC_i \quad (6)$$

while the total profit of the internalization will be:

$$TP = \sum_{i=1}^n SB_i + \Delta SW \quad (7)$$

where

$$\Delta SW = SW_{withexternalcosts} - SW_{basecase} < 0 \quad (8)$$

The latter framework aims at environmental and societal considerations in the following cost benefit analysis.

2.3 Degree of Independency (DoI)

A new concept regarding topological issues, the so called degree of independency (DoI), is introduced in this paper. Between two interconnected nodes (nodes could represent a part of a greater system), which are operating under market conditions, not only the capability to satisfy their own demand is important, but also the availability of transmission capacity for power trade. The DoI is defined as:

$$I_{ij} = \frac{RTC_{ij}}{DP_i}, i, j = 1, 2, 3...n_{nodes}, i \neq j \quad (9)$$

while

$$RTC_{ij} = NTC_{ij} - Pf_{ij} \quad (10)$$

$$DP_i = P_i - D_i \quad (11)$$

where

RTC_{ij} the remaining transmission capacity

DP_i the the energy balance at a node

NTC_{ij} the net transmission capacity

$\mathbf{P}f_{ij}$ the power flow over a line

\mathbf{D}_i the demand at a node

\mathbf{P}_i the production at a node

For a single node the DoI is defined as:

$$I_i = \sum_j I_{ij} = \frac{\sum NTC_{ij} - \sum Pf_{ij}}{D_i - P_i} \quad (12)$$

In a complex meshed network, the operation of one node affects the others. Under the acceptance that every node is participating in a common market, nodes are dependent or not completely independent from each other. The DoI is a bilateral quantitative indicator of the network state which will help us in the following analysis. It signifies that when the network participants are very active in power trading and the lines are overstressed, the independencies between the nodes are very small.

DoI	meaning
zero	congested line between nodes
positive	exporter node
negative	importer node
$\rightarrow \infty$	balanced node

Table 1: DoI legend

An example is given in fig.6 for explanatory purposes. Three nodes with both consumption and production and three transmission lines to connect them to each other are assumed. As shown two lines are congested (2-3) and (1-2), while the capacity of the line (1-3) is much bigger than the needed exported power of node 1. Node 2 is completely dependent on the other two as the production capability is very small in comparison to the demanded power at the node.

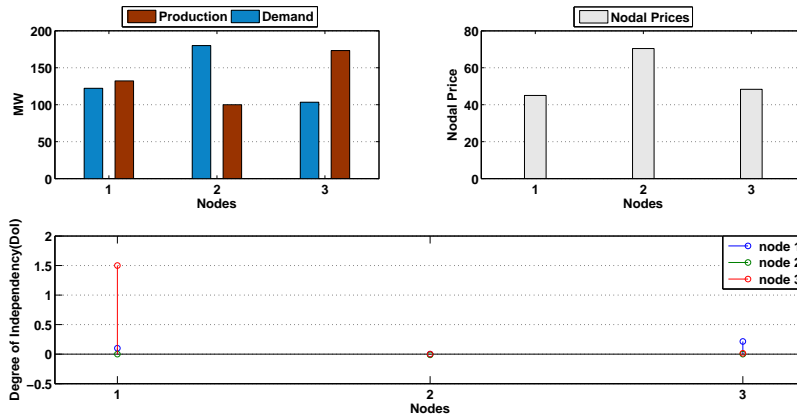


Figure 6: Results of a conceptual network for a better understanding of DoI

2.4 Model description

The studied system is a model of a transnational European electricity network including the four countries Germany, Belgium, France and the Netherlands, originating from the COMPETES (Competition and Market Power in Electric Transmission and Energy Simulator) study of the Dutch Energy Research Center [12]. The Benelux system is represented by five nodes with both consumption and production (Zwol, Krim, Maas, Merc, Gram). Germany and France are modeled by one node each. Additionally some nodes exist, but they just serve as interconnectors, see fig. 7. The model includes

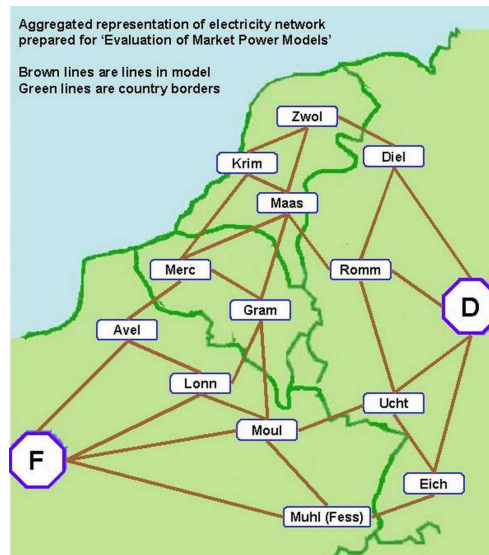


Figure 7: The studied network

82 generation companies represented by step-wise marginal cost functions where the external costs have been internalized. The generation data are mainly based on the World Economic Power Plant (WEPP) database of the year 2001 [13] and public available data of EDF, EnBW, RWE and EoN. Each generator has a certain marginal cost per MWh and a maximum capacity. The external costs have been selected according to the mean values of power plants efficiencies [14] in each country, based on 150 €/MWh for coal and 100 €/MWh for gas power stations. For nuclear thermal plants the external costs have been assumed at 10 €/MWh, while for hydro and renewables have been set to zero.

In table 2.4 the assumed efficiencies and external costs for coal and gas power stations are given.

		BE	FR	DE	NL
Coal	efficiency	0.38	0.39	0.39	0.41
	external cost (€/MWh)	154	150	150	142.5
Gas	efficiency	0.48	0.34	0.34	0.44
	external cost (€/MWh)	59	100	100	70.5

Table 2: Assumed efficiencies and external costs for coal and gas power plants

The loads are represented by mid-term linear demand functions for peak and off peak loadings. The linear factors have been obtained using a price elasticity of -0.3. Additionally the transmission capacity limits and the reactances according to [12] have been used.

Using the aforementioned welfare analysis and the collected data a priority project of the European Union, identified as EL1, between France and Belgium will be evaluated.

3 Results

The results for the different scenarios are presented in the following subsection. Simulations have been executed for winter and summer, peak and off-peak load. The market participants and the DoI are shown only for winter peak loadings as they behave similarly in the other cases as well.

3.1 Base case scenario

The generators that participate in the market in order to satisfy the optimal solution are illustrated in fig. 8.

It is clear that France is the major producer of the region based on huge capacity of nuclear power and then follows Germany based on coal. However, the high generation of Germany is not enough to cover the demanded power during winter period and thus is depicted as importer in fig. 9. There

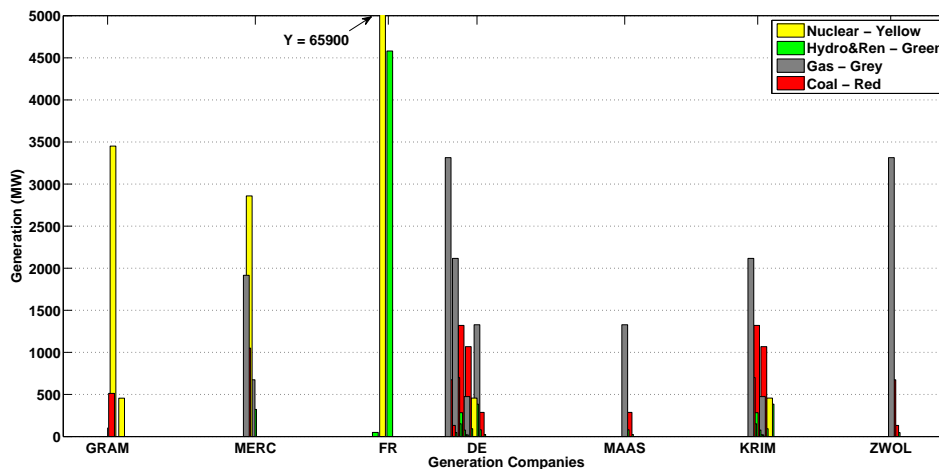


Figure 8: Generation companies in base case scenario

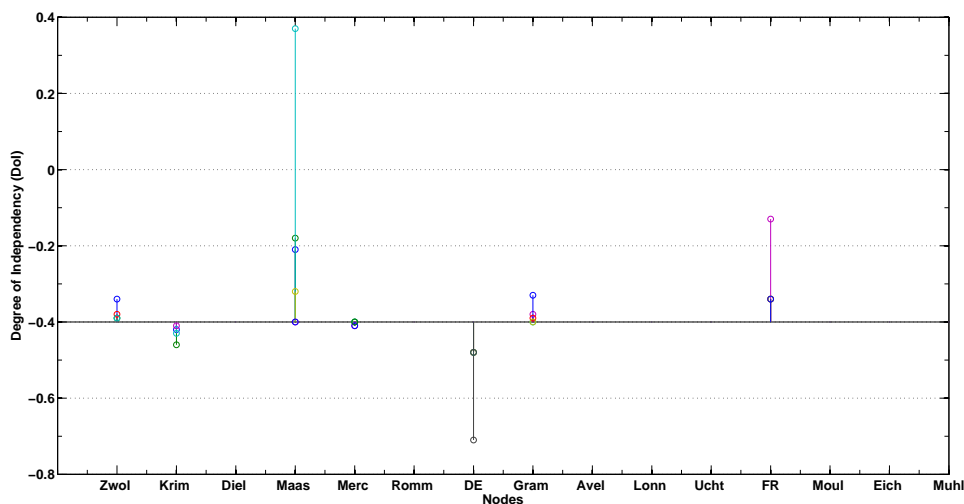


Figure 9: Nodal independencies in base case scenario

is shown that the nodes FR and Maas are quite balanced and therefore the most independent with export capability. Power is also exported from Zwol and Gram without any congested lines at the borders except for the line between Gram and Moul and two other lines between Belgium and Netherlands, Maas - Merc and Maas - Gram.

3.2 Scenario internalizing external costs

Considering the external costs of power production a modification of the price - quantity equilibrium results, according to the theory described in 2.2. As shown, fig. 10, the quantity produced by coal, gas and nuclear

power plants has been reduced due to new entrance of new members into the market or the increase of production levels at other units. More expensive technologies become more competitive but their maximum generation capacity is limited and so the trading is being encouraged. Therefore the market participants depend more on each other and the network lines more loaded, as described in fig. 11. One more line in addition to the base case is congested between the Netherlands and Germany, the line Mass - Romm.

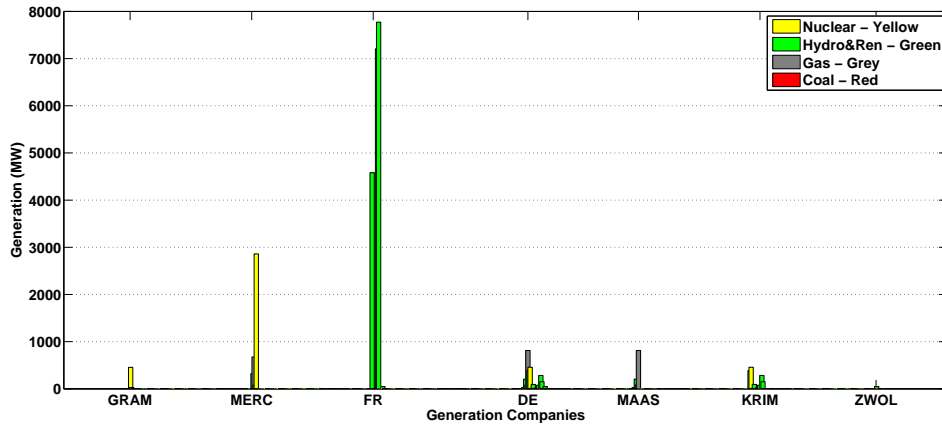


Figure 10: Production companies considering external costs

According to the DoI diagram Germany doesn't play the role of the the importer any more and belongs to the group of exporters together with FR and Gram. The by far largest DoI of FR means that supply and demand in France is very well balanced and the borders are available for export. All other small DoIs, practically zero, indicate that the transmission lines are very close to their capacity limits.

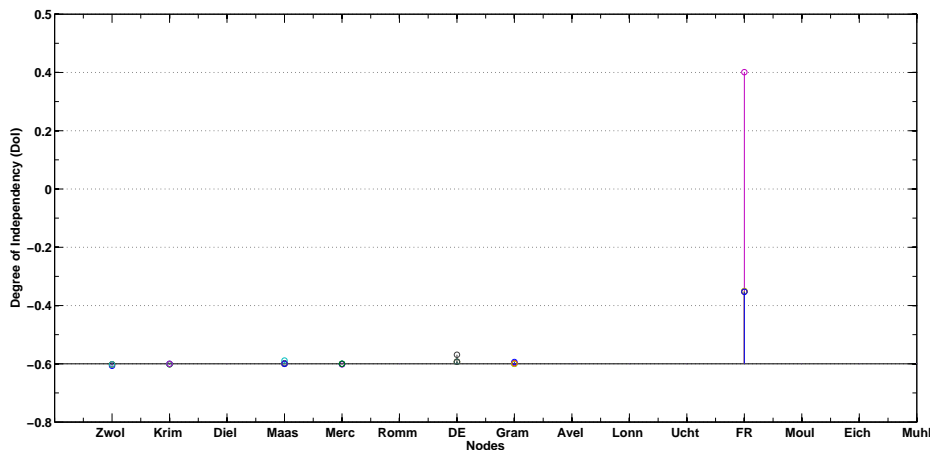


Figure 11: Nodal independencies considering external costs

The environmental and consequently the social benefits from the internalization are presented in the table 3.2 below. As expected Germany profits the most from this action as it reduces the production of coal power plants that represent the biggest amount of external costs. The other countries take also the advantage of providing environmental friendly power.

	NL (€/h)	DE (€/h)	FR (€/h)	BE (€/h)
Winter peak	$0.81 \cdot 10^6$	$7 \cdot 10^6$	$0.59 \cdot 10^6$	$0.34 \cdot 10^6$
Winter off-peak	$0.53 \cdot 10^6$	$3.29 \cdot 10^6$	$0.49 \cdot 10^6$	$0.17 \cdot 10^6$
Summer peak	$0.54 \cdot 10^6$	$5.58 \cdot 10^6$	$0.43 \cdot 10^6$	$0.21 \cdot 10^6$
Summer off-peak	$0.38 \cdot 10^6$	$2.36 \cdot 10^6$	$0.32 \cdot 10^6$	$0.13 \cdot 10^6$
Total per year	$4.37 \cdot 10^9$	$3.08 \cdot 10^{10}$	$3.73 \cdot 10^9$	$1.53 \cdot 10^9$

Table 3: Total social profits, TP eq. (7), after the internalization

3.3 Scenario EL1

As noted above the internalization of external costs promotes the power trading in order to satisfy the demand that cannot be covered by the "domestic" green power plants due to their limited production capability. For that reason new transmission investments are needed. We will evaluate the impact of an already voted plan by the European Union, in the list of the so called priority projects towards a common electricity market, on the environmental profits of the involved and neighboring countries.

The aim of this project is to increase the NTC by 60-65% between the borders of France and Belgium by installing a second circuit on the Aveline (FR) - Avelgem (BE) line (50%) and on the Moulaine (FR) - Aubange (BE) line (10-15%) [15]. In the studied model these lines are represented by Gramm - Moul and Merc - Avel. A 50% increment of the NTC between Gramm and Moul leads to an additional capacity of 400MW and a 15% improvement on the Merc - Avel line corresponds to another 1033MW. The costs of the project burden FR with 17M€ and both FR and BE with 17M€.

Fig. 12 depicts that some of the new market players lost their position and they disappeared from the market or some others decreased their production. The level of generation of German companies remain the same and only one gas company in France has increased its production.

France continues to be the major exporter in the system but more dependent on the other nodes as the exported power is larger in this case. The additional capacity didn't have any impact on the already congested lines due to the fact that the dependencies between the nodes became stronger, see fig. 13.

The total social profits, TP, for one of the two involved parties, France, are either negative or zero. It means that without any coordinated investment in green technologies the augmented exports will again be based on

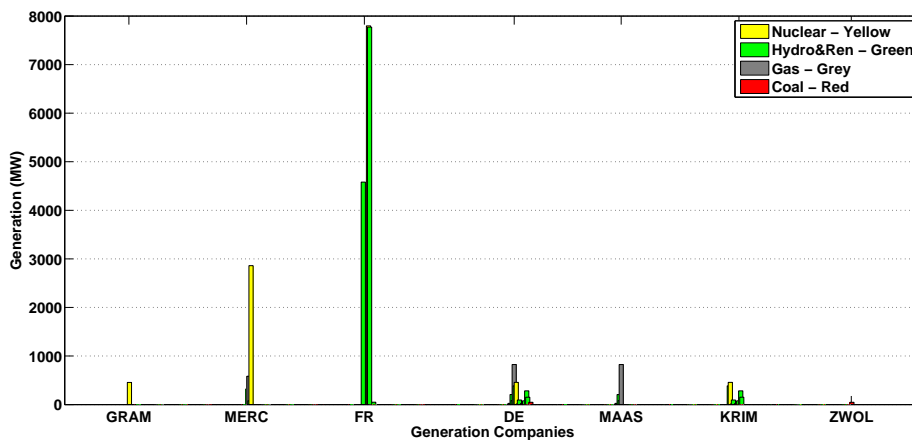


Figure 12: Production companies including external costs and increased capacity

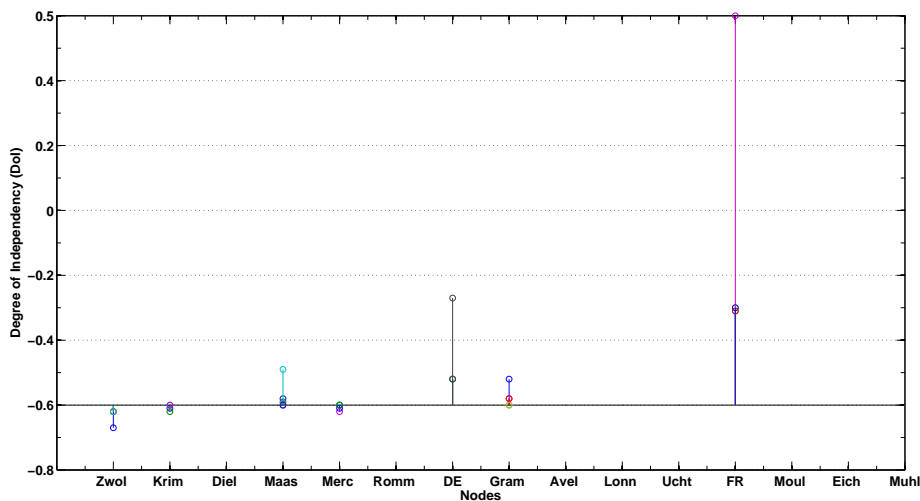


Figure 13: Nodal independencies including external costs and increased capacity

conventional power plants. The expansion is only beneficial to Belgium owing to a total reduction of nuclear power by 300MW. Otherwise, regarding Germany and congested lines the capacity reinforcement has no influence.

Obviously the listed plan is not the optimal decision regarding environmental issues in case the external costs of production have been taken into account. Of course this plan is optimal considering security of supply and power trade as it is reported in [16]. However, a modern investment that costs 17M€ exclusively to France and another 22M€ to both France and Belgium should at least glance at other concerns except for market strengthening, in order to promote the sustainable development of power

	NL (€/h)	DE (€/h)	FR (€/h)	BE (€/h)
Winter peak	$-0.82 \cdot 10^4$	0	$-5.91 \cdot 10^4$	$5.38 \cdot 10^4$
Winter off-peak	0	0	$-5.85 \cdot 10^3$	$2.5 \cdot 10^3$
Summer peak	$9.71 \cdot 10^4$	0	0	$5.35 \cdot 10^4$
Summer off-peak	0	0	0	$4.15 \cdot 10^3$
Total per year	$82.78 \cdot 10^6$	0	$-25.68 \cdot 10^6$	$117.3 \cdot 10^6$

Table 4: Total social profits, eq. (7) after the internalization and the expansion

systems.

As noticed in the subsection 3.2 the internalization of externalities is profitable for every participant in the regional market. Indeed the costs that burden the society at the moment are remarkable larger than the costs of a transmission investment. Using the right internalization policy these costs could change to profits and support investments in future electricity networks. The critical question is who should pay the additional costs and who should be the one who will utilize the arisen profits which is out of the scope of this paper. This question together with a scheme for coordinated multi-objective transmission planning will be the subject of oncoming research.

Conclusions

The results show that the internalization of external costs in that region promotes new entrants in the market but increases the dependencies between the participants. Furthermore, it causes a deficit in social welfare which is much smaller than the total social benefit from the decrease of the fossil fuel power plants production. This profits could be returned to the system including the society, financing new investments and thus accelerating the transition period to future sustainable power systems.

As long as specific values for the external costs are difficult to be set, the taxation or the subsidy is inefficient. Therefore weighting the external costs together with a more completed multi-objective planning tool might be a more reasonable handling of the problem.

Instead of building unsustainable networks based only on antiquated criteria, waiting for the best generation technology to come into the market, is better to force the right price signals and modify the investments criteria as soon as possible. Cause the transition period needs more than 30 years if one imagine that the reinforcement of a transmission line lasts for 10-15 years and more 10-15 years pay back period. Policy initiatives should take the lead in transmission planning before any optimal plan identification.

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