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Sustainability Based Optimal Power Flow A New Planning Tool

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***Abstract*—This paper proposes a multi-objective expansion planning tool in order to support and facilitate the characterization of a transmission or generation investment as beneficial or not. The tool is able to provide information for decision analysis based on economic, environmental and societal criteria, in terms of security of supply, using trade-off curves and weighted internalized external costs. The results describe the impact of policy strategy and transmission network utilization on the social welfare and the social benefits of externalities internalization. Furthermore, the change in system prices and system losses has been studied as well. It has been shown that the level of internalization is a key issue in order to compensate the negative environmental impact of high utilization of transmission lines. In case that green investments are promoted, it may happen that the best solution regarding social benefits doesn't reflect always to the highest system price or to the highest system losses.**

***Index Terms*—external costs, expansion planning, trade-off curves, multi-objective optimization.**

I. Introduction

Traditionally the planning and analysis of electric power systems have put a lot of emphasis on the power production side. Quite often the main purpose has been to show that the annual energy balance can be satisfied, and for that purpose different expansion plans have been evaluated. This is still an important part of the power production planning, but the present requirements in Europe [1] and other places in the world call for new methods and tools [2] to analyze the development of the electricity system, including the transmission and distribution systems.

The reconstruction of the electric power systems around the world is done under increasing end-user energy request, environmental changes and active trading markets. The existing power plants are either insufficient or over-aged and have to be replaced by more effective, competitive and environmentally friendly "green" technologies. As the interconnected systems were primarily built to increase reliability and security, which means that the interconnections were not dimensioned for continuous bulk power transfer required by the current market situation, congestions and outages have become more and more frequent [3]. As a consequence, most often not only new generation is needed but also new transmission capacity to support the extra generation capacity.

As presented in [4] adding new lines does not always mean congestion relief or reliability increment. New lines as well as new generation capacity change the system topology and their influence on an existing system is highly dependent on the range of demand and the operating criteria respectively.

This paper presents a new planning tool which investigates the impact of generation and transmission investments on the market, the society and the environment, in order to indentify an optimal investment strategy. More explicitly the tool in addition to standard power planning tools, embraces

- Power plants of the future
- Load patterns
- Power transmission system
- Indirect costs caused by the electric power system
- Environmental and societal standards.

II. Sustainability based optimal power flow

This planning tool is called Sustainability based Optimal Power Flow (SOPF). It is an optimal power flow that takes into account the widely accepted external costs of energy production as well as transmission constraints, in order to allow for a social welfare analysis that incorporates not only economic criteria, but also criteria of environmental and societal prosperity together with grid security issues.

In the simplest case, an OPF can be viewed as a method that solves the problem of minimizing an objective function [5], e.g minimizing the total operational cost, subject to a number of equality and inequality constraints. In general, OPF is applicable when studying a problem that requires interactive use of conventional power flow and for cases involving conflicting and independent variables and requirements [6], like in our case. Namely, the consideration of external costs is beneficial for the environment and the society but raises the prices in the power market.

The OPF problem can be commonly formulated as in [7]:

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

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, in our case scenarios for new transmission lines and/or new generation capacity and demand growth, and x to the states that minimize the objective function. In the proposed methodology the objective function refers to the social welfare, which is

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defined as:

$$SW = \sum_{i=1}^{k} CB_i - \sum_{i=1}^{n} PMC_i \tag{1}$$

where

CB: Consumer benefit
PMC: Producer marginal cost
k: number of consumers
n: number of producers

For linear demand function and stepwise production marginal costs the equation (1) can be written:

$$SW = \sum_{i=1}^{k} (a_i D_i + 0.5 b_i D_i^2) - \sum_{i=1}^{n} (Q_i * MC_i) \tag{2}$$

where

Q_i: quantity supplied (MW)
D_i: quantity demanded (MW)
MC_i: marginal cost of a power plant (€/MWh)

As the OPF is a static optimization method the SOPF at its current state can provide information only for static models for given production, consumption and transmission data. All three are very sensitive inputs and can affect the results drastically. In production data except for the maximum generation capacity, the marginal production costs are very important and have to be assumed as no specific facts are published. Regarding external costs public data are available ranked by different technologies and countries, published by several European projects like ExternE, NEEDS, CAFE, CASES. In this paper for sake of simplicity we have assumed random values of external costs based on the fact that coal imposes the highest damage and thus, it refers to the highest external costs being followed by gas, solar, wind and nuclear power.

The aggregated characteristics of the SOPF are:

- Weighted optimization that takes economy, environment and security of supply into account.
  A sensitivity analysis is used considering weighting factors and trade-off curves to help along the expansion plan identification.
- Inclusion of internal and external costs for each generation technology according to the updated estimations of several projects.
- Simulation of market behaviour and power trading.
- Consideration of topological grid issues and losses.

Additional features of the SOPF is the examination of investment economic criteria like net present value and internal rate of return and their inclusion in a cost benefit analysis, as presented in [8]. The cost benefit analysis there has shown that the benefits arisen from the internalization of external costs are able to finance coordinated investment projects, even of a very large scale. Furthermore the SOPF provides the possibility to study the congestion revenues and shadow prices, offering a benchmark for interaction between transmission and generation expansion plans.

III. Internalization of External Costs

As shown in [9] the internalization of external costs promotes new entrants in the market and increases the power trading which results to higher dependencies between the participants, because of the limited production capability of environmental friendly technologies. Thus, more congestions may appear in the network. Furthermore, as shown in fig. 1 it causes a deficit in social welfare due to price increment. This deficit is usually smaller than the total social benefit from the decrease of the fossil fuel power plants production.

On the other hand when the transmission lines are used at their limits in order to serve the market requests, the network becomes very vulnerable but the social welfare increases because cheaper, usually conventional power can be dispatched.

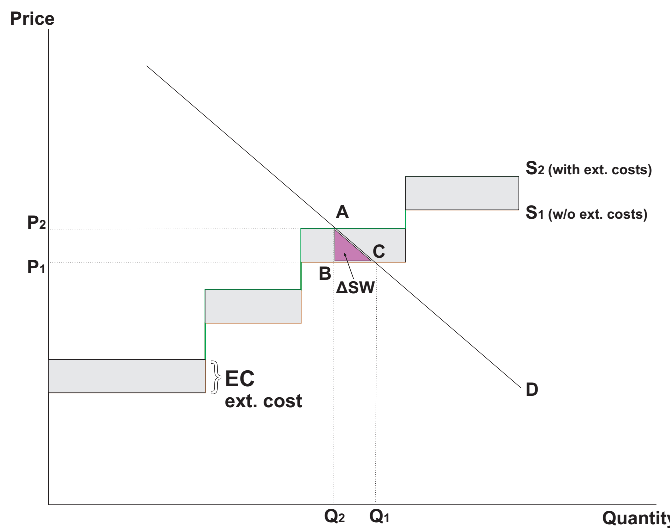

Fig. 1. Internalization of external costs in a stepwise supply function

The stepwise marginal production costs function for power plant i is:

$$P_i = m_i Q_i \tag{3}$$

The external costs function for power plant i is:

$$EC_i = \sum_i V d_j * G_j^i \tag{4}$$

After the internalization the production cost function is:

$$P_i = m_i Q_i + EC_i \Rightarrow P_i = e_i Q_i \tag{5}$$

where

$$e_i = m_i + \sum_j V d_j \tag{6}$$

The social benefit for a power plant i is calculated as:

$$SB_i = \Delta Q_i * EC_i * h_i \tag{7}$$

while the total profit of the internalization will be:

$$TP = \sum_{i=1}^{n} SB_i + \Delta SW \tag{8}$$

where

$$\Delta SW = SW_{withexternalcosts} - SW_{basecase} \tag{9}$$

and

P_i the marginal production cost (€)
Q_j the quantity produced (MW)
EC_i the externality cost (€/ MWh)
Vd_j the value of damage for several emitters (€)
G_i the emitted quantity produced per MWh
h_i the operating hours per year
SW the social welfare

As environmental and societal issues are part of the network operation the transmission planning is not a single dimension process any more and the identification of optimal projects turns to a subject of the decision maker preferences. For that reason this paper proposes a multi-objective optimization tool for expansion planning using weighting factors for the internalization of external costs because of the high calculation uncertainty of their monetary values.

IV. Multi-objective optimization problem

The multi-objective optimization problem maximizes the social welfare, for different internalization levels of external costs and volatile transmission security, introducing a linear dependency between the two terms. The core element of the optimization is based on a direct-current OPF, taking into account transmission losses, step-wise supply curve and linear demand function, subject to the following equality and inequality constraints. The problem described in [10] and [11] is defined in (5):

$$max \sum_{t=1}^{n} \{(1-w) * SW + w * SW_{externalcosts}\} \tag{10}$$

such that:

equalities	inequalities
$Q_i - L_i - \sum Pf_{ij} = \sum Los_{ij}$ $L_i = a_i + b_i D_i$	$Q_i, L_i > 0$ $Q_{i_{min}} < Q_i < Q_{i_{max}}$ $TCL \leq TCL * a$ $0.8 \leq a \leq 1.1$ $0 \leq w \leq 1$

In the optimization the transmission losses have been considered according to the eq. 11, [12]:

$$Los_{ij} = \sum_{i,j=1}^{n} R_{ij} \frac{\theta_i - \theta_j}{X_{ij}} \tag{11}$$

where

Pf_{ij} : Power flow from node i to node j
Los_{ij} : Power losses on the line between node i and node j
θ : Voltage angle
R, X: Line resistance, reactance
TCL: Transmission capacity limit
a: Transmission utilization factor
w: Ext. costs weighting factor

The methodology that is used in this paper is presented on the flow diagram, fig. 2, below. New generation and transmission investment plans can be evaluated according to the preference of the decision maker. The output values update every time a new scenario is proposed and afterwards are compared with the initial values of the existing system. In this paper only four outputs of the SOPF are used, e.g. social welfare, social benefits, system prices and system losses.

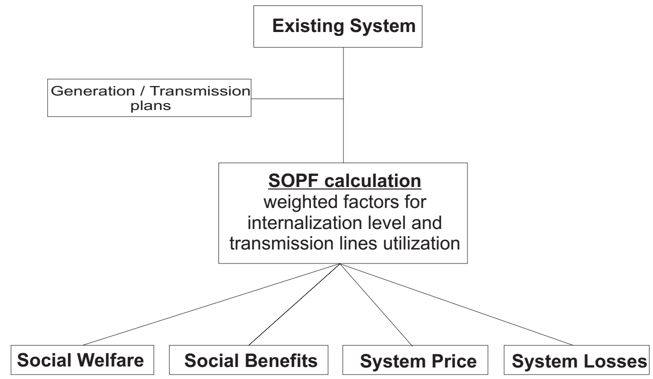

Fig. 2. Applied methodology

V. Results

The presented results have been obtained using a ”copper-plate” model consisting of five nodes and eight transmission lines. The characteristics of the lines have been randomly chosen to correspond to system losses less than 0.5%. Each node is able to produce and consume power and the trading between them is allowed based on nodal prices, that are calculated inside the SOPF. As presented on the table below the external costs for nuclear and wind power have been assumed very small but not zero. As aforementioned conventional power plants appear in the model with the highest external costs. The initialization of the system has been satisfied by the aim of inelastic demand.

TABLE I
Conceptional Model

Node	Production type	Capacity Max (MW)	Consumption (MW)	PMC €	Ext. cost €/MWh
1	Gas	250	120	10	5
2	Nuclear	300	120	5	2
3	Solar	20	120	18	3
4	Wind	30	120	13	2
5	Coal	300	120	8	6

The methodology has been applied once for the base case and once for a scenario of generation expansion in order to compare the results. For the comparison, relative values have been used. The power demanded in both cases has been considered as constant. Under these assumptions, the figures below describe the effect of the internalization of external costs on social welfare, social benefits, system price and system losses when several transmission security levels are applied.

A. Base case

As depicted in fig. 3 the social welfare is minimum where the external costs are fully internalized and a security level of

80% is considered. In case that the maximum social welfare is of preference, then the security criteria become questionable and externalities are not taken into account. This reaction of the system is expected as the internalization leads to higher nodal prices resulting to lower social welfare, however when the transmission limits increase the social welfare increases as well.

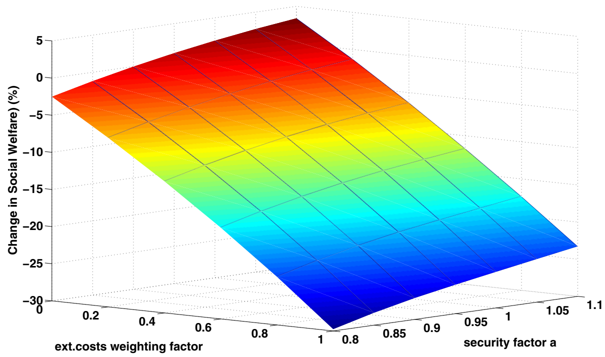

Fig. 3. Trade-off curve social welfare

The social benefits are depending a lot from the energy mix and the level of utilization of the transmission lines. The optimal point reflects to maximum internalized external costs and 80% usage of the transmission lines capacity. For higher usage more power can be delivered to the nodes which in our case comes from conventional power plants as the capacity of gas and coal is larger than nuclear. Thus the minimum point of the figure arises for maximum security factor *a* and zero external costs.

A higher internalization level is required in order to compensate the negative impact of low security constraints, fig.4, however even though for maximum internalization level the maximum social benefits cannot be obtained.

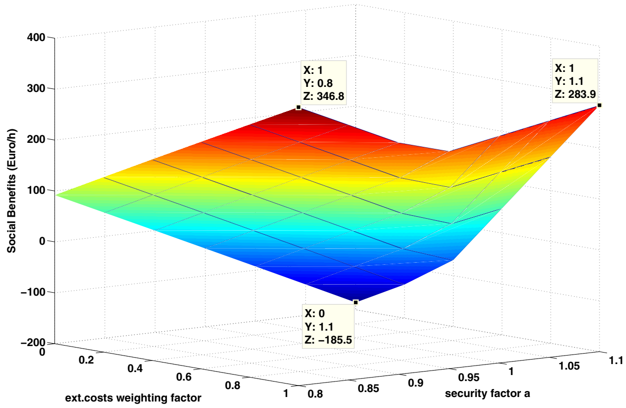

Fig. 4. Trade-off curve social benefits

The same effect is observed in the fig. 5 as well, where the change in system price is presented. The price increases for very high internalization level and decreases when more transmission capacity is available, which means that cheaper power can be dispatched. Thus, the optimal social benefits point corresponds to the highest system price point.

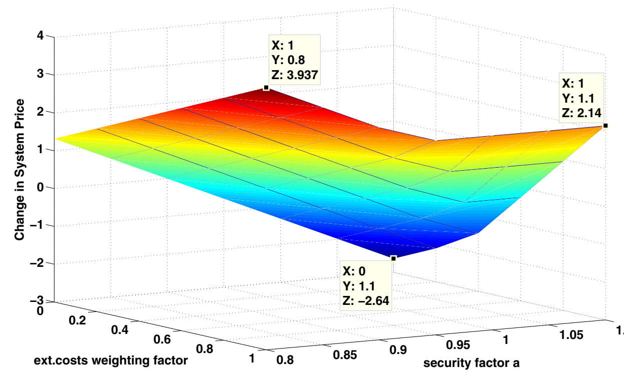

Fig. 5. Trade-off curve system price

On the other hand, the transmission losses behave the other way around as they are very low for lower available transmission capacity and almost constant for different internalization levels, fig. 6. It looks like after a certain value of both terms there is a strong interaction between them and the system losses start to decrease again although the transmission lines are used to their maximum.

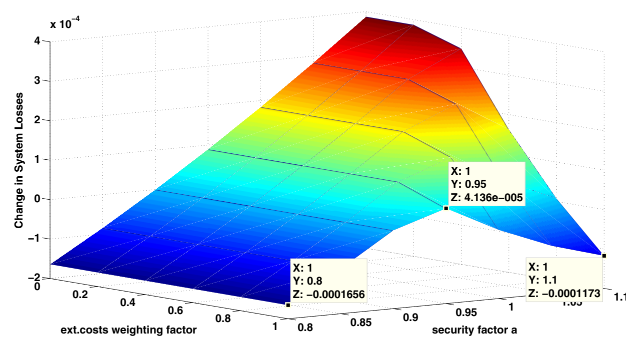

Fig. 6. Trade-off curve system losses

B. Generation Expansion

For the generation expansion scenario we have assumed 80 MW additional wind power on node 4, keeping all other parameters of the system constant. As shown in fig. 7, the behaviour of social welfare remains the same as the relationship between the two terms remains linear.

The major difference is noticed in social benefits where it is obvious that the optimum changed and is no more at the edge of the curve, fig 8. It still corresponds to the highest internalization level but the installation of new "green" power allows 10% higher utilization of the transmission lines, keeping the social benefits to their maximum. Additionally, much higher social benefits are obtained compared with the base case scenario.

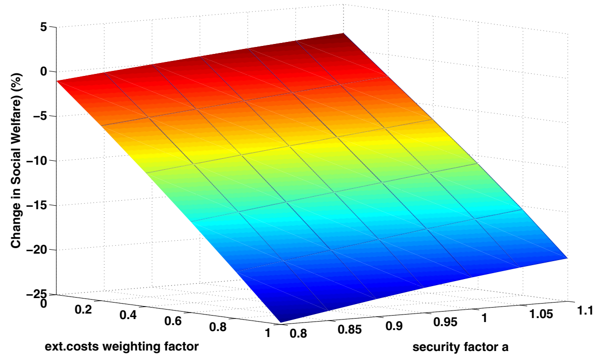

Fig. 7. Trade-off curve social welfare after the generation expansion

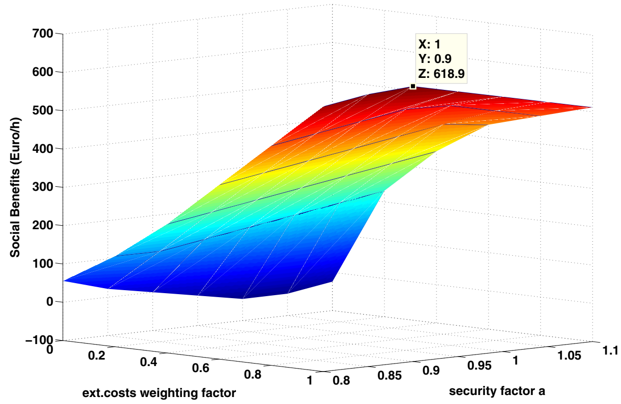

Fig. 8. Trade-off curve social benefits after the generation expansion

Interesting is also that the best solution for social benefits is not the most expensive regarding system price, as shown in fig. 9. For instance, prices are higher for 85% utilization of the transmission lines.

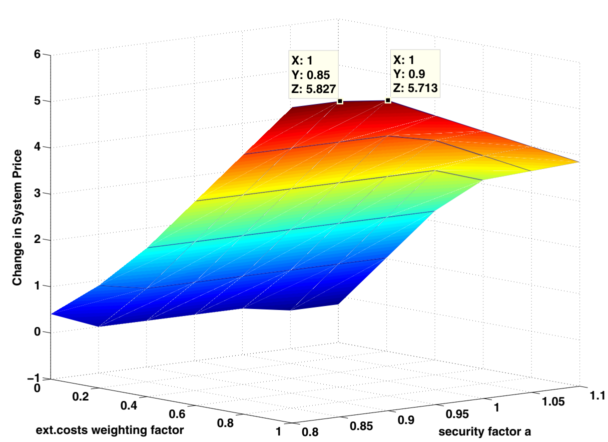

Fig. 9. Trade-off curve system price after the generation expansion

Looking at the power losses, a different behaviour is observed as the losses become higher for higher security factor *a*. In case that the maximum social benefit is the preference of the decision maker then the change of system losses compared with the base case is close to zero. However, for any internalization level and low available transmission capacity the least power gets lost.

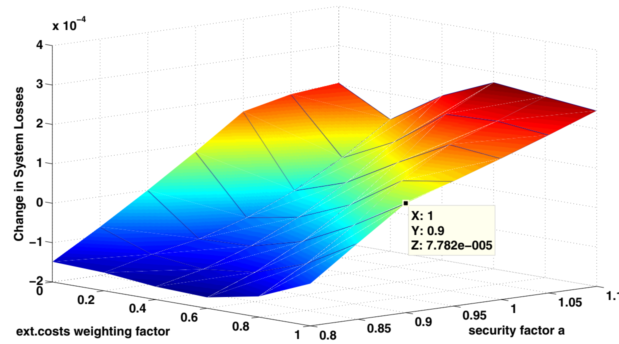

Fig. 10. Trade-off curve system losses after the generation expansion

Summarizing, using as preference the social benefits one can identify the installation of 80 MW on node 4 a beneficial plan despite the loss in social welfare as it results to maximum social benefits, almost to zero change in power losses and not to the maximum system price.

One can argue that the level of internalization of external costs has higher impact on social welfare, social benefits and system price than on transmission losses. There the level of utilization of the transmission lines dominates the analysis, however the influence of external costs remains a key issue.

In the latter analysis the external costs weighting factor represents the policy implementation that the decision maker has decided for. The security factor *a*, can either be used to define the security level of the transmission network or as indicator for new investments in transmission capacity. New "green" generation capacity must be supported from available transmission capacity, and as the investments in transmission create losers or winners, the definition of the targets and the preferences before any investment project is very important issue.

VI. Conclusion

Concluding, this paper proposes a multi-objective expansion planning tool, the so called Sustainability based Optimal Power Flow (SOPF), in order to support and facilitate the characterization of a transmission or generation investment. The tool in its present state is able to analyze static models but is not able to find optimal investments by itself. The target is to help the decision maker on the identification of a proposed expansion plan as beneficial or not, according to his/her preferences.

In the tested methodology only four outputs of the SOPF has been used in order to describe the interaction between the society, the economy and the transmission network. By means of a weighted factor for the internalization of external costs of power production, together with a security factor *a*, for the available capacity of the transmission lines the changes in social welfare, social benefits, system price and system losses have been studied.

As presented using a conceptional model, beneficial plans in the name of social benefits can be found, without leading to the highest nodal prices or transmission losses.

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