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Methodology for Assessing Transmission Investments in Deregulated Electricity Markets

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***Abstract*—Transmission system planning in deregulated markets often includes a set of proposed alternative expansion schemes instead of a single optimal network solution. In this paper, a methodology is proposed for the economic evaluation of alternative transmission expansion plans, based on several indices that measure the market performance of the expansion schemes. The proposed methodology can assess in a realistic way both reliability-driven as well as economic-driven transmission expansion projects. In order to demonstrate the proposed methodology, three possible transmission expansion solutions over the IEEE 24-bus reliability test system are compared. The indices introduced are calculated for each scenario scheme and the results are assessed in order to determine the scenario with the best cost-benefit economic performance. This paper derives from the work performed for the IRENE-40 EU research project.**

***Index Terms*—Cost-benefit analysis, deregulated electricity markets, transmission investments, transmission expansion projects, IRENE-40 EU project.**

I. Introduction

The deregulation of electricity markets has introduced new challenges to the transmission planners since a new approach for evaluating the economic benefits of transmission investments is required. Unlike the previous vertically integrated market where one regulated utility was responsible for serving a load, the restructured wholesale electricity market consists of a variety of parties making decisions that affect the utilization of transmission lines [1]. In vertically integrated power systems, network expansion was intended to meet the present and future system reliability standards at a minimum investment cost [2]. In deregulated electricity markets the new objectives of transmission expansion are (i) to maintain system reliability and security standards, (ii) to keep the environmental impact of expansions at a proper level, and (iii) to improve the economic performance of electricity markets [3].

In order to assess various transmission expansion schemes, Cost-Benefit Analysis (CBA) should be performed for each of the proposed expansions [4]. A project's economic assessment relies on the identification and quantification of its positive and negative economic impacts on the power system. Regarding transmission system expansion, this cost-benefit approach must address the impact of transmission expansion cost on increasing transmission users' access to sources of generation and demand, on creating incentives for new generation investments, and on market competition. The approach should also take into account the inherent random and nonrandom uncertainties associated with key market factors (i.e. future generation location, intermittency of renewable sources production, fuel costs, load augmentation etc.) [5]. In deregulated electricity markets, generation expansion and transmission planning are separated, driven by market-based initiatives. Due to diversified interest of stakeholders and lack of transparency, misleading price signals may force developments towards suboptimal system expansion [6].

In the new deregulated environment there are two types of transmission expansion projects: (i) reliability driven, and (ii) economic driven projects. In the first case, expansion cost is incorporated into transmission's service cost, providing a regulated rate of return for the relative expansion/upgrade to the transmission owner. Reliability driven expansion projects are extremely difficult to quantify in a cost-benefit analysis because it is not easy to enumerate in monetary terms changes in frequency or duration of service interruptions. However, those projects often include a set of alternative candidates, all of which are identified as technically viable solutions, and at least one of them must be selected based on its relative economic advantages.

In case of economic driven projects, investment costs are recovered through congestion revenue(s) deriving from the new line(s) rather than through a regulated rate of return. Transmission expansions relying solely on private transmission investment can lead into shortcomings. Firstly, since transmission upgrades reduce the degree and incidents of congestion, the congestion revenue streams are reduced by the upgrade itself and thus can create a disincentive for investments. Secondly, transmission upgrades offer economic benefits to a wide range of market participants, so the effect of each expansion/upgrade cannot be clearly estimated [4].

This paper proposes a methodology for the economic assessment of transmission expansion schemes in deregulated energy markets taking into account investment costs and benefits deriving from each scheme, while the proposed methodology can assess in a realistic way both reliability driven as well as economic driven transmission expansion projects. Change in social welfare due to an expansion scheme is compared to its investment cost, and several economic indices are computed to assess the market performance of the

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expansion schemes. The proposed methodology is applied on the IEEE 24-bus reliability test system and the results are discussed. The proposed methodology will be applied for the assessment of different transmission expansion schemes for the European Network until year 2050 considering different sets of possible future generation scenarios, within the context of the IRENE-40 EU research project [7].

II. Proposed Methodology

In order to assess the economic benefits of various transmission expansion plans, a set of indices is calculated for each expansion plan, for a set time period. This time period is different from the investment's lifetime, since, due to constant changes in network and generation topology it is very difficult to make a reliable assessment of the investment benefits for a very long period of time. Therefore, all monetary results deriving from those indices are calculated in terms of Present Value (PV). The Present Value of a monetary flow K is computed as follows:

$$PV = \frac{\mathrm{K}_t}{(1+i)^t} \tag{1}$$

where t is the time of the cash flow, i is the discount rate and K_t is the net cash flow at time t.

In this paper, change in social welfare due to an expansion scheme is compared to its investment cost, and several economic indices are computed to assess market performance. With this approach the determination of costs will be based on the calculation of present value of all investment costs throughout the examined time horizon of an examined project. Therefore, it is necessary to know the exact year or decade of each implemented transmission expansion and the lifetime of each considered investment. Furthermore, it is very important to determine if a proposed expansion is economic or reliability driven. In case of economic driven expansions, investments are considered merchant transmission investments and the investment cost is undertaken by private individuals/owners of the lines. In case of reliability driven expansions, the investment cost is undertaken by all users, therefore the investment costs are recovered through a regulated rate of return. Finally, in most cases users are both producers and consumers. If producers don't pay for the use of system charges, then no incentives for installation of generation in areas with generation shortage (congested areas) are created.

Regarding benefits, it is necessary to evaluate the present value of the transmission investment benefits. This can be accomplished by calculating the change in total social welfare regarding the consumer, transmission and producer surplus. In this case, a deterministic approach is required; from the predicted generation cost curves, load and RES time series provided for the examined project time horizon, all benefits should be calculated. Several assumptions are considered for this approach, such as no bidding strategies, since bidding prices are calculated in a perfect market environment. Generally, the benefit of a transmission investment can be evaluated by either the increase of total social welfare or by the decrease of congestion cost, both expressed in present value. However, isolation of a single system investment is very difficult since the network constantly changes and each change affects the load flows in all lines.

Under a probabilistic approach, in order to consider the random uncertainties (intermittent sources, load uncertainty, generators or lines availability) only several snapshots of the system operation are investigated. Those snapshots may derive from an annual system simulation and they can account for some severe situations of the system. However, if the examined system is considered for a large time period, such as in terms of many decades, the capacity factor of the RES and the lines outage probability remains more or less stable, making such an approach non-mandatory. In the proposed methodology, the uncertainties deriving from RES generation, load uncertainty and placement of new generation are considered as input of the various examined generation scenarios. Therefore, for each generation scenario different annual load and RES time series have been created.

The methodology of this paper is introduced in order to weight up the total expected costs and the total expected economic benefits of the considered alternative transmission solutions within each generation scenario, in order to deal with the uncertainty of future streams of costs and benefits. The proposed set of indices for the purpose of this approach is as follows.

A. *Difference in System Producer Surplus (ΔPS)*

System Producer Surplus is defined as the system producers' net profit and it reflects the difference among the value that producers gather from the system and the costs of their production. The *ΔPS* indicator is computed as follows:

$$\Delta PS = PS_w - PS_{w/o} \tag{2}$$

where PS_w and $PS_{w/o}$ is the system producer surplus calculated with and without the proposed expansion, respectively. The System Producer Surplus for each case is given by:

$$PS = \sum_i (\lambda_i - C_i) P_{g_i}, \forall i \in NG \tag{3}$$

where i is the index of generating units, λ_i is the nodal locational marginal price (LMP) of the i-th generating unit, C_i is the bid price for the i-th generating unit, P_{g_i} is the generated power for the i-th generating unit and NG is the total number of generating units.

B. *Difference in System Consumer Surplus (ΔCS)*

System Consumer Surplus is defined as the system consumers' net profit and it reflects the difference between the value that consumers pay to the system operator and the demand offers. The *ΔCS* indicator is calculated as follows:

$$\Delta CS = CS_w - CS_{w/o} \tag{4}$$

where CS_w and $CS_{w/o}$ is the system consumer surplus calculated with and without the proposed expansion, respectively. The System Consumer Surplus for each case is calculated by:

$$CS = \sum_j (B_j - \lambda_j) P_{d_j}, \forall j \in ND \tag{5}$$

where *j* is the index of system demands, λ_j is the nodal LMP of the *j*-th demand, B_j is the offer price for the *j*-th demand, P_{d_j} is the consumed power for the *j*-th demand and ND is the total number of system demands.

C. Difference in System Congestion Revenue (ΔCR)

System Congestion Revenue is defined as the amount of money collected from the system operator due to congestion incidents in transmission network and it reflects the difference between system producers' revenue and demands' payments. The *ΔCR* indicator is calculated as follows:

$$\Delta CR = CR_w - CR_{w/o} \tag{6}$$

where CR_w and $CR_{w/o}$ is the system congestion revenue calculated with and without the proposed expansion, respectively. The system congestion revenue for each case is calculated by:

$$CR = \sum_n (\lambda_n P_{d_n} - \lambda_n P_{g_n}), \forall n \in N \tag{7}$$

where *n* is the index of system buses, λ_n is the LMP for the *n*-th bus, N is the total number of system buses, while P_{d_n} and P_{g_n} are calculated by:

$$\begin{aligned} P_{g_n} &= \sum_i P_{g_i}, \forall i \in NG_n \\ P_{d_n} &= \sum_j P_{d_j}, \forall j \in ND_j \end{aligned} \tag{8}$$

D. Difference in System Social Welfare (ΔSW)

System Social Welfare is defined as the aggregated value of participants' surpluses and it reflects the sum of system producers' surplus, consumers' surplus, and congestion revenue. The *ΔSW* indicator is computed as follows:

$$\Delta SW = SW_w - SW_{w/o} \tag{9}$$

where SW_w and $SW_{w/o}$ is the system social welfare calculated with and without the proposed expansion, respectively. The system social welfare for each case is calculated by:

$$SW = PS + CS + CR = \sum_j B_j P_{d_j} - \sum_i C_i P_{g_i} \tag{10}$$

Generally, when comparing different expansion schemes, a proposed investment is considered successful when the change in social welfare after the implementation of the expansion is greater than the initial investment, while the proposed expansion with the biggest change in social welfare is the one that also provides the best cost-benefit balance.

E. Difference in System Congestion Cost (ΔCC)

System Congestion Cost is defined as the decrease in total social welfare because of transmission constraints in the system. The *ΔCC* indicator is calculated as follows:

$$\Delta CC = CC_w - CC_{w/o} \tag{11}$$

where CC_w and $CC_{w/o}$ is the system congestion cost calculated with and without the proposed expansion, respectively. This avoided congestion cost equals to the difference in system Social Welfare in a lossless network model. The system congestion cost for each case is calculated as follows:

$$CC = SW^0 - SW^1 \tag{12}$$

where SW^0 and SW^1 is the system social welfare without and with transmission constraints, respectively.

In order to analyze and compare future network configurations and future alternative energy scenarios, all the aforementioned indices can be calculated and compared in order to assess the economic performance of the system. The producers' and consumers' surplus can be considered as indicators of the competition level of the alternative scenarios. Similar to the congestion cost, the social welfare can be evaluated for several snapshots of the annual operation of the system, e.g. the most extreme congestion situations, if a probabilistic approach is followed.

As more (less) transmission lines are congested, LMP differences among buses and consequently congestion costs increase (decrease). Therefore, congestion cost is a proper criterion for measuring price discrimination and customer constraints. Consequently, considering the modeling approach followed, annual congestion cost is an appropriate indicator for measuring the degree of competitiveness in an electricity market, providing a suitable indicator for the economic evaluation of a transmission scheme. The comparison of this annual congestion cost among several scenarios will provide the "weakest" competitive scenarios for further market investigation.

F. Congestion Index (CI) and Standard Deviation of Prices (STDP)

In order to further assess the degree of competitiveness, two more indices are proposed [5], [8]. Congestion Index can be calculated as the fraction of the weighted mean value of all prices over the network minus the system clearing price without considering system transmission limits, divided by the weighted mean value of all prices over the network. Standard Deviation of Prices reflects the flatness of price profile over the system due to congestion incidents in transmission network.

In market power analysis, the Lerner Index is used to describe a firm's market power. An effective congestion index (CI) taking from the Lerner index could therefore be used to quantify the congestion effect on prices. This index derives from the ratio of the difference between the average of the LMPs around the system and the uncongested nodal prices to the average of LMPs over the network. When the power transmission capacity is adequate and no transmission line is overloaded, CI would be zero. If transmission limits constraints are active, the congestion price of the congested line will increase rapidly and the network will hold "vertical market power". The average congestion index can be computed for several sets of operating scenarios to quantify the overall performance of the network and the competition level. The Lerner Index for an examined transmission expansion can be calculated as follows:

$$LI_n = \frac{\lambda_n - MCP}{\lambda_n} \tag{13}$$

where n is the index of system buses, λ_n is the LMP for node n, and MCP is the market clearing price.

In order to provide a competitive environment for all participants to purchase and sell energy at the same price, nodal prices must be made equal (flat). As the price profile becomes flatter, differences among LMPs decrease. Therefore, customers purchase and sell energy at less discriminative prices and consequently competition is encouraged. As the price profile deviates, differences among LMPs increase, customers buy and sell at more discriminative prices, and consequently competition is discouraged. Therefore, the flatness of price profile is a proper criterion for measuring the degree of competitiveness in an electricity market and it is necessary in order to evaluate the economic performance of a proposed network expansion scheme. Other market-based criteria that could be used are the standard deviation of mean of LMPs and the weighted standard deviation of mean of LMPs with weights on load and/or generation buses in order to provide a non-discriminatory environment for consumers and/or to encourage competition among producers.

The indices mentioned above are sufficient for measuring the degree of competiveness in a perfect market environment. In cases where bidding strategy is considered, then more indices are applicable, such as the Herfindahl-Hirschman Index (HHI) or the Residual Supply Index (RSI) [3].

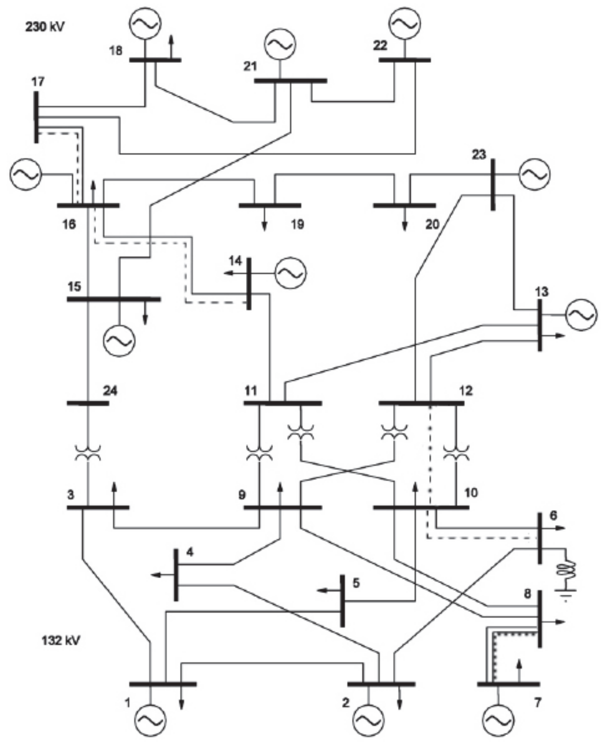
III. Results and Discussion

The methodology of this paper is applied on the IEEE 24-bus reliability test system [9] considering producers' generation data as in [10]. Three transmission expansion scenarios have been considered on a ten-year horizon, while investment costs incur at the beginning of the decade. The rate of return for the annual benefits is set to 10%, although a different social rate of return could be used instead [4]. An LMP based market operation is performed for each year for the three proposed transmission expansion plans.

The test system examined along with the three different proposed expansion plans is demonstrated in Fig. 1. For the purpose of this paper, consumer load increase is set to 1% per year, while a perfect market environment is assumed for generation. Yearly market simulation is carried out based on the reverse yearly load curve provided in [9] by performing a DC-OPF analysis. To allow congestion incidents, the maximum capacity of each line has been reduced to half.

In order to meet the increase on system demand over the examined decade, lines 6-10, 14-16 and 16-17 are required to be added in all the examined plans. In Plan II, an extra line, line 10-12, is required in the network solution, while in Plan III, the extra line needed is line 7-8, resulting in both cases on a bigger investment cost than Plan I where only the three extra lines mentioned above are required. The lines added along with the investment cost for the three proposed expansion schemes are presented in Table 1.

Table 2 presents the values of the indices *ΔPS*, *ΔCS*, *ΔCR*, and *ΔSW* for the three expansion plans. Table 3 demonstrates the calculated ratio between the investment cost and the change in total social welfare for each of the three examined plans, while Table 4 shows the Standard Deviation of System Prices for each year of the examined decade.



Lines Added on all Three Proposed Expansion Plans
Extra Lines Added on Expansion Plan II
Extra Lines Added on Expansion Plan III

Fig. 1. IEEE 24-bus reliability system configuration and lines added for each of the three proposed expansion scenarios.

TABLE 1
INVESTMENT COST AND LINES ADDED FOR THE THREE PROPOSED EXPANSION SCHEMES

Item	Plan I	Plan II	Plan III
Lines added	6-10 14-16 16-17	6-10 10-12 14-16 16-17	6-10 7-8 14-16 16-17
Investment Cost [k€]	63.440	105.910	94.520

TABLE 2
PRESENT VALUE OF THE CALCULATED INDICES FOR THE THREE PROPOSED EXPANSION SCHEMES

INDEX	PLAN I	PLAN II	PLAN III
ΔPS [k€]	40.300	21.736	45.861
ΔCS [k€]	298.157	316.724	304.964
ΔCR [k€]	-249.352	-243.116	-261.604
ΔSW (ΔCC) [k€]	89.105	95.344	89.221

TABLE 3
COMPARISON OF CHANGE IN SOCIAL WELFARE AND INVESTMENT COST FOR THE THREE PROPOSED EXPANSION SCHEMES

INDEX	PLAN I	PLAN II	PLAN III
INVESTMENT COST [k€]	63.440	105.910	94.520
ΔSW [k€]	89.105	95.344	89.221
ΔSW/(INVESTMENT COST)	1,40	0,90	0,94

TABLE 4
STANDARD DEVIATION OF SYSTEM PRICES FOR THE THREE PROPOSED EXPANSION SCHEMES

YEAR	STDP [€/MWh]			
	INITIAL	PLAN I	PLAN II	PLAN III
1	8,702	6,563	6,590	6,507
2	7,873	5,790	7,529	5,735
3	7,853	5,742	7,468	5,687
4	7,783	5,692	6,823	5,638
5	9,313	5,742	6,863	5,687
6	9,213	5,684	6,708	5,630
7	10,303	5,628	6,747	5,574
8	10,446	5,685	6,689	5,512
9	10,253	5,628	6,633	5,454
10	9,783	6,152	6,580	5,403
AV.	**9,152**	**5,831**	**6,863**	**5,683**

TABLE 5
ALLOCATION OF CONGESTION REVENUE AND CONGESTION COST REDUCTION TO PRODUCERS' AND CONSUMERS' SURPLUS INCREASE

INDEX	PLAN I	PLAN II	PLAN III
ΔPS	11,91%	6,42%	13,07%
ΔCS	88,09%	93,58%	86,93%

In Table 2, it is shown that both Plan I and III provide about the same change in social welfare, while Plan II provides a bigger change. Regarding the change in producers' surplus, this is similar for Plans I and III, while the benefit from the proposed expansion of Plan II is lower, almost half, than the other two plans. Regarding the difference in consumer surplus and the difference in congestion revenue, it is more or less similar for all the proposed expansion plans. Therefore, if solely examining benefits, Plans I and III give more or less similar results while Plan II results in the bigger change in system social welfare compared to the initial system condition.

When taking into account the investment cost, from the test cases indicative results, only Plan I provides a change in System Social Welfare greater than the initial investment cost (1,40 as demonstrated in Table 3). Both Plan II and Plan III have a Social Welfare benefit to investment cost ratio that is less than one (0,90 and 0,94 respectively), making them less balanced in terms of cost-benefit economic performance.

As shown in Table 4, the weighted standard deviation of system prices in Plan III is smaller compared to the other two plans, providing a relatively "flat profile" for the prices. Plan I also provides relatively low system prices, while Plan II results on the higher average system prices for the examined decade. Overall, although Plan III offers a greater reduction in system's congestion incidents, thus providing the lowest average system prices between the three examined scenarios, the avoided Congestion Cost is not enough to remunerate for the new line needed between nodes 7 and 8.

Table 5 shows the exact allocation of this producers' and consumers' surplus increase. The comparison of this allocation for the three examined expansion scenarios can be useful for the final decision of the transmission system operator (TSO), since each of those reflects a different policy. In Plan II for example, consumers are undertaking larger portion of the reduction in System Congestion Revenue and System Congestion Cost than in Plans I and III, thus making this scheme more consumer oriented.

Based on the above, the plan that provides the best cost-benefit ratio while allowing market competitiveness is Plan I because of the following reasons: (i) its change in total system social welfare is greater than its initial investment cost; (ii) it provides a relatively flat energy market price profile; (iii) it provides the smallest congestion cost; and (iv) it provides a sufficient benefit margin for both system producers and consumers.

The methodology presented in this paper is planned to be applied to the transmission network investments solutions deriving from the four developed scenarios within the premises of the IRENE-40 EU Research Project.

IV. CONCLUSION

This paper proposes a methodology for economic assessment of reliability driven as well as economic driven transmission expansion investments. Typically in deregulated energy markets, in transmission system planning, expansion projects include a set of alternative candidates, than a single optimal network solution; hence in the approach presented, different transmission expansion schemes are economically evaluated with the aid of several introduced indices. Change in social welfare due to a transmission upgrade is compared to its investment cost in order to identify the expansion scheme with the best cost-benefit balance, while the standard deviation of system prices over the examined timeline is calculated as a degree of the electricity market competitiveness. The methodology is applied on the IEEE 24-bus reliability test system and the results are discussed and assessed. The proposed methodology will be applied for the assessment of different transmission expansion schemes of the European Network until year 2050, in the context of the IRENE-40 EU research project.

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VI. BIOGRAPHIES

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