The European research project REALISEGRID: transmission planning issues and methodological approach towards the optimal development of the pan-European system

A. L'Abbate, *Member, IEEE*, G. Migliavacca, G. Fulli, *Member, IEEE*, C. Vergine, A. Sallati

***Abstract*-- In Europe several issues may strongly impact on the power transmission system, posing new challenges to the TSOs (Transmission System Operators), whose role becomes more complex. The present paper results from some activities carried out within the European research project REALISEGRID, dealing with numerous transmission planning issues. After introducing the European context and reviewing the current transmission planning process and practices in Europe, this paper focuses on the methodology developed to perform the cost-benefit analysis of new grid investments in a pan-European perspective. Some key results of the methodology application on a European transmission network test-bed are also part of the paper.**

***Index Terms*—European transmission system, power system liberalization, RES integration, security, transmission expansion planning, transmission investment cost-benefit analysis.**

I. INTRODUCTION

In Europe different trends and issues may strongly impact on the electric power system, and in particular its backbone, the transmission grid. This is tightly related to the crucial role that the European transmission system plays towards the achievement of the energy and climate change policy targets enforced by the European Union (EU) for 2020 and beyond [1]. In fact, accommodating Renewable Energy Sources (RES) is a key priority, together with keeping acceptable system reliability standards and progressively removing the obstacles towards a unified European energy market. In this frame, the task of European TSOs (Transmission System Operators) becomes more complex, as they are confronted with new challenges towards an effective grid integration of a continuously growing amount of variable RES power plants.

The TSOs have indeed to cope with rapid and less predictable flow changes so as to preserve an adequate level of security for the system. To achieve this goal within a pan-European perspective, TSOs might also exploit possible backup services provided by complementary resources remotely located. However, this can only be implemented at the expenses of a more intense use of already congested cross-border transmission grids sections. To address such issues, the traditional approach of enhancing the power transmission capacity by adding new High Voltage Alternating Current (HVAC) overhead infrastructures is nowadays seriously hampered by economic, social and environmental constraints. This occurs within a background of ageing European transmission assets. Also, looking at further developments of the European power system, it is expected that the increased penetration of distributed energy resources and active demand will impact on the upstream transmission. Then, the need for evolution in the design and operation of the transmission system towards a progressive re-engineering process emerges in Europe. In this frame, transmission expansion planning criteria crucially need to be revised and extended in order to design flexible, coordinated and secure grids based on modern architectural schemes and innovative technological solutions. More robust planning methodologies have to be pursued to address the above uncertainties and challenges faced by TSOs.

The present paper results from some activities carried out within the European research project REALISEGRID (2008-2011) [2], dealing with transmission planning issues. After introducing the European context (Section II) and the main elements of REALISEGRID (Section III), this paper provides first an overview of the current transmission planning process and some practices in Europe (Section IV). Then, it focuses on the methodology developed within REALISEGRID to perform the cost-benefit analysis of new grid investments in a pan-European perspective (Section V). This evaluation, which also takes innovative grid technologies into account, is a crucial stage of the transmission expansion process. Some key results of the cost-benefit analysis methodology application on a European grid test-bed are also part of the paper (Section VI), before conclusions and future outlook (Section VII).

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A. L'Abbate and G. Migliavacca are with RSE (Ricerca sul Sistema Energetico) S.p.A., Milan, Italy (e-mails: Angelo.LAbbate@rse-web.it, Gianluigi.Migliavacca@rse-web.it).

G. Fulli is with the Joint Research Centre of the European Commission, Institute for Energy and Transport, Petten, The Netherlands (e-mail: Gianluca.Fulli@ec.europa.eu).

C. Vergine and A. Sallati are with TERNA S.p.A., Rome, Italy (e-mails: Chiara.Vergine@terna.it, Alessio.Sallati@terna.it).

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II. THE EUROPEAN CONTEXT

The strategic role of the European transmission grid within the EU energy policy has been remarked by different documents of the European Commission (like e.g. [1][3]).

Concerning the development of new transmission infrastructures, the European TSOs have substantially kept a national scope so far. However, this approach has proved unable to provide a pan-European view and consider the cross-border needs originated by complementary generation sources located in different European places [4]. A completely new EU transmission infrastructure policy based on a European vision is then necessary to deliver the energy networks that Europe needs in the next two decades. This also means changing the current Trans-European Energy Networks (TEN-E) [3] practice, featured by predefined (and inflexible) European priority project lists, towards a new pan-European approach. This urgent need has been highlighted by the European Commission in the so-called 2010 Energy Infrastructure Package [1], completed in Oct. 2011 by a proposal for a new regulation [5] (that after its final approval is due to replace the TEN-E instrument from 2013 onwards).

To ensure timely integration of RES generation in Northern and Southern Europe and foster further market integration, in [1] four crucial priority corridors of the European power system, to be more urgently developed and reinforced, are identified. These are (see also Fig. 1):

a. Offshore grid in the North Seas and connection to Northern and Central Europe;
b. Completion of the BEMIP (Baltic Energy Market Interconnection Plan);
c. Interconnections in South Western Europe;
d. Connections in Central Eastern and South Eastern Europe.

In the electricity sector, in addition to these four priority corridors, smart grids deployment and electricity highways development across Europe have been also included as priority areas for infrastructure expansion towards 2020 and beyond [1][5]. These highways, which can be thought as the axes of a potential pan-European supergrid [6], need to be built stepwise, ensuring progressive compatibility with the existing network, based on a modular development plan [1]. This infrastructure policy framework sets the creation of a pan-European approach to prioritize the projects of European interest as a key measure towards EU targets for 2020 and beyond [1][5]. In this direction, a crucial role is played by ENTSO-E (European Network of Transmission System Operators for Electricity), the association gathering the European TSOs, which will have to progressively implement the necessary transmission development evolution steps to address the EU requirements. A first, important contribution to this process was given by the first (pilot) ENTSO-E's Ten-Year Network Development Plan (TYNDP) 2010-2020 [7], to be updated every two years. Although the 2010 TYNDP was still obtained by a bottom-up data collection from the national TSOs, a gradual change of approach in favour of a new pan-European methodology is foreseen in the frame of upcoming 2012 TYNDP and 2014 TYNDP. Such new approach entails fostering the achievement of a coherent policy promoting the most critical and techno-economically viable reinforcements, while overcoming possible local opposition by means of transparent information (on infrastructure costs and benefits) to the public. In this frame, REALISEGRID [2] can provide a useful support and contribute to the fulfilment of the above targets at pan-European level.

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Fig. 1. Priority energy infrastructures in Europe [1].

III. OVERVIEW OF REALISEGRID PROJECT

Transmission planning is the central subject investigated by the European research project REALISEGRID [2], which is co-funded by the European Commission under the 7th Framework Program for Research and Technological Development. The project consortium consists of twenty European partners under the coordination of RSE (former CESI RICERCA/ERSE). It includes four TSOs, five industrial partners and eleven research institutes and universities. The project activities pursue a threefold target:

1) analysis of the most promising technologies able to improve the reliability, capacity and flexibility of the transmission network;
2) study of the impact of different regulatory and socio-economic scenarios on the energy exchanges in Europe in a long term perspective (up to 2030);
3) implementation of a set of methodologies and tools for transmission grid expansion towards the extension of current planning criteria.

In the frame of these activities, a thorough review of the present transmission planning practices has been firstly carried out within REALISEGRID, highlighting critical issues of modern power systems. One of the most important goals of REALISEGRID is to set a pan-European approach for the cost-benefit analysis of new transmission assets to rank investments: this is one of the key steps in the transmission expansion planning process.

IV. TRANSMISSION EXPANSION PLANNING

A. Main elements

The transmission expansion planning process is a complex task in which the network planners need to handle several uncertainties and risk situations.

In the past, before the electricity market liberalisation, in a centrally managed power system the vertically integrated operator could in general control the whole power system: the transmission network was then expanded with the aim to minimise both generation and transmission costs, while meeting static and dynamic technical constraints to ensure a secure and economically efficient operation.

Nowadays, in a liberalised environment, the TSO, responsible for the sole transmission, shall plan the expansion of its network by minimising transmission costs (investment and operation), overcome bottlenecks and pursuing maximum social welfare, when requested by specific regulation, while meeting static and dynamic technical constraints to ensure a secure and economically efficient operation. Socio-environmental constraints must also more and more be duly taken into account in the planning process [8][9].

Some important criticalities make the task of a TSO at the same time crucial and very delicate [7]. In fact, changes in future system conditions significantly affect benefits of transmission expansion. Thus, evaluating a transmission project based only on assumptions of average future system conditions might greatly underestimate or overestimate the true benefit of the project and may lead to less than optimal decision-making. For this reason, transmission planners need to fully capture all impacts a project may have, examining then a wide range of possible system conditions. Furthermore, it generally takes much longer to get a new transmission link approved and built than similar procedures for new generation facilities. Therefore, the development of the transmission grid always lags behind the development of generation. This can only be taken into account by using different scenarios [7][8].

The transmission planning process with its basic scheme and stages can be recalled as depicted in Fig. 2 [10]. The first stage of planning concerns the power system projection (scenarios) over the analysed timeframe in terms of those elements which may impact on the transmission grid evolution over the years of observation. Such elements regard the projected trends of load demand, import/export and production (phasing in and out of respectively new and old generation), which also depend on economic, market, policy and regulatory drivers (like for example the EU 2020 targets). The development of system scenarios, related to the targeted time horizon, provides then the boundary conditions for planning the transmission expansion. In fact, within the frame of the developed scenarios for the specific area under study, transmission planners need to check whether their related network in unchanged conditions (without any expansion, 'doing nothing' alternative) is still reliable, that is secure and adequate. They assess the resilience of the system in different possible situations, such as e.g. high/low load, changing generation dispatch patterns, adverse climatic conditions, and contingencies. This analysis is carried out by applying static and dynamic reliability/security analysis methods, which in general take into account the so-called (n-1) criterion. The application of the (n-1) criterion is a general transmission management practice. It consists in verifying that, in presence of a single contingency (that is, outage of a single network component like line, cable, transformer, generator, controlling device, etc.), parameters like power flows, voltage and current amplitudes regarding the different network elements are all within the respective operational security limits. The contingency analysis includes transient, dynamic and steady-state stability check for both frequency and voltage conditions. In some specific cases, more severe contingencies than those ones applied by the (n-1) criterion can be taken into account by transmission planners, like for example situations of double contingency (when applying (n-2) security criterion), multiple contingencies, loss of busbar(s) [7][10]. Whereas these planning criteria are met, then the network can be considered secure and does not generally need an expansion to accommodate the evolution scenarios. On the other side, whereas the security analysis regarding the unchanged network within the developed scenarios is not satisfied, a transmission reinforcement action must be taken into account by the planners. To address a specific problem in the system, different system expansion solutions may be available, ranging from upgrading/uprating the existing assets to building new ones. The available options span from using conventional technologies such as HVAC overhead lines, transformers, cables to implementing more innovative devices [10][11].

After identifying a first, broad group of possible reinforcement solutions which address a specific issue in the system, transmission planners need to carry out a cost-benefit analysis of the different options: the aim is in fact to compare and rank them to select the most feasible one(s). The cost-benefit analysis of the expansion alternatives consists in a techno-economic assessment of each of them: the benefits provided by every option need to be carefully and quantitatively evaluated against their respective investment and operating costs. This analysis nowadays needs to take account of environmental and social issues as well, considering the crucial role that such aspects play towards the expansion of a transmission system. Until a recent past, a socio-environmental assessment was a further (even optional) stage in the transmission planning process. Nowadays, it is of paramount importance to consider socio-environmental aspects for a more complete and systematic cost-benefit analysis. In some cases, environmental constraints and social opposition have obliged the transmission planners to reshape the rank of the investigated alternatives. Subsequent step of the process is the submission of the selected transmission expansion plan(s) related to top-ranked option(s) to the respective decision-makers (such as the competent ministries and/or regulatory authorities) for their approval. This stage is then deepened by the application of the authorization procedures at all levels (national, regional, local) as required by the respective law. In Fig. 2 the approach to cost-benefit analysis proposed by REALISEGRID is included [10]. It has to be remarked that all transmission planning stages, including scenarios development and innovative technologies analysis, have been investigated within REALISEGRID (see [8]-[22]).

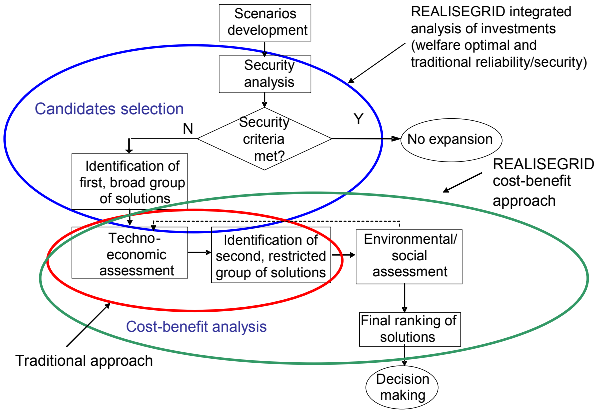


Fig. 2. Basic scheme of the transmission planning process [10].

B. *Review of transmission planning practices in Europe*

By reviewing the transmission planning practices in Europe [8], it can be highlighted that the European TSOs aim at two main objectives when planning the development of their grid: maximising system reliability and security of supply and fostering market, to allow an efficient use of generation, thereby minimising the total costs. This is mostly done by: connecting new (conventional and renewable) generating units to the networks; increasing transmission capacity to allow the most efficient use of generation based on national and European energy and economic objectives.

For a selected number of European countries the objectives of transmission planning and development are [8]:

Scandinavian countries. All parts of the power system shall be designed so that the electric power consumption will be met at the lowest cost. This means that the power system shall be planned, built and operated so that sufficient transmission capacity will be available for utilising the generation capacity and meeting the needs of the consumers in the most economical way. The long-term economic design of the grid aims to balance between costs of investments and costs of maintenance, operation and supply interruptions, given the environmental demands and other limitations.

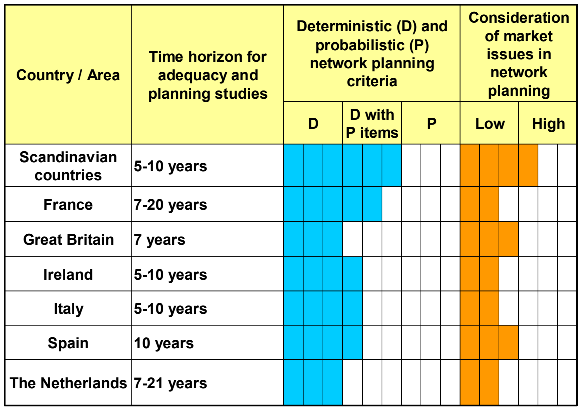
France. The mission of the transmission network development is to guarantee: a grid covering the national territory in a rational fashion and respecting the environment, while interconnected to the networks of the bordering countries; a non-discriminatory connection and access of the users to the network. The TSO ensures the balance of power flows on the network, as well as the system security, safety and efficiency, by taking into account the technical constraints.

Ireland. The primary aim of transmission planning is the maintenance of the integrity of the bulk transmission system for any eventuality. The adequacy and security of supply to any particular load or area is secondary to this primary aim. The technical considerations are continually mitigated by economic issues and all other significant factors brought up by the various stakeholders.

Italy. By developing the transmission grid, the TSO aims at the security, reliability, efficiency, continuity of supply of the electrical energy system as well as at the cost reduction of transmission and supplies. This objective is pursued through suitable planning of the network development, aimed at reaching an appropriate level of quality of the transmission service and reduction of possible grid congestion, while complying with environmental and landscape law restrictions.

As seen in Section IV.A, for their tasks the TSOs rely on scenarios of forecasted consumption, generation development, and power exchanges evolution. For each scenario, they have to take into account the stochastic aspects of the phenomena: load varies on the basis of human activity and weather conditions; generating units may produce or not, depending also upon external factors such as wind or hydro conditions and forced outages; the behaviour and bidding strategies of the different market players may directly impact on scenarios.

Fig. 3 provides a first comparison of key planning practice elements in some European countries. Features like the network planning timeframe, the utilisation of deterministic and probabilistic criteria, also with consideration of market issues, are quantitatively and qualitatively compared [8].
It is evident that the ten-year horizon is the most adopted by European TSOs. This is also the case for Germany, where the four TSOs are firstly preparing a joint network development plan mainly based on a ten-year time horizon (from 2012), while also looking at a twenty-year scenario in the long-term [23]. The ten-year timeline applies now also at pan-European level, as seen for the quoted ENTSO-E's TYNDP [7].



Country / Area	Time horizon for adequacy and planning studies	Deterministic (D) and probabilistic (P) network planning criteria			Consideration of market issues in network planning	
		D	D with P items	P	Low	High
Scandinavian countries	5-10 years	🟦🟦🟦	🟦🟦🟦	⬜⬜⬜	🟧🟧🟧	🟧⬜⬜
France	7-20 years	🟦🟦🟦	🟦🟦⬜	⬜⬜⬜	🟧🟧⬜	⬜⬜⬜
Great Britain	7 years	🟦🟦🟦	⬜⬜⬜	⬜⬜⬜	🟧🟧🟧	⬜⬜⬜
Ireland	5-10 years	🟦🟦🟦	🟦⬜⬜	⬜⬜⬜	🟧🟧⬜	⬜⬜⬜
Italy	5-10 years	🟦🟦🟦	🟦⬜⬜	⬜⬜⬜	🟧🟧⬜	⬜⬜⬜
Spain	10 years	🟦🟦🟦	🟦⬜⬜	⬜⬜⬜	🟧🟧🟧	⬜⬜⬜
The Netherlands	7-21 years	🟦🟦🟦	⬜⬜⬜	⬜⬜⬜	🟧🟧⬜	⬜⬜⬜

Fig. 3[1]. Key features of planning practices in some European countries [8].

From the comparison in Fig. 3, it also emerges that existing transmission planning methods commonly make use of a worst-case scenario approach in which the two main drivers to dimension the system are load and generation. With the increased uncertainty and the many assumptions necessary for

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[1] In the Netherlands the planning horizon of 21 years was used for the strategic Vision2030 document (it is usually 7 years). In Ireland a 15-20 year timeframe is set for a limited set of studies (like GRID25) [8].

the analysis, the need to capture more combinations of load, (renewable) generation and international exchange is becoming essential for gaining a robust planning under a variety of possible scenarios. In this sense, probabilistic planning approaches, which could be of help to get a more complete picture of the evolution of the system, are not yet fully exploited or need further improvements. In some cases, they mainly aim to complement deterministic analyses, upon which the planning decisions are primarily based [8].

For what concerns cost-benefit analyses and market value in the European planning practice, most TSOs, taking also into account the aspects of environmental safeguard, evaluate and rank from the techno-economic point of view the several possible alternatives stemming from the planning analyses and which - as a necessary pre-condition - fulfil the priority target of realising a secure transmission grid. In Italy, for example, the various alternatives are evaluated by comparing the estimated investment costs of each option with the related benefits in terms of reduction of overall system costs (including production, transmission and distribution costs that are passed on to the users of the national electricity system). These cost-benefit evaluations take into account, where possible, costs of grid congestion, foreseeable trends in the electricity market, the possibility of increasing the level of imports/exports with other countries, network losses, and risks of not supplying the users. The benefit attached to the energy unlocked by a new electric link represents one of the most important gains deriving from transmission expansion [24].

In the experience of Scandinavian countries, it is difficult to quantify the costs and benefits in a more well-functioning market. However, it is quite obvious that the energy market will become more robust and efficient when investments are made to remove congestion. Such investments should be based on socio-economic analyses to ensure that the benefits are higher than the costs. After the investments, the prices will be more stable at least in the short-term.

Transmission investments will also help to mitigate the possible exercise of market power, which leads to socio-economic losses. There is a clear link between transmission capacity and the potential exercise of market power. Sufficient transmission capacity contributes to enlarge the market and thereby possibly reduce the risk of abusing market power [8].

V. REALISEGRID METHOD TO TRANSMISSION INVESTMENT COST-BENEFIT ANALYSIS

A. Benefits

Within the cost-benefit analysis, it is crucial to quantitatively assess the possible benefits[2] provided by transmission expansion: this task, especially in a liberalized power system, generally represents a rather complex stage as the evaluation strongly depends on the viewpoint taken for each considered benefit. Manifold aspects in which a new infrastructure can affect the system have to be considered. These benefits can be grouped into several categories: system reliability improvement, quality and security increase, system losses reduction, market benefits, avoidance/postponement of investments, more efficient reserve management and frequency regulation, environmental sustainability benefits, improved coordination of transmission and distribution grids. However, only some of these items are quantitatively significant and can be measured by means of single indicators.

An evaluation of the economic impact of reliability increase can be carried out by multiplying the EENS value (Expected Energy Not Supplied), by an estimation of the VOLL (Value Of Lost Load).

The market benefits provided by transmission expansion can be summarized by two concomitant effects: the decrease of potential for exercising market power by dominant players (strategic effect) and the replacement of local inefficient generation by cheaper imported power due to the removal of existing transmission bottlenecks (substitution effect). Both effects can be measured by the Social Welfare (SW), defined as the sum of generators and consumers surplus [10]. When planning the utilisation of fast power flow controllers such as FACTS (Flexible Alternating Current Transmission System) and HVDC (High Voltage Direct Current), an additional benefit could arise from the system controllability increase enabled by these technologies. This effect translates into an increased substitution effect and is measured then by the SW.

The environmental sustainability benefits by transmission expansion include: a better exploitation of a diversified generation mix (including RES generation), CO_2, NO_x, SO_2 emissions savings and reduction of conventional generation external costs (externalities), reduction of fossil fuel consumption and costs. Transmission upgrades may bring some additional environmental benefits in terms of land use reduction, visual impact abatement and decrease of the electromagnetic field with respect to an existing situation.

Other benefits, which in the future may gain higher consideration, relate to the improved interaction of transmission and distribution grids within systems experiencing high shares of distributed generation and/or even evolving towards smart grid schemes. A transmission reinforcement plan may prevent more complex reinforcements of the distribution networks. However, the evaluation of this benefit implies a manifold process [9][10][13].

In general, the quantification of the different benefits, each one measured by the corresponding key indicator, requires an appropriate power system and market simulation tool. REMARK, the tool developed within REALISEGRID [12], considers the real network situation in which the variability of RES generation as well as the reliability of each element in the grid are both accounted for towards SW maximisation [17].

B. Costs

Capital expenditures for transmission system assets are highly dependent on different parameters, such as equipment type, rating and operating voltage, technology maturity, local environmental constraints, population density and geographical characteristics of the installation area as well as

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[2] It is crucial that the different benefits are not overlapping so as to avoid double-counting when they are summed up.

costs of material, manpower and right-of-way. In general, environmental constraints increase costs and implementation time - e.g. for overhead lines (OHL) - while technological advances in manufacturing usually reduce costs: this is the case for power electronics components, for example. Another aspect that plays a role in the determination of transmission assets costs (especially for innovative technologies) is that equipment prices continuously change due to a dynamic world market: costs of European transmission assets are then influenced and driven by external factors. In order to take into account all these factors, Table I reports up-to-date (average) ranges for the costs of different 400 kV transmission components in continental Europe [11][21].

TABLE I
AVERAGE CAPITAL COSTS (RANGE) OF TRANSMISSION ASSETS.

Cost of components	Rating	Min	Max	Unit
HVAC OHL (single circuit)	1500 MVA	400	700	kEUR/km
HVAC OHL (double circuit)	3000 MVA	500	1000	kEUR/km
HVAC underground XLPE cable (single circuit)	1000 MVA	1000	3000	kEUR/km
HVAC underground XLPE cable (double circuit)	2000 MVA	2000	5000	kEUR/km
HVAC GIL (double circuit)	2000 MVA	4000	7000	kEUR/km
HVDC OHL bipolar	1000 MW	300	700	kEUR/km
HVDC underground XLPE cable (pair)	1000 MW	700	2000	kEUR/km
VSC converter terminal (bipolar)	1000 MW	75000	125000	kEUR
CSC converter terminal (bipolar)	1000 MW	70000	110000	kEUR

In Table I the lower limit (Min) refers to installation costs in continental European countries with low labour costs, while the upper limit (Max) refers to installation costs in European countries with high labour costs. Costs for OHLs refer to the base case, wherein the installation of OHLs over flat landscape and in sparsely populated areas is considered. Costs for installations over hilly and averagely populated land as well as over mountains or densely populated areas are to be taken into account by a surcharge of +20% and +50%, respectively. In the case of underground XLPE (Cross-Linked Polyethylene Extruded) cables and GILs (Gas Insulated Lines), the cost component related to the installation expenses can very much influence the final investment cost, depending on installation location, type of terrain and other local conditions [11][21].

C. Ranking approach

Aim of a full-fledged cost-benefit analysis is to provide a criterion to co-evaluate the effects of each benefit weighing them together to provide one single ranking value. This value represents the degree of optimality of a single expansion project. In this way, different alternatives can be compared and the highest ranked is the most suitable to be financed and realized. In fact, creating a merit order (ranking) between alternative reinforcements means mapping the different evaluations of the benefits of each single infrastructure into one mono-dimensional space. According to the theory of multi-criteria analysis [10], a weighed sum is performed by adding up the value of each benefit and subtracting investment costs to this amount. In order to take into account the long lifetime horizon of the entire investment cycle (authorization time, building time, amortization time following the operation start of the new infrastructure), the Net Present Value (NPV) approach has to be applied. The weights associated to each single benefit mimic the importance associated to it by network planners [9][10][13].

VI. TEST RESULTS: EUROPEAN-SCALE CASES

A real-size test case has been set up and run in order to validate the cost-benefit methodology on a multi-national level. The considered list of expansion candidates is the one included in the TEN-E priority axis "EL2 - Borders of Italy with France, Austria, Slovenia and Switzerland" [3]. The EL2 priority projects of European interest have been aggregated according to three main corridors (see Fig. 4): Corridor A (Germany-Austria-Italy through Veneto region); Corridor B (Slovenia-Italy); Corridor C (Germany-Austria-Italy through Brennertunnel). The impact of the EL2 projects has been investigated in the "tab" years 2015, 2020 and 2030. For each of these reference years, different system models that describe the evolution scenarios of generation, loads and transmission grid have been prepared. The dimension of the test-bed is very wide, covering a large part of the continental European system of ENTSO-E. In fact, it includes the bulk power system of France, Germany, Switzerland, Austria, Italy, Slovenia, Croatia, Bosnia-Herzegovina, Serbia, Montenegro [17].

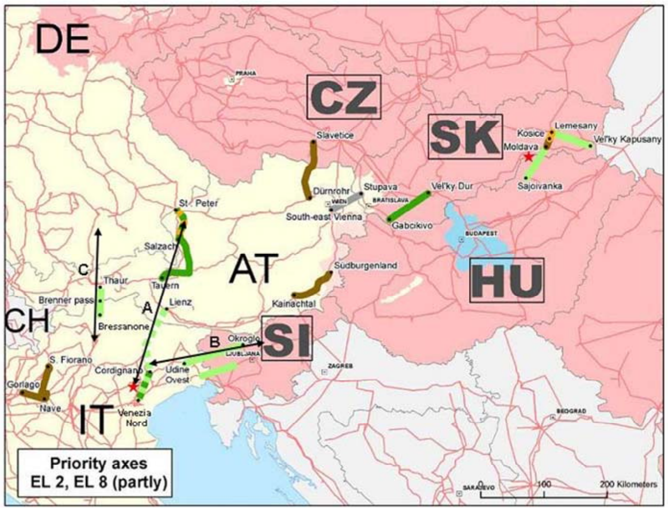

Fig. 4. The investigated TEN-E EL2 projects (2010) (adapted from [4]).

The network model used as a reference for the simulation is based on the continental Europe STUM (Study Model) provided by the ENTSO-E (2008 winter peak). The necessary grid information and data required to update the 2008 model to the reference years (2015, 2020, 2030) have been taken from the ENTSO-E's TYNDP [7] and from public sources (also to include merchant projects). Further data have been provided by the REALISEGRID TSOs and partners as well. The generation park and demand data [17] have been set up according to two scenarios (optimistic and pessimistic), whose trends have been based on the ENTSO-E's System Adequacy Forecast [25] and the long-term scenarios developed within REALISEGRID [22] (see [17] for all details and assumptions made). Based on the relevant situations considered and on the simulation runs of REMARK tool [10][12], the cost-benefit analysis applications have been performed in the cases “with” and “without” the new investigated infrastructure. The benefits considered here are: increase of social welfare; reduction of CO_2 emissions; reduction of losses; reduction of wind curtailment; reliability increase [10][17]. The assets costs are evaluated by the average values presented in Section V.B.

The analysis of the results [17] provides that the benefits, all weighted in an equal (unitary) way, are generally able to recover the costs after few years of operation. Also, from the results it emerges that the SW benefit is the prevailing one.

In general, as expected, the expansion of the interconnections on the corridor Germany-Austria-Italy produces a decrease of the total dispatching costs as well as the reduction of the price differential between the related markets. The results concerning the effect of emissions indicate that, unless specific regulatory provisions are taken, the CO_2 emissions can grow. In fact, the Italian gas generation is in general mostly replaced by less expensive German coal generation whereas the North Sea RES production, due to internal bottlenecks in Germany but also to the relative inadequacy and lower capacity factor of wind power, is mostly limited to German consumption. This is particularly evident in short- and medium-term horizons (up to 2020) and for the pessimistic case also in the long-term (2030), when nuclear power capacity, according to the simulation scenarios, is supposed to be completely phased-out in Germany [17].

In many cases, the results show that grid losses are generally increased by inserting new corridors. This effect could be explained by considering that the new links let the global power exchanges in the network increase and, therefore, the losses (that depend on the power flows) can also rise.

The effects of some other benefits, like the increase of system reliability and the reduction of wind curtailment, play in all cases a very limited role. In fact, the investigated portion of the European transmission network has proven to be sufficiently reliable over the observed timeframe. In addition, the grid expansion over the years, as planned within the timeline and geographic coverage of the study, has resulted to be able to efficiently integrate the expected growth of wind power capacity [17].

From the analysis of the results summarized in Table II, by comparing the three alternative corridors, it can be noted that:

- In the optimistic scenario, Corridor C results to be the most profitable solution, preceding in the rank Corridor A and Corridor B, when taking the NPV as the evaluation indicator for the decision-making. On the other hand, by selecting the investment based on a relative indicator like the PI (Profitability Index), the rank order changes, seeing Corridor A as the most convenient option followed by Corridor B and Corridor C. This rank change can be explained by the high amount of investment needed for building Corridor C.
- In the pessimistic scenario, Corridor A results the most convenient by using both indicators NPV and PI to base the decision, followed by Corridor C and Corridor B or reversely, depending on the indicator adopted (NPV or PI, respectively).

TABLE II
TEST RESULTS OF COST-BENEFIT ANALYSIS APPLICATION.

Scenario	Indicator	Corridor A	Corridor B	Corridor C
Optimistic	NPV [M€]	1728	1342	2208
	PI	8	6	3
Pessimistic	NPV [M€]	2105	1470	2059
	PI	10	7	2

It has to be added that, in both scenarios, the Corridor B option is ranked lower due to internal congestions not solved within the Balkan area region (even in presence of new interconnectors).

In general, the real advance brought by the test case is to show the applicability of the theoretical framework of the cost-benefit analysis elaborated by REALISEGRID to a realistic European scale case [17].

VII. CONCLUSIONS

Due to its neutral and general theoretical features, the proposed REALISEGRID framework, upon further extension, might be appropriate as methodological approach towards the optimal development of the future pan-European transmission system. The need for a harmonised system-wide cost-benefit analysis methodology for evaluating European infrastructure projects of common interest has been recently specifically highlighted by [5]. This represents in fact a key issue that will have to be handled by 2013 firstly by the European Commission, the recently established ACER (Agency for the Cooperation of Energy Regulators) and the ENTSO-E.

The REALISEGRID cost-benefit analysis methodology might be also further useful from the regulatory viewpoint for setting up more comprehensive transmission investment remuneration and incentive schemes. This could help to foster transmission expansion. Moreover, the proposed approach might represent a useful instrument to provide the public with fair information about transmission investments benefits and costs from the system (i.e. society) point of view. This may especially help to communicate the so-called inaction cost in the cases of projects hindered by public opposition [17]-[19].

VIII. REFERENCES

[1] European Commission, “Energy infrastructure priorities for 2020 and beyond - A Blueprint for an integrated European energy network”, COM(2010) 677 final, Nov. 2010.

[2] European FP7 REALISEGRID project http://realisegrid.rse-web.it

[3] European Parliament and Council, “Decision No. 1364/2006/EC of 6 September 2006 laying down guidelines for trans-European energy networks and repealing Decision No. 96/391/EC and Decision No. 1229/2003/EC”, Official Journal of the European Communities No. L 262, 22.09.2006 P. 0001-0023.

[4] European Commission, “Report on the implementation of the Trans-European Energy Networks in the period 2007-2009”, COM(2010) 203 final, May 2010.

[5] European Commission, “Proposal for a Regulation of the European Parliament and of the Council on guidelines for trans-European energy infrastructure and repealing Decision No. 1364/2006/EC”, COM(2011) 658 final, Oct. 2011.

[6] G. Fulli, A. Purvins, S. Rüberg, A. L’Abbate, G. Migliavacca, “Evolutions and challenges towards a potential Pan-European

HVAC/HVDC SuperGrid", Proc. of CIGRE International Symposium, Bologna, Italy, Sep. 13-15, 2011.

[7] ENTSO-E, "Ten-Year Network Development Plan (TYNDP) 2010-2020", Jun. 2010, https://www.entsoe.eu/index.php?id=232

[8] G. Fulli, A.R. Ciupuliga, A. L'Abbate, M. Gibescu, "Review of existing methods for transmission planning and for grid connection of wind power plants", REALISEGRID Report D3.1.1, Jun. 2009.

[9] G. Migliavacca, A. L'Abbate, I. Losa, S. Galant, A. Vaféas, T. Pagano, G. Fulli, H. Auer, M. Gibescu, A. Ciupuliga, K. Jansen, K. Reich, O. Wadosch, E.M. Carlini, P. Antonelli, C. Vergine, P. Adam, X. Gallet, "Prospects for the transmission planning in Europe towards a sustainable energy future: the REALISEGRID project", Proc. of CIGRE 2010 Session, Paris, France, Aug. 22-27, 2010.

[10] A. L'Abbate, I. Losa, G. Migliavacca, A.R. Ciupuliga, M. Gibescu, H. Auer, K. Zach, "Possible criteria to assess technical-economic and strategic benefits of specific transmission projects", REALISEGRID Report D3.3.1, Apr. 2010.

[11] S. Rüberg, H. Ferreira, A. L'Abbate, U. Häger, G. Fulli, Y. Li, J. Schwippe, "Improving network controllability by Flexible Alternating Current Transmission Systems (FACTS) and by High Voltage Direct Current (HVDC) transmission systems", REALISEGRID Report D1.2.1, Mar. 2010.

[12] R. Calisti, M.V. Cazzol, "Tool for the assessment of benefits given by the expansion of transmission infrastructures", REALISEGRID Report D3.3.3, Jun. 2011.

[13] G. Migliavacca, A. L'Abbate, I. Losa, E.M. Carlini, A. Sallati, C. Vergine, "The REALISEGRID cost-benefit methodology to rank pan-European infrastructure investments", Proc. of IEEE PowerTech 2011 Conference, Trondheim, Norway, Jun. 19-23, 2011.

[14] A. L'Abbate, G. Migliavacca, T. Pagano, A. Vaféas, "Advanced transmission technologies in Europe: a roadmap towards the Smart Grid evolution", Proc. of IEEE PowerTech 2011 Conference, Trondheim, Norway, Jun. 19-23, 2011.

[15] A.R. Ciupuliga, M. Gibescu, "Report on extension and harmonisation of transmission planning criteria", REALISEGRID Report D3.1.2, Nov. 2010.

[16] O. Azadegan, R. Hager, F. Leuthold, K. Reich, H. Hatz, G. Layr, C. Todem, C. von Hirschhausen, H. Weigt, O. Wadosch, "Case study: Model-Based Transmission Investment Signals in Central Western and Central Eastern Europe", REALISEGRID Report D3.2.3, Jun. 2011.

[17] I. Losa, R. Calisti, A. L'Abbate, G. Migliavacca, C. Vergine, A. Sallati, "Application of the REALISEGRID framework to assess technical-economic and strategic benefits of specific transmission projects", REALISEGRID Report D3.5.1, Jul. 2011.

[18] A. L'Abbate, G. Migliavacca, A.R. Ciupuliga, M. Gibescu, "Preliminary results on streamlining planning and approval procedures of electricity transmission infrastructures", REALISEGRID Interim Report, Jul. 2010.

[19] A.R. Ciupuliga, M. Gibescu, A. L'Abbate, G. Migliavacca, "Improving consensus on new transmission infrastructures by a thorough presentation of the benefits given by priority projects", REALISEGRID Report D3.7.2, Mar. 2011.

[20] A. Vaféas, S. Galant, T. Pagano, "Final WP1 report on cost/benefit analysis of innovative technologies and grid technologies roadmap report validated by the external partners", REALISEGRID Report D1.4.2, May 2011.

[21] A. L'Abbate, G. Migliavacca, "Review of costs of transmission infrastructures, including cross border connections", REALISEGRID Report D3.3.2, Jun. 2011.

[22] R. Loulou, A. Kanudia, M. Gargiulo, G. Tosato, "Final report of WP2 on results of long term scenario analysis for European power systems", REALISEGRID Report D2.3.2, Jun. 2010.

[23] 50Hertz Transmission GmbH, Amprion GmbH, EnBW Transportnetze AG, TenneT TSO GmbH, "Network Development Plan", 2012, http://www.netzentwicklungsplan.de (in German).

[24] E.M. Carlini, P.P. Pericolo, P. Di Cicco, "Valutazioni tecniche ed economiche delle infrastrutture della RTN", L'Energia Elettrica, Nov.-Dec. 2008, pp. 1-6 (in Italian).

[25] ENTSO-E, "System Adequacy Forecast 2010-2025", Jan. 2010, https://www.entsoe.eu/resources/publications/system-development/adequacy-forecasts/

IX. BIOGRAPHIES

Angelo L'Abbate graduated in Electrical Engineering at the Politecnico di Bari, Italy, in 1999. In 2003-2004 he received his Ph.D. in Electrical Energy Systems at the Politecnico di Bari, Italy, in partnership with the University of Dortmund, Germany. In 2004-2005 he was active researcher at the Mediterranean Agency for Remote Sensing (MARS), Benevento, Italy, and at the University of Ljubljana, Slovenia, as a CNR-NATO Fellow. In 2005-2008 he was contractual scientific agent (post-doc) at the European Commission - Joint Research Centre - Institute for Energy, Petten, The Netherlands. Since 2009 he has been working with CESI RICERCA (now: RSE), Milan, Italy. His fields of interest include modeling and planning of power T&D systems, RES and distributed generation integration, FACTS, HVDC. He has been deeply involved in the European FP7 REALISEGRID project and actively contributes to several other Italian and European research projects. He is currently involved in different CIGRE WGs. He is an IEEE Member.

Gianluigi Migliavacca graduated in Electronic Engineering at the Politecnico di Milano, Italy, in 1991. In 1994 he joined the Automation Research Center of ENEL, Italy, working on mathematical modeling and dynamic simulation of thermal power plants. In 2000 he joined CESI and then CESI RICERCA (now: RSE), Milan, Italy, where he is currently head of the Transmission Network Planning research group. He carries out research on mathematical modeling and regulatory issues concerning deregulated electricity markets, cross border trade issues and transmission planning. During 2005 he was consultant at the Italian Regulator about the development of a common energy market in South-East Europe and about congestion management in Central-South Europe. He is member of the technical committee TC 6.3. Power Plants and Power Systems of IFAC, member of the Technical Committee of the International conference on the European Electricity Market and participates in CIGRE WGs. He has been the coordinator of the European FP7 REALISEGRID project and is actively involved in several other Italian and European research projects.

Gianluca Fulli graduated in Electrical Engineering at the University La Sapienza, Rome, Italy, in 1998. He currently leads the Smart Electricity Systems group at the European Commission - Joint Research Centre - Institute for Energy and Transport, Petten, The Netherlands, where he conducts research on electricity transmission and distribution systems and provides support to the European Community policies on smart grids. He previously worked with the Italian transmission system operator (GRTN/TERNA), where he was responsible for cross-border interconnectors planning and new generation connection, and with the UK gas & electricity company (NGT). He is involved in several research projects and initiatives on smart/power grids, including those linked with the European Strategic Energy Technology Plan, the Energy Infrastructure Package, the Trans-European Networks for Energy and the US-EU Energy Council. He is an IEEE Member.

Chiara Vergine graduated in Electronic Engineering, University La Sapienza, Rome, Italy, 2001. In 2000-2001, she joined ENEA, the Italian Research Institute for Energy and Environment at Casaccia (Rome, Italy) as technical collaborator for designing and building Parallel Program. In 2003 and 2005 she joined respectively GRTN, the former Italian ISO, and TERNA, the current Italian TSO, as expert for the grid planning activities (load flow calculation, voltage and short circuit current analyses). While being within the Investment and Grid Planning Department of TERNA she has been deeply involved in the yearly preparation of the Development Plan of the national grid. In 2010 she contributed to and participated in the set-up of the first Ten-Year Network Development Plan of ENTSO-E. She is currently the head of Grid Connection Department within TERNA.

Alessio Sallati graduated in Electrical Engineering at the University La Sapienza, Rome, Italy, in 2008 and joined the Investment and Grid Planning Department of TERNA (Italian TSO). He works on network analysis of the Italian transmission system. He collaborates on cost-benefit analysis of development projects on the transmission grid, energy market analysis, activities with local network distributors and the preparation of the Development Plan of the national grid. During 2009 he participated in the training on the job of the Albanian TSO. In 2010 he was involved at ENTSO-E in the release of the first Ten-Year Network Development Plan.