Transmission Planning for Wind Energy: Status and Prospects

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Abstract-- **This paper provides an overview of major transmission planning activities related to wind integration studies in the US and Europe. Transmission planning for energy resources is different from planning for capacity resources. Those differences are explained, and illustrated with examples from several regions of the US and Europe. Transmission planning for wind is becoming an iterative process consisting of generation expansion planning, economic-based transmission planning, system reliability analysis, and wind integration studies. A brief look at the policy environment in which this activity is taking place is provided.**

***Index Terms*-- Transmission planning, transmission policy, wind integration.**

I. INTRODUCTION

At the beginning of 2010, nameplate wind capacity in the US had exceeded 35 GW, while that in Europe had risen to 75 GW. More than 37 GW of wind capacity were added globally in 2009, and in spite of the continuing global economic slowdown, the prospects for continued development remain bright. However, one cloud on the horizon is the lack of sufficient transmission capacity to move the wind energy from the best wind resource areas, most of which are remote, to the distant load centers. A critical conundrum has been recognized in the transmission planning area, and is being dealt with the regional, national, and international level. This is the situation where it may take 5-10 years to plan, permit, and construct a transmission line, while a wind project can be planned, permitted and constructed in 2-3 years. A remote wind project cannot be financed until the transmission access is provided, and the transmission line cannot be built with cost recovery certainty until the need for service from the wind plant is shown, thus setting up a scheduling conflict which cannot be resolved. At the regional level in the US, Texas has broken the logjam with the establishment of a Competitive Renewable Energy Zone (CREZ) process, which allows transmission to be built and paid for in advance of the construction of the wind plants. This model is being applied to other parts of the US and is beginning to be explored in Europe, for example for accessing the offshore wind power resources with the planned HVDC VSC offshore "sockets" that the German TSO's have been legally required to install for offshore wind power development zones in Germany. Breaking the transmission planning logjam is critical to achieving a high penetration of renewable energy in the electric system.

II. TRANSMISSION PLANNING FOR ENERGY RESOURCES

A. Traditional Transmission Planning

Before deregulated markets and wind energy resources were available, generation was selected economically from a set of candidate generation types. The amount of generation of each type was chosen to produce the most economical mix of generation from the types available. A trade-off between the capital cost of a generator and the cost to produce energy determined the amount of any one type of generation. The magnitude of the total generation mix was chosen to meet the load plus some reserve margin economically. Transmission was planned based on meeting the peak load hour of the year, and was referred to as reliability-based transmission planning. This method solves problems associated with specific short-term needs, but does not address the issues associated with moving large blocks of renewable energy from remote locations to load centers.

Much of the US wind generation was installed in response to legislative requirements established through a state Renewable Portfolio Standard (RPS), while much of the continued growth of wind power in Europe has been driven by the success of various types of support schemes in different countries (notably the successful feed-in tariff system) linked to achieving mandatory renewables targets set by European legislation. Wind is a non-dispatchable energy resource, as opposed to the more traditional dispatchable capacity resource. As a renewable energy resource, its value is in displacing higher priced fossil fuels and reducing carbon emissions, as opposed to providing for system reliability requirements. As such, traditional capacity-based transmission planning methods need to be modified in recognition of the different attributes of this

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energy source. Remote wind locations may require substantial transmission with significant associated costs. In the capacity planning world, transmission does not have to be able to pay for itself for capacity delivery requirements. In the energy planning world, the RPS or other policy directives require that a certain amount of wind energy be delivered. The wind energy also creates a large pool of low cost energy that may require transmission that must be able to pay for itself to be able to deliver the wind energy.

Once generation is built or contracted, only the cost of producing energy is considered for operation of the generation. Generation is dispatched from the lowest cost energy producing generators first, then the next and so on in a merit order of cost of production, with wind energy having an assumed production cost of zero.

Figure 1 shows a simplified diagram of a mix of generation stacked in the order of the production cost of energy. The most economical generators are at the bottom of the stack and run the most. The load is represented by a load duration curve (yellow line) which is produced by sorting the hourly load for a year in descending order. Generation must supply energy in an area to the left and below the load duration curve.

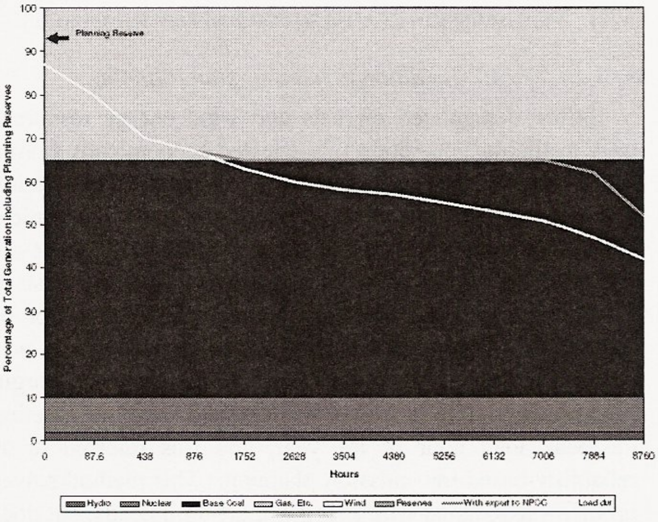

Fig. 1. Exporting system, no wind

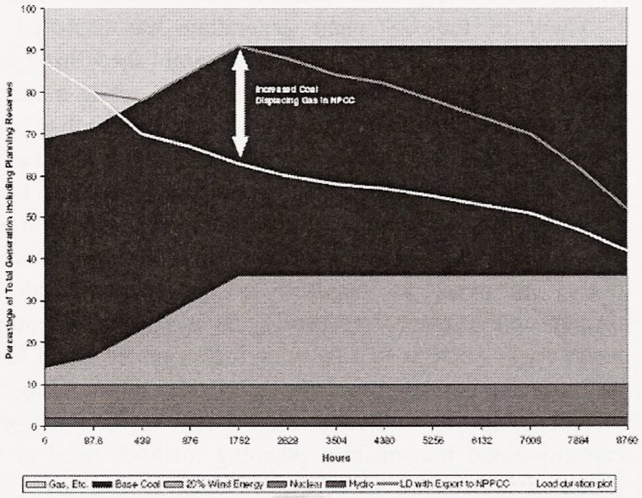

Fig. 2. Exporting system, with wind

Energy available to the right of the load duration curve is available for sale to others. If there is no market for the energy, it will not be produced. The pink line shows a sale to others. The energy sold will displace generation in another market. Figure 2 shows wind wedged into the merit order stack of Figure 1. In this case, generation operation restrictions position wind above nuclear out of merit order. Hydro is economically equivalent to wind in the merit order, but operational constraints may require hydro be taken first. Wind energy displaces higher cost energy resources upward. The net result is that the lower cost energy is exported as shown by the pink line. The amount of energy available to the energy market is much larger in Figure 2 than Figure 1. The transmission capacity needed for export is represented by the vertical distance between the load duration curve and the export curve.

In the US, gas fired generation has almost the same price across the Eastern Interconnection and few energy transactions occur when gas is on the margin for all systems. Coal prices vary from a low in the center of the U.S. to higher prices to the east. Coal energy from the center of the U.S. can displace gas and coal on the east coast.

In addition to building transmission for the generation units and export possibilities, transmission planning considerations can also include relieving existing congestions, arbitrage between markets, and maintaining (or improving) security of supply (transmission adequacy).

B. Transmission Planning for Large Amounts of Energy Resources – Economic Planning

Transmission has an economic value in the Energy Market when low cost energy is delivered to high priced areas. To justify transmission economically, the benefits from the difference in the price of energy between the low cost area and the high priced area has to be greater than the annual capital and operating cost of the transmission overlay. To make this happen, usually a low cost of transmission per unit of energy delivered and a large volume of energy are required to pay for a transmission overlay.

Higher voltage transmission has a lower cost per MW-mile than lower voltage transmission lines. An 800 kV HVDC line's cost to deliver energy is about 20% of a 345 kV line if the 800 kV HVDC line can be loaded sufficiently.

Studies indicate that transmission overlay designs whose benefits are greater than their costs can be developed for the U.S. Eastern Interconnection for wind energy penetration levels from 5%-20%. A core area with 800,000 MW of potential wind energy production occurs in the center of the U.S. with capacity factors estimated to be from 30% to 50%. This is also an area with low fuel cost generation compared to the east coast of the U.S. The upper Great Plains states in the Midwest ISO currently have Renewable Portfolio Standard (RPS) requirements of 22,000 MW of renewable capacity by 2025. The available off peak energy supply and energy price differential between the center of the U.S. and the east coast are sufficient to load three 800 kV HVDC lines economically. The Joint Coordinated System Planning study (www.jcspstudy.org) and the subsequent Eastern Wind Integration Transmission Study (www.NREL/EWITS) are studies which provide examples of high voltage transmission overlays that link multiple markets. The overlays may produce more benefits than their costs by allowing the most efficient use of generation in a large geographical area such as the Eastern Interconnection.

In Europe, cost/benefit considerations of transnational transmission development at European scale are mainly focusing at increasing capacity of existing cross border and national transmission corridors (EWIS [1], ENTSO-E [2], TradeWind [3]), rather than at the addition of EHV overlay transmission backbones. The TradeWind study (initiated by the European Wind Energy Association) highlighted the benefits of enhancing cross-border network capacity in order to better integrate wind generation by exploiting diversity in wind generation output across Europe and sharing backup/reserve facilities. The European Wind Integration Study (EWIS), initiated by a consortium of transmission system operators, examined near term scenarios similar to those derived by TradeWind in order to address the immediate challenges of integrating some 70-120GW of additional wind generation that are expected to double Europe's existing wind generation capacity by 2015. The results from the EWIS study helped populate the initial ENTSO-E Ten Year Network Development Plan.

A special case is the development of a transnational offshore grid in Northern Europe combining the functions of electricity trade and offshore wind power connection, which would involve the construction of new transmission highways for accessing renewable generation. Because of the specific geographic situation where the North Sea and Baltic Sea wind resources are located surrounded by the demand markets UK-IE, Nordic area and Northern Europe, a substantial part of the solution for accessing the offshore wind power would already be provided by better interconnecting the three above mentioned regions [4]. However, in order to deal with the increased transmission needs in the coastal zones as a consequence of the offshore wind generation, an integrated offshore-onshore transmission planning is necessary. Studies and discussions towards a consensus on a common approach and grid architecture are still ongoing [6].

More visionary and long-term approaches for massive long-distance transmission from renewable sources in and outside Europe to load centers within Europe (Desertec [5], Czisch [6], EWEA 2030 Offshore Grid Vision [7]) are being explored, however not yet accompanied by detailed cost/benefit studies.

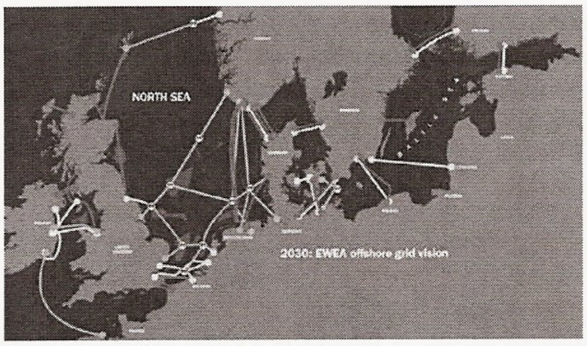

Fig. 3 EWEA 2030 offshore grid vision [7]

III. REGIONAL PLANNING EFFORTS – STATUS AND PROSPECTS

A. Eastern Interconnection Joint Coordinated System Plan (JCSP) [8]

Transmission overlays have to be economical as well as reliable. Three west to east HVDC lines nominally scheduled at 75% of rating, with three terminals per line, cross linked with 765 kV AC for north-south connections, have been shown to form a self contingent design that does not adversely impact the underlying AC system. (See report at www.jcspstudy.org.)

Over 300 constraints on the underlying system are mitigated or removed by the transmission overlay. Designing a system with a few lines is more economical and simpler to implement than upgrading 300 constraints simultaneously. The JCSP provided for an HVDC overlay consisting of seven lines, as shown in Figure 4.

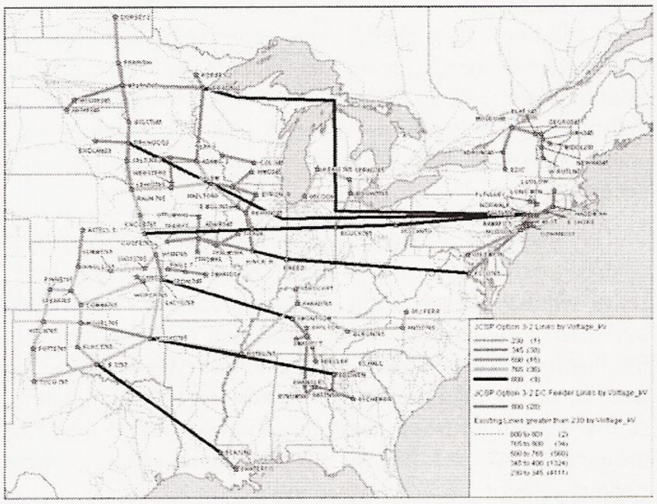

Fig. 4. JCSP HVDC overlay

The estimated cost for the economic transmission in the 5% wind scenario in the JCSP study is \$50B, with a benefit to cost ratio of 1.4 to 1. The annual cost of the economic transmission is 1% of the total cost of energy delivered (annual capital, fuel, O&M and transmission costs). Corresponding numbers for the 20% scenario are \$80B capital cost, with a benefit to cost ratio of 1.7 to 1, and 2% annual cost. The long term (15-20 years) economic top-down process for economic transmission planning, combined with a bottom-up (10 year) process for transmission expansion for capacity and reliability requirements, can produce an economic and reliable transmission system.

B. Eastern Wind Integration and Transmission Study [9]

The wind-rich Great Plains in the United States, extending from Texas to the Canadian border, have seen significant development of bulk-scale wind generation over the past decade. Most of this area, including the northwest portion of Texas, is physically located within the general geographic boundaries of the Eastern Interconnection, a massive synchronous electrical grid that serves approximately two-thirds of the U.S. population, with an installed capacity of nearly 1,000 GW. The US Department of Energy issued a report in the spring of 2008 that sketched the broad outlines of what supplying 20% of the annual electric energy demand from wind generation would look like. The Eastern Wind Integration and Transmission Study (EWITS) was a direct follow-up to that effort, charged with exploring many of the technical details that could not be addressed in detail in the initial summary report.

The study looked at costs and transmission associated with increasing wind capacity to 20% and 30% of retail electric energy sales in 2024 for the study area, which includes MISO, PJM, SPP, NYISO, ISO_NE, and TVA.

The key transmission issues to be addressed by the study are an examination of the benefits from long distance transmission that moves large quantities of remote wind energy to urban markets, while accessing multiple wind resources that are geographically diverse. Tradeoffs between remote and local wind resources will also be made.

In addition, the impact of wind generation variability and uncertainty on system operational impacts and costs will be examined, as well as the role of wind forecasting, and the ability of geographical diversity and balancing area cooperation to help manage system variability and uncertainty.

The analytical methodology for the study is driven by a comprehensive, high quality and resolution data set of time-series wind-speed and wind energy production data created by NREL through meso-scale simulation of the atmosphere for historical years 2004 through 2006. Wind production data for the defined scenarios is combined with load data of similar resolution from the study footprint (scaled to match projected peak and energy for the study year) to drive various parts of the technical analysis.

Four scenarios of wind energy development were created. The first three target 20% of annual energy, and vary the location of the wind resources between the central U.S. and the much more populated East Coast. The 30% annual energy scenario utilizes wind energy from across the model footprint, and includes a significant amount of off-shore wind along the Eastern seaboard. Figure 5 summarizes the installed wind capacity by region and scenario.

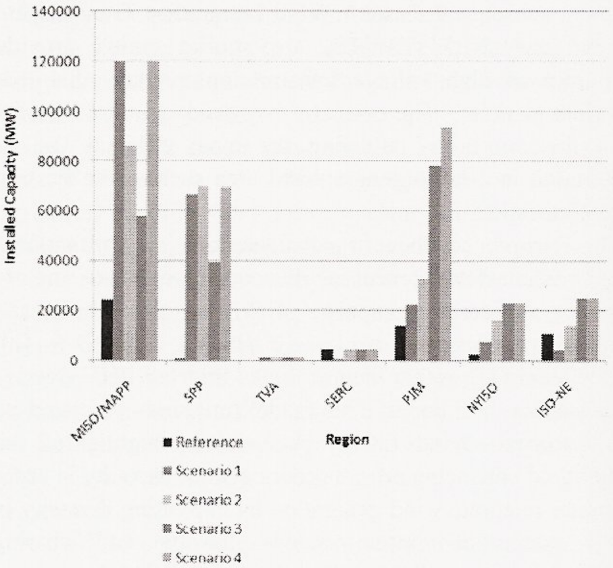

Figure 5 Wind Generation by Region for EWITS Scenarios

Using the production simulation methodology previously described, the operation of the system was simulated over an entire year of hourly data, and then compared with the results from a similar simulation in which constraints on the transmission system were removed. The comparison indicates how regional or interconnection-wide production costs increase because of transmission congestion, or what value could be achieved by eliminating or reducing transmission constraints. Differences between the "constrained" case and the "unconstrained" case yield the following information:

- The areas of economic energy sources and sinks
- The interface flow changes to determine the incremental transfer capacity needs
- The total benefit savings, which in turn provides a rough estimate of a potential budget for building transmission to relieve constraints and reduce congestion costs.

Using these comparative results as a guide, transmission overlays for each scenario were developed. The conceptual transmission overlays, similar to those shown in Figure 4, consist of multiple 800-kilovolt (kV) high-voltage direct current (HVDC) and extra-high voltage (EHV) AC lines with similar levels of new transmission and common elements for all four scenarios. Tapping the most high-quality wind resources found in the Great Plains in all three 20% scenarios, the transmission overlay for Scenario 1 consists of nine 800-kV lines and one 400-kV HVDC line. For Scenario 2, moving some wind generation toward the east resulted in a reduced transmission overlay with seven 800-kV lines and one 400-kV HVDC line. As more wind generation is moved east and more offshore resources are used in Scenario 3, the resulting transmission overlay has the fewest number of HVDC lines, with a total number of five 800-kV lines and one 400-kV HVDC line. To accommodate the aggressive 30% wind target and deliver a significant amount of offshore wind along the East Coast in Scenario 4, the overlay must be expanded to include ten 800-kV lines and one 400-kV HVDC line. The estimates of transmission cost of the four scenarios ranges from $100 to 145 billion in 2024 dollars.

Specific findings and conclusions from development of the transmission overlays for each scenario include the following:

- 800-kV HVDC and EHV AC lines are preferred if not required because of the volumes of energy that must be transported across and around the interconnection, as well as the distances involved.
- Similar levels of new transmission are needed across the four scenarios, and certain major facilities appear in all the scenarios. The study focuses on four possible 2024 "futures"; determining a path for realizing one or more of those futures was outside the study scope. The commonality of transmission elements across the four scenarios does, however, yield important insights into future undertakings.
- The modeling indicates that significant wind generation can be accommodated as long as adequate transmission capacity is available.
- Transmission offers capacity benefits in its own right, and enhances wind generation's contribution to reliability by a measurable and significant amount.

The EHV DC transmission that constitutes a major portion of the overlays designed for the scenarios has benefits beyond those evaluated in the EWITS study. For example, it would be possible to schedule reserves from one area to another, effectively transporting variability resulting from wind and load to areas that may be better equipped to handle it. In addition, the transfer capability of the underlying AC network could be enhanced by using the DC terminals to mitigate limitations caused by transient stability issues.

C. Electric Reliability Council of Texas (ERCOT) [10]

With Senate Bill 20 in 2005, the Texas Legislature enacted a solution to an issue that was undermining wind generation development in Texas: the areas of the State with the best wind resources lacked sufficient transmission to deliver wind generation to far-off load centers. Wind developers who had harnessed the world-class wind resources near the small town of McCamey in far southwestern Texas faced significant wind curtailments, and new transmission improvements were on hold until sufficient additional wind generation was developed to justify the expense to consumers. Given the long-lead times for construction of new high-voltage transmission, wind developers moved to other parts of the state that had good wind resources and some available transmission capacity. Senate Bill 20 was designed to break the impasse between wind generation development and transmission construction, instructing the Public Utility Commission of Texas (PUCT) to designate areas of the state as Competitive Renewable Energy Zones (CREZ) and, prior to construction of wind generation resources, to order specific transmission improvements to connect these areas to major load centers.

Almost three years and a half later, the PUCT designated five CREZ, spanning much of West Texas from Amarillo to McCamey, and ordered $5 billion of transmission improvements to move wind generation from the CREZ to load centers (see Figure 6). Based on planning studies, these transmission improvements are expected to provide adequate capacity for over 18,400 MW of wind generation in West Texas.

The PUCT also designated transmission companies to build these lines and set a deadline for plan completion of December, 2013 – allowing the selected companies less than four years to route, permit, and build over 2,300 circuit miles of new 345-kV transmission.

Implementation has become the focus of current CREZ activities. The selected transmission companies are evaluating potential routes, identifying locations for new substations, and running construction engineering studies. Route applications for the first CREZ lines are being considered by the PUCT under established fast-track scheduling. The last of the CREZ lines will be submitted for approval in August 2010.

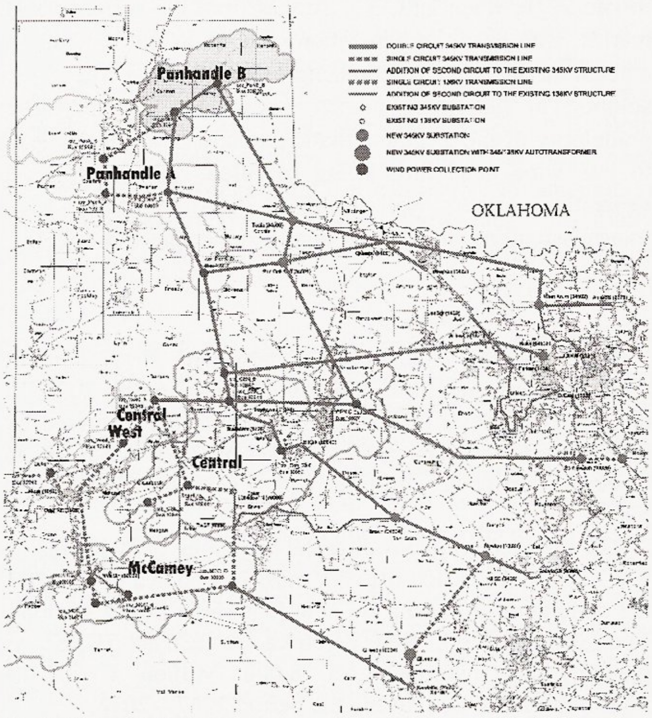

Fig. 6. Texas CREZ locations

ERCOT engineers are evaluating changes to the plan submitted by the transmission companies to reflect routing limitations in order to ensure that these changes do not reduce the overall effectiveness of the CREZ upgrades. ERCOT and the transmission companies are working with a consultant to study the reactive power needs of the new CREZ circuits; the consultant will first optimize the use of series compensation in the plan, and will then recommend specific dynamic and static reactive devices to ensure system reliability. As the wind generation on the new CREZ lines may swing from nearly full output to no output across the span of a day, it is important that the new reactive equipment have sufficient flexibility to meet the system needs across all conditions.

Scheduling line outages for construction will also be an important consideration. Outages of the major existing 345-kV circuits connecting the Abilene and Fort Worth areas will have to be taken during a limited time period to ensure sufficient generation capacity is available to meet loads in West Texas. Other line outages will likely be grouped in the low load periods, generally March, April, October and November. However, these months typically have the highest levels of wind generation, meaning that outages for CREZ construction are likely to have a significant financial impact on existing wind generation facilities. ERCOT does not currently have a methodology to evaluate the economic impact of line outages, but it is likely that the impact of CREZ line construction can be reduced through planning studies.

In the meantime, wind generation facilities in ERCOT are being heavily curtailed, with over 7,500 MW of wind generation in West Texas utilizing transmission capacity sufficient to allow only approximately 4,000 MW of wind generation to serve load. Some congestion relief will come in late 2010, when ERCOT changes from the current zonal market, with portfolio generation scheduling and bidding, to a nodal market. The comprehensive nature of the congestion solution in the nodal market design and the increased granularity of the 5-minute market solutions will likely lead to less wind generation being curtailed. However, wind generation owners will have to wait for the CREZ transmission lines in 2013 for significant congestion relief.

D. Spain [11]

The European Council set a target of 20% share of renewable energies in EU energy consumption by 2020. In terms of electricity in Spain, 40% should be generated by renewable power. The Spanish target by 2020 is 40 GW in onshore wind power, together with 5 GW in offshore wind plants.

The installed wind power at the beginning of 2010 was 19 GW. The transmission network must be updated to integrate the generation produced by new renewable power stations. The Spanish TSO, Red Eléctrica de España (REE), is planning an investment of 8,000 Million € in the transmission network during the period 2007 – 2016.

Table I and Figure 7 show the planned circuits in the Spanish Transmission system at 400 and 200 kV levels. Specific infrastructure planned to integrate renewable power generation totals 4,465 km (35% of planned), 3504 km in 400 kV circuits (48%) and 961 km in 220 kV (9.5%). On the other hand, the refitting of new lines totals 3,850 km of 400 kV circuits and 4,458 km of 220 kV circuits.

TABLE I

PLANNED ELECTRICAL CIRCUITS IN THE SPANISH TRANSMISSION SYSTEM

	Whole planned infrastructure			Specific infrastructure planned to integrate RES		
Lines and cables	Total	400 kV	220 kV	Total	400 kV	220 kV
New circuits (km)	12656	7488	5168	4465	3504	961
Refitting (km)	8308	3850	4458	1730		

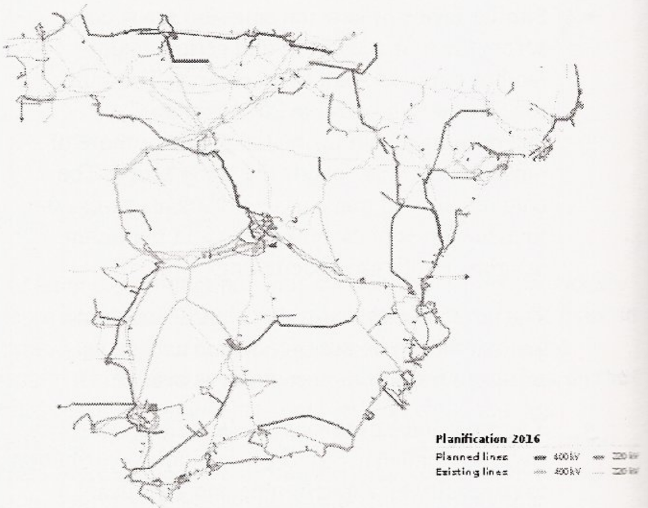

Fig. 7. Planned Spanish transmission system in 2016

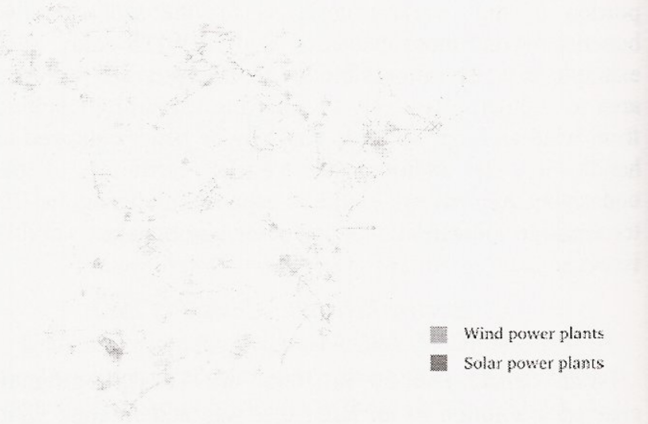

Fig. 8. Wind and solar power generation used for studies in Spanish transmission system in 2016 [11]

Different scenarios have been studied in 2016. The study, [11], was conducted in a summer demand situation with a seasonal non–extreme peak level of 92%. International exchange power was 1,900 MW import from France, 1,000 MW export to Portugal and 600 MW export to Morocco.

Spain is divided in four zones to study the influence of wind power in the transmission system. Wind power generation is set up to 80% of the installed capacity in the studied zone, while the wind power generation in the other three zones is fixed according to studies of statistical production data. Solar generation (thermoelectric and PV) were set to 100%. Figure 8 shows the installed capacity of wind and solar generation considered in this study, taking into account the renewable energy plans of the different

Spanish regions (43.4 GW of wind power capacity and 9.5 GW of solar –thermoelectric and PV– power capacity).

Load flow analysis was conducted to study network contingency situations (N, N-1 and N-2), meeting the criteria of power system operation and safety established by REE. Short circuit scenarios were simulated as well to study the power system recovery after a disturbance, focusing on other topics such as power quality.

Transient stability simulations were solved to validate wind power production scenarios that have been admissible in the previous steady-state studies.

The planned wind and solar power generation must be capable of providing mainly dynamic voltage control, given the massive penetration of these new technologies. These issues were studied in peak demand scenarios.

Other additional services are more appropriate to be analyzed in valley demand situations, such as voltage regulation control and frequency control.

To carry out transient studies, models must adequately represent the behavior of the power system elements during disturbances, [14]. Standard models for all the elements are common, except for wind turbines and wind farms. Given the complexity of manufacturer wind turbine models and confidentiality associated with them, the solution would be to create standard or generic wind turbine models to which all manufacturers could adapt. REE developed a wind farm generic model, [15], capable of reproducing the typical dynamic wind farm technologies by adjusting their parameters, including the new requirements cited in the paragraphs above.

Simulations were carried out during 20 sec from the beginning of the three-phase faults, studying with particular attention the voltage recovery and how wind power penetration affects the power system. Dynamic voltage control implementation is emphasized, since without it, voltage dips will be deeper and more extensive, resulting in an unacceptable situation from the point of view of transient stability. The study conclusions are that the planned 43.4 GW of wind power capacity can be integrated into the Spanish power system, highlighting some requisites:

- Development of all planned transport network in 2016
- Compliance with the actual technical requirements, and the proposed ones in a new grid code draft
- Renewable power stations would be capable of dynamic voltage control
- Significant difficulties in daily operations are highlighted in valley demands and other exceptional situations, due to reserve available in the system

E. Portugal

Recent plans for the transmission network in Portugal have in mind scenarios for the deployment of renewable energy sources in general, and its main driver, wind energy, in particular, according to the European goals for 2020 and the national objective of having 45% of the consumed electricity with renewable origin. The period that witnessed a large development of the Portuguese transmission network extended from 2006 to 2010, where the transmission plans forecasted a growth of wind capacity from 1950 to 4750 MW, most of it in remote mountainous regions of the interior and some to be connected to voltage levels above 150 kV. Unlike as in several other European countries, wind power plants in Portugal have the tendency to be large (in the 50 to 100 MW) with some wind plants above 120 MW. In the period ranging from 2006 to 2010, the investment in transmission lines specifically driven by independent producers (most of it wind power plants) accounted for 16% of the whole network investment.

Fig. 9 represents the transmission lines included in the Portuguese RNT Plan of Investments 2006-2010 [21] depicting the lines driven by wind power plants (or other independent producers) with a share ranging from 100% (red) to 25% (yellow) and passing by a 50% (blue) and 75% (orange) percentage participation.

In the North of the country, the wind projects in the mountains of Montemuro, Alvão, Marão, and Bornes e Nogueira led to the plan of several new substations, the enlargement of existing ones, the installation of phase shift transformers and a new transmission line to connect up to 700 MW of both new wind and hydro power stations.

The centre of the country is one of the windiest, and more than 1500 MW are planned for connection in several substations that need to be constructed of reinforced. In the interior area two of the longest transmission lines with a higher share of wind occupancy were included in the plan: The line between Penela e Espariz (100% wind) and Ferro-Castelo Branco (50% wind, see detail in Fig. 10). Both constitute examples of lines that would never have been constructed in this timeframe if it was not for the integration of wind power production. Some of these lines will initially operate at 220 kV, as their operation is programmed to be upgraded for 400 kV with the increase of wind power plant connections.

In total, just in the 2006-2010 period, almost 300 km of transmission lines, most of them operating at the 220 and 400 kV levels, were included in the transmission network plan, essentially to enable the integration of wind generation. Although the Portuguese RNT has consistently invested in added transmission capacity to integrate the wind production since the beginning of the century (145 M€ in the period 2004-2009), the investment plans for the 2006-2010 period were the ones with a higher wind driven content (16% driven by wind and other smaller independent producers) in the total of 159M€. The following plan for investment [22] for the period 2009 to 2014 (extending to a horizon of 2019) still had 9% (120 M€) of the network investment dedicated to the connection of wind and other (comparatively small) independent producers.

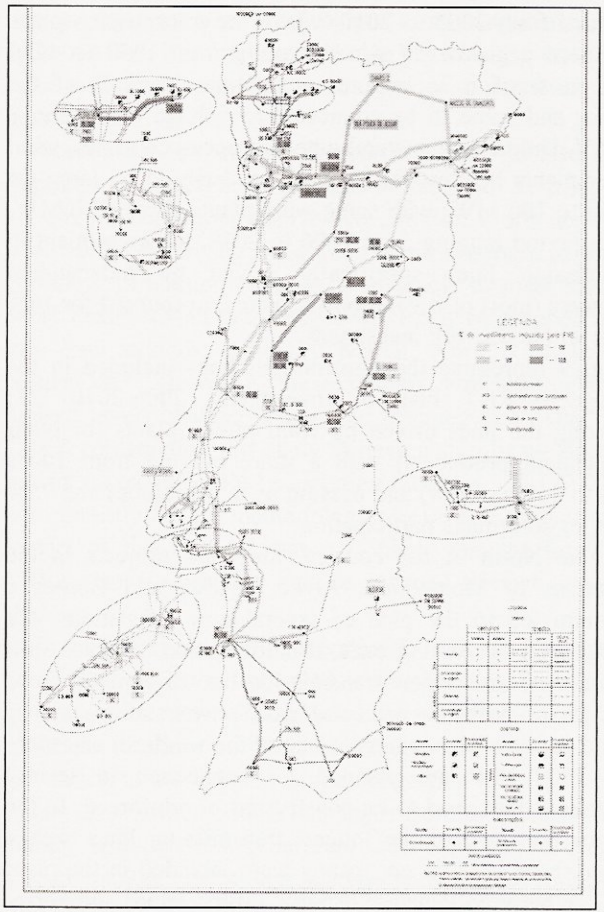

Fig. 9. Representation of the RES driven transmission lines included in the PT RNT Plan of Investments (2006-2010). [21]

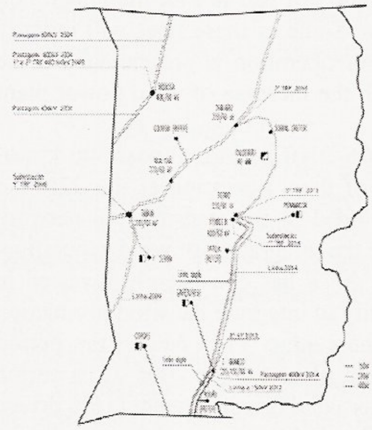

Fig. 10. 220 kV meshed line Ferro-Castelo Branco (50% wind driven), anticipated to integrate the high wind production in the PT region of Pinhal Interior. [21]

In Portugal, the transmission network operation is a Governmental concession to the transmission system operator, REN – Redes Energéticas Portuguesas. Within this concession, the operator must implement the National Energy Policy, namely the Governmental resolutions defining the RES Renewable Energy sources targets to be deployed under the European Directives and the Kyoto Protocol. Two main objectives for wind energy were defined in Portugal: the initial installation of 3750 MW until 2010 under the 2001/77/EC RES target and the later up-rating in 2005 of this national target for 5100 MW, under the national resolution RCM n.o 169/2005. With the governmental targets in mind, the criteria followed by REN was to follow the existing recommend methodologies [23] and to assess the spatial distribution of the wind resource and simulate the injection of wind power in the nearby sub-stations with a common capacity factor of 0.285 as shown in Fig. 11.

To account for internal losses in the wind power plants and spatial correlation effects, a maximum threshold of 80% of the overall maximum capacity of 8050 MW planned for 2019 was introduced.

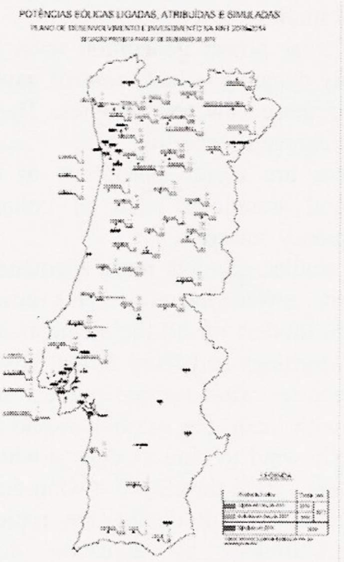

Fig. 11. Spatial distribution of the power injected in the transmission substations for 2010 (total wind capacity of 8050 MW). [22]

With these guiding principles, the planning of new transmission lines and the reinforcement of existing ones was performed by applying the common technical methodology of (n-1) criteria for the whole network below and equal to 220 kV and specific (n-2) criteria only for the 400 kV network and the electrical areas of the larger two Portuguese cities (Lisbon and Oporto). The wind power plants contribution was simulated through power flow models in the range of 0 to 80% of the nominal power and the transient stability of the whole system was assessed by the identification of high probability scenarios [12, 24].

F. Tool for Transmission Planning in the European North Sea [16]

Europe is set to build large amounts of offshore wind power; some of it will be located far from shore with the need for long subsea power cables to the onshore power system. At the same time there is a need to better integrate the power markets in Europe by increasing the transnational power exchange capacity. For a small near shore wind plant, the obvious way to connect it to the power grid onshore is a radial connection with a submarine cable. As offshore wind power plants grow in size and number, and are located farther from the shore, it becomes natural to consider grid connection of wind power in relation to interconnectors between countries and shore power to oil and gas rigs.

Within the Norwegian Research Centre for Offshore Wind Technology (NOWITECH), a new optimization tool for transmission expansion planning has been developed that – in contrast to previous models – can account for the stochastic properties of wind power distributed over large areas. The tool explicitly considers the benefit of transmission capacity between differently priced areas and the value of connecting offshore wind power to the grid versus the investment cost of power cables. The outcome is an optimal grid that answers the question of where to build the new transmission lines/cables and with how much capacity.

This tool has been applied to a case study of the North Sea region where there exists extensive plans for both offshore wind development and new subsea interconnectors between countries. In the study, 33 prospective interconnectors were considered; Figure 12 shows the resulting grid.

From Figure 12 one can see that a meshed structure arises as the optimal one. Such a grid requires that several regulatory issues are solved. Today, the only practice is to build bilateral interconnectors coupled with radial wind plant connections. Simulations with the optimization tool indicate that the socio-economic savings over the lifetime of the grid by allowing a meshed grid structure ranges from 30% to 16% of the investment costs. This is reflected in the higher utilization of the grid infrastructure with a meshed grid.

Locked to radial connections, the wind farm connections will be utilized only as much as the wind farms produce. Typically utilization rises from 45% to 70% by creating a meshed grid.

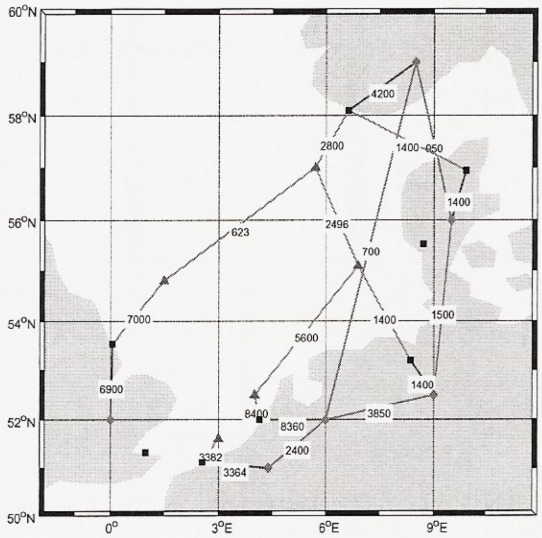

Fig. 12. Optimal grid example for the North Sea region. Green – optimized interconnectors; red – existing interconnectors; blue triangles – major offshore wind farms.

To provide a more detailed analysis, the optimization tool is typically used in an iterative process with a load flow model or a detailed marked model. Such tools can better account for onshore grid bottlenecks and the scheduling of hydro power generation in the planning process. For the example, the Power System Simulation Tool from TradeWind [3] was used to evaluate the resulting grid structure. Preliminary results show that the benefit of a meshed multilateral grid like the one in Figure 12 comes out somewhat higher when analyzed with a detailed market model because the offshore grid also relieves onshore bottlenecks.

Updated studies of the North Sea region will be conducted in the IEE EU projects WindSpeed [17] and OffshoreGrid [18]. The optimization tool will be used to create good initial grid solutions for further in-depth analysis. Altogether, the presented methodology is a valuable decision support tool when planning new off-shore grid investments.

G. Cross Border Transmission in Europe: TradeWind

As Europe is heading for a 25% share of the electricity demand covered by wind power in 2030 [19], cross-border transmission capacity needs to be significantly increased in several corridors, bringing significant economic benefits in terms of reduced operational costs of power generation. This is the conclusion of the TradeWind study [3], after simulating power flows in the European transmission network with the expected wind power capacity deployment scenarios in 2010, 2015, 2020, reaching 300-400 GW in 2030. The study used wind power production calculated from Reanalysis wind data combined with regionally aggregated wind power curves, other generation and demand scenarios from established EU scenarios and an equivalent representation of the European network aggregating the former UCTE region (largest area in Europe), with the Nordic Area, GB and Ireland, asynchronously connected via HV DC links. Chronological hourly optimal power flow simulations with a SINTEF market tool calculated the macro-economic benefits of decreasing transmission congestions, in terms of reduction of operational costs of power generation. Increasing wind power capacity in Europe was found to lead to increased cross border energy exchanges and more severe cross-border transmission bottlenecks in the future, especially with the amounts of wind power capacity in 2020 and 2030. Also the effect of passing storms on cross-border flow and the related potential benefits of increasing transmission capacity were investigated. Wind power forecast errors were found to result in deviations between the actual and expected cross-border power flows on most interconnectors during a substantial part of the time, further exacerbating cross border congestions. The calculated cost reductions were used to determine staged transmission capacity upgrades in selected corridors (grid scenarios), both for offshore and onshore interconnectors. The macro-economic benefits of the grid upgrades were found to be substantial. If the 42 identified onshore and offshore cross-border transmission upgrades are implemented, operational costs of power generation would be reduced by 1.5 Billion € per year (after 2030). The identified benefits can be considered a conservative estimate because other benefits of transmission upgrades such as reduced losses, less need for on-line reserves and lower start-up costs were not considered. Thus the TradeWind study, rather than looking into detailed joint wind and transmission planning approaches, identified specific cross-border transmission upgrades to be addressed as a function of time and wind power capacity development.

In addition to transmission needs, TradeWind also evaluated the effect of improved power market rules and quantified these in terms of reduction of the operational costs of power generation. The establishment of intra-day markets for cross-border trade is found to be of key importance for market efficiency in Europe as it will lead to savings in system costs in the order of EUR 1-2 Billion per year as compared to a situation where cross-border exchange must be scheduled day-ahead. In order to ensure efficient interconnector allocation, they should be allocated directly to the market via implicit auction.

Intraday rescheduling of the generation portfolio, taking into account wind power forecasts up to three hours before delivery, results in a reduction in operational costs of power generation of EUR 260 M/yr (compared to day-ahead scheduling) thanks to the decrease in demand for additional system reserves. Consequently, the TradeWind analysis concluded that the European electricity market needs intraday rescheduling of generators and trade, a consolidation of market areas, and increased interconnection capacity in order to enable efficient wind power integration.

H. European Wind Integration Study Results

The EWIS study is the first time that a year-round market analysis (necessary to represent the effects of wind on a pan-European basis) has been coupled with detailed representations of the networks (necessary to comprehensively address network performance limitations and so ensure reliability and economy). A key recommendation from EWIS is that pan-European modeling, coordinated and adjusted by more precise regional or national models, should be further developed and used as appropriate to assess future development of the European transmission network, especially as the proportion of wind generation increases. This will be a demanding task and require a significant ongoing effort by TSO's to achieve.

The immediate network strengthening actions identified by EWIS are shown in Figure 13. In areas where cross-border flows are the subject of controllable links (Ireland and Northern Ireland to Great Britain, Great Britain to continental Europe, Iberian Peninsula to continental Europe and between the Nordic countries and continental Europe) physical flows can follow market transactions and so little need for additional measures to those already identified by those countries were anticipated or found.

However, in the mainland Europe synchronous area under the high wind north snapshot, the difference between actual physical flows and the market exchanges can be very substantial (due to so called "loop flows"). TSOs are already experiencing issues due to these loop flows but analysis of the 2015 snapshots identified:

- High power flows in the areas with large wind power installations in Germany (higher than previous national studies had anticipated and existing planned reinforcements can accommodate).
- Substantial loop flows through Poland and the Czech Republic increasing flows significantly above those that are currently expected to result from market transactions.
- Also high loop flows through Benelux countries, similarly increasing flows.

These large flows, if unmitigated, would risk reducing network reliability by causing overloads and low voltages such that there is a risk of cascade failures and disruption should a fault event occur. On the German-Czech Republic border, flows could exceed line capacities even with all circuits in service, risking network failure without an initiating fault event. On the German-Poland border, flows reach line limits with all circuits in service, risking network disruption in the event of a fault. Unless other risk measures are instigated, the conditions would suggest that the transmission capacity that could be offered to the market would need to be substantially reduced. Some potential overloads on network lines and unacceptable voltage conditions within the German market price area which cannot be acceptably controlled by reducing transfer capacities have been identified and offered to the market. Network capacity enhancements are therefore essential.

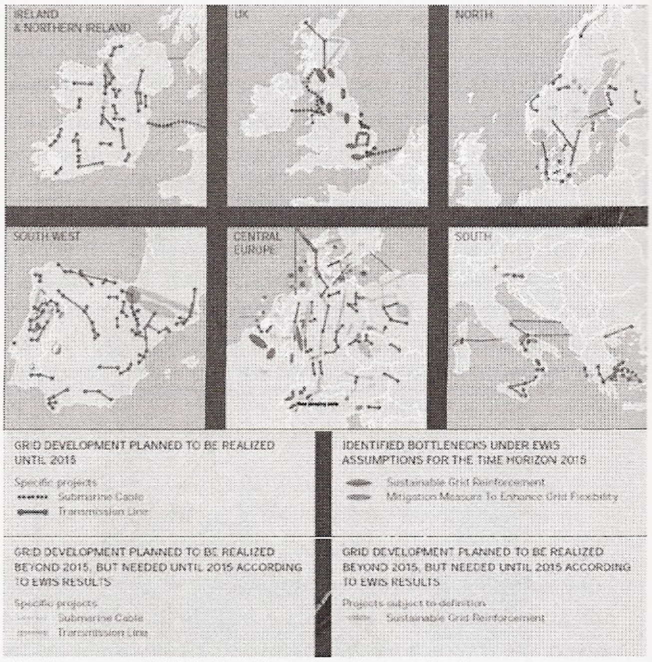

Fig. 13: Summary of EWIS identified network strengthening measures

These measures have a capital cost of circa €10.5b and therefore represent a network cost of circa €4/MWh of wind produced (nb although in practice they address issues that are not solely due to the operation of wind generation in the European market and they would bring benefits to market participants other than just wind generation).

These network strengthening measures are unlikely to all be achieved by 2015 and so it is necessary to also introduce measures that make best use of existing network capacity. Throughout Europe, improved wind forecasting techniques together with use of within day markets to capture the latest production positions are being developed. Capacity enhancement measures already planned include:

- Pilot projects to implement dynamic line ratings (measuring line temperatures that reflect actual ambient conditions including wind cooling and the effects of line loadings).
- Phase shifting transformers (which permit power flow sharing between parallel circuits to be controlled in order to maximise available capacity).
- Special protection schemes that trip certain generation facilities in the event of network faults that would otherwise cause overloads and potential cascade failures.
- Reactive compensation devices to improve network voltage performance.
- New lines (although the speed of establishment of these facilities depends on consenting procedures).

Looking beyond the immediate measures to strengthen and make best use of existing networks, EWIS also examined the benefits of enhancing cross-border interconnection capacity and identified those links which are likely to have congestion reducing benefits that exceed the likely capital costs. These are illustrated in Figure 14 and include some 30 links with a total capital cost of circa €12b.

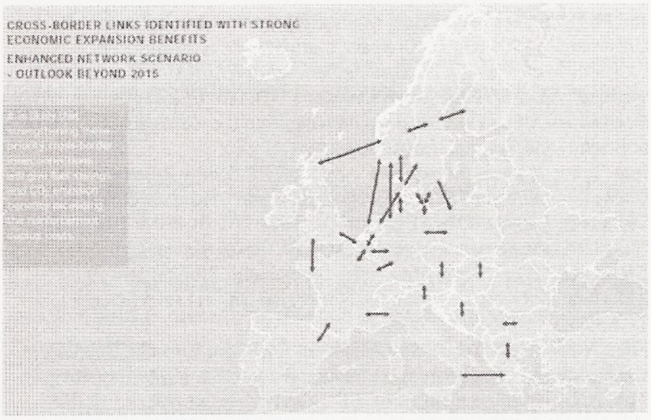

Figure 14. Cross-border reinforcements with potentially strong economic benefits

IV. HIGH LEVEL TRANSMISSION POLICY

In the near term in the US, meeting the ambitious targets that have been set for renewable energy will require the upgrading of existing lines and the construction of new ones. Because of the long distances and the multiple state and regional boundaries that must be crossed to move the renewable energy to market, as well as the critical national security and long-term environmental sustainability issues involved, it is clear that there is an appropriate role for the federal government. The exact nature of that role is currently being debated in Washington among the administration, the Congress, and the Federal Energy Regulatory Commission. Legislation has been introduced which requires interconnection-wide transmission planning to be performed, an interconnection-wide cost allocation for high voltage backbone transmission line costs, and federal backstop authority for transmission line siting. It is not clear if or when such legislation will be passed, but it is an indication of the growing importance with which the critical need for an expanded transmission infrastructure is being viewed.

Similar discussions are being held in European countries and at the EU level. As in the US, there is a growing consensus at the political levels that increased transmission is essential for reaching in the renewables targets, and that there is a strong role for a coherent European policy. Traditionally (in the former decade) cross border transmission planning at a European scale was linked to the development of a single internal market for electricity. One of the EU promotion instruments was the Trans European Networks for Electricity programme TEN-E [20] (currently under revision in 2010). However this instrument was not aiming at developing transmission for large amounts of renewables. More recently, the European Commission is working on a new "European Energy Infrastructure Package" (expected November 2010) that has to facilitate the realization of the renewables targets of the Commission (20% renewables by 2020), containing more specific proposals, a.o. with respect to a Blueprint for Offshore Grids in Northern Seas of Europe and a new energy infrastructure instrument as a successor of the former TEN-E Programme. Within the same overall policy framework – achieving competitive, sustainable and secure electricity supply in a single electricity market – the European Commission is presently implementing the so-called Third Package Liberalisation legislation involving a much stronger cooperation of transmission system operators in Europe in a new association ENTSO-E. This body created in 2009 released its first version of the (non-binding, community-wide) 10-year network development plan [2] which mentions significant infrastructure investment needs for massive integration of renewables in Northern (mainly wind) and Southern Europe (wind, hydro and solar). One of the real hot issues, namely how to finance and recover costs of transnational transmission against a diversified backdrop of regulatory frameworks, has been hardly touched upon in these political deliberations.

V. SUMMARY AND CONCLUSIONS

There is a growing recognition around the world that wind energy is different from more conventional sources of energy and requires a different approach to transmission planning. Traditional capacity-based methods must be modified and expanded to incorporate the unique characteristics of wind as an energy resource with limited capacity attributes and value. Regional approaches to transmission expansion planning have unleashed a number of creative approaches to planning and building transmission for wind. Transmission has become recognized as a key enabler to reach renewable energy goals and carbon reduction goals. Policy initiatives are underway at the national level in the US to establish interconnection-wide transmission planning processes, enable interconnection-wide transmission cost allocation for a high voltage backbone system, and provide federal backstop transmission line siting authority.

Policy initiatives are underway in Europe to catalyze the process of transmission expansion for a sustainable energy supply at a European level. As a consequence of the liberalisation package, ENTSO-E was established and came with a first release of its 10 Year Network Development Plan. The European Commission is preparing to release later in 2010 its Energy Infrastructure Package setting out directions for the renewed Energy Security and Infrastructure Instruments and a first outlook on a blue print for offshore grids in Northern Europe.

VI. ACKNOWLEDGMENT

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