Transmission Infrastructure Investment Requirements in the Future European Low-Carbon Electricity System

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Abstract— this paper presents case studies projecting European cross-border electricity transmission infrastructure requirements for a range of future European electricity system scenarios. In calculating the requirements and to attain to the least cost solution, we use a Dynamic System Investment Model. The optimization model minimizes the total investment and operating costs taking into account: (i) the coordination needed between generation and transmission investment; (ii) the need to maintain reliability and feasibility of system operation; and (iii) the applications of load control technology. The model has been used to quantify the transmission requirements for five different European future generation and demand scenarios developed in the “Infrastructure Roadmap for Energy Networks in Europe”, IRENE-40, FP7 project. These include Business-as-Usual, Renewable, DESERTEC, CCS, and the High Efficiency pathways. This paper also presents a discussion on the plausible network technologies to fulfill the requirements and the potential benefits of demand side management in reducing the capacity requirements.

Index Terms—renewable, optimization, transmission planning

I. INTRODUCTION

Europe’s path towards a sustainable and low-carbon energy system will inevitably require a major shift in the structure of electricity generation technologies, primarily targeting intermittent renewable resources and large-scale low-emission or zero-emission technologies such as nuclear power or Carbon Capture and Storage. Large scale deployment of these technologies raises complex challenges in planning the supporting electricity infrastructure and real time operation management of the system.

In this context, the efficient planning of the European cross border transmission system (ECBTS) will play a key role in the future development of a sustainable and low-carbon European energy system. Around €140bn of network investment will be required for Europe to deliver on its climate and energy objectives [1]. The main functionalities of ECBTS are centered on the following aspects:

- to allow access to low marginal cost energy sources and investment of renewable sources in the best locations, recognizing the fact that good sources of wind and hydro power are in Northern Europe while stronger solar power is in Southern Europe;
- to share capacity and reserves between regions by exploiting the benefits of diversity in demand and (renewable) generation; and enable access for control and flexibility from neighboring systems. This will improve the overall utilization of the infrastructure, increase security of supply, and the system flexibility to balance demand and supply in real time.

In order to design a multi-purpose interconnection, there is a need for an integrated planning approach that considers simultaneously the requirements of generation, for capacity and system balancing, and transmission infrastructure whilst taking into account security and economic considerations [2]. The key challenge will be to include full representation of system operational requirements (i.e. delivery of response, reserve, variability in production of intermittent renewable, taking into account available demand response and energy storage) in a (multi) year-round network design framework that deals with economics of bulk energy transport, seasonal/weakly allocation of hydro resources and reliability/security of supply. For this purpose, we use Dynamic System Investment Model (DSIM) to calculate the optimal requirement for ECBTS.

The model has been used to evaluate the capacity requirements for five different future generation scenarios, namely: Business-as-Usual (BaU), Renewable (RES), DESERTEC (DES), Carbon Capture and Storage (CCS), and High Energy Efficiency (EFF) scenarios related to year 2050. The scenarios were developed in the IRENE-40 project with the objective to test the range of ECBTS capacity requirements under different scenarios [4].

The structure of this paper is as follows: section 2 will describe the optimization methodology, the key input data and the key output data of DSIM. It is followed by a short description of the system characteristics and key results of the simulation for each future system scenarios, and some discussions on the challenges in network technologies and impact of DSM on the capacity requirements. Finally, the
The conclusion of our findings is presented in the last section.

II. METHODOLOGY

The power system planning and operation problem in DSIM is formulated as a Linear Programming problem. If required, binary or integer variables can also be incorporated at the expense of higher computation cost.

DSIM considers a number of different optimization problems applied across different time horizons moving from the planning to the operation stage as illustrated in Figure 1.

Figure 1 Overview of the modelling approach

The optimization problem with the shortest time horizon considered in DSIM is the hourly dispatch problem. Operating reserve requirements are included in order to address the system balancing problems that have sub hourly time resolution. To balance the investment cost and operating cost, we use one year round optimization problem with annuitized investment cost. All investment and hourly operation problems are solved simultaneously in order to guarantee the optimality of the solution.

Consequently, for a realistic system the size of DSIM optimization problem is very large and may involve millions of variables and constraints. The size of the problem is limited by the amount of computer memory and the CPU.

An overview of the DSIM model structure is given in Figure 2.

Figure 2 Structure of the Dynamic System Investment Model (DSIM)

The objective function of DSIM is to minimize the overall investment and system operating cost. The investment cost includes capital cost of new generating and storage units, and the reinforcement cost of transmission and distribution networks. The capital cost is modeled as a linear cost function of the installed capacity / ratings of the unit in question. In the particular case of storage, the capital cost also consists of the capital cost of storage energy capacity.

The system operating cost consists of the annual generation operating cost and the cost of energy not served (load-shedding). Generation operating cost consists of variable cost as a function of electricity being produced, no-load cost as a function of a number of running hours, and start-up cost. Generation operating cost is determined by fuel prices and carbon prices.

There are a number of equality and inequality constraints that have to be respected while minimizing the overall cost. These constraints are described as follows:

- Power balance constraints: these constraints ensure that supply and demand is balanced at any time;
- Operating reserve constraints include slow reserve and frequency response (fast reserve) constraints. The amount of operating reserves is calculated as a function of the uncertainty in generation and demand across various time horizons. We generally use three times the standard deviation of wind (and other renewable sources) variability within 15 minutes to calculate the additional response requirement and the variability within 4 hours for the additional slow reserve. The rationale of this approach was consistently analyzed and proved to be adequate to capture the 99.7 percentile of wind variability. The amount of spinning and stand-by reserves is optimized ex-ante to minimize the cost of providing these services;
- Generation operating constraints include Minimum Stable Generation constraints (MSG), ramp up and down constraints, minimum up and down time constraints, frequency response and reserve constraints, and maximum output constraints. In order to minimize the size of the optimization problem, generators are grouped based on their technologies. The typical size of a thermal unit is pre-defined;
- Generation investment in DSIM is carried out by increasing the number of generating units. DSIM optimizes the portfolio and location of new generating units such that it minimizes overall cost. The number of new units that can be added is constrained by generation investment constraints. These constraints are used to limit the maximum of investment in particular generation technologies and in particular locations. The limits can be specified as input data;
- Annual load factor constraints are used to limit the utilization level of a thermal generating unit. This is mainly to capture the effect of maintenance to the utilization of this plant. For wind, solar, marine units, and hydro run-of-river with no reservoir capacity, their maximum electricity production is limited by the available energy during that time, given as input data. The marginal cost of their electricity production is zero and therefore the optimization will maximize the utilization of these units. In a condition where the system is constrained, their electricity output can be curtailed.

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- For a hydro with reservoir capacity or a storage unit, the electricity production from this plant is limited not only by the power rating but also by the energy available in the reservoir or storage. The amount of energy that can be put into or discharged from the reservoir is limited by the size of the reservoir. It is also possible to apply minimum energy constraints in DSIM to ensure a certain amount of energy that has to be maintained within the reservoir, for example, to ensure the stability of the reservoir.

- For storage, the storage efficiency losses are taken into consideration during the charging and discharging periods. This results smaller energy that can be discharged compared to the energy charged to the storage.

- Demand side response constraints include constraints for different type of loads. DSIM models a number of different load types e.g. (i) independent weather related loads, e.g. lighting, (ii) heat driven electricity loads, (iii) loads from electric vehicles, and (iv) smart appliances electric loads. Different type of loads may have different flexibility which is measured by the amount of daily energy consumption that can be time-shifted within the same day. The constraints ensure that the amount of daily energy consumption after the optimization is at least equal to the scheduled consumption given in the input data. Losses due to time-shifting loads can be modeled if necessary. Other constraints ensure that the amount of energy that being shifted within the day and at particular snapshot is limited to the flexibility defined in the input data.

- Power flow constraints limit the power flow within the installed capacity of the network in question. The network capacity can be enlarged if it is allowed and optimal to do so. DSIM can handle power flow constraints in each flow direction. Transmission networks/ interconnectors are one of important keys to facilitate efficient integration of large renewable. Interconnectors allow access to renewable sources and improve the diversity of loads and renewable sources which reduces short term reserve requirement. Interconnectors also allow sharing of reserves that reduces long term capacity requirement.

- Emission constraints limit the amount of carbon emissions in one year. These constraints will limit the electricity production from a plant that emits high carbon emissions such as oil or coal fired power plant. These constraints may also trigger investment in low carbon plant such as nuclear, or CCS (coal/gas) to meet the constraints.

- Security constraints ensure that there is enough generating capacity to supply demand in the system. The constraints measure the capacity margin of generating capacity and estimate the loss of load probability (LOLP). The maximum of annual Loss of Load Expectation (LOLE) is constrained to a pre-defined number given in the input data. In this study, we will use LOLE equal to 4 hours as a security criterion.

III. CASE STUDIES

As transmission requirements are case specific, we use DSIM to evaluate capacity requirements for the ECBTS in 2050 for five different future generation scenarios, namely: BaU, RES, DES, CCS, and EFF scenarios. DSIM will calculate the additional capacity requirement on top of the 2010 ECBTS capacity shown in Figure 3.

![Figure 3 Cross border capacity in 2010](image)

A. Business as Usual (BaU) scenario

BaU scenario is characterized by a diverse mix of the generation portfolio of which fossil fuel generation technologies remain the favoured to supply energy demand. Thus, BaU scenario is constituted by the less ambitious generation mix for emission reduction targets. The deployment of renewable energy sources meets the 2020 emission reduction targets; however the subsequent uptake is relatively slow. Low carbon generation technologies and renewable energy sources contribute moderately to the electricity of supply in 2050. Figure 4 summarizes the BaU generation mix and peak demand for each European country considered in the analysis.

![Figure 4 Generation portfolio and peak demand in 2050 BaU scenario](image)

Consequently, the additional ECBTS capacity requirements are relatively moderate except for few boundaries, e.g. DE-DK-SE and PL-LT with capacity within 5GW- 10GW range. The results are summarized in Figure 5.
B. **Renewable (RES) scenario**

RES scenario is characterized by an ambitious generation technology mix for achieving emission reduction targets and strong policy support is therefore assumed to drive the deployment of renewable energy sources especially after the year 2020. Energy renewable sources replace conventional power plants (coal, gas and oil) even before technical end-of-life. Thus, the use of fossil fuels generation technologies decreases from 45% in 2020 to 8% in 2050. The installed capacity of nuclear power plants is also significantly reduced in 2050. The geographical distribution of the renewable energy resources includes large clustered offshore and onshore wind farms in the northwest, solar and wind in the south, hydropower and biomass in central and northern Europe. Figure 6 summarizes the RES generation mix and peak demand for each European country considered in the analysis.

C. **DESERTEC (DES) scenario**

DES scenario is characterized by an ambitious generation technology mix for achieving emission reduction targets and strong policy support is therefore assumed to drive the deployment of renewable energy sources especially after the year 2020. The DES scenario assumes a strong development of renewable energy sources very similar to the Renewable scenario. The main difference is that part of Europe’s electricity of supply will be generated in North Africa, and then transported via electricity “high-ways” to Europe entering at Spanish and Italian borders. The DES scenario aims to supply 3% of Europe’s electricity demand by 2030 and 15% in 2050 from solar power generation located in North Africa. Figure 8 summarizes the DES generation mix and peak demand for each European country considered in the analysis.

Figure 5 Cross border capacity required in 2050 BaU scenario

Figure 6 Generation portfolio and peak demand in 2050 RES scenario

Figure 7 Cross border capacity required in 2050 RES scenario

Figure 8 Generation portfolio and peak demand in 2050 DES scenario

Similar to RES scenario, DES requires significant reinforcement in most of ECBTS corridors especially the interconnections between Southern Europe to Central Europe driven by high penetration level of PV and between Northern Europe to Central Europe driven by high capacity of wind power.
D. Carbon Capture and Storage (CCS) scenario

CCS scenario is characterized by an ambitious generation technology mix for achieving emission reduction targets. The emission reduction targets are identical to Renewable scenario however are achieved differently. Renewable electricity capacity grows less rapidly, being complemented by nuclear power and by thermal power plants outfitted with CCS. Broadly, renewable energy sources are still supported as one of several low-carbon technologies but without priority in this scenario. CCS technology is assumed to mature successfully. It is added to the existing power stations and integrated into new power plants mainly in north-western Europe from 2030 onwards. Thus, CCS technology makes a successful transition from pilot projects to a commercially mature viable option by 2030 from which its deployment develops very significantly all over Europe. Figure 10 summarizes the CCS generation mix and peak demand for each European country considered in the analysis.

E. High Energy Efficiency scenario

EFF scenario is characterized by a substantial extra effort in enhancing the efficiency resulting in a lower final electricity demand compared to the other scenarios. In all scenarios the demand growth is due to a mix of volume effects (increasing electricity demand due to growth in production) and structural effects (improving efficiency, and effects due to a changing fuel mix in final demand). In the EFF scenario the continued strong efficiency improvements almost cancel the demand growth due to volume effects and structural (fuel shift) effects. The total final electricity demand increases only 10% over the period 2010–2050. Figure 12 illustrates the EFF generation mix and peak demand for each European country considered in the analysis.

In EFF scenario, installed capacity of renewable power is smaller compared to RES and DES while delivering the same carbon reduction. Consequently, the impact on ECBTS is relatively moderate as shown in Figure 13 although there are still some corridors that need major reinforcement.
F. Network technology challenges

There are a number of technology options to meet some of the future requirements for ECBTS [6][7]. Ultra High Voltage AC and DC have started being deployed with transfer capability around 10GW across long distance [8]. However, there is still a significant gap in transmission technologies to meet significant upgrade in capacity, such as the 32 GW capacity requirements between Spain and France in DES and the development of efficient European Super HVDC grid. Figure 14 shows various technology options for different ranges of capacity requirements; however the technology selection is likely to be case specifics.

G. Impact of Demand Side

As demand for future ECBTS capacity is often triggered by renewables, there is potential opportunity for demand side to reduce these requirements by improving “self-consumption” of the renewable energy. Figure 15 shows that some reduction of ECBTS capacity requirement contributed by Flexible Demand (FD). A larger reduction can be observed particularly for scenarios with high renewables capacity.

IV. CONCLUSION

Demand for ECBTS capacity will depend on the future development in generation and load growth in Europe. The studies demonstrate that demand for ECBTS capacity is often triggered by large installed capacity of renewables. Because of that the application of flexible demand can be effective in reducing the requirements. As the future demand for ECBTS capacity can be very high, development of new technologies to facilitate higher power transfer across long distance more efficiently is becoming of increasing importance.

REFERENCES