# 欧洲电网的发展及其与全球能源互联网的兼容性

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**摘 要:** 全球能源互联网(Global Energy Interconnection,GEI)旨在通过建立洲际输电走廊来实现可再生能源发电在全球范围内的自由调度。研究表明,GEI 愿景可有效促进全球去碳化。然而,各地区电网的现有发展计划分别以独立的愿景为基础框架,其与 GEI 的兼容性尚不清晰。文章旨在讨论由欧洲输电网运行商联盟(European Network of Transmission System Operators for Electricity, ENTSO-E)提出的欧洲电网发展十年计划(Ten Years Network Development Plan, TYNDP)与 GEI 愿景的兼容性,提出一种结合电力系统技术经济分析模型和社会经济决策支持工具的多准则优化方法。通过该方法,在充分考虑环境、社会和政治因素的影响下,对 GEI 跨洲互联通道在欧洲电网本地的落脚点进行优化配置,并计算了 2030 年和 2050 年 GEI 情景下欧洲电网规划模型内部的最优潮流。结果显示,在 GEI 情景所预测的高负荷水平下,斯堪的纳维亚地区和欧洲大陆之间将出现分布广泛的阻塞,从而限制来自北极地区风电向欧洲大陆的调度。研究认为,GEI 的发展与实施需要各地区电网间的密切配合。

**关键词:** 欧洲电网; 欧洲输电网运行商联盟(ENTSO-E); 全球能源互联网(GEI); 电网十年发展计划(TYNDP)

## Development of European Power Grid and Its Compatibility with Global Energy Interconnection

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**ABSTRACT:** The Global Energy Interconnection (GEI) vision is to enhance the deployment of renewable energy generation on a global scale by building intercontinental power transmission corridors, thereby promoting global decarbonization. Under the premise of a unified electrical market, this paper discusses the compatibility of current development plans of European power grid, proposed by European Network of Transmission System Operators (ENTSO-E), with the long-term GEI scenarios in 2030 and 2050. To fully consider the environmental, social, and political elements in the network expansion, a novel methodological approach is proposed, which combines the techno-economic models with socio-economic decision-making support tools, as the multi-criteria analysis. By this method, the paper computes the optimal power flows in the European network model in the GEI scenarios of 2030 and 2050. The study shows that, at the high load level projected in the GEI scenario, a widely distributed congestion between the Scandinavia area and the European continent would appear, limiting the dispatch of transmission corridors from the Arctic area. The results demonstrate that the planning of GEI will require close coordination and management between transmission system operators (TSO) and institutions in various regions.

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**KEYWORDS:** European power grid; European Network of Transmission System Operators (ENTSO-E); Global Energy Interconnection (GEI); Ten Years Network Development Plan (TYNDP)

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## 0 Introduction

The current global energy system is mostly dependent on fossil fuels that profoundly affect both society and environment[1]. Thus, there is a need for the transition of the existing energy paradigm towards a more sustainable one with high-deployed clean energy resources (e. g. , solar, wind, and hydro sources)[2]. This process of "clean replacement"[3] from fossil fuels to renewable sources will probably induce a transformation of the end-uses towards massive electrification.

In this framework, as a part of the energy system, the power sector inevitably plays an essential role in the transition process. Bompard et al.[4] well described this concept by introducing the so-called "electricity triangle", which consists of three main elements: i) high renewable penetration in the power mix; ii) high level of electrification of final energy uses; iii) high availability of energy through efficient power transmission grid. Global Energy Interconnection (GEI) vision, firstly introduced by Liu[3], is an extreme representation of this context. GEI vision aims at promoting higher final uses electrification and renewable energy sources (RES) penetration, by the construction of a super grid connecting the main RES production areas (e. g. the Arctic for wind and the Equator regions for solar) to the significant consumption zones (e. g. Europe, the United States, and the Asian countries). Li et al.[5] have discussed the three main pillars on which GEI based, which are: i) "high carbon to low carbon"; ii) "low efficiency to high efficiency"; and iii) "local balance to wider-scale distribution". In other words, GEI can be defined as a combination of renewable and clean energy, ultra-high voltage transmission networks, and smart grids; indeed, in its broader concept, the vision could accommodate electricity generated through central and distributed structures, allowing for high smart control, connectivity and flexibility[6].

Recently, thanks to the possible benefits that could arise from this vision, academicians and professionals demonstrated significant interest on the topic. Indeed, the large-scale deployment of renewable energy sources is perceived as a key element to reduce greenhouse gas (GHG) emissions in the atmosphere, and thus to achieve the advocated low-carbon transition[5]. Moreover, due to the concerns related to the volatility and stability of renewable sources, and thus to the consequence on the security of power supply, the construction of the high-quality GEI transmission grid will help solve this issue, by allowing to balance the different world time zones, seasons, and resource availabilities[6]. Besides energy and environmental benefits, other positive consequences deriving from the exploitation of the GEI vision are depicted, as the increase of energy security, due to the reduction of countries dependence on fossil fuels, as well as the enhancement of energy cooperation and sharing[5], and the possible creation of new job position in RES industry. Despite the benefits, GEI realization is characterized by several obstacles and challenges, among which governance and management issues, cost allocation, which need a close cooperation between governments and institutions to be faced[4].

In order to better tackle both benefits and obstacles of such global energy infrastructure, large-scale energy models are usually used as the basis for broader strategic energy planning[7]. The same consideration is valid for the power sector, of which the evolution towards a renewable system should be studied, not only in techno-economic terms, as usually implemented in power system analysis, but also considering possible environmental, social, political implications.

An analysis of the interconnected power system on a global basis is presented in Brinkerink et al.[8], who discussed the process of developing and simulating a global interconnected power model. The paper describes the development of an intermediate model of interconnection between Europe and North America, as a first step towards the realization of a global model[8]. In particular, a 30-nodes European model (EU28 plus Norway and Switzerland) was connected through intercontinental ultra-high voltage connections to a North America model, composed by a 20 nodes model for the United States and an eight-nodes model for Canada. The analysis has shown that, thanks to the presence of different time-zones, the demand peaks in the two main consumption areas (Europe and North America) occurred in different moments, and that, in many cases, peaks in Europe were counterbalanced by off-peaks in North America and vice versa. The model, simulated over an entire year, explored how the flow is directed towards Europe, due probably to the least-cost generation in North America. Besides the obtained results and the methodology validation, the authors clearly stated the difficulties in the achievement and simulation of these models[8]. Indeed, data availability is the major obstacle to the realization of global-scale models, since open access data are not always available for many world regions; moreover, in some cases, transmission system operators are not interested in sharing their data, thus complicating the analysts' work[8]. To partly overcome this difficulty, a common approach implemented for such simulations is to use existing generation and demand profiles of similar regions (e. g. in terms of population, GDP, electricity generation portfolio, etc.) and to scale them according to time zone, electricity demand, and peak values. This approach was implemented in Crespi et al.[9], in which techno-economic modelling research on GEI was conducted, simulating a simplified world power model with 19 equivalent nodes, each one characteristic of a world region. The optimal power flow (OPF) analysis showed that, despite the considerable growth in demand from a global scale, the intercontinental power corridors would stimulate the global electricity trading, and additionally contribute to the world decarbonization by improving the accessibility to remote RES installations.

However, the work was based on the implementation of enhanced power grids, capable of effectively dissipating the massive power flows from intercontinental power corridors. However, nowadays, this assumption is far from reality. As coming from, high-quality wind and solar sources are concentrated in polar and equatorial regions, very far from the main consumption centers[7]. Since the existing power grid cannot meet the clean energy allocation forecasted by the GEI vision, strong efforts should be made to improve the capacity of the system. In this context, the paper aims to explore the European readiness to an eventual GEI scenario. In the latest Ten Year Network Development Plan (TYNDP 2018[10]), the European Network of Transmission System Operators for Electricity (ENTSO-E) published the future European Union (EU) network plans under three scenarios up to 2040, offering visions of different pathways to the EU climate targets. Starting from these scenarios, the paper intends to discuss the compatibility of the official EU network plan, following the ENTSO-E's forecasts, with a scenario of intense intercontinental power corridors, such as the GEI, to be able to accelerate the pace for the global climate targets.

The paper is structured as follows: in section 1, the methodological steps used for the work are summarized, and then detailed in the subsequent sections 2, 3, and 4, including the literature review for the identification of the baseline model, and all the analysis developed for forecasting it up to 2030 and 2050. Finally, section 5 reports the results obtained in this study, while the final section contains the main conclusive remarks and the future developments of the work.

## 1 Methodology

As previously mentioned, the paper aims to explore the compatibility of the EU network plan from ENTSO-E with the GEI scenario.

In particular, the paper followed three main methodological steps:

1) Based on a literature review on existing power system models, a baseline model was selected for the subsequent scenario analysis up to 2050; in parallel, a review on the TYNDP 2018 network plan for the EU power system was performed, in order to evaluate the transmission capacity expansion already planned for 2030 and 2050 to be applied to the selected baseline model. This step is reported in section 2.

2) Based on existing statistics on future forecasts of electricity generation, demand, and levelized costs of electricity, a GEI electricity scenario was developed. This step, which allowed the dimensioning of the modeled power corridors from a simplified GEI model, provided the boundary conditions (also seen as external opportunities) to the EU grid under the umbrella of the GEI. This step is reported in section 3.

3) The core of the analysis represented the development of a novel approach to transmission network expansion planning, by combining a multi-criteria analysis with an optimization algorithm to evaluate the capability of the planned EU grid to maximize the use of power corridors (external opportunities) to address the load growth (internal challenges). This step is reported in section 4.

## 2 EU network modelling

### 2.1 Baseline model selection

There are currently many data sources for the static model of the EU network. The model that the ENTSO-E uses presently in the study of power grid planning includes 7 321 buses, covering infrastructures rated from 7.5 to 750 kV. Besides, Zhou et al.[11] built up another open-source network model by manually extracting the geographic information of buses from a raster map of the ENTSO-E. However, these models mentioned above are not applicable for this research due to their lack of either accurate geographic information or part of the network.

Hösch et al. [12] constructed an open-source model of 257 buses by k-means clustering over 6 000 buses automatically obtained from the ENTSO-E online grid map[13]. The model has been validated by using linear optimal power flow with the European peak-load hour and considering around 70% as an approximation of the N-1 security constraints to the network. As shown in Fig. 1, it contains the geographic coverage and the connectivity of the EU power grid that are essential to consider the interconnections from different directions. Therefore, the presented research takes it as a baseline for the network model expansion.

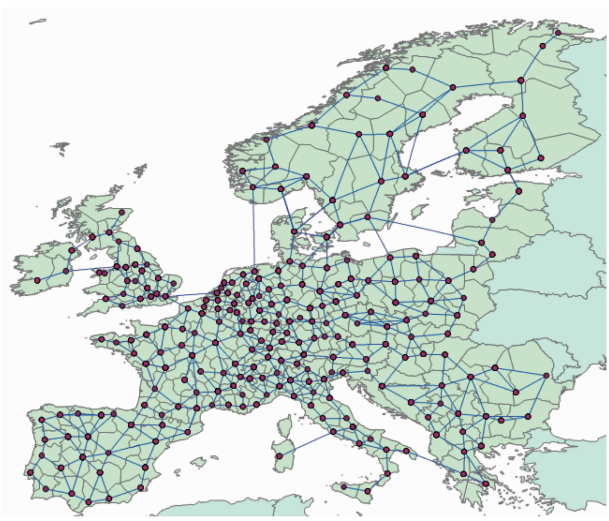

**Fig. 1　The simplified EU network from[12]**

## 2.2　EU network development plan

The latest TYNDP[14] is developed following the framework in Fig. 2. It has listed the power lines with expected commission year up to 2040 or even later[14]. All planned projects in the list have been verified from the three scenarios, respectively, to make sure that they are no-waste projects. Fig. 3 and Fig. 4 respectively show the numbers of newly planned AC and DC lines between 2017, 2030, and 2050.

## 2.3　Model expansion for 2030 and 2050

The expansion of the baseline model from 2017 up to 2030 and 2050 is obtained by importing the planned projects in Fig. 3 and Fig. 4. Due to the incomplete information in the TYNDP 2018, some assumptions are needed:

1) The highest levels available (400 kV for AC and ± 515 kV for DC) are considered for the lines with no information on rated voltages.

2) The definition of the line capacities complies with the correspondence to the rated voltages in Table 1 and Table 2.

3) The modelling of the newly planned AC lines uses the standard parameters of overhead lines in Table 3.

# 3　GEI scenario

As mentioned before, the GEI achievement comes from three main pillars: i) construction of a global super grid; ii) installation of large-scale renewable in remote areas; and iii) massive electrification of final uses (i. e., building, industry, transport). The benefit of the construction of the global super grid is twofold: on the one hand, it allows to improve the connectivity between consumers and producers; on the other hand, it helps to reduce the impacts of local renewable energy fluctuations on the stability of the local grid and to promote the installation of generators in renewable-rich areas, far from the main load centers. Indeed, thanks to the super network, the GEI

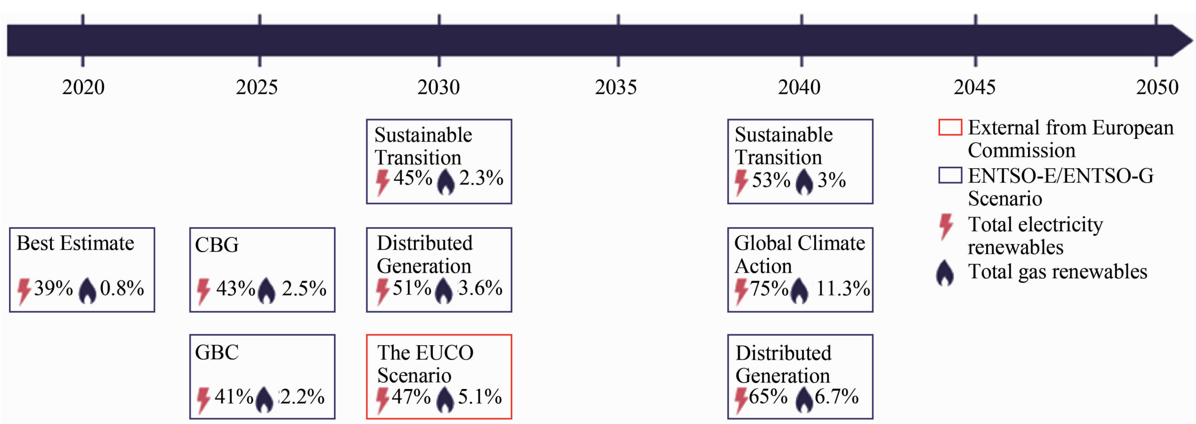


**Fig. 2　Scenario building framework for TYNDP 2018 for the period 2020—2040[14]**

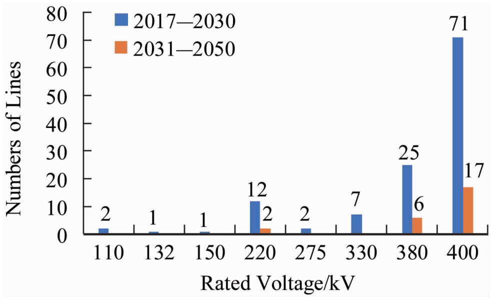


**Fig. 3 The numbers of new AC lines in the EU network**

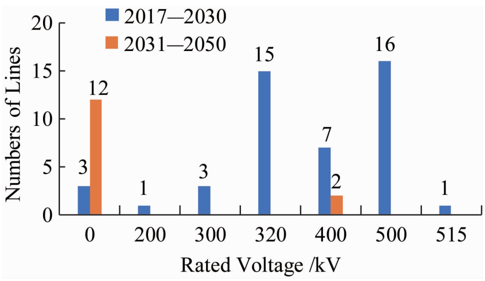


**Fig. 4 The numbers of new DC lines in the EU network[14]**

**Table 1 The capacities of AC lines vs. rated voltages**

| Voltage /kV | Capacity /(MV·A) |
|---|---|
| 0 | 1 698 |
| 110/132/150 | 492 |
| 220 | 492 |
| 275/330 | 1 005 |
| 380/400 | 1 698 |

**Table 2 The capacities of DC line vs. rated voltages**

| Voltage /kV | Capacity /(MV·A) |
|---|---|
| 0 | 3 000 |
| 200 | 600 |
| 300/320 | 1 000 |
| 400 | 2 000 |
| 500/515 | 3 000 |

**Table 3 The standard line types for overhead AC lines[12]**

| Volt. Level /kV | Number of wires | Series resist. /(Ω·km$^{-1}$) | Series ind. react./(Ω·km$^{-1}$) | Shunt capac. /(nF·km$^{-1}$) | Current therm. limit/A |
|---|---|---|---|---|---|
| 220 | 2 | 0.06 | 0.301 | 12.5 | 1 290 |
| 300 | 3 | 0.04 | 0.265 | 13.2 | 1 935 |
| 380 | 4 | 0.03 | 0.246 | 13.8 | 2 580 |

can take full advantage of the abundant renewable resources in the Arctic and Equator regions and considers them as future energy exporters. According to Liu's predictions[3], the total export capacities of Arctic wind power in 2030 and 2050 would reach 50 and 3 000 TW·h, respectively. Table 4 shows the assumed installed capacities in the Arctic and Equatorial zones derived from the aforementioned power flow predictions[1].

**Table 4 The installed capacities in the Arctic and Equator regions derived from[1]** MW

| Installation | Region | 2030 | 2050 |
|---|---|---|---|
| Wind installation in Arctic Region | Greenland | 0 | 289 193 |
| | Norwegian and Barents Sea | 0 | 121 766 |
| | Kara Sea | 5 708 | 136 986 |
| | Bering Strait | 5 708 | 136 986 |
| Solar Installation in Equator Region | Africa | 139 269 | 1 027 397 |
| | Middle East | 76 104 | 951 293 |
| | Australia | 0 | 380 518 |
| | Rest of Latin America | 22 831 | 380 518 |

Meanwhile, the GEI predicts noteworthy increases in global power load. As shown in Table 5, the global demand reaches 73 PW·h, more than tripled from the level of 2010. The scenario attributed the growth to the remarkable electrification of final uses, considering that the widely deployed generations from the Arctic and Equator regions would enhance the competitiveness of the power sector to other energy industries, and thus, promote the advancement of technology and the habits of consumers.

**Table 5 Electricity demand from 2010 to 2050[1]** PW·h

| Region | 2010 | 2030 | 2050 |
|---|---|---|---|
| Asia | 8.7 | 18.8 | 38.0 |
| Europe | 5.4 | 7.8 | 9.5 |
| North America | 5.3 | 7.6 | 10.2 |
| South America | 1.1 | 2.3 | 5.1 |
| Africa | 0.6 | 2.0 | 9.5 |
| Oceania | 0.3 | 0.5 | 0.7 |
| World | 21.4 | 39.0 | 73.0 |

## 3.1 Intercontinental power corridors

The power corridors can globally reduce the requirements for installed capacities because, on the large geographic scale, the load profile in the GEI would tend to be more constant and, thus, to bring down the requirement for redundancy in local generators. Therefore, it is necessary to assess the capacity requirements of the 2030 and 2050 scenarios for the transmission corridor before the follow-up study.

The earlier study proposed by Crespi at al. [9] established a simplified GEI network model of 19 nodes, each representing a regional grid (see Fig. 5). Fifteen of these areas have already-installed infrastructures, and the other four are Arctic wind farms that have been proposed in the GEI scenario and have not yet started. The equivalent node for each region contains the data acquired from the primary statistical sources[15-16], along with the projections from the GEI scenario[1]. The network model proposed to connect all nineteen regional nodes with twenty-eight power corridors, each of which consisted of several ultra-high voltage DC transmission lines.

An OPF analysis, with the assumption of a unified global electricity market, was performed to understand the global power flows in the possible peak-load day for the years 2030 and 2050. The results suggested the required capacities of the power corridors for fully exploiting the benefits that can arise from the GEI realization. Based on the simplified global model, it was possible to identify the connections of Europe with the main surrounding areas, namely the Arctic region, Russia, China, Eurasia, and Africa. Table 6 introduces the capacities of the EU power corridors and the number of lines requested per each of them.

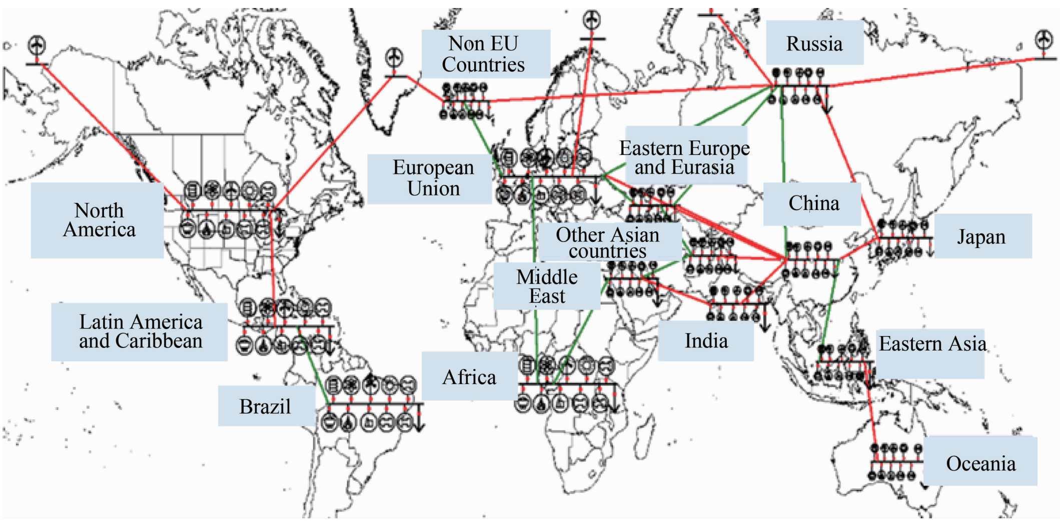


**Fig. 5　The simplified GEI network model[7]**

**Table 6　The capacities of the intercontinental corridors and numbers of interconnectors in demand for 2030 and 2050[7]**

| Connected macro-area | 2030 | | 2050 | |
|---|---|---|---|---|
| | Capacity/GW | Lines | Capacity/GW | Lines |
| Africa | 300 | 25 | 900 | 75 |
| Arctic region | 100 | 9 | 1 000 | 84 |
| China | 200 | 17 | 500 | 42 |
| Eurasia | 100 | 9 | 300 | 25 |
| Russia | 100 | 9 | 200 | 17 |

## 3.2　EU power sector in the GEI

### 3.2.1　Load projection

Load information was acquired from the ENTSO-E transparent platform[17]. From the published historical hourly electricity demands per each member country, there was a reasonable estimation of the demand of each node by a 60 – 40% split principle based on a linear regression analysis of the per-country data[12]. From the baseline above, the projection adopted the growth rates derived from Table 5, where the European demand would see swift growths by 34.8% in 2030 and 64.4% in 2050, from the level of 2014.

### 3.2.2　Installed capacity projection

The EU network model in [9] already includes the existing conventional generators. The statistics were completed by additionally updating the latest RES installations from GEI projections[1]. From an economic point of view, the levelized cost of electricity (LCOE) was used as an economic indicator for the analysis. Considering the high LCOE values for Europe, GEI predicts that the local electric demand increases would primarily rely on the installed RES generators from the neighboring areas, while the installations in the region would still follow the current official plans. Thus, the projections adopted the growth rates of generation in the "Current Policy" scenario from World Energy Outlook (WEO) 2017[15]. Fig. 6 introduces the projection ratios of each installed capacity of 2030 and 2050 from the level of 2014.

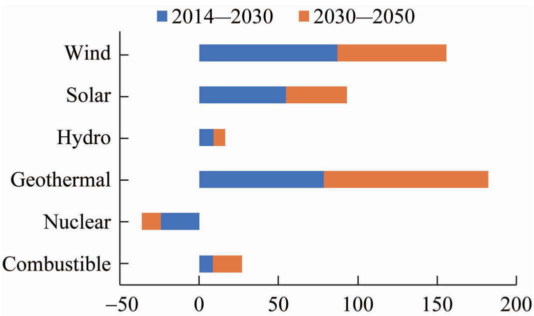


**Fig. 6 Projection ratios of EU installed capacities based on WEO 2016[15]**

## 4 Compatibility analysis

The core of the paper was the development of a novel methodological approach to the transmission expansion planning process, offering the feasibility to integrate the techno-economic common aspects of power system modelling framework with environmental, political, and socio-economic characteristics, usually not accounted in traditional power system analysis.

The approach was to explore the challenges that a GEI vision could pose to the EU network. Indeed, the basis of the official EU power grid plan comes from the scenarios that consider moderate growth in demands, progressing RES penetration in generations, and a boost of local installation for meeting the peak load. In contrast, the GEI scenario does predict a significant increase in the final demand at a global level, including the EU. However, a business-as-usual approach was used in relation to locally installed capacities. Thus, a specific part of the EU demand would come from the intercontinental power corridors in Table 6, introducing power flows that are beyond the consideration of the current planned EU network, which would likely cause internal congestions. With a proper configuration of interconnectors, the congestion level would be kept to the minimum level. With the assumption of an integrated European electricity market, this chapter describes the strategy of accommodating the interconnectors and power flows from GEI into the EU power grid planned in TYNDP 2018. It includes two steps described in the following sections:

1) Allocation of the interconnectors to EU countries based on the hybrid analytic hierarchy process and strengths, weakness, opportunities, and threats analysis (A'WOT) method.

2) Optimization of interconnector accessing nodes within each country.

### 4.1 Step 1: allocation of interconnectors to EU countries by the hybrid A'WOT method

In order to develop and simulate a detailed European model in line with the vision of GEI, an understanding of the interested countries is needed. In particular, it is essential to understand which countries could locate the interconnectors given in Table 6 and the numbers of lines per each of these countries. To accomplish this, a hybrid evaluation method named A'WOT[18] was used to define the most promising EU countries to host the five power corridors from outside Europe. A'WOT model represents a combination of the typical strengths, weaknesses, opportunities, and threats (SWOT) analysis, usually used in decision-making processes, with multi-criteria decision analysis, the latter in the form of the Analytic Hierarchy Process. Multi-criteria analysis is often employed as a support tool for power expansion planning, thanks to its capability of dealing with a decision problem by aggregating different dimensions, facets of the energy issue, and diverse stakeholders' perceptions and interests[19]. Specifically, the A'WOT appears to be a strategic tool for decision-making support, allowing to identify a set of key performance indicators (KPIs) or criteria belonging to different domains (environmental, political, social, economic, and energy), based on which strategical decisions could be made. Per each specific power corridor, the method scores the candidate countries considering their strengths, weaknesses, opportunities, and threats in relation to the realization of the corridors, and then assigns the interconnectors according to each candidate's weight. Fig. 7 and Fig. 8 summarize the interconnectors needed for the five corridors in the years of 2030 and 2050, respectively, and their allocations in the candidate countries. The significant differences between the two timespans arise in Africa and the Arctic region, due to the assumptions of the GEI scenarios; these areas, indeed, host most of the installations of solar power (Africa) and wind power (Arctic region) assumed by the GEI vision, thus requesting increases in corridors capacities.

As a result of the A'WOT methodology used to evaluate the location of the interconnections, each European country was assigned a certain number of interconnectors, which constitute the access points of the five power transmission corridors from GEI in Europe. This result provides a useful and practical constraint for the second step, by dramatically reducing the complexity and freedom of optimization.

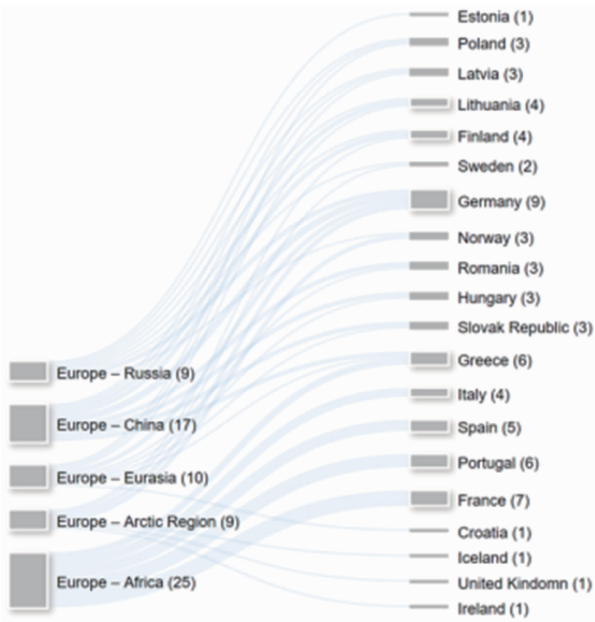


**Fig. 7　Intercontinental power corridors and their landing countries for 2030**

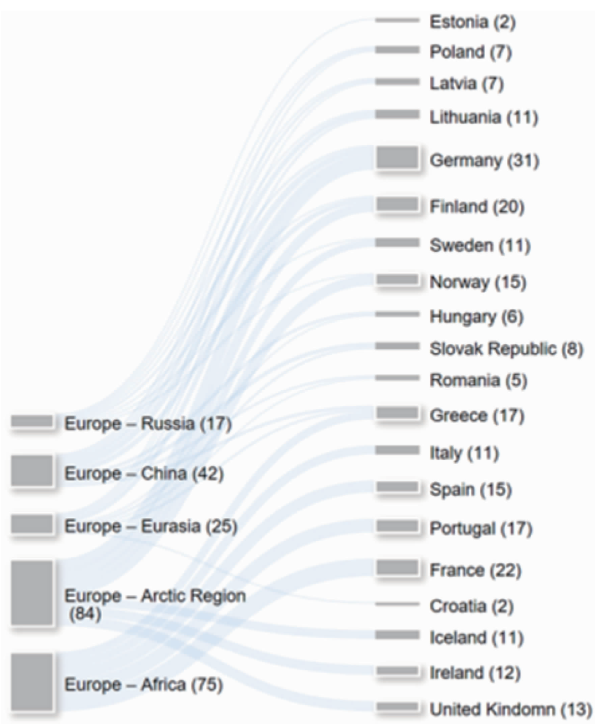


**Fig. 8　Intercontinental power corridors and their landing countries for 2050**

### 4.2　Step 2: optimization of interconnector accessing nodes within each country

Based on the EU power grid model projected in section 1, this step conducts the optimization of interconnector accessing nodes in each country. The algorithm, developed in MATLAB, allows a multi-objective optimization, with on two objective functions:

O1. Minimization of the congestion in the EU network.

O2. Minimization of the electricity costs from the EU generators under the unified EU electricity market assumption.

and on the following constraints:

C1. The power balance of the entire network should be guaranteed.

C2. The power should avoid exceeding the maximum current rating of transmission lines (if possible).

C3. The distribution of the needed interconnections should be as even as possible.

C4. The set of interconnector-connected buses in 2030 should be a subset of the one of 2050.

Fig. 9 illustrates the scheme of the optimizing methodology.

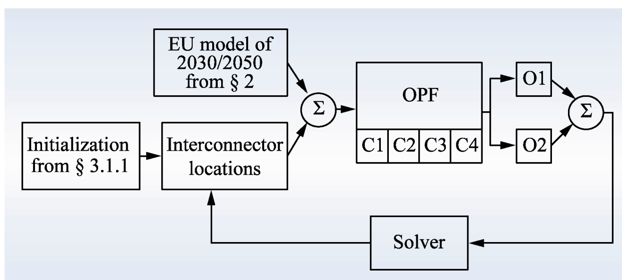


**Fig. 9　Scheme of the optimizing interconnector locations**

## 5　Results and discussion

By the methodological approach explained, optimization was performed for 2030 and 2050, aiming to evaluate how the power flow distribution in GEI would request future updating of the current plan of development of the EU transmission grid. For this reason, the network planned in TYNDP was used in combination with the power flows obtained, assuming the presence of GEI. The next sections report the results for 2030 and 2050, showing potentialities and criticalities of the planned EU grid.

### 5.1　Results of 2030

Fig. 10 shows the EU network power flow distribution with the optimized connecting schemes for

GEI for 2030.

From Fig. 10, it is possible to observe that in the Northern part of the Scandinavian states, the interconnectors cause the maximum utilization of the transmission network (noticing that the level of the legend is set to 120%, to show that no branches have reached the overloaded level). Operating at the upper limit is also the case for the interconnections of Norway with Germany and Finland with Sweden. Besides, the interconnections among Sweden with Lithuania and Lithuania with Poland even reach a very high level (almost 100%). The results show that the interconnections from Russia, China, and Greenland will mostly cause problems of the internal interconnections overload, as the Scandinavian network with the continental EU was not designed to transfer extra energy from other geographical regions. Therefore, if the power corridors from Russia, Greenland, and China would arrive at the Scandinavian countries, these internal interconnections should be reinforced. This potential congestion is also in line with the traditional development of the EU network, whose northern part operates internally synchronously and meanwhile asynchronously with the EU continent; thus, it is not out of expectation that the links among them would be weak when a large amount of energy needs to flow among them.

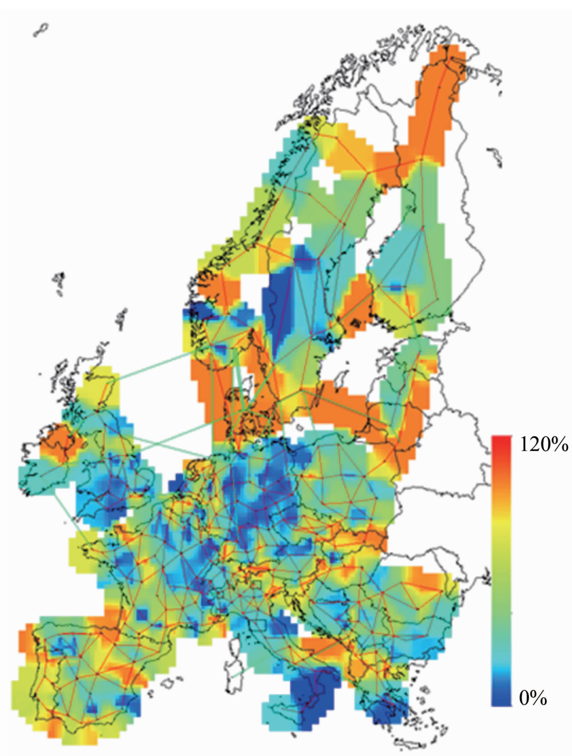


**Fig. 10 Power flow distribution for the GEI in 2030**

To the northwest, one line connecting the UK and Ireland is also operating at the limits; however, the interconnections from Greenland, do not contribute to this.

Finally, the interconnections located in the southern part of the EU causes moderate stress to the network. The most problematic interconnections are the ones from China in Slovakia and from Italy to Montenegro (the latter not involving GEI). Moreover, to the southwest, the flows of the interconnections among Spain and France and the northern part of the Spanish network approach to the maximum of their limits. This situation is coherent with the current condition of the cross-border interconnections between Spain and France, which are comparatively weak.

## 5.2 Results of 2050

Fig. 11 shows the power flow distribution of the EU network in 2050, according to the GEI scenario.

For the Scandinavian states, the situation keeps nearly similar to the 2030 case. For a particular example of Finland, due to the accommodation of the energy exchange with Russia, China, and the Arctic region, the entire Finnish network will be under much stress. However, as the ENTSO-E did not plan it to exchange electricity with those areas, the reinforcement of the Finnish grid is not currently under consideration. With the execution of some high voltage direct current (HVDC) projects, as the HVDC connection from Denmark to the Netherlands, the situation in some areas might improve. For example, compared with 2030, the overload in central Denmark would be removed.

To the northwest, the situation keeps more or less the same as in the case of 2030. However, due to the interconnections from the Arctic region, the whole UK network starts to experience congestions, with the sole exception of Wales.

The interconnections located in the southern part of the EU begin to have congestions under the 2050 scenario. Compared to the 2030 case, the most problematic interconnections are not only the ones already concerning in 2030; indeed, also Romanian, Greek, Croatian, Italian, Spanish, and Portuguese networks will experience large-scale congestion. Finally, as the Portuguese network accommodates much electricity from Africa, the entire Portuguese power system appears to be under much stress. Therefore, better network management techniques should be put in place, if network enhancement plan will not be considered by ENTSO-E ( the reason is similar to the case of Finland, as both of them are border countries, and initially not expected to have many connections in the current assumption of the ENTSO-E network development plans).

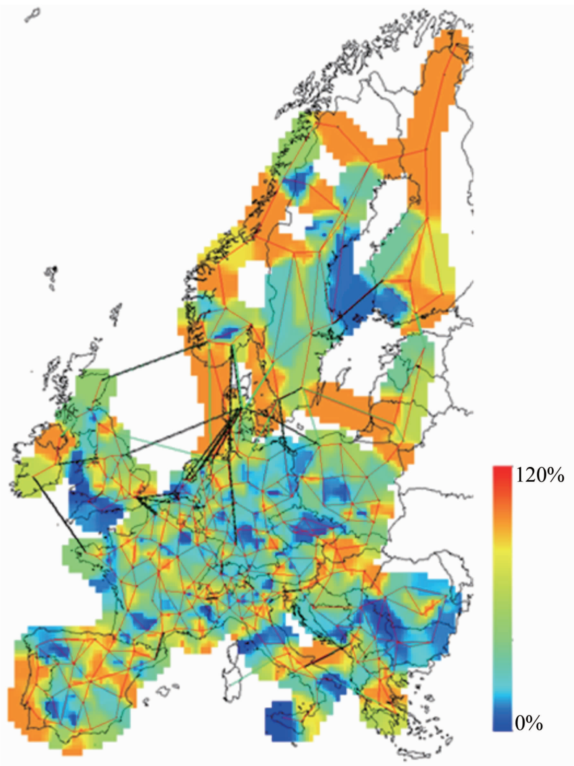


**Fig. 11　Power flow distribution for the GEI in 2050**

## 6　Conclusions

GEI has been proposed as a possible solution for the global decarbonization need. However, while widely deploying renewable energy sources, GEI has also set new challenges to regional power grids, by changing their internal power flow distribution. Therefore, further work should be done to study the compatibility of local power grids with GEI solution.

Under the premise of a unified global electricity market, this paper analyzes the European power grid development plan within a GEI scenario background. In particular, an innovative methodological approach is used for the analysis, combining traditional expansion planning techniques with socio-economic modelling, thanks to the use of a multi-disciplinary multi-criteria study as input to the power system traditional modelling. After fully optimizing the access nodes of the intercontinental power corridors, the distribution and congestion of internal power flow in 2030 and 2050 are computed.

The results show that there is a large scale of congestion between the Scandinavia area and the European continent, which makes it impossible to fully dispatch the wind power resources from the Arctic and the Nordic Sea, under the assumptions done.

Besides the description of a picture of the future European power grid in the context of the GEI scenario, the paper also wants to demonstrate that the planning of GEI requires close coordination between transmission system operators (TSO) and institutions in various regions to put in place this ambitious power grid paradigm.

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