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# Estimating the benefits of transmission expansion projects: An Aumann-Shapley approach

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ABSTRACT

This paper proposes a novel methodology to estimate the benefits produced by transmission expansion projects that are part of an expansion plan. Any methodology applied should be coherent with the technical and economic principles that underlie an efficient planning of the network expansion, where expansion projects are selected to be part of the plan according to the benefit they produce when considered jointly with the rest of projects. The methodology developed is based on the idea that projects to be undertaken should be evaluated jointly, instead of individually, because the benefits produced by each of them depend on other projects in the plan. We formulate a cooperative game to allocate the benefits of the plan to individual projects using the Aumann-Shapley concept. Then, players in the game are expansion projects. The method proposed is able to capture interactions among projects. Moreover, it is highly computationally efficient and therefore can be applied to real —large— expansion plans. Two case studies are used to compare the performance of the methodology proposed to that of existing methods. The results show that the proposed methodology provides regulatory authorities with the most relevant information for the identification of high-priority expansion projects.



## 1. Introduction and background

The evolution of the power sector from a fossil fuel based to a low-carbon economy requires the installation of very large amounts of renewable energy source (RES) generation, which will require a significant amount of transmission investments [1]. However, according to the European Commission (EC) and authorities in other regions, there is a significant risk of not undertaking the required investments —not even the priority ones— under the current regulatory framework [2].

The main barriers identified that jeopardize the deployment of these infrastructures concern the regulatory treatment given to them [3]. Some States of the European Union (EU) are developing dedicated regulatory frameworks to achieve the realization of important expansion projects[1] [4]. In line with this, together with planning authorities in the region, the EC is defining Projects of Common Interest (PCI). PCIs are projects that provide a high value to the EU's internal electricity market. In order to ensure their deployment, PCIs are subject to a facilitated permit granting process and improved regulatory treatment [5]. In the USA, reinforcements aimed at integrating RES generation also have priority status, as established in the Energy Policy Act, 2005, and the American Recovery and Reinvestment Act, 2009. Therefore, once the project benefits have been defined (economic, environmental and energy security benefits, through the integration of RES generation, or others), authorities need to identify the projects within the plan that should be considered priority projects.

*Abbreviations:* ACER, Agency for the Cooperation of Energy Regulators; AS, Aumann-Shapley; B/C, Benefit to Cost ratio; CAISO, California Independent System Operator; CBA, Cost-Benefit Analysis; CSW, Continental South-West; EC, European Commission; ED, Economic Dispatch; ENS, Energy Not Served; ENTSO-E, European Network of Transmission System Operators for Electricity; EU, European Union; FACTS, Flexible Alternating Current Transmission System; MENA, Middle East and North of Africa; PCI, Projects of Common Interest; PINT, Put IN one at a Time; RES, Renewable Energy Source; SW, Social Welfare; TEP, Transmission Expansion Plan; TOOT, Take Out One at a Time; TYNDP, Ten-Year Network Development Plan; USA, United States of America.

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[1] A project is normally composed of several transmission investments (lines, transformers…) that need to be installed at the same time for the system to take advantage of these investments.

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Nomenclature

| | | |
|---|---|---|
| Variables | | |
| $gp_{g,t}$: | power production of unit $g$ in each time period $t$ | [MW] |
| $ens_{i,t}$: | amount of energy demanded by a consumer in node $i$ that is not served in each time period $t$ | [MW] |
| $f_{l(ij),t}$: | power flow through line $l$, which connects nodes $i$ and $j$, in each time period $t$ | [MW] |
| $\theta_{i,t}$, $\theta_{j,t}$: | voltage angles of nodes $i$ and $j$, respectively, in each time period $t$ | [rad] |
| Parameters | | |
| $VC_g$: | variable production cost of unit $g$ | [€/MW] |
| $CO2Cost$: | per unit cost of $CO_2$ emissions | [€/MtCO2] |
| $ECO2_g$: | $CO_2$ emission rate of unit $g$ | [MtCO2/MW] |
| $ENSCost_i$: | unit cost of ENS at node $i$ | [€/MWh] |
| $y_{l(ij)}$: | admittance of line $l$ | [p.u.] |
| $\overline{F_{l(ij)}}$: | power flow capacity of line $l$ | [MW] |
| $\overline{GP_g}$: | maximum power production of unit $g$ | [MW] |
| $D_{i,t}$: | power consumption at node $i$ in each time period $t$ | [MW] |
| $W_t$: | weight (or duration) of time period $t$ | [h] |

Previously, in the EU, priority projects were defined through a negotiation process between the EU authorities and member states. However, in recent regulations [5], the EC states that priority projects should be identified using a cost-benefit analysis (CBA).

### 1.1. Background

Computation of the costs and benefits of transmission projects is not straightforward. A large number of works focus on the development of methodologies for the CBA of projects in a multiplicity of contexts, such as infrastructure investments [6] and smart grid projects [7].

Most research focuses on identifying and characterizing the types of benefits provided by expansion projects, or on the measurement and comparison of benefits of different kinds. A comprehensive catalog of potential benefits is presented in Ref. [8]. The authors in Ref. [9] carry out a CBA of two new EU interconnections and provide recommendations for further research. The CBA methodology developed in California by CAISO [10] is an important reference in this field. The EU has also funded numerous research projects to estimate the benefits and costs of projects. CBA methodologies have been developed in Refs. [11] and [12]. The authors in Ref. [11] provide a methodology to jointly consider all types of benefits of infrastructure investments in the EU, while the authors in Ref. [12] jointly determine the benefits of a set of projects to be deployed in the long term, leading to a transformed network.

Typically, when analyzing large transmission expansion plans (TEP) or groups of projects,[2] benefits are assessed for the whole plan, and not for each individual project in it. However, the allocation of the benefits of the whole expansion plan to each of the individual expansion projects that comprise it remains largely unexplored.

A growing number of authors highlight the need to assess the benefits of each specific project as part of a TEP to be deployed in a certain time frame [13] or the potential of these projects for bringing these benefits depending on the different uncertainties present, such as the Real Options Valuation approach in Ref. [14]. Assessing the benefits of projects as part of a plan -or group of projects-implies taking into account interactions occurring among these projects. Ignoring these interactions may imply misestimating the effects of expansion projects on system operation. Thus, the CBAs of projects on an individual project basis may be deemed inappropriate. The benefits of individual projects have traditionally been determined adopting a simple, though arguably inaccurate, approach. This involves comparing the system social welfare (SW) in two operation situations: the so-called "with" situation, where the expansion project being assessed is deemed to be in place in the system, and the "without" situation, where the project is considered not to be deployed. Similarly, ENTSO-E[3] proposes two approaches [15]: the Take Out One at a Time (TOOT) and the Put In one at a Time (PINT) methodologies. TOOT computes the benefits produced by each expansion project assuming that the other expansion projects in the plan have already been undertaken. PINT, however, computes the benefits of the concerned project by comparing the operation of the system with and without this project when none of the other projects considered have been undertaken.

TOOT and PINT methodologies have been employed by ENTSO-E for the assessment of the projects in the Ten Year Network Development Plan (TYNDP) [16]. Besides, in Ref. [17], the authors employ TOOT to evaluate the benefits provided by each of a previously defined set of projects. In Refs. [18] and [17], the authors recommend that benefits of projects be estimated both using the PINT and TOOT methodologies. Then, if the benefits estimated with both methodologies differ significantly, the authorities should carry out further analyses to obtain a reliable estimate of these benefits.[4]

More complex approaches have also been adopted. Works in Refs. [18] and [19] involve the application of the Shapley approach. According to this approach, the benefits created by each project are estimated as the average incremental benefit resulting from its deployment over all the possible orderings of the deployment of projects in the plan. In Ref. [18], the authors determine the benefits of four transmission projects using the Shapley value. In Ref. [19], the Shapley value is used to compute the incentives that should be provided to transmission investors.[5]

### 1.2. Aumann-Shapley approach: previous applications

The Aumann-Shapley approach (AS) is a generalization of the Shapley value. AS (or methods based on this concept) has been applied, among others, to the allocation of telephone costs to users [19], firm-energy rights to hydro plants [20], and electricity transmission losses [21] as well as congestion costs [22] to network

[2] A transmission expansion plan can be obtained as a whole (top-down approach) or by joining different groups of projects (bottom-up approach). The methodology proposed here can be applied in both cases.

[3] European Network of Transmission System Operators for Electricity.

[4] Besides, the authors in Ref. [17] acknowledge that, "*if the timing of construction of the interconnectors were according to schedule, the analysis could be carried out based on the construction order,…*". This point is further discussed in Section 2.

[5] Notice that changing the set of projects to be undertaken would automatically result in a change in the benefits produced by each project, which could potentially lead to a network expansion that departs from the most efficient one.

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