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Beneficiaries of transmission expansion projects of an expansion plan: An Aumann-Shapley approach

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HIGHLIGHTS

- Novel methodology to calculate the benefits of users from expansion projects.
- The methodology proposed is based on the Aumann-Shapley concept.
- Consistent with the technical and economic principles of network expansion.
- The methodology can be employed for regulation and policy-making.

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ABSTRACT

The objective of this paper is to propose a novel methodology to compute the benefit obtained by the individual transmission network users from each of the transmission expansion projects within an expansion plan. The benefits computed should be coherent with the technical and economic principles that underlie the development of the expansion plan. Thus, this methodology is based on the idea that the benefits produced by each project of a plan should be determined considering all projects jointly, instead of individually. Some benefits obtained by users from projects evolve continuously with the deployment of the expansion plan, while others are discrete, since they occur at certain points of the deployment of this plan. A separate Aumann-Shapley game is solved to allocate continuous benefits, and each discrete one. In the second case, the standard Aumann-Shapley algorithm for the allocation of benefits is modified to cope with the fact that the function of each user's benefits is not continuous with the size of projects deployed. Two case studies are used to compare the methodology proposed with existing ones and demonstrate its applicability to real-life decision making processes. The results show that the methodology proposed is able to overcome problems detected in other methodologies, providing more accurate and sound results. The good properties of the methodology proposed make it applicable to problems related to network expansion regulation, such as the cost allocation of new investments. Although the methodology proposed is particularized to electric power systems, its concept and fundamentals can also be applied in other energy sectors, such as gas.

1. Introduction

Large network investments are required to integrate the renewable energy source (RES) generation expected to be deployed in subsequent years [1,2]. In addition to the difficulty of planning the expansion of the network[1] [3,4], there are also relevant barriers to the construction of the required investments [5], mainly of a regulatory nature. The lack of socio-political acceptance of the decision on how to allocate the cost of the new investments is among the most significant barriers [6]. Moreover, with the involvement of several countries or states in the development of new transmission assets, this barrier is expected to grow in importance.

The cost allocation problem has been extensively studied in the literature, and several methods have been proposed for this during

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[1] Recent works are trying to coordinate the transmission expansion planning with the generation expansion planning.

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Nomenclature

gp_g power production of unit g [MW]
ens_c amount of energy demanded by a consumer c that is not served [MW]
$f_{l(ij)}$ power flow through line l, which connects nodes i and j [MW]
θ_i, θ_j voltage angles of nodes i and j, respectively [rad]
VC_g variable production cost of unit g [€M/MW]
$CO2Cost$ per unit cost of CO_2 emissions [€M/MtCO$_2$]
$ECO2_g$ CO_2 emission rate of unit g [MtCO$_2$/MW]
$ENSCost$ unit cost of ENS [€M/MW h]
$y_{l(ij)}$ 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_c power consumption of a consumer c [MW]
GB_g, CB_c, TB_l generators', consumers' and TOs' benefits in the dispatch [€M/yr]
$\Delta GB_g^k, \Delta CB_c^k, \Delta TB_l^k$ discrete change generators', consumers' and TOs' benefits in the dispatch produced in step k [€M/yr]
$Vgp_{g'}^l, Vens_{c'}^l Vf_{l''}^l$ total change caused by project l in the production of g', ENS of consumer c' and flow through line l'' [MW]
$Cgp_{g'}^l, Cens_{c'}^l Cf_{l''}^l$ relative contribution of project l to the change in the production of g', ENS of consumer c' and flow through line l'' [%]
$DGB_{g,k}^l, DCB_{c,k}^l, DTB_{l',k}^l$ discrete benefits of generator g, consumer c and TO l' produced in step k by project l [€M/yr]
$GB_g^l, CB_c^l, TB_{l'}^l$ total benefits of generator g, consumer c and TO l' produced by project l [€M/yr]

the years [7,8]. The authors of [9] analyzed the impacts of different cost allocation schemes on the expansion of the transmission network. Furthermore, the cost allocation problem is not only important for the expansion of the transmission network, it is also relevant for the efficient expansion of the distribution network [10], and for the development of new generation capacity in the system [11]. Nonetheless, many of the proposed methods for the cost allocation do not comply with one of the basic principles of transmission pricing [12]: allocation of the costs of a transmission project in proportion to the benefits that each network user[2] or system comprising a set of network users is expected to obtain from it, which is called the "beneficiary pays" principle.

European Union (EU) and US authorities have recently adopted this principle as the basis to perform the cost allocation of new infrastructures[3] [14,15]. However, applying this principle is not easy, due to the difficulty in determining the benefits that each expansion project produces and in identifying the stakeholders (beneficiaries) that obtain these benefits [16]. The need to jointly assess the benefits produced by a multitude of projects planned over the coming years/decades for wide regions, due to the interdependencies existing among these projects, adds to the complexity of the problem [17].

1.1. Methods to identify the beneficiaries and their benefits of transmission expansion projects

A significant amount of work has been carried out in recent years to identify and describe the benefits of transmission expansion projects [13,18–20]. Nonetheless, limited attention has been paid to developing a comprehensive methodology to determine the benefits that each network user or national/local system is expected to obtain from expansion projects, especially when said projects are part of large expansion plans. Typically, benefits and beneficiaries are assessed for the whole plan, and not for each individual project [21,22]. However, allocation of the benefits of the whole expansion plan to each of the individual projects that comprise it remains largely unexplored. Nevertheless, the beneficiaries and their benefits of each project –and not of the plan– must be determined if the "beneficiary pays" principle is to be applied.

The benefits and beneficiaries of individual projects have traditionally been determined following a simple –through arguably inaccurate– approach. This involves comparing the social welfare (SW), or the increase in the benefits obtained by each user of the transmission network, in two situations: the so-called "with" situation, where the expansion project to be evaluated is considered to be in place in the system, and the "without" situation, where the project is considered not implemented. In order to cover the limitations of this approach, the European Network of Transmission System Operators for Electricity (ENTSO-E) proposed two different, but complementary, approaches [23]: The Take Out One at the Time (TOOT) and the Put In one at the Time (PINT). The TOOT method involves excluding the new project to be assessed from a future grid where all the rest of planned expansion projects have been included. On the other hand, the PINT method involves starting from the already existing network and including in it, one at a time, only the new network expansion project to be assessed at this time. For both methods, and as explained above, the benefits result from comparing the operation of the system in the target time horizon with and without the concerned project in place. The Shapley value is proposed in [24] to assess the benefits and beneficiaries provided by four expansion projects. According to this approach, the benefits and beneficiaries of each expansion project are determined as the average incremental overall benefits resulting from its deployment and, within those, the average incremental benefits obtained by each user, over all the possible orders of the deployment of projects in the plan. This approach has also been used in [25] in order to compute the expansion of the network.

These approaches have been analyzed in previous works [26–30]. In [26], the authors introduce the characteristics that a benefit assessment method of expansion projects should have in order to be consistent with the technical and economic principles behind the expansion of the network. These principles are briefly explained in Section 2.1.

1.2. Aumann-Shapley approach: previous applications

The Aumann-Shapley approach (AS) is a well-known cooperative game theory solution concept. Cooperative game theory has been widely used in the literature, adopting different solutions concepts. For example, Shapley value together with the core were used to analyze how market rules may affect the deployment of microgrids [31]. Another application of cooperative game theory to determine the sharing of the profits inside a virtual power plant was presented in [32] using the Shapley value and the Nucleolus.

[2] Here we differentiate three kinds of users in the same way they are considered in [13]. Generators employ the network to transport the electricity they produce to load centers. Consumers transport the electricity they consume from generators to where they are located. The owners of each specific transmission line transport themselves some power from one point in the network to another.

[3] The EU only requires it to be used for Projects of Common Interest, while US authorities require it to be used for inter-regional projects.