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InfraFair: Infrastructure cost allocation

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ABSTRACT

Networks play a pivotal role in the energy transition, integrating renewable energy sources and facilitating sustainable energy systems. A huge amount of investment in energy networks is still required to make the energy transition a reality. When constructing network infrastructures, especially among countries at the regional level, the allocation of costs must be well-aligned with the economic benefits each cost-bearing party expects to obtain from the corresponding investments. However, efficiently allocating the cost of infrastructure networks has proven to be a difficult task, especially for cross-border infrastructure. Such a task is expected to become even more difficult in the future as networks become more meshed and coupled between the different sectors. InfraFair is a cost allocation tool for networks, both national and regional. It allocates the costs of different assets in the network to users based on their expected or actual usage. InfraFair is the first open-source software to provide this functionality for all flow-based infrastructure networks, such as electricity, hydrogen, gas and heat. It has been used in studies to allocate transmission network costs in Africa at the regional power pool level and has been developed as part of the OpenMod4Africa project. It is now available open-source for use by the wider scientific community.

1. Metadata

Nr	Code metadata description	*Please fill in this column*
C1	Current code version	InfraFair v1.1.0
C2	Permanent link to code/repository used for this code version	https://github.com/IIT-EnergySystemModels/InfraFair
C3	Permanent link to reproducible capsule	https://codeocean.com/capsule/9648975/tree
C4	Legal code license	The InfraFair code is provided under the GNU General Public License: • the code cannot become part of a closed-source commercial software product. • any future changes and improvements to the code remain free and open.
C5	Code versioning system used	Git
C6	Software code languages, tools and services used	Python
C7	Compilation requirements, operating environments and dependencies	Python packages: pandas, numpy, matplotlib, time
C8	If available, link to developer documentation/manual	https://infrafair.readthedocs.io/en/latest/index.html
C9	Support email for questions	Mohamed A.Eltahir Elabbas, mohamed.a.eltahir@hotmail.com

2. Motivation and significance

Networks play a pivotal role in the energy transition, integrating renewable energy sources into existing infrastructures and facilitating sustainable energy systems [1]. Different types of energy network would be required depending on the energy source and other considerations that vary across the different regions [2]. Generally, a huge amount of investment in energy networks is still required to make the energy transition a reality [3]. When building network infrastructures, especially regional[1] ones, the allocation of costs must be transparent and well-aligned with both the economic benefits each cost-bearing party expects to obtain from the corresponding investments and the use they intend to make of the new network elements [4].

Nevertheless, efficiently allocating the cost of infrastructure networks has proven to be a difficult task, especially for cross-border

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[1] In this paper, the term regional refers to an area or scope larger than a single country.

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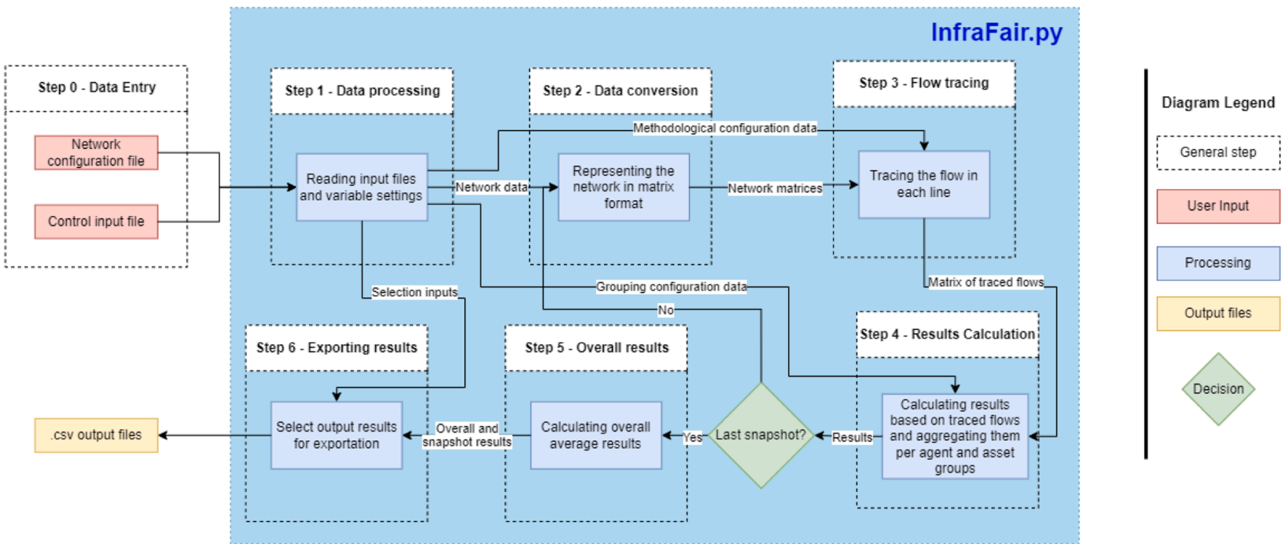


Fig. 1. InfraFair architecture showing the execution steps with an arrow representing the movement of data between them.

Table 1
Input data in the network configuration file.

N.	Sheet name	Column name	Description of the content	Mandatory/ Optional	Data type	Unit (if applicable)
1	Flows	Line	All the assets in the network. The asset name consists of the two connected nodes separated by "-"	Mandatory	String	No unit
2		Flow	The flow in each asset	Mandatory	Float	Watt or multiples of it
3		Losses	The losses on each asset	Optional	Float	Watt or multiples of it
4	Network	Node	All the nodes in the network. The node name must be an integer value	Mandatory	Integer	No unit
5		Generation	The generation (injection) at each node	Mandatory	Float	Watt or multiples of it
6		Demand	The demand (withdrawal) at each node	Mandatory	Float	Watt or multiples of it
7		Country	The country of each node	Mandatory	String	No unit
8		SO 1	The first system operator of each node	Optional	String	No unit
9		SO 2	The second system operator of each node	Optional	String	No unit
10	Asset attributes	Line	Similar to the column in the Flows sheet	Mandatory	String	No unit
11		Type	The type of each asset numerically coded	Mandatory	Integer	No unit
12		React	The reactance-to-length ratio for each asset	Optional	Float	p.u.
13		Capacity	The rated capacity of each asset	Optional	Float	Watt or multiples of it
14		Length	The length of each asset	Optional	Float	Km
15		Exist/Planned	"Exist" for existing asset or "Planned" for planned asset	Optional	String	No unit
16		Voltage	The voltage level of each asset	Optional	Float	kV
17		Regional assets	1 for regional asset or 0 for national asset	Optional	String	Binary
18		Cost	The cost of each asset to be allocated	Optional	Float	Currency unit (e.g., dollar)
19		SO Owner 1	The name of the first owner of each asset	Optional	String	No unit
20		SO 1 Ownership	The ownership percentage of the first owner for each asset	Optional	Float	Percentage
21		SO Owner 2	The name of the second owner of each asset	Optional	String	No unit
22		SO 2 Ownership	Contains the ownership percentage of the second owner for each asset	Optional	Float	Percentage

infrastructure, given the financial implications for the different parties [5]. Allocating the costs of infrastructure facilities to their economic beneficiaries is challenging in practice due to the lack of adequate information on the behavior of agents, which hinders the consideration of all types of benefits [6]. For this reason, network utilization or usage is commonly used as a proxy for benefits. Different methods exist in the literature for measuring network utilization [7–9]. Such methods and their practical implementation also differ from sector to sector, and the choice of cost allocation method is a contentious issue, even within the same sector [10]. As networks become more meshed and coupled between different sectors, cost allocation is expected to become more complex in the future. Thus, the absence of a transparent tool for cost allocation will further complicate efforts to achieve consensus on the development of new infrastructure projects.

InfraFair is the first open-source modelling tool for allocating the costs of different flow-based infrastructure networks, both national and cross-border [11]. It aims to facilitate consensus on new infrastructure investments by providing a transparent way for allocating the costs of different assets in the network to users based on their expected, or actual, usage. It does so by employing a method called the Average Participations Method (APM). APM assigns the responsibility for energy flows caused by producers and consumers through a simple heuristic rule that uses only the actual (historical or estimated) pattern of flows in the network (for more details, see [10,5]). APM has been evaluated against other cost allocation methods for the electrical transmission

Table 2
Required input data in the control input file.

N.	Control input variable	Description	Data range/ type
1	Nodal Aggregation	To determine the variant of Average Participations to be applied, 1 for aggregating demand and generation at the same node, 0 for treating them separately	Binary
2	Demand Cost Responsibility (%)	The percentage of demand responsibility for the cost of the assets	0–100
3	Generation Cost Responsibility (%)	The percentage of generation responsibility for the cost of the assets	0–100
4	Length per Reactance (p.u.)	In case the length of the assets is given in terms of reactance, how many km length corresponds to 1 per unit reactance	0–1000
5	Voltage Threshold (kV)	The voltage threshold for the transmission assets to be considered (in kV)	Positive value
6	Number of Snapshots	The number of hourly snapshots to be considered jointly for representing the annual usage	1–8760
7	Snapshots Weights	The number of hours each snapshot represents, the total should be 8760 h (one year)	Set of 8760 sum
8	Cost Allocation Option	1 to allocate the full cost, 2 to allocate only the cost of the used capacity, 3 to allocate full cost if the assets are classified as 'Exist' and the cost of the used capacity if they are classified as 'Planned', 4 is to allocate the cost based on the utilization threshold, if the asset is utilized more than the threshold, allocate the full cost, otherwise, allocate the cost of the used capacity	1–4
9	Utilization Threshold (%)	If the ratio between the used asset capacity and the asset rated capacity is equal or above this percentage, the asset cost will be fully allocated, otherwise, only the cost of the used capacity will be allocated. This will be used only if 'Cost Allocation Option' is set to 4	0–100
10	Cost of Unused Capacity	To determine what to do with the cost of unused capacity in case the 'Cost Allocation Option' is not set to 1. 0 to do nothing, 1 to allocate it equally among agents who use the asset, 2 to allocate it equally among all agents of the country(ies) owning the asset, 3 to allocate it equally among all agents	0–3
11	Demand Socialized Cost Responsibility (%)	The percentage of demand responsibility to the socialized cost of the assets. Only used when the 'Cost Allocation Option' is not set to 1 and 'Cost of Unused Capacity' is not set to 0	0–100
12	Generation Socialized Cost Responsibility (%)	The percentage of generators responsibility for the socialized cost of the assets. Only used when 'Cost Allocation Option' is not set to 1 and 'Cost of Unused Capacity' is not set to 0	0–100
13	Asset Types	Mapping the asset type with its code	Integer value
14	Snapshots Results	1 or 0 to enable or disable separate results for each snapshot, respectively	Bool
15	Agent Results	1 or 0 to enable or disable results per agent, respectively	Bool
16	Country Results	1 or 0 to enable or disable results per country, respectively	Bool
17	SO Results	1 or 0 to enable or disable results per system operator, respectively	Bool
18	Intermediary Results	1 or 0 to enable or disable intermediary results in terms of flow-km contribution and utilization percentage, respectively	Bool
19	Aggregated Results	1 or 0 to enable or disable aggregated results per asset group, per country assets and per system operator assets, respectively	Bool
20	Losses Allocation Results	1 or 0 to enable or disable allocating transmission losses per agent per asset	Bool
21	Demand Losses Responsibility (%)	The percentage of demand responsibility to the losses of the assets	0–100
22	Generation Losses Responsibility (%)	The percentage of generators responsibility to the losses of the assets	0–100
23	Losses price ($/MWh)	The price of energy lost. The energy unit should be the same as the flow	Positive value
24	Regional losses	1 to allocate losses in regional assets only, 0 to allocate losses in all assets	Bool
25	Cost of regional assets	1 to allocate the cost of regional assets only, 0 to allocate the cost of all assets	Bool

p.u. indicates the per unit value of the reactance. Note that there is no need to provide any information about the reference base value. The only condition for consistent calculation is for entry 4 in Table 2, Length per Reactance, to be also given in a per unit value calculated using the same reference base values.

network and has demonstrated superior consistency with economic, engineering, and regulatory principles [12,13,10] .[2] This establishes infraFair as a solution for addressing a significant gap in cost allocation practice, where the open-source, cross-sectoral application of such models remains underdeveloped. This paper describes the software architecture, inputs, outputs and functionalities. The usefulness of InfraFair is illustrated by several examples.

3. Software description

InfraFair has been created using Python 3.9.19 and uses an xlsx format for its inputs and a csv format for its outputs. The InfraFair software is not built for a specific operating system but can rather run on any machine with a compatible version of Python, including Windows, MacOS, and Linux. The core of the software is a simple matrix manipulation that repeatedly tracks energy flows in each of the selected operational snapshots (see the mathematical formulation in [14]).

The following subsection describes the software architecture, its inputs and outputs, and its main functionalities.

3.1. Software architecture

An overview of the InfraFair software is shown in Fig. 1. Before running the software, the user performs an initial step (Step 0) manually. In this step, the user prepares the case study in the network configuration file and fills out the required inputs in the control input file. Upon its execution, the program first requests the user for the case study path, the

[2] Justifying that APM provides the best approximation to network usage for all flow-based energy infrastructure is beyond the scope of this paper. APM has been applied only in the electricity sector, and its application to other network infrastructures remains a potential use.

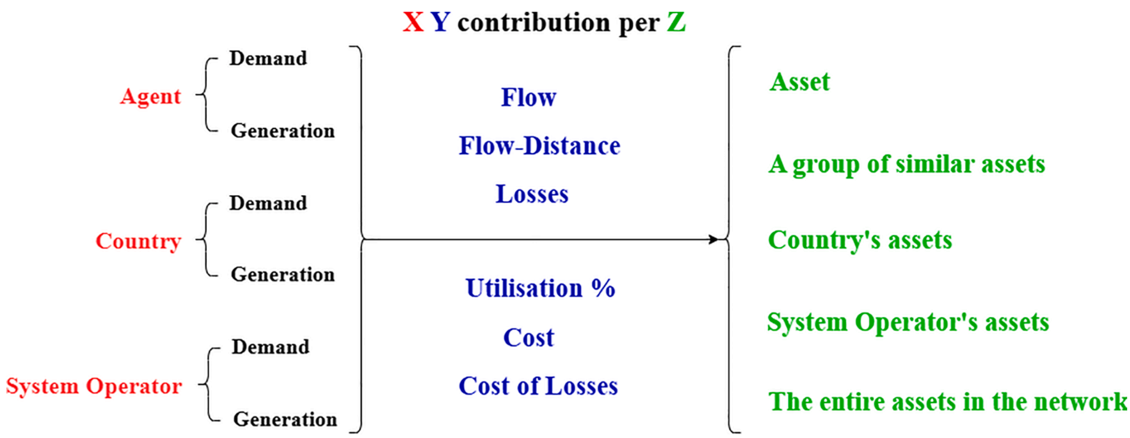
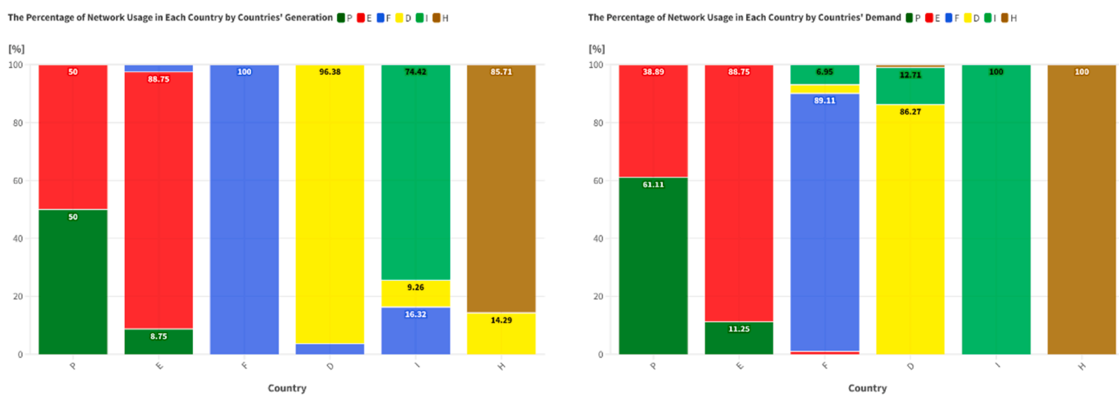


Fig. 2. Naming format of output files.



(a) Generation results (b) Demand results

Fig. 3. Electricity network utilization of each country by network users of other countries.

name of the case study file, and the configuration file. Based on this, the module loads the input files in Step 1 and converts the case study input file to matrix format in Step 2. In Step 3, the software applies APM using the output from Step 2 and the methodological configuration specified in the control input file. The result of Step 3 is a matrix of the contribution factors of each agent in the network to the flows of all the assets. This matrix is used in Step 4 to allocate costs and compute intermediate results, including grouping results by country or system operator. Then, in Step 5, the software calculates the hourly weighted average results of all the snapshots to give the overall annual results. Finally, the results are exported in Step 6 according to the user preferences specified in the control input file.

The model inputs consist of the map of flows (i.e., the flow in each asset) and the injections and withdrawals of energy at each node. Additionally, the rated capacity and the capital cost of each asset must be provided for the model to be able to allocate costs to network users. However, they are not required for the basic function of tracing the flows in the network. Other information, such as the voltage and the length of each asset, can be provided to produce optional categorized results.

Table 1 shows the various entries in the network configuration file and whether they are optional or mandatory. If the optional data is not provided by the user, the software will ignore it. For instance, if no data is provided for the system operators column, then aggregation by system operator will not be considered. On the other hand, mandatory data must be provided in full for the software to run successfully. Note that the cost data is optional because it is not required for the basic function of the software (tracing the flow), but it must be provided in order to allocate the costs. Table 2 shows the required inputs to be filled in the control input file. Inputs that have the same measuring unit must also have the same unit prefix. For instance, flow, losses, generation, demand, and capacity have all a power unit of Watt; thus, if flow is given in MW, all of them should also be provided in MW. The model does not deal with possible inconsistencies in the units used to express different input parameters of the same type. However, inputs that have different units can have different unit prefixes (e.g., voltage could be given in kV while flow is given in MW). The software does not perform any unit conversion or pre- or post-treatment.

The software can be installed using the instructions in [14]. The Python code attempts to follow the PEP 8 recommendations.

The output of InfraFair is a series of .csv files. The name of each file indicates the type of results it contains. The general format of the names is *X Y contribution per Z*, where X is the type of user or group of users, Y is the type of contribution they make, and Z is the asset or group of assets (e.g., country demand flow contribution per asset). Fig. 2 shows the different combinations of the three elements. Note that grouping the allocation results by country or system operator simply means adding up all the agents' results (e.g., agents allocated cost) within each country or system operator area. Additionally, the outputs are produced in the same units as the inputs (e.g., if the cost is given in thousands of dollars, all the cost contribution files are in thousands of dollars).

3.2. Software functionalities

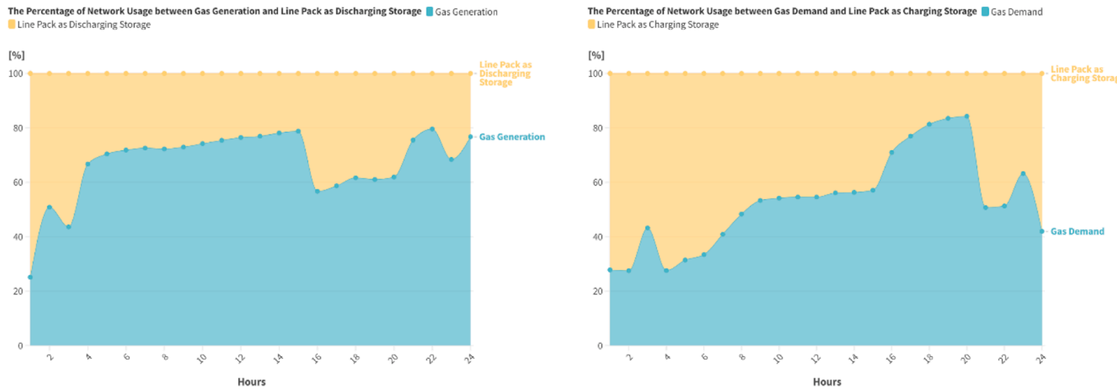
InfraFair determines the network utilization of agents, system operators and countries. Based on this utilization, accepted as a proxy of and assuming that it reflects the economic benefits or, equivalently, of

Table 3
Compensation among countries for the use of their generation.

	ZB	ZG	ZI	DB	DD	DE	DF	DI	DJ	EA	EB	EC	ED	EF	EG	EH	EI	FF
ZB	236,462	22,598	4321	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ZG	499	18,705	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ZI	723	0	599,871	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DB	0	0	20,149	214,977	9491	93	1	0	0	543	1123	0	0	0	1628	420	0	0
DD	0	0	7478	0	34,546	3412	272	0	0	0	2563	0	0	0	0	0	0	0
DE	0	0	12,913	0	7977	246,952	28,756	0	0	0	4783	2450	0	0	0	0	0	0
DF	0	0	1518	0	1094	13,250	67,513	0	0	0	0	1610	414	0	0	0	0	0
DI	0	0	4884	0	0	0	12	82,918	2562	0	0	0	0	0	0	0	0	0
DJ	0	0	275	0	0	1788	18,814	7210	54,265	0	0	0	0	0	0	0	0	0
EA	0	0	0	0	0	0	0	0	0	1809	1139	0	0	0	1181	117	0	0
EB	0	0	0	0	0	531	0	0	0	0	29,865	2553	0	0	0	47	473	0
EC	0	0	0	0	0	0	0	0	0	0	0	1471	0	0	0	0	4	0
ED	0	0	0	0	0	0	4520	0	0	0	0	0	206,162	0	0	0	0	0
EF	0	0	0	0	0	0	0	0	0	0	0	0	0	3151	1839	0	0	0
EG	0	0	0	0	0	0	0	0	0	418	130	0	0	321	2831	132	0	0
EH	0	0	0	0	0	0	0	0	0	0	31	102	0	0	0	15,594	1554	675
EI	0	0	0	0	0	0	0	0	0	0	0	1119	1038	0	0	0	15,805	1010
FF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	392	4	241
Cost to receive	26,919	499	723	33,448	13,725	56,879	17,886	7458	28,087	2437	3605	4	4520	1839	1000	2361	3167	396
Cost to pay	1222	22,598	51,539	0	18,563	19,074	52,374	7210	2562	960	9770	7834	1452	321	4647	1107	2036	1684
Net	25,698	−22,099	−50,816	33,448	−4838	37,804	−34,488	248	25,525	1477	−6165	−7829	3068	1518	−3647	1254	1131	−1288

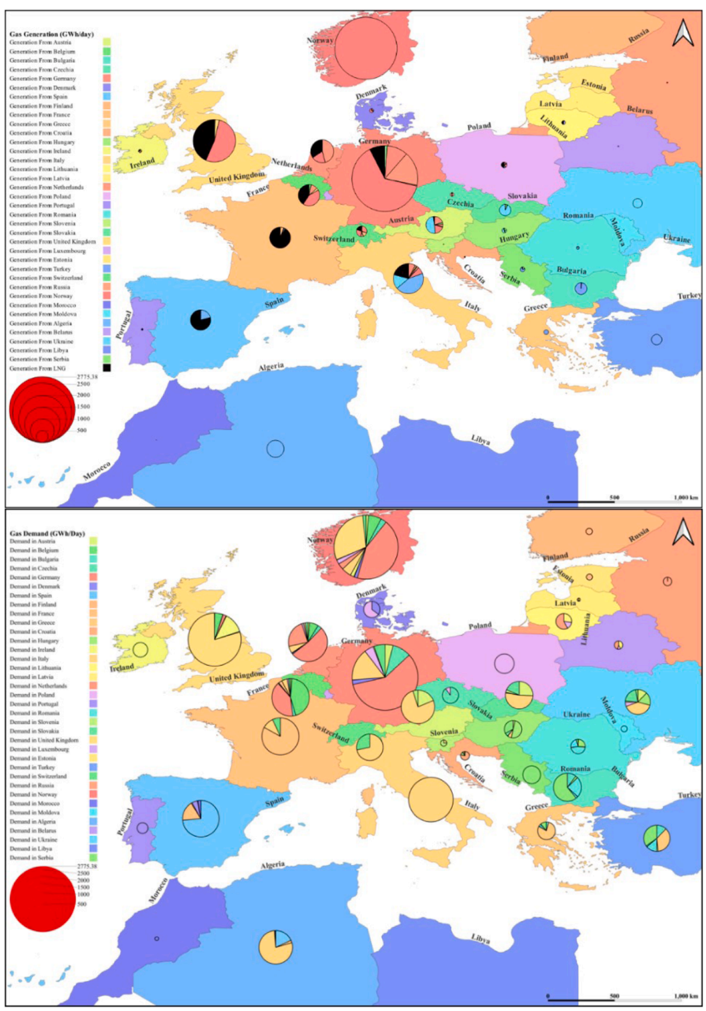
Table 4
Compensation among countries for the use of their demand.

	ZB	ZG	ZI	DB	DD	DE	DF	DI	DJ	EA	EB	EC	ED	EF	EG	EH	EI	FF
ZB	262,666	317	399	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ZG	1054	18,150	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ZI	2600	0	584,641	5763	1810	1057	10	4711	1	0	0	0	0	0	0	0	0	0
DB	0	0	0	248,425	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DD	0	0	0	14,759	31,659	1852	1	0	0	0	0	0	0	0	0	0	0	0
DE	0	0	0	609	958	280,593	18,862	275	2535	0	0	0	0	0	0	0	0	0
DF	0	0	0	238	56	20,227	61,440	175	2547	0	0	0	717	0	0	0	0	0
DI	0	0	0	0	0	0	0	81,576	8801	0	0	0	0	0	0	0	0	0
DJ	0	0	0	0	0	0	0	5552	76,799	0	0	0	0	0	0	0	0	0
EA	0	0	0	712	0	0	0	0	0	3123	0	0	0	0	412	0	0	0
EB	0	0	0	1780	1245	6726	11	0	0	1530	21,966	0	0	0	195	17	0	0
EC	0	0	0	0	0	853	100	0	0	0	521	0	0	0	0	1	0	0
ED	0	0	0	0	0	0	413	0	0	0	0	856	207,684	0	0	0	1729	0
EF	0	0	0	0	0	0	0	0	0	0	0	0	0	4053	936	0	0	0
EG	0	0	0	955	0	0	0	0	0	267	0	0	0	519	2090	0	0	0
EH	0	0	0	284	0	0	0	0	0	13	429	0	0	0	520	16,709	0	0
EI	0	0	0	0	0	0	0	0	0	0	615	9	0	0	0	3318	15,030	0
FF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	637	0	0
Cost to receive	716	1054	15,952	0	16,612	23,237	23,960	8801	5552	1124	11,504	1476	2998	936	1742	1247	3942	637
Cost to pay	3653	317	399	25,100	4069	30,716	19,396	10,714	13,883	1811	1566	865	717	519	2063	3974	1729	0
Net	−2937	737	15,553	−25,100	12,543	−7478	4563	−1913	−8330	−687	9939	611	2281	417	−321	−2727	2213	637



(a) Generation results (b) Demand results

Fig. 4. Hourly utilization of the Belgian gas network by generation, demand and line pack.



(a) Generation results

(b) Demand results

Fig. 5. Geographical representation of the European gas network showing the network utilization of each country by other countries.

Table 5
Overall average flow exchange among the different areas in South-Holland District Heating Network.

Area	Rotterdam network users	The Hague network users	Lansingerland network users
Rotterdam network	805.985	4.24	51.11
The Hauge network	26.325	120.885	0.13
Lansingerland network	94.09	0	118.215
Flow created in the area by other users	55.35	26.455	94.09
Flow created by the users in other areas	120.42	4.24	51.24
Net flow	−65.07	22.215	42.85

the responsibility of the agents associated to each piece of infrastructure, InfraFair allocates the cost of each network component to each agent. Additionally, it can attribute energy losses in the assets to the agents. When provided with hourly representative snapshots of these inputs,[3] InfraFair can calculate (per snapshot and overall annual weighted average):

- Individual agent flows, losses and cost contributions to each asset in the network.
- Country flows, losses and cost contributions to each asset in the network.
- Individual agent and country utilization of each asset in the network.
- Individual Agent flows, losses and cost contributions to similar aggregated assets.
- Country flows, losses and cost contributions to similar aggregated assets.
- Individual agent and country utilization of similar aggregated assets.
- Individual Agent total cost contribution to be paid.
- Individual agent and country utilization of the whole network.
- Country flows, losses and cost contributions made of the use of each other country.
- Country total flow and cost contributions made of the use of the rest of the network.
- Country flows, losses and cost incurred from the use made by the rest of the countries.

4. Illustrative examples

We include five case examples, which can be downloaded from [11], to demonstrate the functionalities and applications of InfraFair for the different infrastructure networks. The software runtime depends on many factors, including the capabilities of the machine, the size of the network and the number of snapshots considered, and the user's choice of which results to export. The runtime given in each example here was obtained using a Dell Latitude 7320, Intel Core i7–1185G7 machine. Note that the figures shown are obtained with external visualization tools. Future versions of InfraFair will include such graphical representations of results.

Example 1. *Simple Electricity Network*

This example uses a simplified electricity network of six countries, thirteen lines, six demands and six generators. The map of flows in this example comprises a single operational snapshot. The basic output results (identical to those obtained in [10]) consist of the traced flow on each line to generators and demands. These results can be grouped by country assets as well as by country demand and generation to give the percentage of network usage for each country by other countries, including itself, as shown in Fig. 3. Runtime is <1 second.

Example 2. The European Union Regional Electricity Network

The network presented in this example represents an old snapshot of the European transmission network that includes eighteen countries with detailed network representation: 3383 nodes and 5681 transmission lines. A single operational snapshot is used in this example to trace the flow. Table 3 shows the costs allocated to country generation (columns) based on their use of other countries' assets (rows). The diagonal costs reflect the cost that a country has to pay itself according to the use of its own generators. The row "cost to receive" indicates per country the total cost it should receive due to other countries' generators using its assets (which is the sum of the country's row minus the cost it should pay itself). The row "cost to pay" indicates per country the total cost it should pay due to the use its generators are making of other countries' assets (which is the sum of the country's column minus the cost it should pay itself). The "Net" row shows the compensation that each country should pay (negative) or receive (positive). Similarly, Table 4 shows the costs allocated to the country's generation (columns) based on their use of other countries' assets (rows). Runtime is <2.5 min.

Example 3. The Belgian Gas Network

The network presented in this example is an outdated representation of the Belgian high-calorific gas network, which includes two primary supply units and ten consumption nodes. There are twenty physical nodes in the network and twenty-four pipelines. However, due to the storage capacity of the gas pipelines (referred to as line pack [15]), a virtual node was added for each pipeline to model its storage. In this example, exports and imports are not considered. The map of flows used in this example is obtained from an optimal dispatch of the system for a 24-hour period (For further details, please see [15,16]). Fig. 4 shows the hourly network utilization results by demand, generation and line pack. Runtime is 5 s.

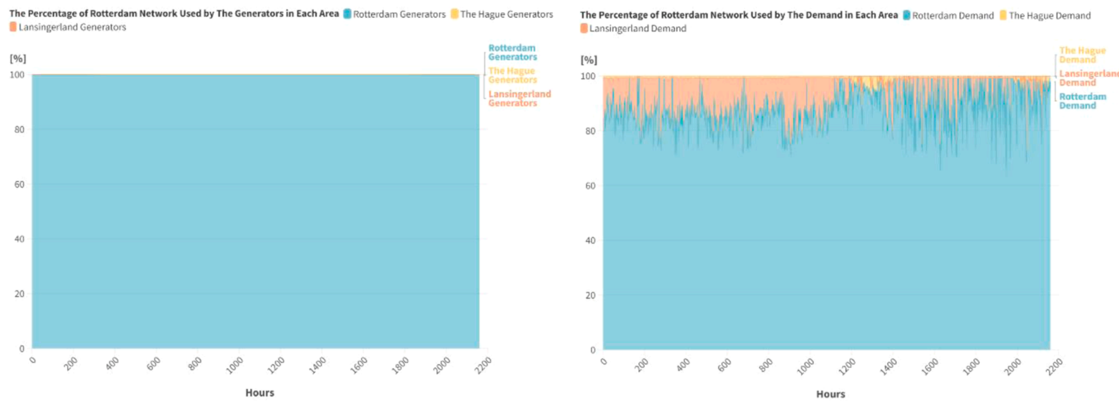
Example 4. The European Union Regional Gas Network

The network presented in this example represents the European Regional Gas Network [17], which includes fifty-two countries in continental Europe, four other countries, and liquefied natural gas (LNG) terminals. Each of these is represented by a single node, for a total of 57 nodes with 63 interconnection pipelines. The example includes daily aggregated data (GWh/day) corresponding to the maximum gas demand day in 2022, which was December 13. It is assumed that interconnection pipelines are shared equally between the interconnected countries. Furthermore, this example does not consider the impact of the line pack. Fig. 5 contains the geographical map of the countries and a pie chart showing the usage of each country's network by demand or generation of other countries, including its own demand or generation. Runtime is 1 second.

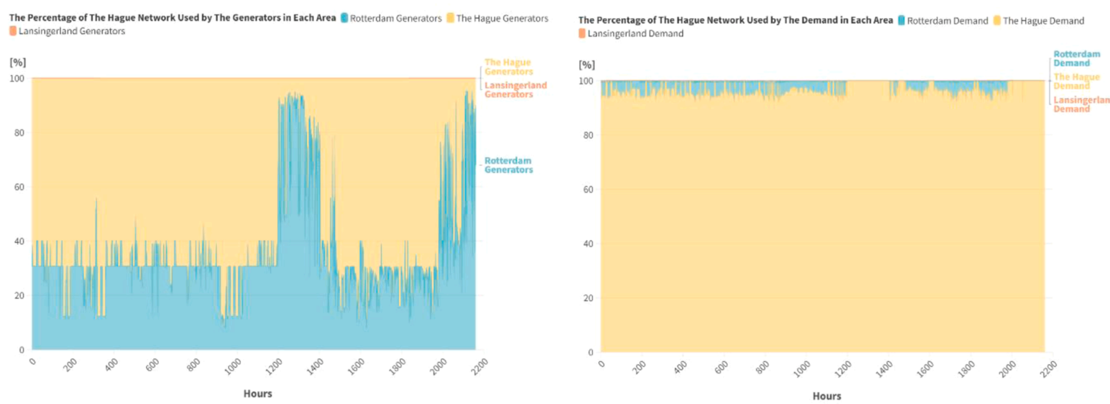
Example 5. Heat Distribution Network in The Netherlands

The network presented in this example represents the South-Holland District Heating Network (DHN), which connects the cities of Rotterdam, The Hague and the region of Lansingerland (B-triangle). It is operated by Eneco and connects buildings (households, companies) to the waste heat of the port of Rotterdam, waste incineration plants, steam and gas turbines, and heat buffers that function as heat storage. Some of the gas pipelines are bidirectional (with two arrows), while the majority are unidirectional. This example employs an hourly-projected demand of the three cities in the first three months of 2030 (total of 2160 h). This total demand is supplied by the 25 supply units using optimal economic dispatch, which considers future fuel and CO2 prices (for more details, see [18]). The map of flows obtained from the optimal dispatch is employed as input data to determine both the overall and hourly network utilization. Table 5 shows the overall results (averaged equally over the 2160 snapshots) of the flow traced to both demand and generators (50–50) in each network area. The diagonal flows represent the local flow created by network users. Fig. 6 illustrates the hourly network utilization of each area by demand and generation. Runtime is <10 min.

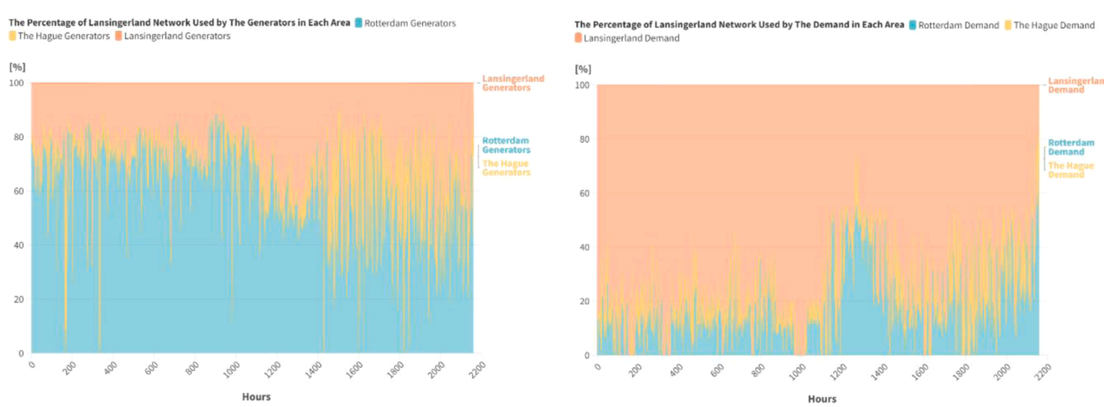
[3] It should be noted that InfraFair does not perform any clustering of inputs. If the number of snapshots is large, the process of clustering them into representative snapshots and computing their hourly weights must be conducted externally to the model and subsequently fed into the software.



(a) Rotterdam hourly heat network utilization.



(b) The Hague hourly heat network utilization.



(c) Lansingerland hourly heat network utilization.

Fig. 6. Hourly utilization of South-Holland District Heating Network grouped by area.

5. Impact

InfraFair introduces a decision support tool for cost allocation and tariff design, enabling regulators and stakeholders to evaluate cost distribution under diverse operational scenarios and to address various regulatory research questions, such as the distribution of costs among different types of network users (generation and demand). This functionality is particularly relevant for cross-border network usage, where varying split keys (between 0 % to 100 %) can be assigned to generation and demand, resulting in different net positions for exporting and importing countries. InfraFair facilitates sensitivity analysis for cost allocation across different combinations of demand and generation split keys.

As a primary functionality, in the context of cross-border trade, InfraFair enables the tracing of network flows and the identification of network users who are predominantly responsible for the utilization of external networks and, hence, external network compensation. The model includes a range of variable control inputs, allowing users to customize cost allocation to different network users and asset types. This feature is particularly useful for distinguishing between new planned assets and existing ones, as well as between regional and national assets, enabling differentiated treatment in the cost allocation process. These capabilities ensure that network tariff calculations are both flexible and transparent, accommodating a wide range of operational scenarios and regulatory requirements. This flexibility supports accurate and equitable distribution of costs, promoting fairness and clarity in tariff design. The model is currently being used in this context within the OpenMod4Africa project.

InfraFair can be used with different levels of spatial and temporal granularity for network representation. As with any software, increasing the level of granularity requires more computational resources. Users must carefully consider this trade-off and ensure that data for an adequate set of representative operational scenarios considering the required granularity level are available. By allowing for varying levels of spatial and temporal detail, InfraFair enables comprehensive assessments of current tariff methodologies against relevant performance indices. The tool has been specifically applied to evaluate the tariff methodology within the West African Power Pools, underscoring the need for changes in cross-border cost allocation rules to promote regional power trade beyond bilateral contracts. Stakeholders have endorsed the model as a viable tool for regional cost allocation. Moving forward, the model will further facilitate negotiation and consensus-building processes, enhance infrastructure planning and investment, and ensure that countries in the region receive equitable compensation for their network usage.

To the best of our knowledge, InfraFair is the first open-source software to offer these different functionalities for all flow-based infrastructure networks, including electricity, gas, hydrogen and heat. As a result, it is expected to contribute to streamlining cost allocation processes for future multi-sectoral networks and to facilitating agreements for new cross-border investments. The software reflects the extensive experience accumulated at IIT Comillas throughout many projects for public and private entities. All this experience has been made available to the energy regulator community by offering the model as open-source.

6. Conclusions

InfraFair is a versatile modeling tool for cost allocation across various types of energy infrastructure networks. It is designed primarily as a decision support tool for the energy regulator community, but can, potentially, also be used by other stakeholders like the system planner or the network users wanting to learn in advance about the network charges they may face. Then, this tool can potentially be used by researchers, policymakers, and the broader community of energy modelers and stakeholders. The software was developed as part of the HORIZON—CL5–2022-D3–02 project OpenMod4Africa and is based on the extensive experience of infrastructure cost allocation developed by the Universidad Pontificia Comillas, encompassing both academic contributions and practical project applications. It distinguishes itself as the only open-source tool currently available to the public.

CRediT authorship contribution statement

Mohamed A. Eltahir Elabbas: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Luis Olmos Camacho:** Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Ignacio Pérez-Arriaga:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Mohamed A.Eltahir Elabbas reports financial support was provided by the European Union. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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