Where do Germany's electricity imports come from? (Supplementary material)

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1 Input data

All data is taken from the ENTSO-E transparency page [1] unless otherwise stated. In the following n represents a region (either a country or a bidding zone), and t denotes a specific hour. If a time series is originally published with a higher temporal resolution (quarter-hourly, for instance), its average for the given hour is calculated. The following data is used:

- Actual Generation per Production Type $g_{(n,\alpha),t}$ at time t in region n, where α denotes the production type (like Fossil Gas or Lignite, for instance) [2]. The generation mix $r_{(n,\alpha),t}$ in region n at time t is defined as
$$r_{(n,\alpha),t} = \frac{g_{(n,\alpha),t}}{\sum_{\alpha} g_{(n,\alpha),t}} \ . \tag{1}$$
- Scheduled Commercial Exchanges from region k to region n at time t, with $f^{C:DA}_{k\to n,t}$ denoting the Commercial Schedules after Single Day-Ahead coupling (SDAC), and $f^{C:T}_{k\to n,t}$ representing the Commercial Schedules after Single Intraday Coupling (SIC) [3].
- Cross-border physical flows $f^{P}_{k\to n,t}$ from region k to region n at time t [4].

2 Origin of imports

In the following we define various measures $IM_{n,m,t}$ defining the electricity imports at region n from region m at time t. These measures can be based on economic or physical intuitions, and potentially correspond to different total imports $\sum_m IM_{n,m,t}$. Once the imports are defined, we calculate the composition of total imports by the sum over all imports weighted by the associated generation mix:
$$IM_{n,\alpha,t} = \sum_{m} IM_{n,m,t} \cdot r_{(m,\alpha),t} \ . \tag{2}$$

Results depend on the temporal resolution t. Assume that generation mixes $g_{(n,\alpha),\tau}$ and imports $IM_{n,m,\tau}$ have been aggregated over a period $\tau = [t_1, t_2, \ldots, t_\tau]$. Then

$$\begin{aligned} IM_{n,\alpha,\tau} &= \sum_m IM_{n,m,\tau} \cdot r_{(m,\alpha),\tau} \\ &= \sum_m \left(\sum_{t\in\tau} IM_{n,m,t} \right) \cdot \left(\frac{\sum_{t\in\tau} g_{(m,\alpha),t}}{\sum_\alpha \sum_{t\in\tau} g_{(m,\alpha),t}} \right) \\ &\neq \sum_{t\in\tau} \cdot \left(\sum_m IM_{n,m,t} \cdot r_{(m,\alpha),t} \right) \end{aligned} \tag{3}$$

2.1 Economic interpretation

Origin of import based on commercial flows In this approach, imported electricity is defined as the scheduled commercial exchanges (total, i.e. after intraday market coupling). The value $f^{C:T}_{m\to n,t}$ then denotes an export for region m, and an import for region n in this hour:

$$IM^{C:T}_{n,m,t} = f^{C:T}_{m\to n,t} \ . \tag{4}$$

Origin of import based on netted commercial flows The scheduled commercial exchanges (total) often contain flows in both directions due to transactions in the intraday market. We first define netted commercial flows $f^{C_{net}:T}_{m\to n,t}$ as

$$f^{C_{net}:T}_{m\to n,t} = \max\left[f^{C:T}_{m\to n,t} - f^{C:T}_{n\to m,t}, 0 \right] \ . \tag{5}$$

Here $\max[x, 0]$ is x for $x > 0$ and zero for $x \leq 0$. The corresponding import of region n from region m according to this measure is then just

$$IM^{C_{net}:T}_{n,m,t} = f^{C_{net}:T}_{m\to n,t} \ . \tag{6}$$

The Bundesnetzagentur's electricity market information platform "SMARD" visualizes the Energy mix of electricity imported (aggregated per month or per year) [5] based on this definition. The underlying methodology is documented in an article published on the same platform [6].

Origin of import based on pooled netted commercial flows In this interpretation we assume that all outgoing netted scheduled commercial exchanges are pooled (excluding the region, for which the origin of import is calculated), and ingoing scheduled commercial exchanges are composed according to the mix in that pool. The definition of this measure $IM^{C_{net}:T:pool}_{n,m,t}$ for $n \neq m$ is given by

$$\begin{aligned} IM^{C_{net}:T:pool}_{n,m,t} &= \left(\sum_k f^{C_{net}:T}_{k\to n,t} \right) \cdot \frac{\sum_{k'} f^{C_{net}:T}_{m\to k',t}}{\sum_{m'\neq n} \sum_{k'} f^{C_{net}:T}_{m'\to k',t}} \\ &= \frac{\left(\sum_k f^{C_{net}:T}_{k\to n,t} \right) \cdot \left(\sum_{k'} f^{C_{net}:T}_{m\to k',t} \right)}{\sum_{m'\neq n} \sum_{k''} f^{C_{net}:T}_{m'\to k'',t}} \ . \end{aligned} \tag{7}$$

Origin of import based on pooled net commercial imports Whereas for the last measures we considered data for individual connections, we now calculate the net import $IM_{n,t}^{C_{net:T}}$ or net export $EX_{n,t}^{C_{net}:T}$ of a region n based on commercial flows:

$$IM_{n,t}^{C_{net}:T} = \max\left[\left(\sum_k f_{k\to n,t}^{C:T}\right) - \left(\sum_k f_{n\to k,t}^{C:T}\right), 0\right] \tag{8}$$

$$EX_{n,t}^{C_{net}:T} = \max\left[\left(\sum_k f_{n\to k,t}^{C:T}\right) - \left(\sum_k f_{k\to n,t}^{C:T}\right), 0\right] . \tag{9}$$

The origin of imports based on pooled net commercial imports total is then given by

$$IM_{n,m,t}^{net:T:pool} = IM_{n,t}^{C_{net}:T} \cdot \frac{EX_{m,t}^{C_{net}:T}}{\sum_k EX_{k,t}^{C_{net}:T}} \tag{10}$$

2.2 Physical interpretation

Origin of import based on pooled net physical flows For this interpretation we consider the net physical import $IM_{n,t}^{P_{net}}$ and net physical export $EX_{n,t}^{P_{net}}$ of region n at time t:

$$IM_{n,t}^{P_{net}} = \max\left[\left(\sum_k f_{k\to n,t}^{P}\right) - \left(\sum_k f_{n\to k,t}^{P}\right), 0\right] \tag{11}$$

$$EX_{n,t}^{P_{net}} = \max\left[\left(\sum_k f_{n\to k,t}^{P}\right) - \left(\sum_k f_{k\to n,t}^{P}\right), 0\right] . \tag{12}$$

The origin of imports based on pooled net physical flows is then given by

$$IM_{n,m,t}^{P_{net}:pool} = IM_{n,t}^{P_{net}} \cdot \frac{EX_{m,t}^{P_{net}}}{\sum_k EX_{k,t}^{P_{net}}} \tag{13}$$

Flow tracing (aggregated coupling) We follow the calculation in [7] and define $q_{n,m,t}$ as the share of outflow from region n originating at region m at time t. Here outflow refers to both flows to neighboring regions and to potential imports of the region itself. We assume conversation of partial flows and full mixing in each region [7]:

$$\delta_{n,m} EX_{n,t}^{P_{net}} + \sum_k q_{k,m,t} f_{k\to n,t}^{p} = q_{n,m,t} \cdot \left[IM_{n,t}^{P_{net}} + \sum_j f_{n\to j,t}\right] . \tag{14}$$

This can be rewritten as the matrix equation $EX_t^{P_{net}} = A_t \cdot q_t$, with

$$\left(EX_t^{P_{net}}\right)_{n,m} = \delta_{n,m} EX_{n,t}^{P_{net}} \ , \tag{15}$$

$$(A_t)_{n,m} = \delta_{n,m}\left[IM_{n,t}^{P_{net}} + \sum_k f_{n\to k,t}\right] - f_{m\to n,t} \ , \tag{16}$$

$$(q_t)_{n,m} = q_{n,m,t} \ . \tag{17}$$

Inverting the matrix A we can calculate $q_{n,m}$. The amount of imports in region n associated with region of origin m is then given by

$$IM_{n,m,t}^{FT:agg} = q_{n,m} IM_{n,m,t}^{P_{net}} \ . \tag{18}$$

Flow tracing (direct coupling) For *direct coupling flow tracing* we also need the generation $g_{n,t}$ and the demand $d_{n,t}$ in region n at time t. Again assuming conversation of partial flows and full mixing in each region it holds [7]:

$$\delta_{n,m} g_{n,t} + \sum_k q_{k,m,t} f_{k\to n,t}^p = q_{n,m,t} \cdot \left[d_{n,t}^+ \sum_j f_{n\to j,t}\right] \ . \tag{19}$$

Note that here $q_{n,m,t}$ has to be interpreted as the share of outflow (to neighboring nodes or into the local consumption) in region n associated with generation at region m. This can be rewritten as the matrix equation $g_t = \tilde{A}_t \cdot q_t$, with

$$(g_t)_{n,m} = \delta_{n,m} g_{n,t} \ , \tag{20}$$

$$\left(\tilde{A}_t\right)_{n,m} = \delta_{n,m}\left[d_{n,t} + \sum_k f_{n\to k,t}\right] - f_{m\to n,t} \ , \tag{21}$$

$$(q_t)_{n,m} = q_{n,m,t} \ . \tag{22}$$

Inverting the matrix $\tilde{A}$ and multiplication with g_t yields $q_{n,m}$. The amount of imports in region n associated with region of origin m for $n \neq m$ is then given by

$$IM_{n,m,t}^{FT:direct} = q_{n,m,t} d_{n,t} \ . \tag{23}$$

It should be emphasized that here imports refer to a share of consumption, whereas for aggregated flow tracing imports refer to a share of net imports.

3 Examples

In this section we apply the measures defined in the last sections to two examples and one for measures based on an economic interpretation, one for measures based on a physical interpretation.

3.1 Economic interpretation

Consider the network with five different nodes shown in Fig. 1. The different nodes represent regions, the links define connections between the regions. The arrows depict commercial flows total for a given time step (note that for some connections, flows occur in both directions). We assume the following values

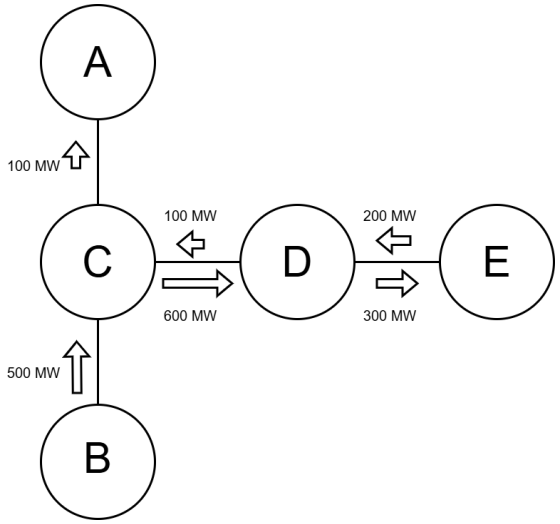

Figure 1: Exemplary network. Nodes represent regions, flows represent scheduled commercial exchanges totals (commercial flows).

for the flows (the lengths of the arrows in the figure are not proportional to the flow values):

$$f^{C:T}_{B\to C} = 500 \text{ MW} , \tag{24}$$
$$f^{C:T}_{C\to A} = 100 \text{ MW} , \tag{25}$$
$$f^{C:T}_{C\to D} = 600 \text{ MW} , \tag{26}$$
$$f^{C:T}_{D\to C} = 100 \text{ MW} , \tag{27}$$
$$f^{C:T}_{D\to E} = 300 \text{ MW} , \tag{28}$$
$$f^{C:T}_{E\to D} = 200 \text{ MW} . \tag{29}$$

All other flows are zero.

According to the measure based on *commercial flows*, the imports of region D are directly given by the incoming scheduled commercial flows total:

$$IM^{C:T}_{D,C} = f^{C:T}_{C\to D} = 600 \text{ MW} , \tag{30}$$
$$IM^{C:T}_{D,E} = f^{C:T}_{E\to D} = 200 \text{ MW} . \tag{31}$$

The *netted* commercial flows are:

$$f_{B\to C}^{C_{net}:T} = 500 \text{ MW} , \quad (32)$$
$$f_{C\to A}^{C_{net}} = 100 \text{ MW} , \quad (33)$$
$$f_{C\to D}^{C_{net}:T} = 500 \text{ MW} , \quad (34)$$
$$f_{D\to E}^{C_{net}:T} = 100 \text{ MW} . \quad (35)$$

According to *netted commercial flows*, the imports of region D are thus entirely attributed to region C:

$$IM_{D,C}^{C_{net}:T} = 500 \text{ MW} . \quad (36)$$

For the measure based on *pooled netted commercial flows* we ignore the network structure in Fig. 1 and assume that all outgoing netted commercial flows except the ones from region D are mixed, and this mix is attributed to the sum of incoming netted commercial flows to this region. The total outgoing netted commercial flows are

$$\sum_{m\neq D}\sum_{k} f_{m\to k}^{C_{net}:T} = 500 \text{ MW} + 100 \text{ MW} + 500 \text{ MW} = 1100 \text{ MW} . \quad (37)$$

Out of these 1100 MW, 500 MW are attributed to region B and 600 MW are attributed to region C. The total netted commercial inflows to region D are 500 MW. The imports based on *pooled netted commercial flows* in region D are thus given by

$$IM_{D,B}^{C:T:pooled} = \frac{500 \text{ MW}}{1100 \text{ MW}} \cdot 500 \text{ MW} = \frac{2500}{11} \text{ MW} \approx 227.27 \text{ MW} , \quad (38)$$
$$IM_{D,C}^{C:T:pooled} = \frac{600 \text{ MW}}{1100 \text{ MW}} \cdot 500 \text{ MW} = \frac{3000}{11} \text{ MW} \approx 272.73 \text{ MW} . \quad (39)$$
$$(40)$$

For *pooled net commercial imports* we first calculate net imports/exports for all regions:

$$EX_{B}^{C_{net}:T} = 500 \text{ MW} , \quad (41)$$
$$EX_{C}^{C_{net}:T} = 100 \text{ MW} , \quad (42)$$
$$IM_{A}^{C_{net}:T} = 100 \text{ MW} , \quad (43)$$
$$IM_{D}^{C_{net}:T} = 400 \text{ MW} , \quad (44)$$
$$IM_{E}^{C_{net}:T} = 100 \text{ MW} . \quad (45)$$

Note that the sum over all net exports is equal to the sum over all net imports. The total net exports in the system are 600 MW, with 500 MW attributed to region B, and 100 MW attributed to region C. The net import of region D is 400 MW. The imports according to *pooled net commercial imports* for region D

are thus

$$IM_{D,B}^{net:T:pooled} = \frac{500 \text{ MW}}{600 \text{ MW}} \cdot 400 \text{ MW} = \frac{100}{3} \text{ MW} \approx 333.33 \text{ MW} , \quad (46)$$

$$IM_{D,C}^{net:T:pooled} = \frac{100 \text{ MW}}{600 \text{ MW}} \cdot 400 \text{ MW} = \frac{200}{3} \text{ MW} \approx 66.67 \text{ MW} . \quad (47)$$

3.2 Physical interpretation

Consider the network with three different regions shown in Figs. 2 and 3.

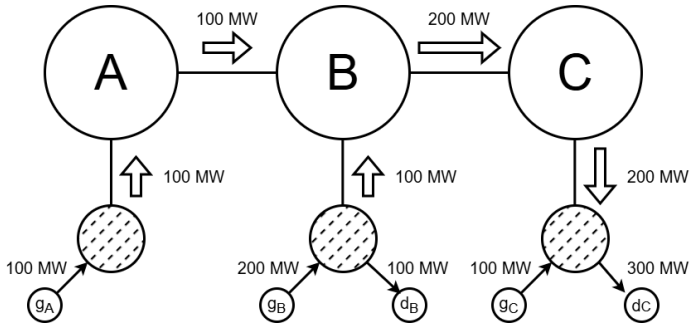

Figure 2: Exemplary network (aggregated coupling). Nodes represent regions, flows represent physical flows. Dotted nodes represent net imports/exports of each region, smaller nodes define local generation and demand.

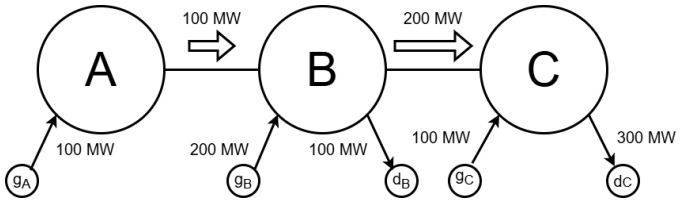

Figure 3: Exemplary network (direct coupling). Nodes represent regions, flows represent physical flows. Local generation and demand (smaller nodes) are directyl coupled to the network.

In Fig. 1, the dotted nodes represent the net imports/exports of the different regions:

$$EX_A^{P_{net}} = 100 \text{ MW} , \quad (48)$$

$$EX_B^{P_{net}} = 100 \text{ MW} , \quad (49)$$

$$IM_A^{P_{net}} = 200 \text{ MW} . \quad (50)$$

It can be seen that 50% of the exports originate in region A, with the other 50% being associated to region B. The imports at region C according to *pooled net*

physical flows are thus given by

$$IM_{C,A}^{P_{net}:pool} = \frac{100\ \text{MW}}{200\ \text{MW}} \cdot 200\ \text{MW} = 100\ \text{MW}\ , \tag{51}$$

$$IM_{C,B}^{P_{net}:pool} = \frac{100\ \text{MW}}{200\ \text{MW}} \cdot 200\ \text{MW} = 100\ \text{MW}\ . \tag{52}$$

Since region C is the only net importer in this system, the same result holds for *aggregated coupling flow tracing*. The matrix A is given by

$$A = \begin{pmatrix} 100 & 0 & 0 \\ -100 & 200 & 0 \\ 0 & -200 & 200 \end{pmatrix}\ \text{MW}\ . \tag{53}$$

The inverse matrix A^{-1} reads

$$A^{-1} = \begin{pmatrix} 1/100 & 0 & 0 \\ 1/200 & 1/200 & 0 \\ 1/200 & 1/200 & 1/200 \end{pmatrix}\ \text{MW}^{-1}\ . \tag{54}$$

The matrix q then follows from $A^{-1} \cdot EX^{P_{net}}$:

$$q = A^{-1} \cdot EX^{P_{net}} = \begin{pmatrix} 1/100 & 0 & 0 \\ 1/200 & 1/200 & 0 \\ 1/200 & 1/200 & 1/200 \end{pmatrix} \cdot \begin{pmatrix} 100 & 0 & 0 \\ 0 & 100 & 0 \\ 0 & 0 & 0 \end{pmatrix} \tag{55}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 1/2 & 1/2 & 0 \\ 1/2 & 1/2 & 0 \end{pmatrix}\ . \tag{56}$$

This yields the expected result

$$I_{C,A}^{FT:agg} = q_{C,A} \cdot IM_{C}^{P_{net}} = 100\ \text{MW}\ , \tag{57}$$

$$I_{C,B}^{FT:agg} = q_{C,B} \cdot IM_{C}^{P_{net}} = 100\ \text{MW}\ . \tag{58}$$

For *direct coupling flow tracing* we also have to consider local generation and demand as depicted in Fig. 3. The matrix $\tilde{A}$ is calculated as

$$\tilde{A} = \begin{pmatrix} 100 & 0 & 0 \\ -100 & 300 & 0 \\ 0 & -200 & 300 \end{pmatrix}\ \text{MW}\ . \tag{59}$$

The inverse matrix A^{-1} reads

$$A^{-1} = \begin{pmatrix} 1/100 & 0 & 0 \\ 1/300 & 1/300 & 0 \\ 1/450 & 1/450 & 1/300 \end{pmatrix}\ \text{MW}^{-1}\ . \tag{60}$$

The matrix q follows from $\tilde{A}^{-1} \cdot g$:

$$q = \tilde{A}^{-1} \cdot g = \begin{pmatrix} 1/100 & 0 & 0 \\ 1/300 & 1/300 & 0 \\ 1/450 & 1/450 & 1/300 \end{pmatrix} \cdot \begin{pmatrix} 100 & 0 & 0 \\ 0 & 200 & 0 \\ 0 & 0 & 100 \end{pmatrix} \quad (61)$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 1/3 & 2/3 & 0 \\ 2/9 & 4/9 & 1/3 \end{pmatrix} . \quad (62)$$

The composition of the local demand in region C is calculated as

$$IM_{C,A}^{FT:direct} = d_C \cdot q_{C,A} = \frac{2 \cdot 300}{9} \text{ MW} \approx 67.67 \text{ MW} , \quad (63)$$

$$IM_{C,B}^{FT:direct} = d_C \cdot q_{C,B} = \frac{4 \cdot 300}{9} \text{ MW} \approx 133.33 \text{ MW} , \quad (64)$$

$$IM_{C,C}^{FT:direct} = d_C \cdot q_{C,A} = \frac{1 \cdot 300}{3} \text{ MW} = 100 \text{ MW} . \quad (65)$$

The last entry again could be interpreted as a self-import, corresponding to local generation used in the same region C. It should be emphasized that direct coupling flow tracing provides a partition of local *demand*, whereas aggregated coupling flow tracing addresses the origin of *net imports*. In the given example the total imports according to both measures coincide for region C, but the conceptual difference becomes apparent for region B. Whereas in aggregated coupling flow tracing there is no net import for region B, direct coupling flow tracing yields

$$IM_{B,A}^{FT:direct} = d_B \cdot q_{B,A} = \frac{1 \cdot 100}{3} \text{ MW} \approx 33.33 \text{ MW} , \quad (66)$$

$$IM_{B,B}^{FT:direct} = d_B \cdot q_{B,B} = \frac{2 \cdot 100}{3} \text{ MW} \approx 67.67 \text{ MW} . \quad (67)$$

This shows that for this measure, region B has imports of $IM_{B,A}^{FT:direct} = 67.67$ MW despite being a net importer [7].

References

[1] ENTSO-E, Transparency Platform, `https://transparency.entsoe.eu`.

[2] ENTSO-E, Actual Generation per Production Type [16.1.B&C].

[3] ENTSO-E, Scheduled Commercial Exchanges [12.1.F].

[4] ENTSO-E, Physical Flows [12.1.G].

[5] SMARD, Energy mix of imports, `https://www.smard.de/page/en/topic-article/212250/215472`.

[6] SMARD, Energy mix of electricity imports and exports, `https://www.smard.de/page/en/wiki-article/5884/214270`.

[7] M. Schäfer, B. Tranberg, D. Jones, A. Weidlich, Tracing carbon dioxide emissions in the european electricity markets, in: 17th International Conference on the European Energy Market (EEM), 2020.