Energy System Modelling
Summer Semester 2020, Lecture 15

Dr. Tom Brown, tom.brown@kit.edu, `https://nworbmot.org/`
Karlsruhe Institute of Technology (KIT), Institute for Automation and Applied Informatics (IAI)

Table of Contents

Introduction to Flow Allocation

Who uses transmission lines?

Consider a single transmission line in a complicated meshed grid.

Can we say which consumers and generators are using it at any time?

Source: Comillas EC report, 2002

Who uses transmission lines?

Basic answer: **not uniquely**. Electricity gets **thoroughly mixed** in the grid; electrons do not carry markers that say ‘from nuclear plant A’ or ‘from wind plant B’.

Source: Comillas EC report, 2002

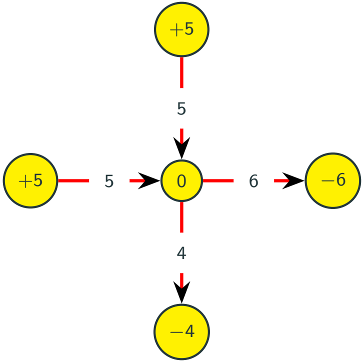
What is flow allocation?

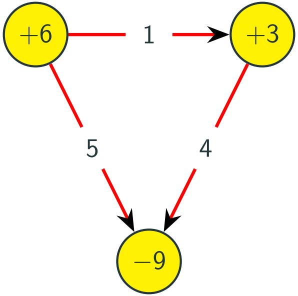
Flow allocation refers to algorithms that assign the flow of power in electricity network assets (e.g. lines and transformers) to particular users (e.g. generators and consumers).

Source: Comillas EC report, 2002

Why flow allocation is non-trivial and non-unique

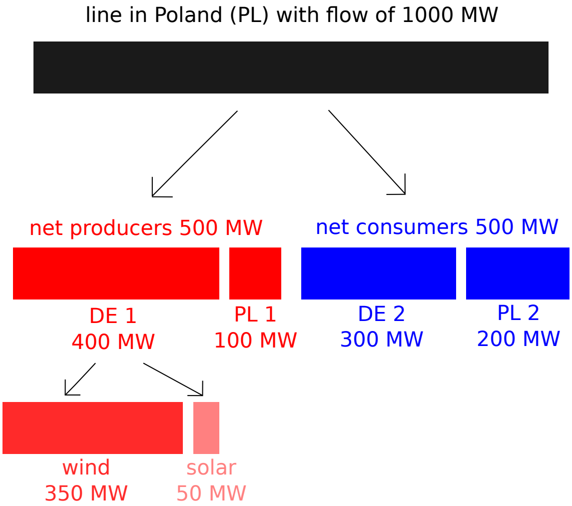
There is **no unique** way to do flow allocation. There are **ambiguities** both at network junctions and due to multiple paths through the network (i.e. closed cycles).





What is flow allocation?

Flow allocation gives a **break-down** of the flow in each asset in terms of the network users.



Source: Brown et al, IET, 2014

What is flow allocation?

Different algorithms deliver **different results**, including:

- Assigning fractions of flow on each line to individual generators and consumers
- Assigning fractions of flow on each line to pairs of generators and consumers
- Matching consumers of power to generators of power via particular paths in the network
- Assigning fractions of flows to different groups, e.g. national vs. international, renewable vs. non-renewable

Some methods may not be suitable in certain circumstances, e.g. for HVDC lines or aggregated networks (principally because of cyclic flows).

What is flow allocation useful for?

Flow allocation can be used to **assign costs** to particular network actors of ...

- operation and maintenance costs for existing network assets
- compensation for network losses
- new network assets
- grid connection charges for new generators
- redispatch
- international redispatch (multi-lateral remedial actions (MRAs))

Nota Bene: Most of these use cases would **not** be necessary in a market with **nodal pricing** at (partial) **equilibrium**. These use cases compensate for **imperfect market design**.

Flow allocation can also be used to increase understanding of the network, e.g. to increase public acceptance by seeing the source of network flows.

Algorithms for Flow Allocation

What algorithms exist in the literature?

There are many algorithms for flow algorithms in literature, but **no consensus** on best one.

- **Flow tracing** (also called Bialek's method or Average Participation) assumes flow divides at junctions like water flow
- **Marginal participation** uses the PTDF matrix to assess the flow sensitivity
- **Aumann-Shapley** uses game theory for agents in the network
- **With- and without transits** looks at domestic versus international transmission loading
- **Virtual injection patterns** modifies flow tracing

We'll look at first two.

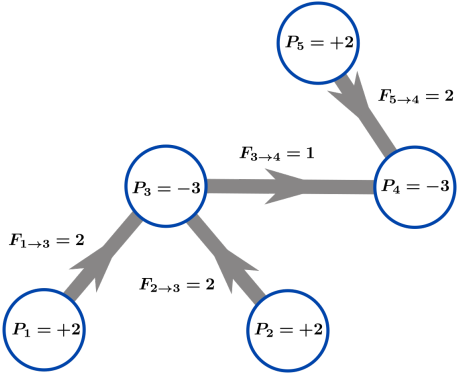
Flow tracing: Conservation of partial flows

Power conservation from KCL

$$p_{n,t} = \sum_{\ell} K_{n,\ell} f_{\ell,t}$$

Separating **in-flows** and **out-flows**,

$$[p_n]_+ + \sum_m f_{m\to n} = [p_n]_- + \sum_m f_{n\to m}$$



Source: Jonas Hörsch

Flow tracing: Conservation of partial flows

Power conservation from KCL

$$p_{n,t} = \sum_{\ell} K_{n,\ell} f_{\ell,t}$$

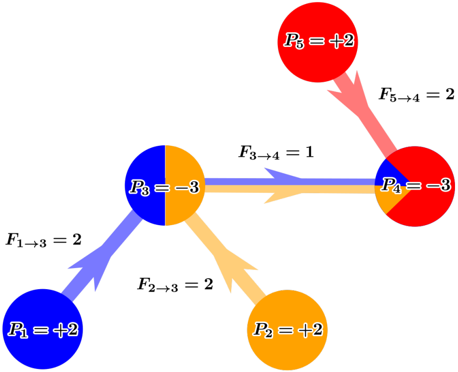
Separating **in-flows** and **out-flows**,

$$[p_n]_+ + \sum_m f_{m\to n} = [p_n]_- + \sum_m f_{n\to m}$$

allows to **label** the energy entering the network by source α and determine its mixing $q_{m,\alpha}$ at each node m

$$[p_{n,\alpha}]_+ + \sum_m q_{m,\alpha} f_{m\to n,t} = q_{n,\alpha}\left([p_{n,t}]_- + \sum_m f_{n\to m,t}\right)$$

Mixing is tracked all the way from sources to sinks, assuming that all in-flows are mixed equally in out-flows.

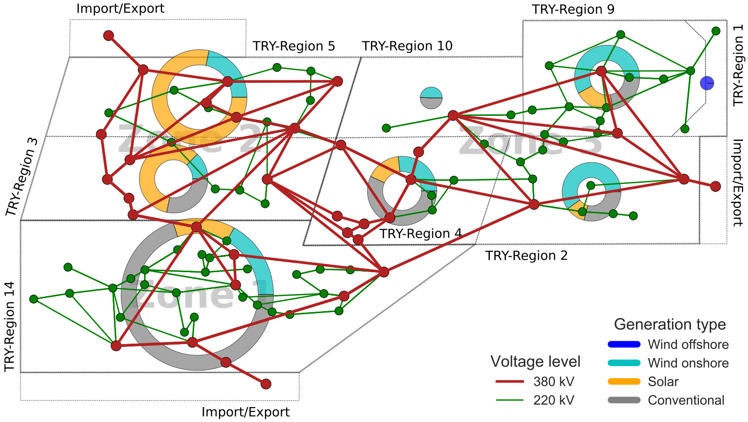


$\alpha \in \{blue, orange, red\}$

Source: Jonas Hörsch

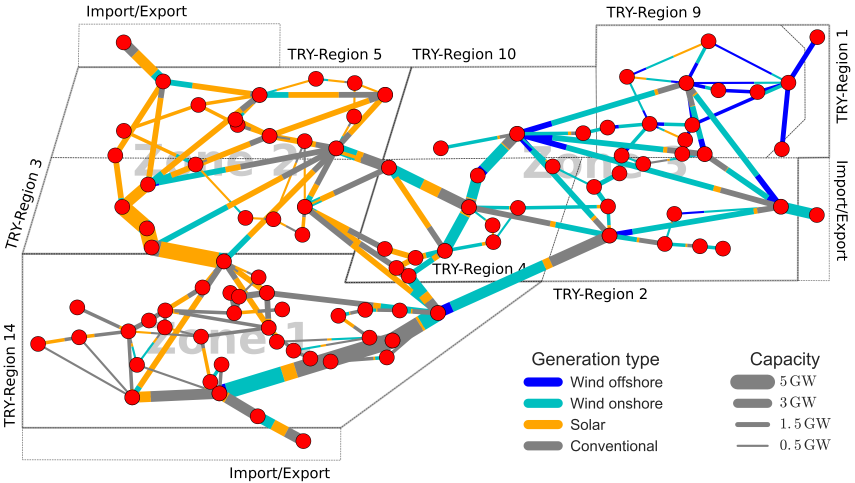
Flow tracing: Synthetic 118-bus demonstration case

Electrical transmission grid model with a **topology from IEEE 118-bus** test case embedded into a figurative country bordered by an **eastern coast for offshore wind** and equipped with **conventional and renewable generators and loads**.



Source: Hörsch et al, 2017

Flow tracing: Usage of individual transmission lines



Source: Hörsch et al, 2017

Marginal participation: Use the PTDF matrix

The Power Transfer Distribution Factor (PTDF) gives a linear relationship for the linear power flow between the nodal power injections p_i and the flows f_ℓ

$$f_\ell = \sum_i \mathrm{PTDF}_{\ell i} p_i$$

This is already basically what we want - a **sensitivity** of the flow in line ℓ to the power injection at node i.

But remember that the PTDF **depends strongly on the slack node**, related to a freedom to add a constant c_ℓ, $\mathrm{PTDF}_{\ell i} \to \mathrm{PTDF}_{\ell i} + c_\ell$. This has **no effect** on the physical flow:

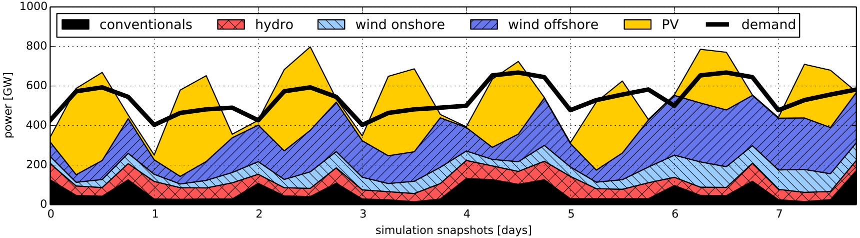
$$f_\ell = \sum_i \mathrm{PTDF}_{\ell i} p_i \to \sum_i (\mathrm{PTDF}_{\ell i} + c_\ell) p_i = \sum_i \mathrm{PTDF}_{\ell i} p_i + c_\ell \sum_i p_i = \sum_i \mathrm{PTDF}_{\ell i} p_i$$

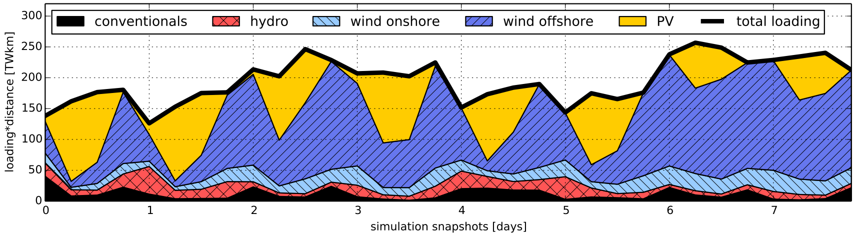
We can use this freedom to choose the c_ℓ such that there is an equal contribution of net consumers and net generators to each line.

Marginal participation: Application to high-renewable European power system

Top graph: power generation in Europe over 8 simulated days.

Bottom: total line loading in TWkm in the European system - offshore wind dominates.

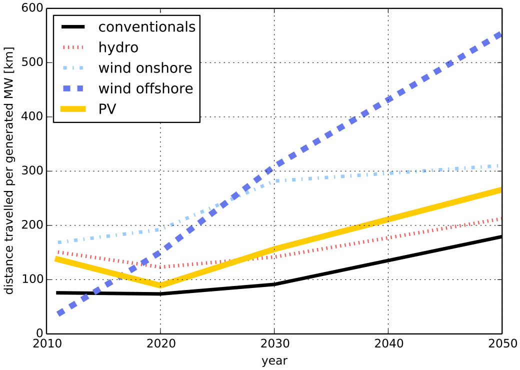




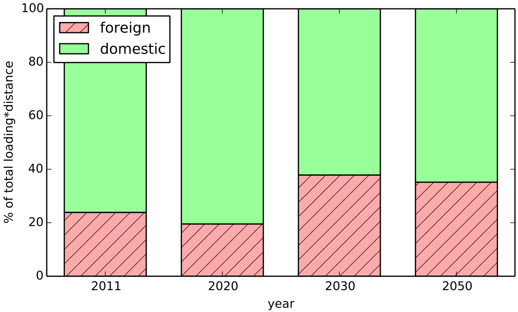
Source: Brown, 2014

Marginal participation: Application to high-renewable European power system

Wind travels on average further than other energy sources, particularly in the case of offshore wind.



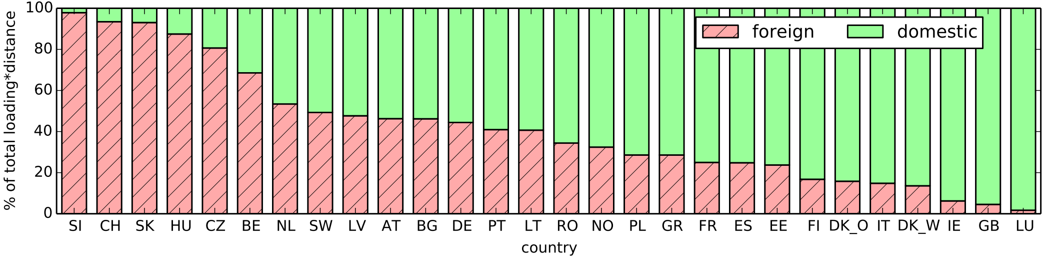
The share of electricity flowing outside domestic borders also increases as countries share renewable resources.



Source: Brown, 2014

Marginal participation: Application to high-renewable European power system

Some country have lots of flows caused by other countries (SI: Slovenia, CH: Switzerland, SK: Slovakia), others have mostly domestic use of their tranmission grids (GB: United Kingdom, IE: Ireland, LU: Luxembourg).



Source: Brown, 2014

Practical Applications of Flow Allocation

Where is flow allocation currently used?

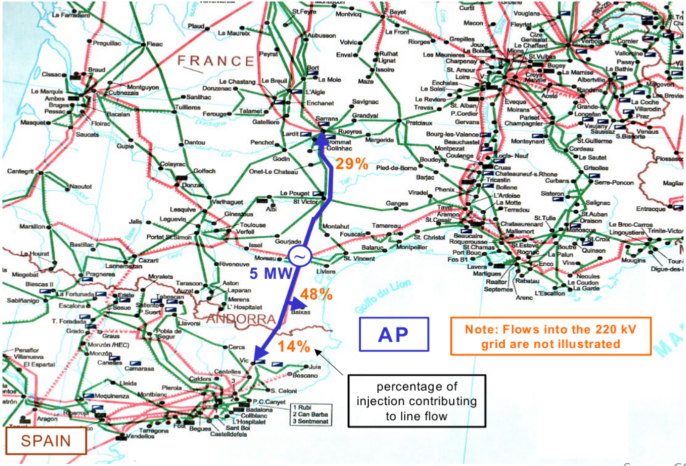
Commission Regulation (EU) No 838/2010 sets the terms for inter-TSO compensation (ITC) in Europe for costs incurred by cross-border flows ('transits') for

- **infrastructure usage** (total compensation limited to 100 million €/a until new metholodogy can be implemented; distributed today using transit-load factor 'postage stamp' method)
- **losses** (total compensation was 153 million € in 2015 (losses valued at around 50 €/MWh), assessed using With and Without Transit (WWT) method)

Flow allocation is also used around the world for cost allocation, e.g. in South America, the United States and Great Britain (where it's used for the G- and L-components of Transport Network Use of System (TNUoS)). German TSOs also examining using flow allocation for MRA cost-sharing.

Application example in Europe: Flow tracing

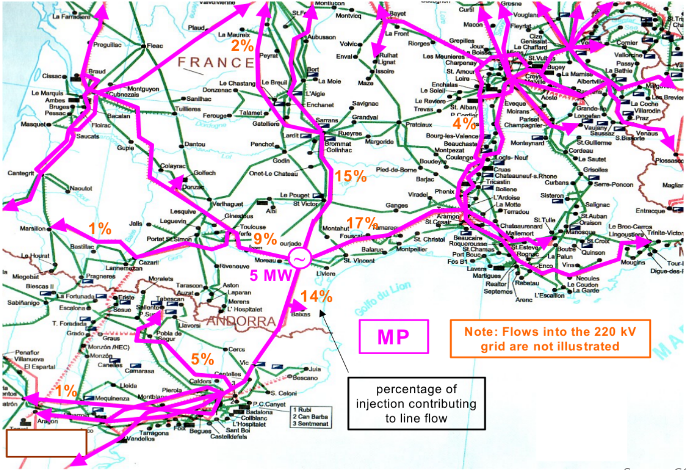
For example the Bialek **flow tracing method** (also called Average Participation (AP)) is like a "water flow" and stays relatively **localised**:



Source: CONSENTEC, Frontier EC report, 2006

Application example in Europe: Marginal participation

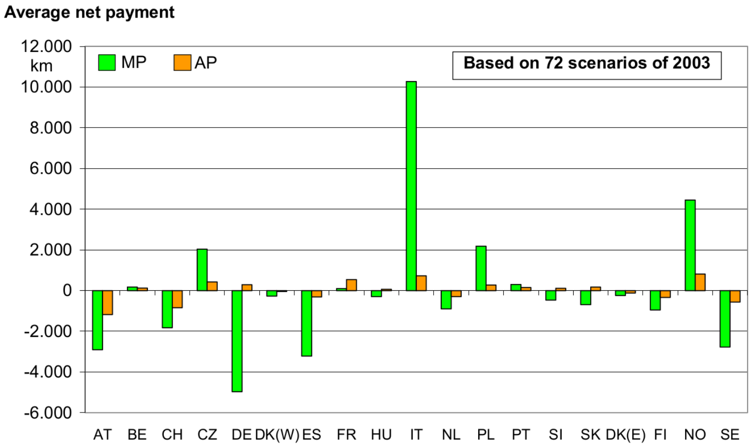
Whereas the **power-flow-sensitivity method** (also called Marginal Participation (MP)) sees effects from nodes **across the network**:



Source: CONSENTEC, Frontier EC report, 2006

Why flow allocation is non-trivial and non-unique

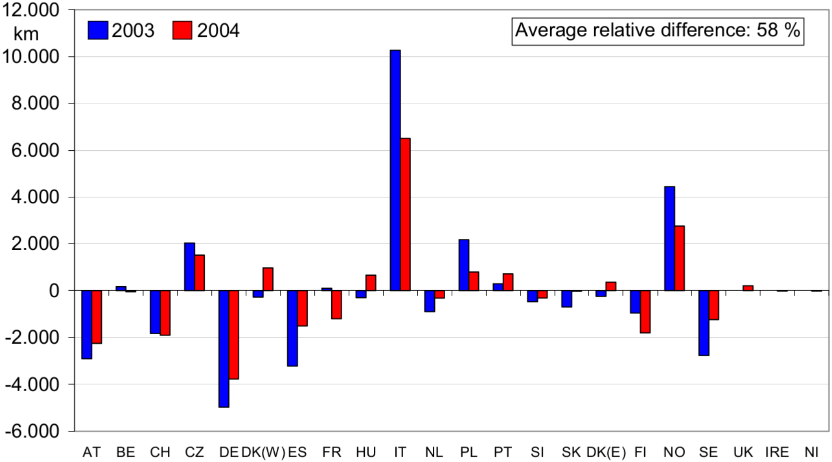
This results in **very different** assessments of the amount of compensation due to each European country for **transit flows** from other countries (AP versus MP for 2003):



Source: CONSENTEC, Frontier EC report, 2006

Why flow allocation is non-trivial and non-unique

They are also **unstable** from year to year (example of MP for 2003 and 2004):



Source: CONSENTEC, Frontier EC report, 2006

Why flow allocation is non-trivial and non-unique

Therefore it is **no wonder** that in the 7 years since Commission Regulation (EU) No 838/2010, there has been **no agreement** on a new methodology for inter-TSO compensation.

Private quotation from Midcontinent Independent System Operator (MISO) employee:
"Flow allocation is the **single most contentious subject** I've ever encountered".

We are looking at economics-based flow allocation, based on **benefit to each user of line**.