Flowtracing for Flow Pattern Analysis

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Flowtracing is power flow colouring

Goal: Direction of flows/Use of the power lines

Want to answer (at least) two questions:

1. Do the weather patterns and conventional generation dispatch lead to a central direction (or maybe two or three) by which the power flow traverses the network?
2. Who uses the power lines the most? (And maybe should pay more for its construction.)

Active power flow

The active power flow in an electricity system is not unlike a water pipe system. At least it satisfies the Kirchhoff current law that the power flow through node n is conserved,

$$P_n^+ + \sum_m F_{m\to n}^{in} = P_n^- + \sum_m F_{n\to m}^{out} \,, \quad (\textsc{Conservation of active power}) \tag{1}$$

where the power injection from generators and loads at bus n has been split into its positive and negative part $P_n = P_n^+ - P_n^-$ and $F_{m\to n}^{in}$, $F_{m\to n}^{out}$ are the power in- and outflows from bus m to n.

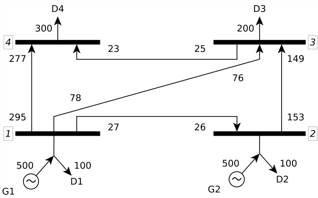


Figure 1: Active power flow component of the AC power flow in a simple 4-node network with two generators and four loads

Flowtracing

$$P_n^+ + \sum_m F_{m\to n}^{in} = P_n^- + \sum_m F_{n\to m}^{out} \;, \quad \text{(Conservation of active power)} \qquad (2)$$

Flowtracing

$$P_n^+ + \sum_m F_{m\to n}^{in} = P_n^- + \sum_m F_{n\to m}^{out} \ , \quad \text{(Conservation of active power)} \tag{2}$$

Flowtracing adds colour to this equation by splitting all terms into its colour components using partitions for input $\left\{q_{n,\alpha}^{in}\right\}_\alpha$ and output $\left\{q_{n,\alpha}\right\}_\alpha$, s.t.

$$q_{n,\alpha}^{in} P_n^+ + \sum_m q_{m,\alpha} F_{m\to n}^{in} = q_{n,\alpha} P_n^- + \sum_m q_{n,\alpha} F_{n\to m}^{out} \ .$$
$$\text{(Conservation of colour components)} \tag{3}$$

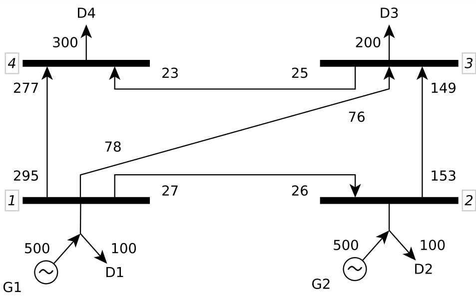
Flowtracing: Colour?

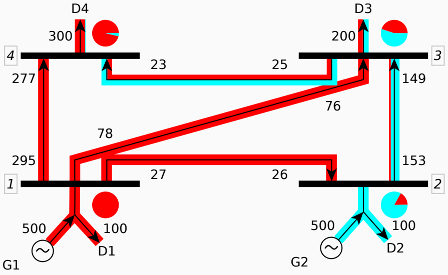
$$q^{in}_{n,\alpha} P^{+}_{n} + \sum_{m} q_{m,\alpha} F^{in}_{m \to n} = q_{n,\alpha} P^{-}_{n} + \sum_{m} q_{n,\alpha} F^{out}_{n \to m} \ . \qquad \text{(Conservation of colour components)} \quad (4)$$

Flowtracing: Colour?

$$q^{in}_{n,\alpha} P^+_n + \sum_m q_{m,\alpha} F^{in}_{m\to n} = q_{n,\alpha} P^-_n + \sum_m q_{n,\alpha} F^{out}_{n\to m} \ .$$

(Conservation of colour components) (4)

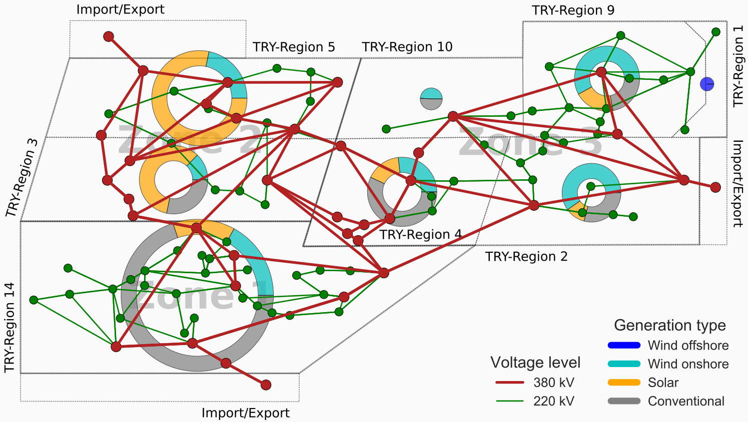




Electrical transmission grid model

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.



Energy flows

Energy flows in the demonstration case 1/2

From an in-partition $q^{in}_{\alpha,n}$ which separates the injections of different regions

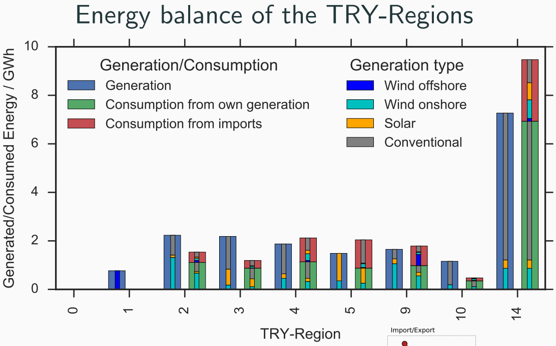
$$q^{in}_{\alpha,n} = \begin{cases} 1 & \text{for node } n \text{ in region } \alpha, \\ 0 & \text{else.} \end{cases} \quad , \tag{5}$$

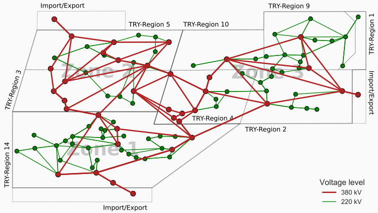
flow tracing derives the out-partition $q^{out}_{\alpha,n}$. On average, the energy flowing from region α to region β is then given by

$$E_{\alpha,\beta} = \sum_{n \text{ in region } \beta} \left\langle \, q^{out}_{t,\alpha,n} \cdot P^{-}_{t,n} + q^{in}_{\alpha,n} \cdot (L_{t,n} - P^{-}_{t,n}) \, \right\rangle_t \;, \tag{6}$$

since there is also energy which has been consumed directly in bus n with a share $q^{in}_{\alpha,n}$.

Energy flows in the demonstration case 2/2





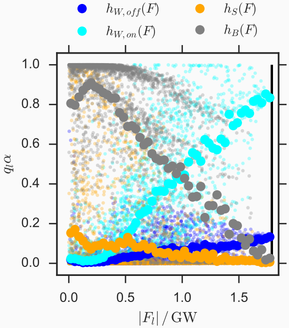
Transmission capacities

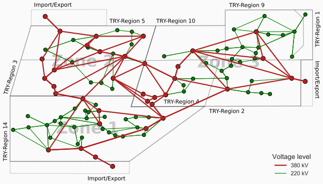
Technology mix on a Transmission line

Usage shares of the transmission lines for generation types τ are captured by the flow partition $\{q_{t,l,\tau}\}_\tau$ which results from flow tracing on an input partition

$$q^{in}_{t,n,\tau} = G^{\tau}_{t,n} / \sum_{\tau} (\cdot) \quad , \tag{7}$$

based on the hour-sharp energy generation mix $G^{\tau}_{t,n}$.



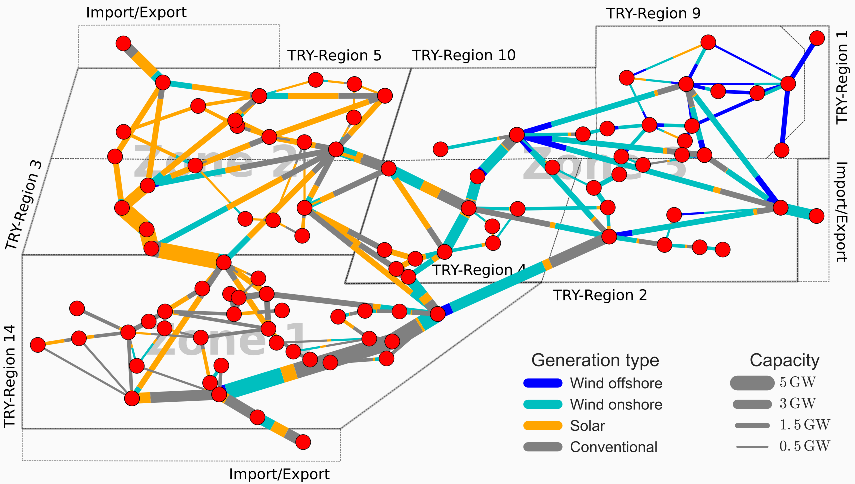


Usage measure of a transmission line

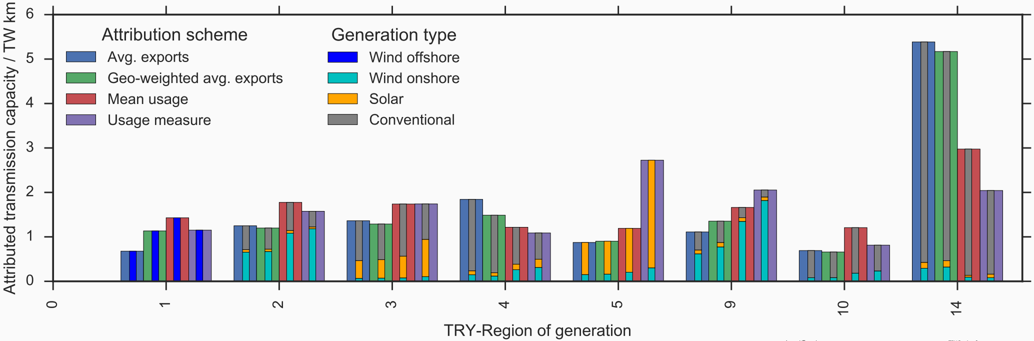
Since the cost-drivers of transmission lines are length and capacity, their usage includes the absolute amount of energy flows as well as the correlation of flows to line-loading for integrating the ensemble $(F_{t,l}, q_{t,\tau,l})$.

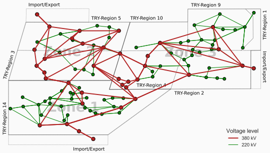
$$\mathcal{K}^T_{\tau,l} = \int_0^{\mathcal{K}^T_l} \frac{\mathrm{d}|F_l|}{1 - P_l(|F_l|)} \int_{|F_l|}^{\mathcal{K}^T_l} p(|F'_l|) \left\langle\, q_{\tau,l} \,\middle|\, |F'_l| \,\right\rangle \mathrm{d}|F'_l| \,. \quad \text{(Usage measure)} \tag{8}$$

Usage of individual transmission lines



Usage of the transmission grid

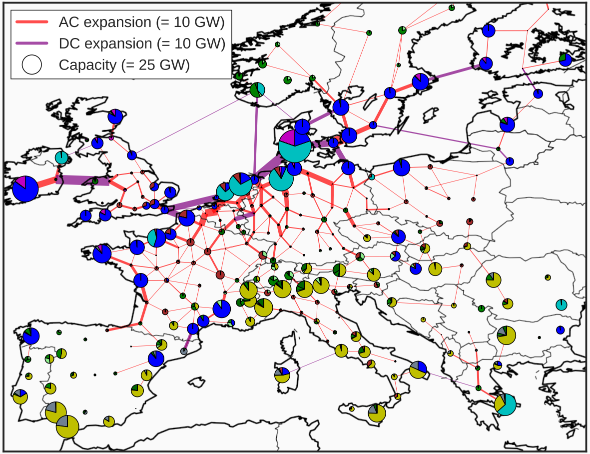


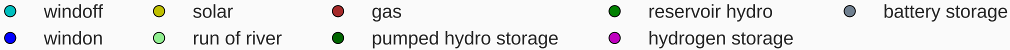


Grid expansion and power flows in an optimized 95% VRE scenario?

- Flow tracing
- consumer benefit vs. generator benefit

Expansion to 2 x today's line volume at 256 clusters





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