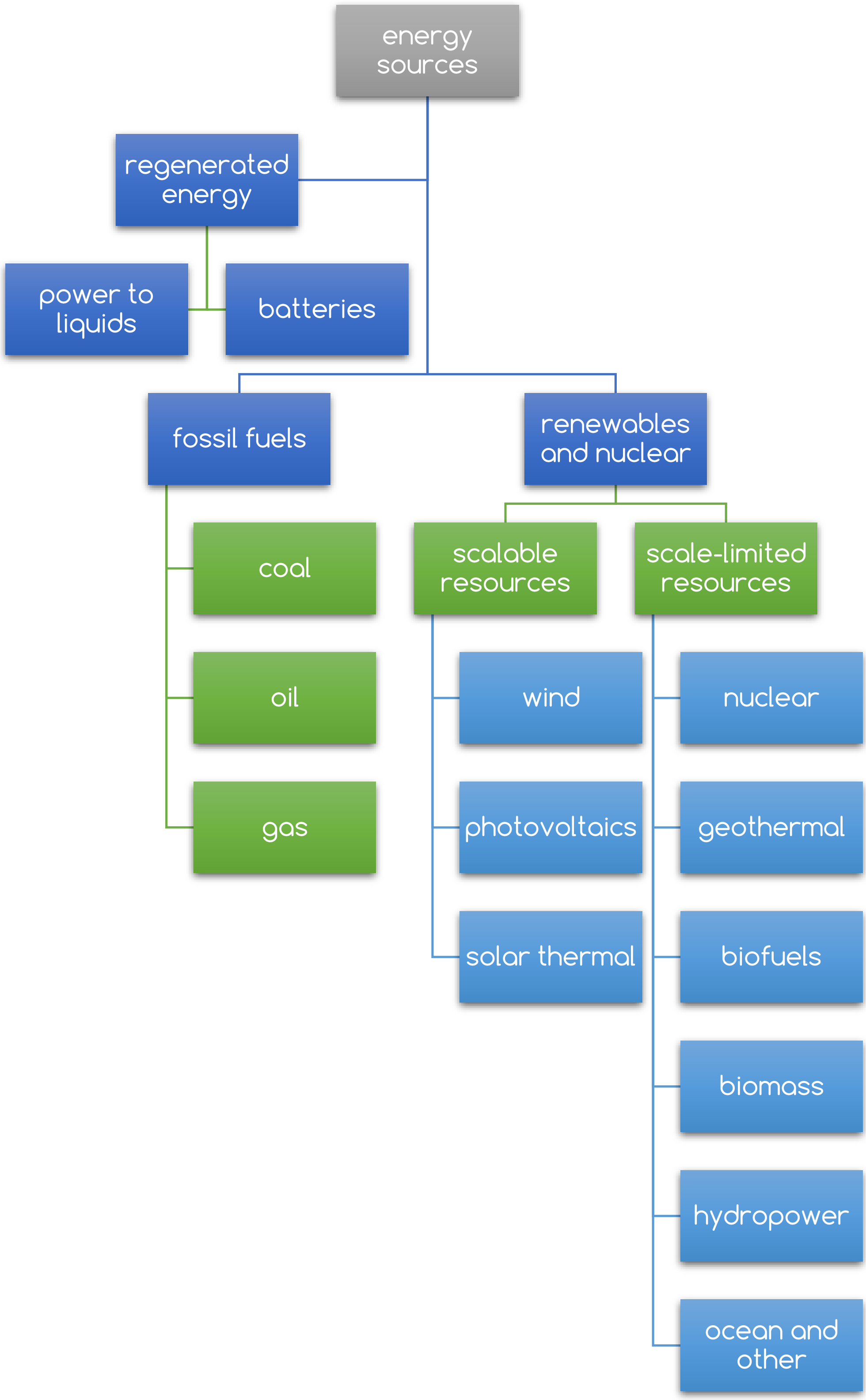
NETSET algorithm | energy source chart



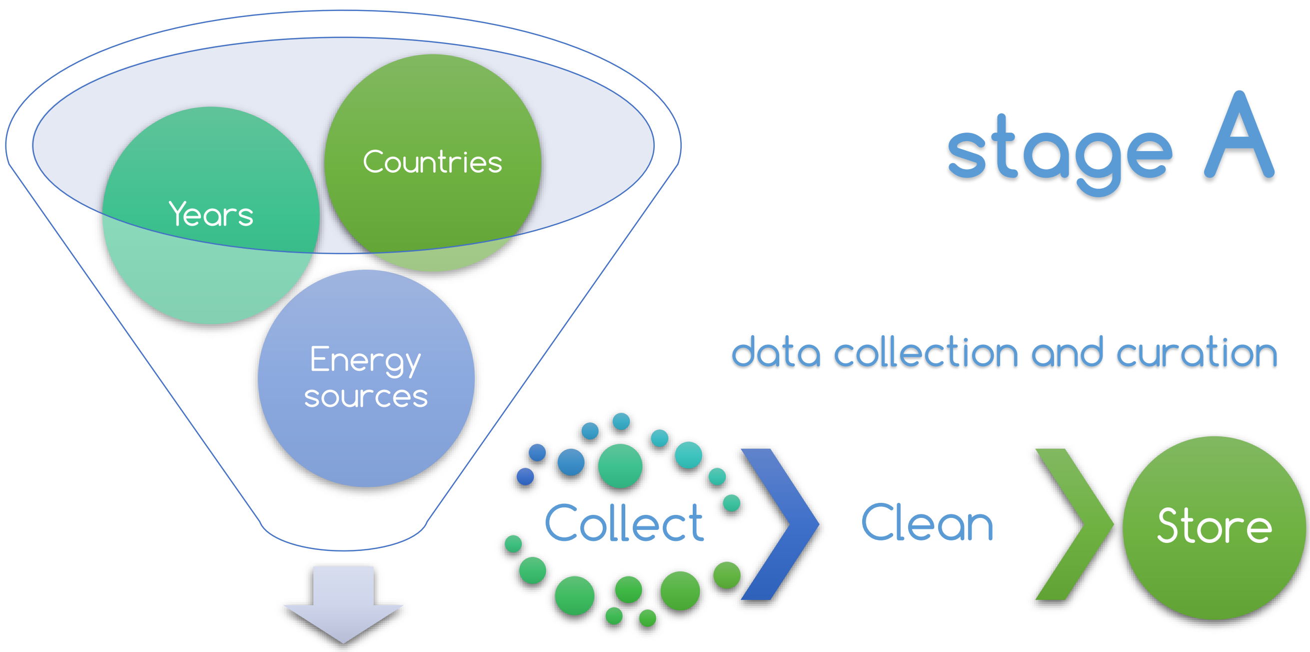
NETSET algorithm | process overview

stage	topic
A	• data collection and curation
B	• demand profiles for primary and secondary energy sources
C	• fossil fuel phase-out profiles and climate change scenarios
D	• renewable energy potentials and resource utiization
E	• transaction cost matrix and country influence matrix
F	• universal governing rules of global energy trade
G	• benchmarking energy investment costs and availability
H	• global energy trade mechanism and NETSET dynamics
I	• total NETSET energy cost estimation and sensitivity analysis

NETSET algorithm

stage A

data collection and curation



A 1
- Collect **population** data
- UNSD 1950-2300 (medium forecast from 2012)

A 2
- Collect **energy** data | **production** & **consumption**
- Average of EIA 1980-2014 and BP 1965-2015

A 3
- Collect **generation capacity** data
- Average of EIA 1980-2014 and BP 1965-2015

A 4
- Collect **emissions** data for fossil fuels
- Average of EIA 1980-2014 and BP 1965-2015

A 5
- Collect **reserves** data for fossil fuels
- Average EIA 1980-2014 and BP 1965-2015

A 6
- Collect **GDP** data
- WDI 1971-2014

NETSET algorithm | stage B

demand profiles for primary and secondary energy sources

A 1 › A 2

B 1
- Calculate historical per capita energy demand (consumption)
- Calulate **per capita average power**

B 2
- Define the desired per capita average power for 2015-2100
- Use an overall final target based on Marechal et al. (2005)
- Follow a smooth, S-shaped transfer function from today's values

B 3
- Collect **reduction rates** in primary energy demand
- Jacobson (2015) and The Solutions Project 100% renewables (2016)

B 4
- Adjust per capita average power as a result of replacing thermal primary energy with electricity and raising the overall process efficiency

B 5
- Collect **minimum power-to-liquid** energy generation shares
- Jacobson (2015) and The Solutions Project 100% renewables (2016)

A 2 › A 3

B 6
- Calculate minimum energy to be supplied by power-to-liquids
- Taking into account differences in capacity factors and conversions

G S
- Run **global SETand TFI sensitivity**, identify most feasible investment ratios
- Record energy generation capacity growth rates and investment budgets

NETSET algorithm | stage C

fossil fuel phase-out profiles and climate change scenarios

C 1
- Collect **emissions budget** and confidence bounds IPCC AR5 (2014)
- Distribute emissions budget across fossil fuels (initially equally)

G S → **C 2**
- Re-estimate budgets for scenario policies (equal share/ fuel switch)
- Run global SET and **estimate energy investment budgets** (*seed*)

A 2 → **A 4** → **C 3**
- Calculate **characteristic emissions intentities** for fossil fuels
- Convert emissions budgets (minus *seed*) to **energy reserves**

C 4
- Calculate unrestricted energy generation profiles for fossil fuels
- After Maggio & Cacciola (2009) based on recoverable reserves

C 5
- Calculate **Hubbert-driven energy phase-out profiles** for fossil fuels
- After Maggio & Cacciola (2009) based on new, restricted reserves

C 6
- Collect **hisorical bilateral energy trade** data in $
- UN COMTRADE 1962-2015

C 7
- Collect historical energy prices and convert $ trade data into energy
- WB GECM 1960-2015

C 8
- **Distribute** global fossil fuel phase-out profile **across producers**
- After McGlade & Ekins (2015) location-based extraction costs

C 9
- Distribute exports of fossil fuel producers across trade partners
- Keep 2015 trade partners, distribute proprotionally with 2015 amounts

NETSET algorithm | stage D

renewable energy potentials and resource utilization

D 1
- Collect **renewable resource maps**: power density data by NREL (2013)
- Create histograms of available energy per NREL power class

A 2 → **D 2**
- Create existing **renewable energy generation histograms** by distributing the country-based production into power classes

D 3
- **Normalize resources and generation across sources** by converting generation power class histograms into resource quality deciles

D 4
- Calculate **normalized resource utilization**: generation-weighted average quality over the same metric for resources

D 5
- Benchmark the **global technical EROEI**, using reported EROEI values and the normalized resource utilization of their locations

D 6
- Calculate the **resource quality advantage**: the resource-weighted average quality of a source over the average of all sources

D 7
- Collect **energy storage requirements** and fractions by technology
- Breyer et al. (2014-2106)

D 8
- Calculate **storage adjusters** based on **ESOI** of storage technologies
- Brandt et al. (2013)

NETSET algorithm | stage E

transaction cost matrix and country influence matrix

C 7 → **E 1**
- •Create directed network (matrix) of all-time electricity trade partners
- •Designate this matrix as the **existing international electricity grid**

E 2
- •Collect country centroid GPS information (Gothos)
- •Create **normalized country to country distance** matrix

E 3
- •Create country neighbor matrix
- •Create country on same continent matrix

E4
- •Create **transaction cost matrix**: unit distance-based costs for energy trade conducted over sea, grid, new neighbor gird or continental grid

C 7 → **E 5**
- •Create 2 import and 2 export matrices: original and reverse flows
- •Imports of A from B are also recorded as exports of B to A

E 6
- •Normalize trade matrices
- •Divide matrices by the average energy trade volume or each country

E 7
- •Create **trade partner importance matrix**: the average (weighted, higher weight for import) of normalized trade matrices of all flows

E 8
- •Define country influence of B on A as the trade importance factor of B for A, and create **country influence matrix** (i.e. the transpose of E7)

E 9
- •Create the **country influence vector**, defined for each country as their energy-trade-volume-weighted average influence on others

NETSET algorithm | stage F

universal governing rules of global energy trade

When developing the dynamic energy trade network, first we must set the **universal rules** governing **global energy trade**. This will set the **power balance** in the network between importers and exporters, i.e. the trade demand of importers or exporters will prevail upon conflicting results – and the openness of trade, i.e. how important is locally-produced energy compared to traded energy.

1. Power balance

   An **importer-driven** structure results in a **top-down hierarchy**, where the importers "demand" and "force" the producers into supplying their products, leading a lock-in of partners – with the most influential countries in the trade influence vector taking the best resources first. This world has the structure of a **multiplayer prisoner's dilemma game**.

   An **exporter-driven, bottom-up structure** resembles a free market (as exporter's cannot really "force" their products on importers but rather they list them on the open energy market, with prices ultimately deciding the flows), or **a public goods game**. In this case, in the event of conflicting demand for the same resource, the exporters partition the resource proportionally to the country influence factors of the aspiring importers.

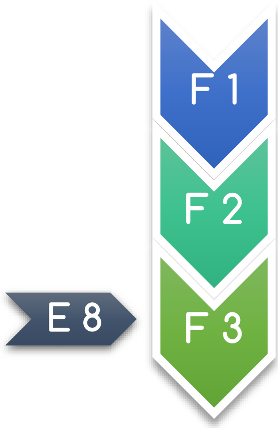
2. Openness of trade

   Both of these worlds can exist in **"cooperate"** or **"defect"** modes, analogous to countries maximizing the total system benefits or their own. In our particular case the system benefit is the total energy investment needed to complete the SETs of all countries.

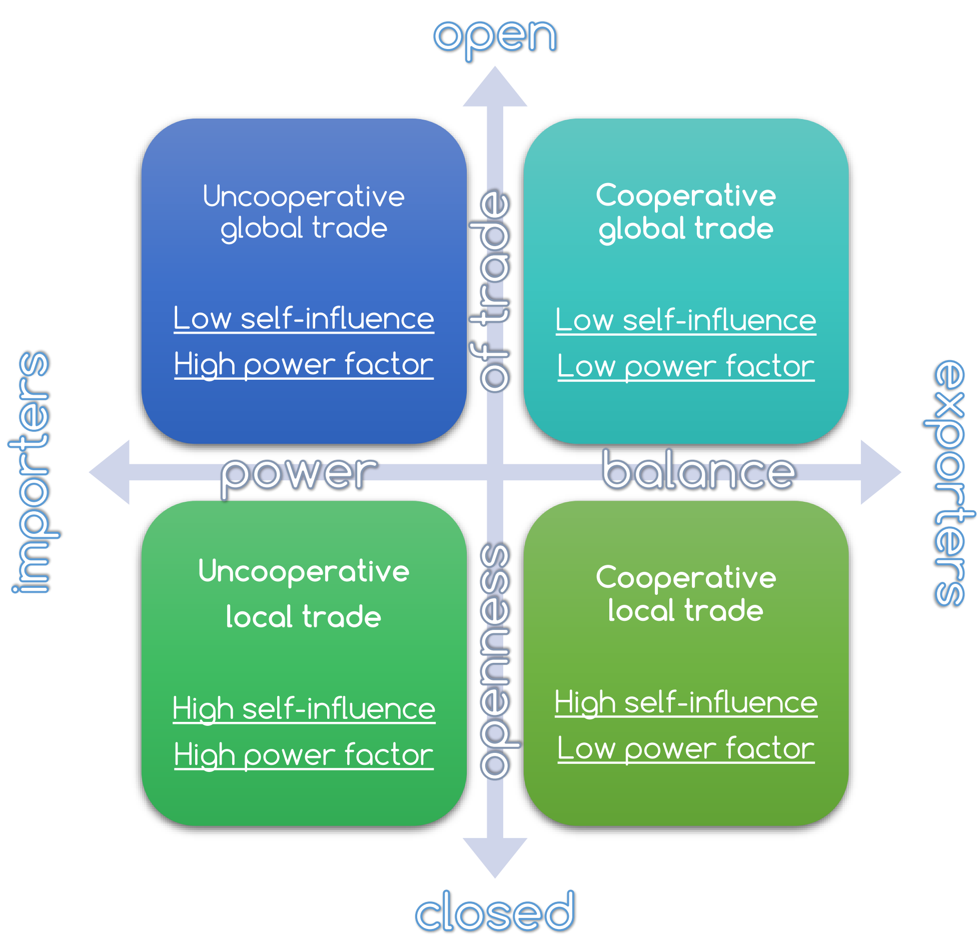
In both cases, the way in which the **country influence** is calculated becomes crucial. The openness of trade will be decided by the **self-influence factor**, i.e. how much countries value trading with themselves – expanding energy generation in-country – compared to the importance of their average trade partner. This will be diagonal of the country-influence matrix. The power balance will be decided based on the **influence power factor**, deciding on the spread of country influence, i.e. how much more influence does the most important trade partner of a particular country have compared to that the average trade partner.

NETSET algorithm | stage F

universal governing rules of global energy trade



- Set **self-influence factor**
- Set **influence power factor**
- Update country influence matrix



NETSET algorithm | stage G

benchmarking energy investment costs and availability

When trying to engineer a coordinated, networked sustainable energy transition for all countries, one single factor has paramount importance: the renewable energy investment ratio. Fossil producer and especially large exporter countries will have to decide how much are they willing to ramp up production in the immediate period before and in the early years of the transition – in essence, bringing forward future energy emissions reserves in time, that enables to build up the renewable energy generation capacity, acting as energy seed for the transition. This, of course, curtails their remaining emissions budgets, but it is unavoidable for a successful transition – as we see from the global SET TFI results.

We have already used the most feasible values of the renewable energy investment rates from the global SET to benchmark the fossil energy production budgets in step C2. This leaves us with well-defined trajectories of demand and fossil fuel availability, along with exogenous profiles of scale-limited resources. This decision, at first glance, seems to lie solely with the exporters, to decide whether they want to alter their business-as-usual production profiles and ramp up production in the near future. However, as saw in stage F, importers can also govern exporter production rates – but the renewable energy investment eventually might not happen at the same pace in all countries. At first run of the model, we use indicative values of global set. In a manner similar to the global SET process, we then alter the initial fossil investment budget and run NETSET again until we have a conversion towards the emissions cap (after 3-4 iterations the deviation is <1%).

After this, we need to determine (guided by the global SET TFI values) the maximum yearly growth rates ("ramp-up speed") of renewable energy production for each technology – putting a constraint on the maximum extractable >= tradeable amount of energy year-to-year. In theory, resource renting would also exist, where countries would invest into building generation capacity from their own energy budgets, for export back home in other countries with good resource quality (such as DESERTEC). In this case both energy investment and the energy consumption would be in the consuming country, therefore in essence "altering" the resource distribution of that particular country. However, because of the geopolitical uncertainties of such solutions, currently we rule them out.

G1

- Set maximum yearly growth rates of renewable energy production
- Create maximum tradeable renewable energy profiles

NETSET algorithm | stage H

global energy trade mechanism and NETSET dynamics

The NETSET model will be solved year by year, by allocating the energy amounts needed by countries to match the gap between fossil fuel availability (plus the non-scalable energy production) and energy demand. Then energy trade flow directions and the traded resources will be determined by country influence and the transaction cost picked by countries in the order or the country influence vector. The global systemic goal of NETSET is set to minimize energy investment for a given preference of domestic production by country, therefore the adjusted EROEIs (based on resource utilization, resource advantage and ESOI) will also be deciding factors in the trade flows, as well as a diversification factor ω_{min} (a minimum share in energy consumption for each resource within a country – for energy security and grid stability reasons).

Following the order set by the influence vector, importer countries will pick their best trade partners until they have matched all of their demand. In-country production is considered trade with self and does not behave differently from trade with other countries. In the event that a country's increase in demand cannot be matched in a certain year (for very large consumers with rapid growth – limited by the production growth-rates of all other trade partners), the in-country limit on growth-rate is lifted and demand is matched by expanding in-country renewable production, regardless. At this stage country's trade pick is not implemented as a trade flow, but rather recorded as a bid. The actual trade flow amount will be decided by the exporters, based on the global trade rules set in F, after all countries have recorded their bids.

After all countries in the influence vector have places their trade bids, there will be overlapping requests recorded for the same resources. This conflict is possible to solve through one of the following two relaxation methods:

- Trade volumes are divided amongst bidders based on their country influence (therefore not matching their entire demand) and the bidding process is recursively repeated until all demand has been matched. After z iterations, when the trade bid amounts have decreased significantly, trade bids are set as binding all trade volume is allocated to the bidder.
- Total volumes are tiered into smaller amounts, and a tier trade is considered immediately binding after the bid has been placed. As long as the country bidding order is decided by the trade influence vector (therefore preserving the distribution by influence proportionality), this process is discrete equivalent to the other, with a predefined number of recursive z iterations resulting in z tiers.

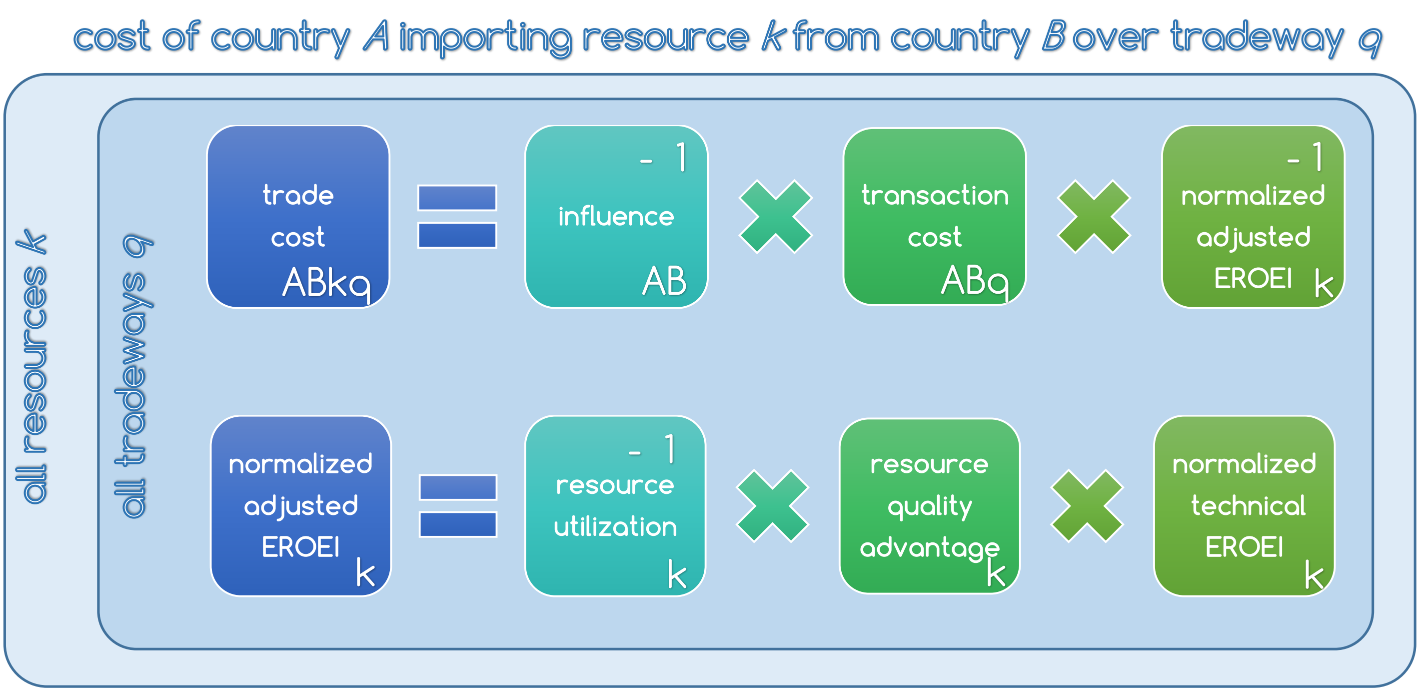
After all trade bids have been fulfilled, a situation might arise, where country A imports all of the energy production of country B, which in turn imports all of its energy from country C, purely due to the differences in trade influence. We call this a trade chain. Depending on the difference in country influences of AC (influence of A on C) and AB + BC, we can choose to relax the trade chains. In particular, the amounts of energy traded in the chain will be distributed as follows:

- An amount proportional to AB + BC – AC, i.e. the influence advantage of B on C over A, will be kept as a trade chain, while the rest will be shifted on the direct trade route AC.

Trade chains can exist several levels deep (A to B to C to D ...), at this stage because of significant computational complexity, we will only consider level 0 – no trade chains – or level 1.

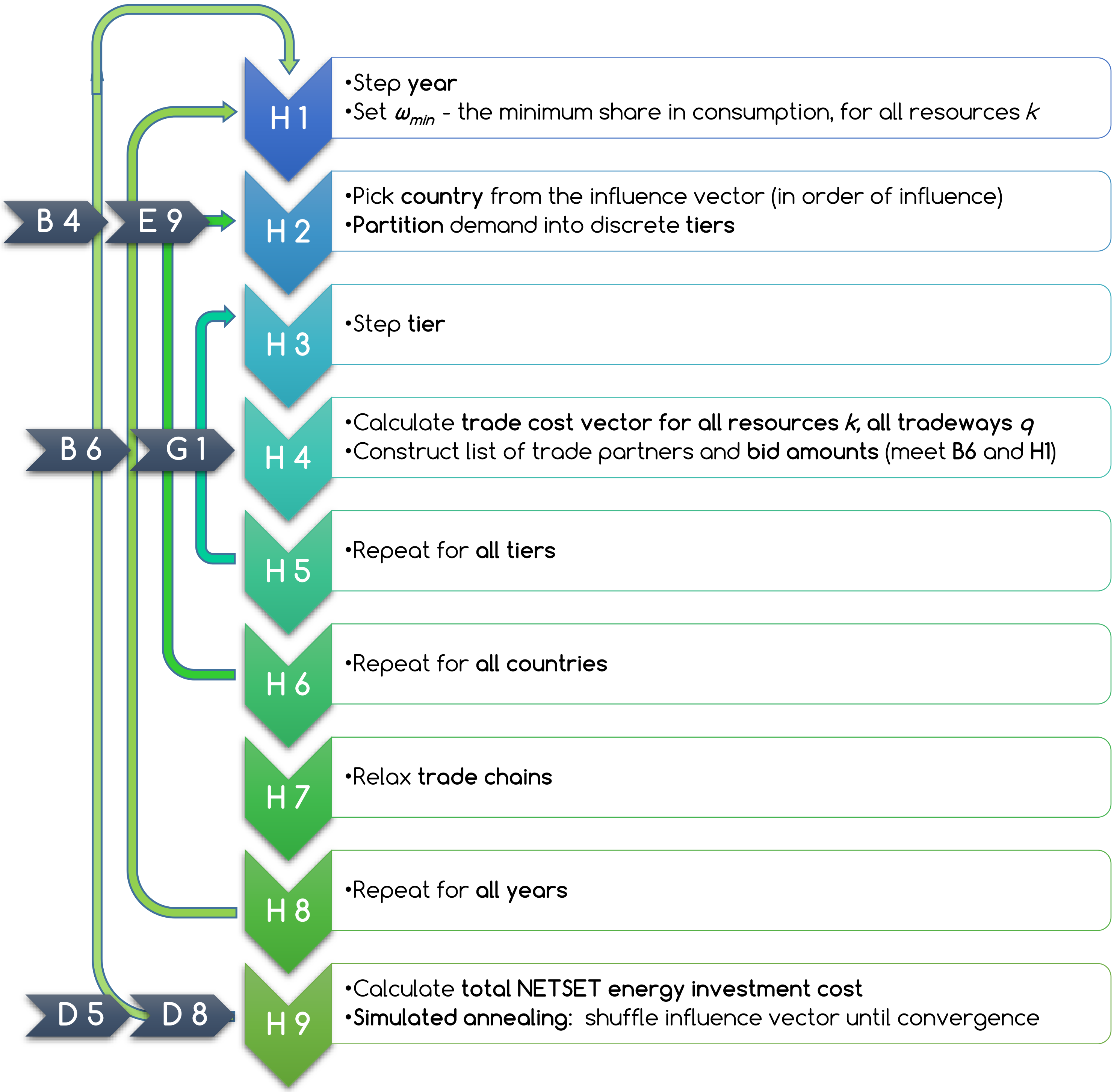
Finally, while the bidding order of the country influence vector might reflect the geopolitical realities of energy trade, it might not necessarily lead to the overall lowest energy investment and thus not the lowest overall energy transition cost. In order to find the optimal energy investment cost, we do a simulated annealing on the country influence vector: we switch two countries at random in the country influence vector and repeat the entire trade allocation process. If the resulting total energy investment cost of the transition is lower than before, we keep the two countries switched in the order. We repeat the switching process until the energy investment cost starts to converge.

The deciding metric of a trade flows will be the trade cost vector. At each trading step (e.g one trading tier) the importer country will create and maintain a trade cost vector, which will include the costs of trading with partners, over various tradeways (as in E4). This will be the product of 5 normalized (around 1.0) factors: the reciprocal of country influence, the transaction cost and the reciprocal of the normalized adjusted EROEI, in turn composed of reciprocal of resource utilization, the resource quality advantage and the normalized technical EROEI. The chosen trade partner and tradeway will be the one carrying the lowest cost. Once implemented, a trade flow will be in effect for $L_{contract}$ (contract lifetime) number of years.



NETSET algorithm | stage H

global energy trade mechanism and NETSET dynamics



NETSET algorithm | stage I

total NETSET energy cost estimation and sensitivity analysis

In order to test the NETSET model for robustness against the uncertainties in the assumptions, at the final stage of the NETSET algorithm, we have incorporated a set of sensitivity tests.

The main sources of uncertainty in the networked part of SET are stemming from the parameter values defining the universal governing rules of global energy trade. We conduct all 4 combinations of a high and low values of self-influence and power factor.

The maximum yearly growth rates of renewable energy production also play an important role when choosing the trade partners, therefore we try two different values, as well as for the diversification factor ω_{min}, as these two parameters play a crucial role in eliminating potential trade flows not satisfying the constraints set by these parameters within a particular trading tier.

Lastly, to check for the consistency of the simulated annealing, we execute the process with 3 different random seeds.