



PROJECT REPORT

# Modeling framework of Energyscope Transitional Pathway (ESTP)

Special documentation for internal usage for DGE-DIREN, Canton de Vaud

## Authors

Xiang Li  
Prof. François Maréchal

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# Acronyms

**CCUS** carbon capture, utilization, and sequestration. viii

**COP** Coefficient of Performance. xxiii

**DAC** direct air capture. xxiii

**DEC** Decentralized heating. iii

**DHN** District heating. iii, xi, xii

**ESTP** Energyscope Transitional Pathway. i

**EUDs** End Use Demands. iii, x, xviii

**FECs** Final Energy Consumptions. vii, xi

**HP** Heat pump. xii

**LHV** Lower heating value. x, xii

**MILP** Mix integer linear problem. iii

**Mpkm** Million passenger kilometer. xi

**Mtkm** Million tonne kilometer. xi

**NG** natural gas. iv, ix

**PV** Photovoltaic. xiii

**SH** space heating. xiv, xv

**SNG** Synthetic natural gas. iv, xi, xii

**VD** Canton de Vaud. i, xv

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# 1. Context

## 1.1. General project background

This documentation serves as an explanatory material on the project Energyscope Transitional Pathway (ESTP) development for Canton de Vaud, under grant agreement *ENE-20009* between DGE-DIREN and IPESE. This project consists in adapting the Swiss “snapshot” Energyscope model<sup>1</sup> developed by IPESE, to a “dynamic” Vaud-specific transitional pathway model, facilitating user-tailored scenario definition, simulation, and techno-economic-ecological assessment, in favor of trade-off analyses among heterogeneous energy pathways for rational decision-making. The results can be accessed in the local files, or visualized via an integrated local website. Initial documentation for Energyscope is available in the publication [5, 7, 12]. A considerable amount of data were collected, analyzed, and calibrated by DIREN and Statistique Vaud, including the installed capacities (from 1990 to 2017), productions, demands, and emissions. These data are elaborated in another report, thus not repeated here. This documentation focuses on presenting the major modifications to the modeling framework dedicated to Canton de Vaud (VD).

## 1.2. History of Energyscope model

For energy planning, two methodologies are commonly used, namely optimization and simulation. Each methodology has pros and cons, summarized in Fig. 1. Due to the difficulty of dealing with loop issues arising with increasing penetration of renewables, storage, and carbon capture, use, and storage (CCUS), the recent ESTP model adopted the optimization methodology as detailed in the next section. For instance, for the fuel cell vehicle and battery electric vehicle, both are based upon green energy and it is difficult to predict how much to be deployed for each category of the vehicles. In such case, an optimization is able to generate solutions quantifying the optimal configuration of the vehicles within the defined ranges.

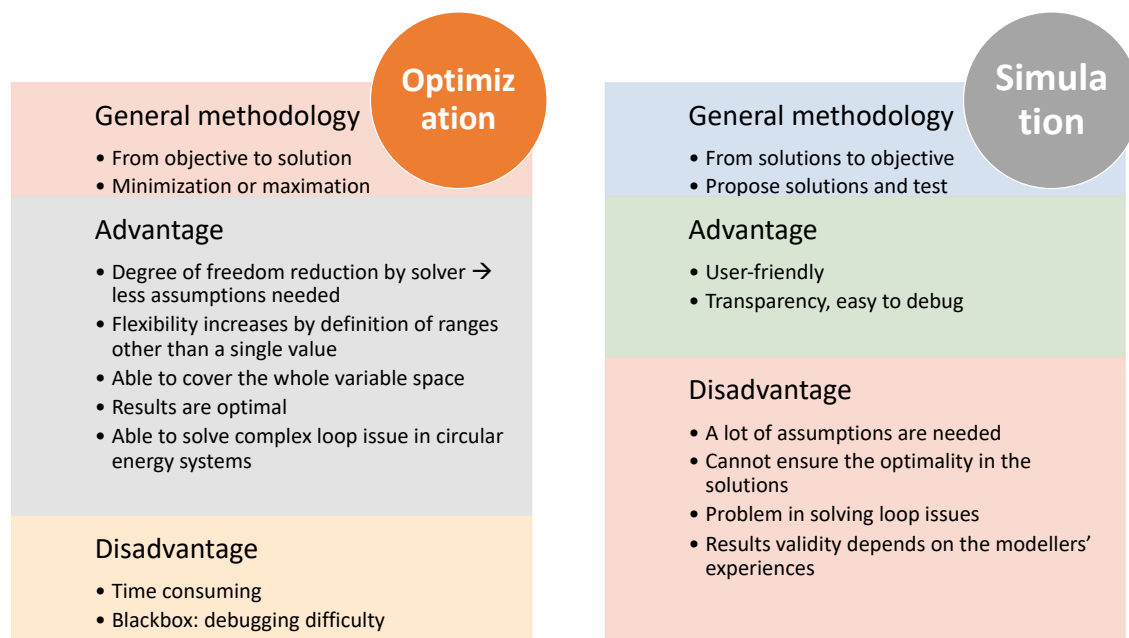


Fig. 1: Pros and cons of optimization models and simulation models.

<sup>1</sup>Initial version available in <https://www.energyscope.ch>

The development of Energyscope has undergone three phases:

- Phase 1: a simulation model. This version is based upon the excel input file by Victor Girones in IPESE. Easy for users to use, which however lacks a modeling depth, very limited consideration on biomass, carbon capture, etc. No optimization. Snapshot model, implying only for a certain year in the future.
- Phase 2: optimization by AMPL (a non-open source mathematical programming language). This version can calculate the optimal cost and emissions, however, not able to achieve net-zero emission due to a lack of complete carbon flow chains. Besides, it is still a snapshot model.
- Phase 3: multi-stage optimization in GLPK (an-open source optimization language similar to AMPL). The major contribution is to develop the snapshot model into a transitional pathway model and keep computational efficiency.

The next chapter will elaborate on the modeling framework for the updated model.

## 2. Modelling framework

The platform, Energyscope Transitional Pathways (ESTP), is composed of multi-individual snapshot models, as shown in Fig. 2. Each model represents one stage of the optimization algorithm. Each stage corresponds to one/several year(s). Different from the commonly-known Markov chain, the decision of each stage depends not only on the previous stage, but on all stages' results and the macro drivers ( $\mathcal{D}$ ) e.g. population, etc., and the evolutionary data ( $\mathcal{V}$ ) such as the technology cost, as well as historical data ( $\mathcal{H}$ ) before the reference year that indicate the expected decommissioning time in coming years. For each stage, the annualized system total cost (or annual total emission) is minimized given all the information of previous stages  $\Phi$ , and all changes covering technology cost evolution, resource price evolution, efficiency improvement, availability update, etc.

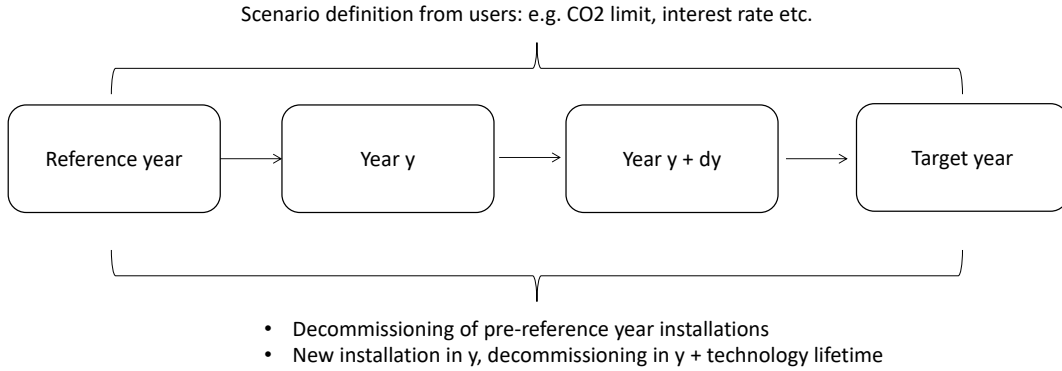


Fig. 2: General model structure: multi-stage optimization. Each box is a Mix integer linear problem (MILP), in order to minimize the system total cost, subjected to decisions taken in previous years and the constraints defined by users for the current stage, for instance, banning fossil fuel importations in a certain year.

### 2.1. Objective function

The objective function in ESTP can be either the minimization of the system total cost, or minimization of the carbon emission. Without specification, the objective function is set to minimization of the system cost. CO<sub>2</sub> emission is set as a  $\varepsilon$ -constraint in the following section.

The objective cost function for each stage is expressed as Eq.1, where  $inv$ ,  $maint$  and  $op$  represent the investment cost (CAPEX), maintenance cost (fixed OPEX) and operational cost (variable OPEX) respectively. Here  $\mathcal{E}$  denotes the technology set, and  $\mathcal{R}$  the resource set. Take a natural boiler for example, the variable OPEX in the model refers to the purchase of natural gas [GWh], while the CAPEX and fixed OPEX are proportional to the installed capacity [GW].

$$\min TC(y) = \min \left( \sum_{i \in \mathcal{E}} C_{inv}(i, y) + \sum_{i \in \mathcal{E}} C_{maint}(i, y) + \sum_{r \in \mathcal{R}} C_{op}(r, y) \mid \Phi(y' < y) \right), \quad y, y' \in \mathcal{Y} \quad (1)$$

### 2.2. Model constraints

In general, the major constraints in ESTP include:

- **demand balance:** energy supplies should satisfy the End Use Demands (EUDs) at any period. For instance, the heating demand in households should be balanced by the District heating (DHN) and the Decentralized heating (DEC) heating supply. In this model, DHN and DEC could be supplied by gas, oil, electricity, etc.

- **conversional balance:** for technology, the input energies should equal the output energies plus the dissipated energy. For instance, in a wood gasification process, the energy carried by wood equals to sum of the energy in the product Synthetic natural gas (SNG), the heat consumed in the process and the heat to the ambient environment.

In parallel, **carbon balance** is witnessed. The input carbon in the wood should be equal to the sum of the carbon in the SNG and the CO<sub>2</sub> emitted to the atmosphere.

- **resource balance:** the total inputs from imported resources, *e.g.* natural gas (NG), and the synthetic resources (*e.g.* SNG), should equal to the total consumption (*e.g.* NG/SNG boiler, gas motors etc.) and storage (store: positive; release negative) in any time period.

Apart from the three major balances, other constraints will be elaborated in the following. To better understand the structure of the model, the parameters and variables in the model can be categorized into two levels :

- **local:** these parameters and variables only exist within one stage optimization. One example is the installed capacity  $F$ , which is a *memoryless* individual variable indifferent to stages.
- **global:** it refers merely to the parameters, excluding the variables. These parameters are supposed to be dynamically updated across stages. For instance, the  $f_{loss}(i, y)$ , ( $i \in \mathcal{E}, y \in \mathcal{Y}$ ) represents the expected natural decommission at year  $y$ , the values of which in next stages depend on the historical energy stocks and the investment decision on the current stage.

The objective of distinguishing the categories is to reduce the dimensionality of decision variables for improving computational efficiency. After one stage optimization at  $y$ , the global parameters will be updated for all the stages  $Y$  ( $Y \geq y$ ) following Eq. 2-7. First, the effective installed capacity  $F$  in the year  $y$  is determined by the total installed capacity  $f_{mult}$  in the previous stage  $y - ts$ , the new installation  $F_{new}$ , the capacity that is set aside  $F_s$ , and the expected decommission capacity  $f_{loss}$ . Here  $ts$  denotes the time step  $\Delta y$ .  $F_{new}(i)$  and  $F_s(i)$  are not supposed to be positive simultaneously subject to the cost minimization objective. This reinforces the utilization of existing capacities (which may be set aside in previous years) rather than developing greenfield projects. One example of a CCGT plant, which might not be used in a certain period due to emission limitations, but can be reused in the future as long as it is still within its lifetime, for instance, if SNG is used as the fuel to replace NG. This dynamism contributes to the flexibility of the model to make the best choices at each time step.

$$F(i) = f_{mult}(i, y - ts) + F_{new}(i) - F_s(i) - f_{loss}(i, y), \quad i \in \mathcal{E}, y \in \mathcal{Y} \setminus \{y_{ref}\} \quad (2)$$

$$F(i) \geq 0, F_{new}(i) \geq 0, F_s(i) \geq 0, \quad i \in \mathcal{E}, y \in \mathcal{Y} \quad (3)$$

Then the total capacity  $f_{mult}$  (including all installed capacities regardless in use or not) at year  $y$  for technology  $i$  is expressed as :

$$f_{mult}(i, y) = F(i) + F_s(i), \quad i \in \mathcal{E}, y \in \mathcal{Y} \quad (4)$$

It should be noted that the decommission may occur in different years within the current period (implying the years between  $y-ts$  and  $y$ ), which should be aggregated as the total expected decommissioning during the period, as shown in Eq. 5. The sum of the capacity set aside and expected decommission is supposed to be less than or equal to the total capacity in the previous stage.

$$f_{loss}(i, y) = \sum_{y-ts < y' \leq y} f_{loss}(i, y'), \quad i \in \mathcal{E}, y \in \mathcal{Y} \setminus \{y_{ref}\}; \quad (5)$$

$$F_s(i) + f_{loss}(i, y) \leq f_{mult}(i, y - ts), \quad i \in \mathcal{E}, y \in \mathcal{Y} \setminus \{y_{ref}\}; \quad (6)$$

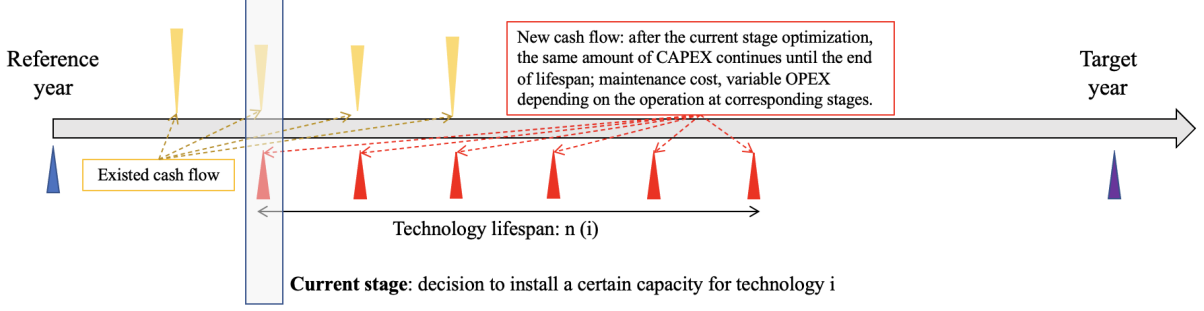


Fig. 3: Cash flow example following one optimization decision for investment at a stage for one technology. The existed cash flows (in yellow) resulted from historical stocks ( $< y_{ref}$ ) and installations in previous stages  $[y_{ref}, y - ts]$  will be updated by integrating the new cash flows (marked in red) for the next stages, based upon a fixed-load amortization assumption depending on the load rate in the current stage.

The loss is updated:  $n(i)$  representing the expected lifespan for a technology  $i$ . For cases where  $y + n(i) \notin \mathcal{Y}$ , the loss is distributed to the closest next stage  $y_l$ .

$$\begin{aligned} y_l &= \min_{y' \in \mathcal{Y}} \{y' \mid y' \geq y + n(i)\}, \\ f_{loss}(i, y_l) &= f_{loss}(i, y_l) + F_{new}(i) \end{aligned} \quad i \in \mathcal{E}, y \in \mathcal{Y} \quad (7)$$

In correspondence, the investment cash flows in the next stages are calculated following the decision-making of year  $y$ . The overall investment at a certain year  $y'$  is thus decided by the new installed capacity and all historical remaining bills denoted by a dynamic parameter  $c_{inv,existed}$  in Eq.8, which is updated after every stage following Eq. 9. Additionally, the maintenance cost is proportional to the effective installed capacity in Eq. 10, and the variable operational cost is decided by the amount of fuel consumption in Eq. 11. Here  $\mathcal{T}$  represents the time periods in the model within a year  $y$ .

$$C_{inv}(i, y) = c_{inv}(i, y)F_{new}(i)\tau(i, y) + c_{inv,existed}(i, y), \quad i \in \mathcal{E}, y \in \mathcal{Y} \quad (8)$$

$$c_{inv,existed}(i, y') = c_{inv}(i, y)F_{new}(i)\tau(i, y) + c_{inv,existed}(i, y'), \quad i \in \mathcal{E}, y, y' \in \mathcal{Y}, y \leq y' < y + n(i) \quad (9)$$

$$C_{maint}(i, y) = c_{maint}(i, y)F(i), \quad \forall i \in \mathcal{E}, y \in \mathcal{Y} \quad (10)$$

$$C_{op}(r, y) = \sum_{t \in \mathcal{T}} c_{op}(r, y)F_t(r, t)t_{op}(t), \quad \forall r \in \mathcal{R}, y \in \mathcal{Y} \quad (11)$$

Figure 3 illustrates in general the cash flow modeling in the model. Despite various ways of investment modeling, we assume a straight-line based amortization approach based upon interest rate in the investment year when a new installation decision is made, due to a lack of information on specific investment strategies *a priori*. Concretely, the yearly amortization is determined by the annualization factor  $\tau$  depending on the interest rate  $\alpha$  at the initial investment year  $y$  and the expected lifespan  $n(y)$  of the technology, as shown in Eq. 12, where  $r_\tau(y)$  denotes the ratio of the interest rate in the year  $y$  compared to the reference year.

$$\begin{aligned} \tau(i, y) &= \frac{\alpha(y)(1 + \alpha(y))^{n(i)}}{(1 + \alpha(y))^{n(i)} - 1}, \quad i \in \mathcal{E}, y \in \mathcal{Y} \\ \alpha(y) &= r_\tau(y)\alpha(y_{ref}), \quad y \in \mathcal{Y} \end{aligned} \quad (12)$$



In terms of the evolution of specific technology costs,  $r_{inv}, r_{maint}$  represent the ratio of the expenditure in year  $y$  compared to the reference year for investment and maintenance respectively. Apart from technology cost, the same methodology is applied for operational cost evolution  $c_{op}$  for purchasing resources, as well as the annualization factor  $\tau$ .

$$\begin{aligned} c_{inv}(i, y) &= c_{inv}(i, y_{ref})r_{inv}(i, y), & i \in \mathcal{E}, y \in \mathcal{Y} \\ c_{maint}(i, y) &= c_{maint}(i, y_{ref})r_{maint}(i, y), & i \in \mathcal{E}, y \in \mathcal{Y} \\ c_{op}(r, y) &= c_{op}(r, y_{ref})r_{op}(r, y), & r \in \mathcal{R}, y \in \mathcal{Y} \end{aligned} \quad (13)$$

Eq. 14 limits the annual output  $X$  for a given year  $y \in \mathcal{Y}$  for technologies. The consumption by resource over the whole year is capped by the availability  $\gamma$  in Eq.15.

$$\begin{aligned} out_{min}(i, y) &\leq X(i) \leq out_{max}(i, y), \\ X(i) &= \sum_{t \in \mathcal{T}} F_t(i, t)t_{op}(t) & i \in \mathcal{E}, y \in \mathcal{Y} \end{aligned} \quad (14)$$

$$\sum_{t \in \mathcal{T}} F_t(r, t)t_{op}(t) \leq \gamma(r, y), \quad r \in \mathcal{R}, y \in \mathcal{Y} \quad (15)$$

All the formulas above are of granularity of year. Hereafter the monthly-level constraints are presented, noted with  $t$  as a subscript of the parameters and variables.

The output of technology in a period  $t$  in a year  $y$  should be less than its corresponding installed capacity times the period capacity factor  $c_{-p.t}$ , expressed by Eq. 16. It is highlighted that this constraint only works on intermittent technologies  $\mathcal{E}_{imt}$  with significant monthly input variation, namely wind, solar thermal, solar power, hydro dam, and hydro river. For other technologies, Eq. 17 is applied, where an annual capacity factor  $cp$  is defined. This approach allows a flexible operational strategy for deploying non-intermittent resources across different periods.

$$0 \leq \mathbf{F}_t(i, t) \leq F(i)c_{-p.t}(i, t, y), \quad i \in \mathcal{E}_{imt}, t \in \mathcal{T}, y \in \mathcal{Y} \quad (16)$$

$$\sum_{t \in \mathcal{T}} F_t(i, t)t_{op}(t) \leq F(i) * cp(t, y) * \sum_{t \in \mathcal{T}} t_{op}(t), \quad i \in \mathcal{E} \setminus \mathcal{E}_{imt}, t \in \mathcal{T}, y \in \mathcal{Y} \quad (17)$$

In order to reflect the energy balance, an input-output table represented by a two-dimension matrix  $io$  is introduced. For a certain layer  $l$ , e.g. the electricity, the supply by technologies, import and export, storage, and consumption ( $eud$ ) at any period in Eq. 18 should be balanced, including the losses from power grids and heating networks, calculated in Eq. 19. The end-use demand evolution is driven by the macro drivers represented by the parameter  $r_{eud}(l, y)$  in Eq. 20, namely the ratio of the demand in year  $y$  compared to the reference year, based upon user inputs.

$$\sum_{i \in \mathcal{R} \cup \mathcal{E}} layers\_in\_out(i, l)F_t(i) - eud(l, t, y) = 0, \quad \forall l \in \mathcal{L}, \forall t \in \mathcal{T}, \forall y \in \mathcal{Y} \quad (18)$$

$$Loss(g, t) = \%_{loss}(g) \sum_{i \in \mathcal{R} \cup \mathcal{E} | io(i, g) > 0} f(i, g)F_t(i), \quad \forall g \in \mathcal{G}, \forall t \in \mathcal{T} \quad (19)$$

$$eud(l, t, y) = r_{eud}(l, y)eud(l, t, y_{ref}), \quad \forall l \in \mathcal{L}, \forall t \in \mathcal{T}, \forall y \in \mathcal{Y} \quad (20)$$

A more straightforward interpretation of Eq. 18 is given by:

$$\sum_{s \in \mathcal{S}} EUD(s, t) + Export(t) + \sum_{i \in \mathcal{E}} Consumption(i, t) = \sum_{i \in \mathcal{E}} Prod(i, t) + Import(t) - Loss(t), \quad \forall layer \quad (21)$$

Fig. 4 illustrates the layer concept in the model. Take **electricity layer** as a concrete example to understand Eq. 21: the sum of electricity as end use demands in all sectors (residence, service, industry, and mobility), and electricity consumption for system coupling (not EUD, e.g. by a heat pump for heating,

where the heating is EUD while electricity is the Final Energy Consumptions (FECs)), and the electricity exportation, should be balanced by the total electricity production within VD by all electricity supply technologies (PV, waste power plants etc.), plus the electricity import from abroad and other cantons in Switzerland, excluding the power grid loss. The equation holds for every period, implying January to December in one stage optimization.

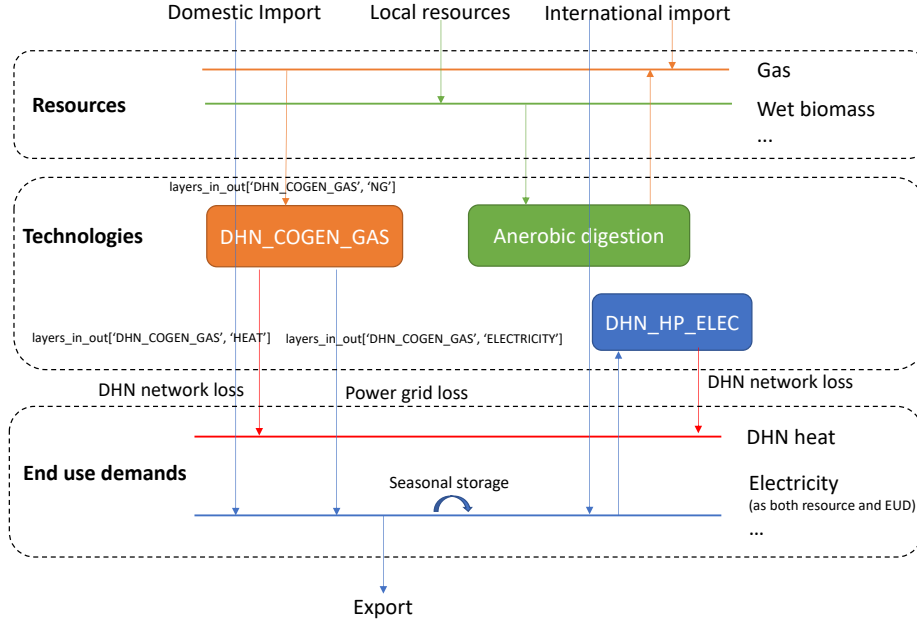


Fig. 4: Example of the energy layers in ESTP: each layer (horizontal solid lines) within each period defined in the model is balanced by a number of inputs and outputs, including intermediate processes (e.g. storage), except the End use demands layers, where the differences reflect the EUDs.

District heating (*DHN*) is becoming an increasingly important heating source. Eq. 22 and 23 enforce the *DHN* installed capacity needs to be at least  $\alpha_p$  ( $\alpha_p \geq 1$ ) times the nominal size in order to ensure supply security in peak demand periods.

$$F(DHN) = \sum_{j \in DHN\_TECH} F(j) \quad (22)$$

$$F(DHN) \geq \alpha_p \max_{t \in \mathcal{T}} \{eud(DHN, t, y)\}, \quad y \in \mathcal{Y} \quad (23)$$

A couple of constraints are dedicated to renewable energies. Eq. 24 and 25, expressed in a compact non-linear formulation, where the nominator represents the low-temperature heat demand from district heating and decentralized heating in period  $t$ , and the denominator stands for the total low-temperature heat demands of space heating (*SH*) and hot water (*HW*) of the whole year. It renders the model more realistic by defining the operating strategy for decentralized heating: the relative technology use in each period is thus constant, except for the solar thermal (DecSolar): if solar thermal  $k$  is installed ( $Y_{Solar} = 1$ ), then at maximum one technology  $j$  is used as a backup. To reflect the impact of increasing penetration of intermittent renewables, an empirical formulation[7] is applied in correspondence to the total installed intermittent capacities, with a specific additional investment cost  $\beta$  in Eq. 26. Eq. 27 simulates the behavior of energy storage, using two binary variables  $STO_{in,r}$  and  $STO_{out,r}$  representing the store and release with efficiency parameter  $\eta$ , plus a continuous and circular constraint of the storage level  $SL$  with time  $t$ .  $\mathcal{S}_r$  denotes the storage technologies. The instant capacity of storage/release is capped by

the second and third inequalities in Eq. 27 while the annual storage is capped by the 5 inequalities.

$$F_t(j) + F_t(k)Y_{\text{Solar}}(j) \geq \frac{eud(DHN,t,y) + eud(DEC,t,y)}{EUD(SH,y) + EUD(HW,y)} \sum_{t \in \mathcal{T}} F_t(j)t_{op}(t), \quad (24)$$

$$k = DEC_{\text{Solar}}, \forall j \in DEC, j \neq k, \forall t \in \mathcal{T}, \forall y \in \mathcal{Y}$$

$$\sum_{j \in \mathcal{E}} Y_{\text{Solar}}(j) \leq 1 \quad (25)$$

$$F(\text{GRID}) = 1 + \beta \frac{F(\text{WIND}) + F(\text{PV})}{f_{\text{max}}(\text{WIND},y) + f_{\text{max}}(\text{PV},y)}, \forall y \in \mathcal{Y} \quad (26)$$

$$\begin{aligned} STO_{in,r}(t) + STO_{out,r}(t) &\leq 1, \quad \forall t \in \mathcal{T} \\ 0 \leq F_{t,in}(j) &\leq STO_{in,r}(j,t)f_{\text{max}}(j,y), \quad \forall j \in \mathcal{S}, \forall t \in \mathcal{T}, \forall y \in \mathcal{Y} \\ 0 \leq F_{t,out}(j) &\leq STO_{out,r}(j,t)f_{\text{max}}(j,y), \quad \forall j \in \mathcal{S}, \forall t \in \mathcal{T}, \forall y \in \mathcal{Y} \\ SL_j(t) &= SL_j(t-1) + F_{t,in}(j)t_{op}(t)\eta_{in}(y) - F_{t,out}(j)t_{op}(t)/\eta_{out}(y), \quad \forall j \in \mathcal{S}, t \in \mathcal{T}, \forall y \in \mathcal{Y} \\ SL_j(t) &\leq out_{\text{max}}(j,y), \quad \forall j \in \mathcal{S}, t \in \mathcal{T}, \forall y \in \mathcal{Y} \end{aligned} \quad (27)$$

In terms of the operation, the wet biomass and waste cannot be stored for a long time, whereas their generation is quasi-constant over the year. Therefore:

$$F_t(r,t) \sum_{t' \in \mathcal{T}} t_{op}(t') \geq \sum_{t' \in \mathcal{T}} F_t(r,t')t_{op}(t') \quad \forall r \in \mathcal{S}, \forall t \in \mathcal{T} \quad (28)$$

In ESTP, a novel modeling structure for simulating the circular carbon flows in a system of high penetration of biomass and CO<sub>2</sub>-to-X technologies. Specific carbon sources and sinks are identified. *e.g.*, carbon sources are divided into biogenic and non-biogenic parts: both could be used to produce electricity and heat, or converted to other fuels, for instance, bio-diesel. By applying carbon capture technologies, a part of emission could be sequestered underground, or reused in the presence of excess electricity to synthesize e-fuels. These fuels are supposed to be consumed as fossil fuels, *e.g.* by a car, leading to carbon emissions to the atmosphere again, which can only be compensated by biomass or direct air capture.

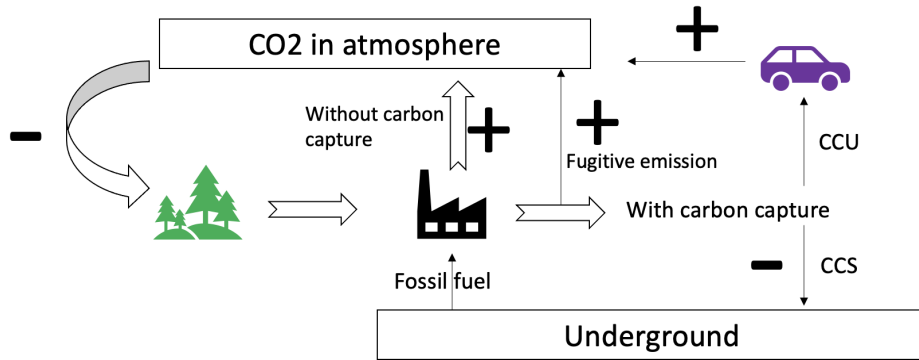


Fig. 5: Illustrative flows of biogenic and fossil carbons, with and without carbon capture, utilization, and sequestration (CCUS). The complex carbon loops necessitate an optimization model.

Different from the majority of models which simply set the carbon emission of biomass as net-zero, the approach in ESTP, taking into account both positive and negative emissions, allows for tracking the whole carbon flow chain in the energy system. In the meanwhile, it evades the difficulty of artificially distinguishing the biogenic and non-biogenic carbon sources in specific processes, *e.g.* in waste incineration where biogenic and non-biogenic carbon sources are likely to co-exist. The carbon balance in

ESTP is handled by the CO<sub>2</sub> layers, which behave as tanks with incoming carbon flows from various sources and outgoing flows to different locations. The following list summarizes the CO<sub>2</sub> layers defined in the model:

- CO2\_A: the carbon emission from carbon-intensive fields, such as a NG power plant. This amount of carbon emission is capturable by applying conventional carbon capture technologies, *e.g.* pre-combustion capture, post-combustion capture, etc. In Energyscope, all centralized emissions are computed into this category.
- CO2\_C: the captured carbon, which is assumed to either be used or stored; in this level, CO<sub>2</sub> storage could be further categorized as:
  - CO2\_S: sequestration, where the CO<sub>2</sub> is buried in an underground formation and cannot be reused;
  - CO2\_SS: temporary storage, implying the CO<sub>2</sub> can be used later when there is excessive electricity.
- CO2\_E: in contrast to CO2\_A, the CO2\_E refers to the carbon emissions from non-concentrated spot sources, *e.g.* a car or a household wood boiler. Apart from that, fugitive emissions from conventional carbon capture technologies are also included into CO2\_E. These emissions are not supposed to be capturable without biomass photosynthesis or direct air capture. In ESTP, all emissions stemming from decentralized technologies belong to this category.

All technologies in ESTP are linked to a/several CO<sub>2</sub> layer(s) with corresponding emission factors. Take one carbon flow cycle for example, such as wood: when it is converted, *e.g.* to SNG, part of its carbon goes to form the hydrocarbon molecules, and the other part is released into the atmosphere (CO2\_A) that can be captured in place and converted to CO2\_C to be treated by following sequestration or re-utilization processes. If sequestered, negative emission will be realized; if reused and not captured anymore, the associated positive emission will be compensated by the negative emission in wood formation (negative CO2\_E), resulting in net zero emission. Following this logic, the total emission ( $TE$ ) of the energy system is thus expressed as the sum of the carbon emissions in the layers CO2\_A and CO2\_E, which is subject to a  $\varepsilon$ -control representing the decarbonization objective in 29, where  $F_t(j)$  denotes the output for technology  $j$  in the time period  $t$ , and  $\theta(j, k, y)$  reflects the emission factor for this technology to a certain CO<sub>2</sub> layer  $k$  in year  $y$ , which can be positive, zero or negative.

$$TE = \sum_{\substack{j \in \mathcal{E}, \\ k \in CO2\_A \cup CO2\_E, \\ t \in \mathcal{T}}} F_t(j) \theta(j, k, y) t_{op}(t) \leq \varepsilon(y), \quad \forall y \in \mathcal{Y} \quad (29)$$

From the carbon flow perspective, the captured CO2\_C can either be transformed into fuels or be stored temporarily or permanently (sequestered underground). This concept is translated into Eq. 30, reflecting that the carbon balance of carbon sources and sinks, where the inputs stem from all carbon capture technologies  $CC$ , and the outputs flow to  $CCS$  and  $CCU$ , representing all the carbon sequestration and utilization technologies respectively.

$$\sum_{j \in CC} F_t(j) = \sum_{j \in CCS} F_t(j) + \sum_{j \in CCU} F_t(j) + \sum_{j \in CTS_{in}} F_t(j) - \sum_{j \in CTS_{out}} F_t(j) \quad \forall t \in \mathcal{T} \quad (30)$$

The remaining constraints in ESTP for auxiliary purposes are not included here for simplicity. Next, we elaborate on the modeling of energy demands, technologies, and resources.

## 2.3. Major concepts in the model

### 2.3.1. End use demands (EUD)

The EUDs are defined as the energy directly consumed by the user at their location, as opposed to primary energy which is the energy that is harvested from natural resources, commonly at a different location as the demands. For instance, if the wood is used in a residential boiler for providing space heating, then the heat provided is the EUDs, while wood is considered as Final energy consumption, where there is a conversional efficiency from energy in wood (Lower heating value (LHV)) to the energy that we finally consume (EUD).

The EUDs in the model are categorized by sector, which needs to be satisfied by energy supplying technologies. Table 1 lists all the EUDs in ESTP.

Table 1: EUDs in ESTP. The concrete values need user inputs (see Appendix. 6.1). Put zero in certain cases where the demand does not exist, for instance, high temperature (process) heating in transportation

Demand category	Sector
ELECTRICITY	HOUSEHOLDS
ELECTRICITY	SERVICES
ELECTRICITY	INDUSTRY
ELECTRICITY	TRANSPORTATION
LIGHTING	HOUSEHOLDS
LIGHTING	SERVICES
LIGHTING	INDUSTRY
LIGHTING	TRANSPORTATION
COOLING	HOUSEHOLDS
COOLING	SERVICES
COOLING	INDUSTRY
COOLING	TRANSPORTATION
HEAT_HIGH_T	HOUSEHOLDS
HEAT_HIGH_T	SERVICES
HEAT_HIGH_T	INDUSTRY
HEAT_HIGH_T	TRANSPORTATION
HEAT_LOW_T_SH	HOUSEHOLDS
HEAT_LOW_T_SH	SERVICES
HEAT_LOW_T_SH	INDUSTRY
HEAT_LOW_T_SH	TRANSPORTATION
HEAT_LOW_T_HW	HOUSEHOLDS
HEAT_LOW_T_HW	SERVICES
HEAT_LOW_T_HW	INDUSTRY
HEAT_LOW_T_HW	TRANSPORTATION
MOBILITY_PASSENGER	HOUSEHOLDS
MOBILITY_PASSENGER	SERVICES
MOBILITY_PASSENGER	INDUSTRY
MOBILITY_PASSENGER	TRANSPORTATION
MOBILITY_FREIGHT	HOUSEHOLDS
MOBILITY_FREIGHT	SERVICES
MOBILITY_FREIGHT	INDUSTRY
MOBILITY_FREIGHT	TRANSPORTATION

The values of EUDs are only a function of the drivers, such as the population, energy efficiency

improvement (*e.g.* renovation), etc, implying they are independent of the usage of fuels. The same EUDs could be fed by a variety of supply mixes, for instance, the space heating demand could be supplied by full electricity, or by natural gas.

In execution, the optimization algorithm reads first the user input annual EUD by demand category and by sector. Then the algorithm will calculate the monthly EUDs:

- for space heating, lighting, cooling: the algorithm will multiply a monthly profile share (see the parameter `heating_month` and `cooling_month` in the `data_s.dat` file) to distribute the annual demands into months in order to reflect the obvious seasonal demand differences. The monthly profiles are based upon historical observation.
- for the other EUDs, we assume the demands are constant over the year. Thus the model divides the EUDs by 8760h to get the hourly energy demands.

Thus the unit for EUDs is either GW or Mpkm/h or Mtkm/h, representing the average required capacity for a certain month. Here Million passenger kilometer (Mpkm) is for passenger mobility, and Million tonne kilometer (Mtkm) is for freight mobility. The monthly EUDs are to be satisfied by the monthly energy supply. It should be noticed that the EUD electricity is only for baseload electricity, *e.g.* in lighting, or by electronic appliances in households. Electricity used for system coupling, *e.g.* in a heat pump to provide heating, is not regarded as electricity end-use demand. In this case, the heat is the end-use demand, other than the electricity. This approach contributes to the optimization of the system by selecting more efficient supplying methods given the same EUDs.

### 2.3.2. Final energy consumption

Final energy consumption covers all energy supplied to the final consumer for all energy uses [3]. Take the same example: if the wood is used in a boiler for space heating, then wood is the final energy consumption. However, if the wood is used in gasification for SNG, then it is not considered as FEC, even with possible partial heat recovery in such process.

In ESTP, the FECs encompass:

- Natural gas: import, or generated within VD via bio processes
- Diesel: import. or generated within VD via bio processes
- Gasoline: import, or generated within VD via bio processes
- Heating oil: import, or generated within VD via bio processes
- Coal: only import
- DHN: district heating, which may come from different sources, for instance, waste cogeneration, or deep geothermal. If a resource is used in DHN, for instance, NG, the amount used in DHN will not be accounted in NG used in other applications.
- Electricity, which can be desegregated according to their sources:
  - Import, either from other cantons in Switzerland, or import from abroad.
  - Waste: used in the waste incineration plants in VD.
  - Wood: from VD, including a variety of categories of woods following the definition from SCCER-BIOSWEET project.
  - Solar: from VD
  - Wind: from VD
  - Geothermal: from VD

- Hydro: from VD
- Gas: import, or generated within VD via bio processes
- Oil: import, or generated within VD via bio processes

Users have the control over the resource (RES) utilization via the parameters:

- `avail_max[RES, y]`: the maximal potentials of the resource in a given year  $y$ . Unit GWh by default. The maximal potentials of these cantonal resources are assessed in another report.
- `avail_min[RES, y]`: the minimal utilization of a certain resource, by default zero, unit GWh by default. Change to a non-zero value enforces the system to use the resources. Users can use this to simulate the energy policy, for instance, set the minimum solar energy has to be more than XXX GWh in 2035.

For fossil fuels, the avail parameters imply the minimal and maximal annual import amount. For wood and wet biomass, we set the maximal availability to the estimated cantonal potentials for VD by default. However, the users can set a value larger than the potential, implying importation. A hidden hypothesis here is the cantonal resources are prioritized; importation only occurs when the cantonal resources are not enough.

### 2.3.3. Resources

The resources in ESTP refer merely to energy resources, which could be used, directly or indirectly, for energy purposes. Resources are a concept broader than FEC. For instance, natural gas can be directly used as FEC while wet biomass commonly needs to be converted to SNG before utilization for energy purposes. Here wet biomass is a resource whilst not FEC. So the difference between FEC and energy resources is if it is directly participated in supplying the EUD.

Apart from the resources used as FEC aforementioned, hydrogen is also a resource, though not natural. It could be generated in VD, *e.g.* via electrolysis, or imported. Uranium for nuclear power plant is not counted, since VD does not have it and do not plan to have it according to the phasing out nuclear plan by the energy policy of Switzerland.

In ESTP, the conversion between mass and energy for resource is based upon LHV. For each resource, a parameter called `carbon_content` (kt-C/GWh) is defined as the ratio between the mass share of C element in the resource (kt-C/kt-resource) and the LHV (GWh/kt-resource). The carbon content by resource is available in the `data_s.dat`.

### 2.3.4. Technology

In ESTP, the definition of technology is a process that converts a series of inputs to certain products. Therefore, technology is regarded as a bridge connecting the energy resources and the EUDs.

**Naming convention** The name of the technologies follows a **ternary form**, such as `DEC_BOILER_OIL`. Here DEC implies the technology is dedicated to decentralized heating, BOILER denotes the technology, and OIL is the type of fuel. In ESTP, there are technologies serving merely as intermediate processes, such as wood gasification for SNG, implying not directly participating in satisfying EUDs.

One important parameter for technology is the `layers_in_out` ( $i,l$ ) (hereafter named LIO), which denotes the conversional efficiency of a certain technology  $i$ . A negative value of LIO for layer  $l$  implies  $l$  is an input for this technology. In contrast, a positive value of LIO means  $l$  is an output layer for this technology. For instance, a Heat pump (HP) for DHN consumes -0.25 GWh electricity to produce 1 GWh heat. Then: `layers_in_out` (“DHN\_HP\_ELEC”, “ELECTRICITY”) = -0.25, and `layers_in_out` (“DHN\_HP\_ELEC”, “HEAT\_LOW\_T\_DECEN”) = 1. If a technology generates CO<sub>2</sub> emissions, the unit is ktCO<sub>2</sub>.

It should be highlighted that the item where the  $layers_{in\_out} = 1$  is regarded as the **main output** of the technology. All the technology-associated parameters, like specific investment cost, maintenance cost, etc., are based upon the main output. For instance, a 1 GW decentralized heat pump (*DEC\_HP\_ELEC*) implies the **heat** capacity is 1 GW, not the **electricity** capacity (which is only 0.333 GW if the COP of the heat pump is 3), since the  $layers_{in\_out}["DEC\_HP\_ELEC", "HEAT\_LOW\_T\_DECEN"] = 1$ , which can be found in the `techs_glpk.dat` file.

The energy technologies in ESTP can be categorized into the following categories. Here IND implies industrial usage, DEC implies decentralized usage, and DHN implies district heating usage. COGEN is short for cogeneration of power and heat. HP stands for heat pumps. The main output of all cogeneration units is heat, except DHN\_COGEN\_GAS where electricity is taken as the main output.

- Centralized heating: namely district heating for low-temperature heat supply (space heating and hot water), which can be supplied by DHN\_HP\_ELEC DHN\_SOLAR (solar thermal) DHN\_COGEN\_GAS DHN\_COGEN\_WOOD DHN\_COGEN\_WASTE\_HEAT DHN\_BOILER\_GAS DHN\_BOILER\_WOOD DHN\_BOILER\_OIL DHN\_DEEP\_GEO HT\_LT\_DHN (industrial waste heat for DHN) DHN\_RENOVATION (building renovation). The last technology is, strictly speaking, not a technology since it helps to reduce the heating demand other than supply heat. It is however treated as a technology for modeling purposes. Users can use `out_min` and `out_max` parameters to limit the range of energy savings due to renovation. In addition, the DHN\_DEEP\_GEO refers to the usage of geothermal energy for direct heating, not for power generation. The one that is for power generation is called “GEOTHERMAL” in the Electricity supply item.
- Decentralized heating: non-district heating for low-temperature heat supply (space heating and hot water), namely DEC\_HP\_ELEC DEC\_COGEN\_GAS DEC\_COGEN\_OIL DEC\_ADVCOGEN\_H2 DEC\_BOILER\_GAS DEC\_BOILER\_WOOD DEC\_BOILER\_OIL DEC\_SOLAR DEC\_DIRECT\_ELEC DEC\_RENOVATION HT\_LT\_DEC. The last-second refers to renovation, and the last one implies industrial waste heat for decentralized heating.
- Process heating: industrial process heating demand. These demands are commonly of high temperature. IND\_COGEN\_GAS IND\_COGEN\_WOOD IND\_COGEN\_WASTE\_HEAT IND\_BOILER\_GAS IND\_BOILER\_WOOD IND\_BOILER\_OIL IND\_BOILER\_COAL IND\_BOILER\_WASTE IND\_HP\_ELEC IND\_DIRECT\_ELEC
- Electricity supply: Photovoltaic (PV) WIND IND\_COGEN\_WASTE\_ELEC DHN\_COGEN\_WASTE\_ELEC IND\_COGEN\_GAS IND\_COGEN\_WOOD DHN\_COGEN\_GAS DHN\_COGEN\_WOOD CCGT DEC\_COGEN\_GAS DEC\_COGEN\_OIL HYDRO\_DAM NEW\_HYDRO\_DAM HYDRO\_RIVER NEW\_HYDRO\_RIVER GEOTHERMAL. Here the difference between the HYDRO\_DAM and NEW\_HYDRO\_DAM is that the former represents the existing capacity while the latter is the capacity to be built.
- Storage: ELEC\_STO H2\_STO SNG\_STO. Here the storage (electricity, hydrogen, synthetic gas) refers to the seasonal storage. Short-term storage is not included due to time granularity. ELEC\_STO corresponds to the hydro storage.
- Fuel generation: intermediate processes that generate fuels, including METHANATION (CO<sub>2</sub> to SNG) GASIFICATION\_SNG (biomass gasification to SNG) PYROLYSIS (Biomass to heating oil) AN\_DIG (Anaerobic digestion of wetbiomass for SNG) HYDRO\_GAS (Hydrothermal gasification of wetbiomass for SNG) FT (Biomass Fischer Tropsh process for diesel and gasoline) CO2-To-Diesel (CO<sub>2</sub> to diesel and gasoline) ALKALINE\_ELECTROLYSIS (for hydrogen) PEM\_ELECTROLYSIS (protein exchange membrane for hydrogen) SOEC\_ELECTROLYSIS (solid oxygen electrolysis cell for hydrogen) GASIFICATION\_H2 (biomass gasification for hydrogen);



- Freight mobility: TRAIN\_FREIGHT TRUCK TRUCK\_NG TRUCK\_FUEL\_CELL (hydrogen truck), TRUCK\_BEV (battery electric truck);
- Passenger mobility, including:
  - Private mobility: CAR\_GASOLINE CAR\_DIESEL CAR\_NG CAR\_HEV (hybrid electric vehicle) CAR\_PHEV (plug-in hybrid vehicle) CAR\_BEV (electric car with battery) CAR\_FUEL\_CELL (hydrogen car);
  - Public mobility: TRAMWAY\_TROLLEY BUS\_COACH\_DIESEL BUS\_COACH\_HYDIESEL (elec+diesel) BUS\_COACH\_CNG\_STOICH (compressed gas bus) BUS\_COACH\_FC\_HYBRIDH2 (hydrogen bus) TRAIN\_PUB (train for passenger);

All the technical parameters are available in our Gitlab folder Energy technologies [1], except for the investment cost for vehicles. In the initial version of Energyscope, the costs for vehicles are treated as zero. However, if costs are not taken into account, the energy system tends to choose the most energy-efficient technologies, namely the electric vehicles, that may not reflect the fact that the electric cars are commonly more expensive than conventional cars. In ESTP, we collected the data for various vehicles (see Appendix - Vehicle costs) in 2017, and integrated these costs into the model. By consequence, the model is able to take the economic part of the vehicles into account in addition to energy efficiency.

For industrial waste heat, we defined two parameters, namely *share\_wh\_dhn\_min* and *share\_wh\_dhn\_max*, to reflect the minimal and maximal shares of industrial heat for DHN out of the total industrial heat. Similar for *share\_wh\_dec\_min* and *share\_wh\_dec\_max* in terms of DEC heating.

### 2.3.5. Energy efficiency

Energy efficiency improvement is commonly regarded as an effective method contributing to carbon neutrality. In ESTP, we take the following two aspects into account:

#### 1. Demand side reduction, covering industry, residence/services, and mobility.

- Industry heat recovery: a part of industrial waste heat is promising to be recovered for district heating. In the model, two parameters are defined, namely: *share\_wh\_dhn\_min*(*y*) and *share\_wh\_dhn\_max*(*y*), representing the minimal share and maximal share of available waste heat in the industry at year *y*.
- Building renovation: the potential energy saving in space heating (SH) by building renovation is estimated by Statistique Vaud, reflected by the EUDs variation. Specifically, the demand evolution ratios ( $EUD_y/EUD_{y_{ref}}$ )  $r_{dem}[HEAT\_LOW\_T\_SH',INDUSTRY']$ ,  $r_{dem}[HEAT\_LOW\_T\_SH',HOUSEHOLDS']$ , and  $r_{dem}[HEAT\_LOW\_T\_SH',SERVICES']$  are influenced by different levels of renovation.
- Electrification in mobility: a new parameter *ev\_share\_min* is defined quantifying the minimal share of electric vehicles in passenger mobility. For freight mobility, freight electric train minimal and maximal shares are set by the parameters *share\_freight\_train\_min* and *share\_freight\_train\_max*.

#### 2. Supply side growth: with the technology development, the conversional efficiencies, in particular for low-carbon technologies, are supposed to rise in the future. In other words, the same resource inputs can lead to increasing outputs. In ESTP, we have two ways to depict the technology efficiency:

- monthly capacity factor *c\_pt*: defined as the maximal ratio between the real production and the theoretical production for a given installed capacity for a certain month in a certain year. For instance, we installed 1  $MW_e$  PV panel in 2022. In January, the theoretical electricity

production is thus 744 MWh. However, this output cannot be realized in reality due to the intermittency of solar irradiation. The maximal electricity production in January in VD is estimated to be 39 MWh according to geographical-climatic analysis [7]. By consequence, the  $c_{p,t}$  equals to 5.3%.

Users can adjust the value of  $c_{p,t}$  value if obvious technology development is expected to achieve. For instance, if the efficiency of PV increases by 10% in 2041, then the  $c_{p,t}$ (“PV”, $t$ ) for 2041 are supposed to be its old value \* 1.1 for all  $t \in 1, 2, \dots, 12$  representing the 12 months. The same for the following years (2042-2050), except there are further data on the efficiency estimation in those years.

### 3. Major assumptions

1. As a common approach applied in energy planning, we optimized the energy system by cost minimization, under the carbon mitigation objective. However, the real market might not be always perfect, and as a result, the energy pathways are likely to divert from the projected ones. Nevertheless, this assumption allows an estimation of the least cost that society needs to pay for the energy transition.
2. As explained above, the fuel costs in this model refer to merely the import costs, excluding taxes, to reflect the system cost without political intervention. Users can add the energy tax by change the  $c_{op}$  parameter in case needed.
3. The energy demands are driven by population, GDP, energy reference area etc, based upon the estimations from Vaud Statistique. The assumptions used for projecting the macro drives are supposed to impact the results. Details are available in the data report.
4. The conventional efficiencies and costs for low-carbon technologies vary with time. In the model, we defined specific parameters ( $r_{eff}, r_{inv}$ ) to estimate their evolution in the future based on a broad literature review. However, for non-renewable technologies, e.g. a NG boiler, the cost and efficiency are assumed to be invariant due to their technical maturity. However, the fuel costs, namely oil (gasoline, diesel, heating oil), natural gas, and coal, are supposed to be volatile. To reflect their variation, we took the estimation from IEA [4].
5. Apart from SH and cooling, which shows significant monthly disparities, the other EUDs are assumed uniformly distributed over months.
6. To estimate the decommissioning timing of technologies in the future, we took the typical lifetimes (by technology), which might be slightly different from the real lifetimes of these existing capacities. However, this assumption is necessary for a macro-energy planning model, which can give an overall projection of the possible deficits in the coming years.
7. The interest rate is assumed to be 2.215% according to [10], which is highly uncertain in reality. Sensitivity analysis can be made in case needed by varying the  $r_i$  parameter in `user_input_vd.xlsx`.
8. The grid losses, including electricity grid and DHN grids, are based upon today’s data in Switzerland and VD respectively, due to a lack of valid projection methods for the future.
9. As no wind farm is installed in VD for the moment, no Vaud-specific data is available for calculating the wind monthly capacity factor. As a result, we took the values [7] from existing installations in Mont-Soleil and Mont-Crosin, assuming similar performances. Such values can be easily updated in the `user_input_vd.xlsx` file when pilot projects are in place in VD.

## ESTP

- 2017\_input.xlsx: inputs for EUD by sector in reference year
- user\_input\_vd.xlsx: definition of scenarios by user inputs for evolutionary data after the reference year
- r\_dem\_efficiency.xlsx: inputs for efficiency shares only for employment module
- \_\_main\_\_.py: main program
- treating: python files collecting/treating data and realizing dynamic interactions with GLPK models in execution.
  - \_\_init\_\_.py: initialization file
  - main.py: the main file for scenario running
  - data.py: definition of static data and evolutionary data
  - auxiliary.py: definition of auxiliary functions for ESTP
  - postcompute.py: results tidy-up and analyses
- SES\_MODELS: GLPK optimization models
  - \*.mod: two model files for the reference year and other years respectively
  - \*.dat: data files including:
    - data.ini.dat: EUD in the reference year generated based upon user input
    - data\_s\_init.dat and data\_s.dat: static data including lighting/heating/cooling profiles and fuel prices
    - techs\_glpk.dat: technology parameters *e.g.* the specific investment cost and conversional efficiency
  - Scenario\_X: Repositories generated by the program, including:
    - Start (i.e. the reference year)
      - \*.dat one data file for dynamic data
      - RESULTS: results for the reference year
        - \*.csv: 32 csv files for storing results
        - \*.out: a report file generated by GLPK
    - 20XX
      - MODEL: part of the models for the year 20XX
        - \*.dat two data files for static and dynamic data respectively
      - RESULTS: results for the year 20XX
        - \*.csv: containing 32 csv files for storing results
        - \*.out: a report file generated by GLPK
    - Others: Summary of results across years
- app.py: generating visualization website

## 4. Model utilization

This section explains how to use ESTP, including installation, data input, scenario creation, model execution, and results visualization.

### 4.1. Installation

ESTP necessitates two tools, namely Python and GLPK<sup>2</sup>. Corresponding installation instructions are summarized below.

1. Open terminal: Under Windows system, move the mouse pointer to the bottom-left corner of the screen and Right-click, or press Windows key + X. In the power user task menu, select Command Prompt (Admin). This will open the Command Prompt window. In MAC, type terminal in the spotlight search.
2. Go to a repository via terminal where you wish to install ESTP, type: `git clone https://gitlab.com/ipse/energyscope/case-studies/diren.git`  
(To make sure you have the right access to the gitlab folder, please contact IT [Michel Lopez](#) at IPESE before installation.)
3. Installation of python3 (recommended version v3.7), downloadable from <https://www.python.org>, and pip tool <https://www.liquidweb.com/kb/install-pip-windows/>
4. Installation and configuration of virtual environment
  - Go to the father folder of ESTP in terminal
  - Following the steps in <https://uoa-eresearch.github.io/eresearch-cookbook/recipe/2014/11/26/python-virtual-env/>
5. Install all python libraries listed in Table 2
6. Installation of GLPK, an open-source optimization tool, recommended version GLPK LP/MIP Solver, v4.65: downloadable from <https://www.gnu.org/software/glpk/>. GLPK should be added to the environmental variables of the operation system.  
To test if the GLPK is well installed, open a terminal and type: `glpsol`. If the terminal shows `GLPSOL: GLPK LP/MIP Solver, v4.65`, then your GLPK is successfully installed.

Once the program is well installed, put all the .xlsx files listed in section 3 under ESTP repository. Those .xlsx files are for users to input historical data (e.g. the existing capacities) and define scenarios (e.g. CO2 emission limit, PV potential, etc.). A full list of available parameters that users can define is available in the appendix. It is recommended to create a python virtual environment for running. Hereinafter, we name the repository ESTP as the **root repository** of the project. A detailed tree graph illustrating the structure of the program, is available in section 3, with an explanation of the major functionalities by file/repository. For the users, **the most important files are the three .xlsx files** where the definition of scenarios can be made or updated (basic way). Apart from directly modifying the .xlsx, ESTP allows users to define scenarios in the `__main__.py` file (advanced way). The next section will present how to define scenarios in detail in the data input section.

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<sup>2</sup>GNU Linear Programming Kit, a package intended for solving large-scale linear programming (LP), mixed integer programming (MIP), and other related problems. It is a set of routines written in ANSI C and organized in the form of a callable library.

## 4.2. Data input

Three excel files are necessary for users to input:

- 2017\_input.xlsx: the EUDs, see Table 1.
- user\_input\_vd.xlsx: see section 4.3.1
- r\_dem\_efficiency.xlsx: the share of the EUD variation that can be attributed to employment. Concretely:  $EUD_{2017} * r\_dem(y) * r\_dem\_efficiency(y)$  is the amount of energy (GWh) that can be used as a basis to compute employment changes in the EUD sector according to the model by V. Moreau [6]. Here 2017 is the reference year and  $EUD_{2017} * r\_dem(y)$  gives the EUD demand in year y.

## 4.3. Scenario definition

By default, 2050 is chosen as the end year and the year slice is 3 years. In the `__main__.py` file, user can change the `end_year` and time step. The definition of scenarios in ESTP is reflected by the modification of parameters, such as the `co2_limit`, the interest rate, the maximal or minimal production of a series of technologies, maximal import amount of resources in certain coming years. These scenarios could be used to simulate the policy impact on the energy system.

In `__main__.py`, users can define as many scenarios as possible. The number of scenarios should be the same as in the `user_input_vd.xlsx`. There are two ways to modify the scenario, either from `user_input_vd.xlsx`, or directly in `__main__.py`.

### 4.3.1. Scenario definition in user\_input\_vd.xlsx

The file `user_input_vd.xlsx` is dedicated to parameters that depend on the time horizon (year). The users need to define these parameters a priori. It includes two categories:

- control parameters: for instance `co2_limit`, `share_heat_dhn_max` (maximal district heating share in low-temperature heating supply), etc.
- non-control parameters: for instance interest rate ratio of a certain year with respect to reference (start) year.

Each sheet in the file represents a parameter, as listed below. Without specification, the parameter is unitless. Such parameters are all year (y)-dependent.

- `r_i(y)`: interest rate evolution ratio in the year y (between 2017 and 2050) with respect to 2017, by default 1. This parameter could be modified by reasonable assumptions.
- `co2_limit(y)`: unit ktCO<sub>2</sub>, by default a huge value, 1000000, representing no constraints. This needs to be modified by users' decisions.
- `ev_share_min(y)`: the minimal share of electric vehicles (battery electric car) in the private passenger mobility (MOB\_PRIVATE).
- `ev_share_max(y)`: the maximal share of electric vehicles (battery electric car) in the private passenger mobility (MOB\_PRIVATE).
- `share_wh_dhn_min(y)`: the minimal share of industry heat used for district heating.
- `share_wh_dhn_max(y)`: the maximal share of industry heat used for district heating.
- `share_wh_dec_min(y)`: the minimal share of industry heat used for decentralized heating.

- `share_wh_dec_max(y)`: the maximal share of industry heat used for decentralized heating.
- `share_heat_dhn_min(y)`: the minimal share of district heating in low-temperature heat supply.
- `share_heat_dhn_max(y)`: the maximal share of district heating in low-temperature heat supply, by default 100%, and modification expected.
- `share_freight_train_min(y)`: the minimal share of a freight train in freight transportation
- `share_freight_train_max(y)`: the maximal share of a freight train in freight transportation, by default 100%, and modification needed.
- `share_mobility_public_min(y)`: the minimal share of public transportation in passenger transportation.
- `share_mobility_public_max(y)`: the maximal share of public transportation in passenger transportation, by default 100%, modification needed.
- `amb_heat_min(y)`: unit GWh. The minimal heat from the ambient environment that is extracted by heat pumps, including district and decentralized heat pumps.
- `amb_heat_max(y)`: unit GWh. The maximal heat from the ambient environment that can be extracted by heat pumps, including district and decentralized heat pumps.
- `r_op(RES,y)`: ratio of variable operational cost (for purchase of resources) in the year  $y$  compared to reference year for each resource RES. This parameter can be used to define the cost evolution of fuels. Take natural gas for instance, the price in the reference year 2017 is 0.03 CHF/kWh, but for 2023 in the scenario 2, it is estimated to be 10 times the price in 2017 due to Russia/Ukraine war. Then simply input in the sheet `r_op` in the excel file that ELECTRICITY, 2023, scenario 2 (VALUE\_2) equals 10.
- `r_cc(y)`: ratio of carbon content in electricity import compared to the reference year. Users can specify different values for domestic import (ELECTRICITY\_D) and international import (ELECTRICITY).
- `r_inv(TECHS,y)`: ratio of investment cost (CAPEX) of an energy technology in the year  $y$  compared to the reference year. This parameter can be used, e.g. for definition of cost reduction for renewable technologies in the future.
- `avail(RES,y)`: maximal availability of resources [GWh for energy or kt for CO<sub>2</sub>] in the year  $y$ , by default 1000000, to be modified according to the resource potentials in the considered region and policy, e.g. uranium will be 0 after 2034. The resources include electricity import from abroad (ELECTRICITY), domestic electricity import (ELECTRICITY\_D) and electricity export (ELEC\_EXPORT).
- `avail_min(RES,y)`: minimal availability of resources [GWh for energy or kt for CO<sub>2</sub>] in the year  $y$ , by default 0;
- `r_dem(DEMAND,SECTOR,y)`: end-use demand (in a certain sector) ratio in the year  $y$  with respect to reference year, by default 1. For instance, the electricity demand in industry in 2050 is 0.9 times the reference value, then `r_dem ("ELECTRICITY","INDSUTRY",2050) = 0.9`.
- `f_min(TECHS,y)`: the minimal installed capacity of a certain technology in the year  $y$ , by default 0; unit by default GW, which can be kt/year or Mtpm/year or Mpkm/year for certain technologies (depending on the main output).

- `f_max(TECHS,y)`: the maximal installed capacity of a certain technology in the year `y`, by default 1000000; unit by default GW, which can be kt/year or Mtpm/year or Mpkm/year for certain technologies (depending on the main output).
- `out_min(TECHS,y)`: the minimal output of a certain technology in the year `y`, by default 0; unit by default GWh, which can be kt or Mtpm or Mpkm for certain technologies (depending on the main output noted as 1 in the `layers_in_out` parameter).
- `out_max(TECHS,y)`: the maximal output of a certain technology in the year `y`, by default 1000000; unit by default GWh, which can be kt or Mtpm or Mpkm for certain technologies (depending on the main output).
- `fmin_perc(TECHS,y)`: the minimal supply share of a certain technology among the corresponding end-use energy supply in the year `y`, by default 0;
- `fmax_perc(TECHS,y)`: the maximal supply share of a certain technology among the corresponding end-use energy supply in the year `y`, by default 100%;
- `r_eff((TECHS,ITEM), y)`: evolution of efficiency compared to the reference year. Since the efficiency in ESTP is defined by the input and output tables, for instance for a decentralized heat pump, if the efficiency in 2030 is improved by 10%, then put the factor 0.909 ( $=1/(1+10\%)$ ) in the item `DEC_HP_ELEC,ELECTRICITY`, since a high efficiency leads to less energy input when ensuring the same heating demand. In case the technology generates CO<sub>2</sub>, the emission should be divided by the factor also.
- `c_inv_year(TECHS,y)`: unit MCHF, a parameter used to record the investment cost in different years. Only the values for existing stocks before the reference year are needed. It will be updated by investment for new installation capacity whilst running the optimization model. For instance, if we install a wind in 2025 with lifetime of 20 years, then the model will calculate the annual cost that we need to pay for the wind turbine, and allocate the money from 2025 to 2045. Details in Eq. 8-9.
- `f_mult_loss(TECHS,y)`: a parameter used to record the decommission capacity of technology in the year `y` due to life end. Only the values for existing stocks are needed. Unit by default GW, which can be kt/year or Mtpm/year or Mpkm/year for certain technologies (depending on the main output). It will be updated (Eq. 4-7) by the decommission capacity aroused by new installation capacity whilst running the optimization model. E.g. 0.5 GW PV is installed in 2023 and its lifetime is 25 years, then its decommission year will be 2048.
- `f_mult(TECHS,y)`: a parameter used to record the effective installed capacity in the year `y`. Unit by default GW, which can be kt/year or Mtpm/year or Mpkm/year for certain technologies (depending on the main output). Only the values for the initial year are needed, which will be updated after each optimization stage following the Eq. 4-7.
- `c_p.t(TECHS,y)`: monthly capacity factor for Hydro dam, Hydro river, PV, Wind in a certain year `y`. It can be modified according to climate changes. Definition of `c_p.t` available in Eq. 16.

### 4.3.2. Scenario definition in `__main__.py`

ESTP allows users to directly define scenarios by programming in `__main__.py`. Herebelow is an example:

```
SEN = {
    0: [],
    1: [['co2_limit', {2022:3200, 2030: 2000, 2050: 0}], ],
    2: [['out_max', {2025: 250, 2050: 3000}, "PV"], ],
```

```
3: [],  
...
```

Here 0, 1, 2 and 3 are the scenario numeration. The general command for modifying scenarios is

```
scenario_number: [['parameter1 name', {year:value, year: value, ...}],  
['parameter2 name', {year:value, year: value, ...}], ... ],
```

In this example, we keep scenarios 0 and 3 as they are, implying no modification. For scenario 1, the command changes the parameter `co2_limit` (1 dimension parameter, namely year dependent) in the years 2022, 2030, and 2050 to 3200kt, 2000kt, and 0 kt respectively. Piece-wise linear interpolation will be automatically carried out for 2017-2022, 2022-2030, and 2030-2050. For scenario 2, the command changes the parameter `out_max` (2 dimension parameter, namely technology and year dependent, in terms of the maximal output) in the years 2025 and 2050 to 250 GWh and 3000 GWh respectively. Piece-wise linear interpolation will be automatically carried out for 2017-2025 and 2025-2050. If users need to modify many parameters for one scenario, just to add parameter2 (and so on) as shown above. This methodology allows to quickly update scenarios. The effect is the same as the definition in the `user_input_vd.xlsx`.

### 4.3.3. Sensitivity analysis

Two types of sensitivity analysis could be made:

1. single-factor sensitivity: This is to highlight a single factor in the energy system. For instance, we can define different CO2 limits in different scenarios, without modification of other parameters in the `user_input_vd.xlsx`.
2. multi-factor sensitivity: This allows modeling the uncertainty of the energy system under different inputs. These inputs may come from technology cost variations, energy policy on import/autonomy, variation of interest rate, technology efficiency improvement, etc. By modifying corresponding parameters listed in 4.3.1, the model can be used for uncertainty analysis.

## 4.4. Running

Once the scenarios have been defined, it is easy to launch ESTP in the terminal.

- Go to the ESTP repository in terminal (type: `cd folder_path`)
- Type: `python3 .` (the `.` in the end is obligatory). Then the algorithm will be launched. Depending on the timeslice defined by the users, the execution time usually will last within mins.

## 4.5. Results visualization

After the execution of the program, all the results will be stored in local csv files, as shown in Fig. 3. The results can be visualized by an internal website generated by Plotly. To launch the website, open the `app.py` file, and make sure the `end_year`, time step, and number of scenarios are the same as in the `__main__.py`. Then locate the root repository via command line, type:

```
python_app.py
```

An interactive website will be generated and automatically shown in your default browser. In case not shown, type `http://127.0.0.1:8050/` in any browser (recommended browser: Edge in Windows and Safari in Mac).

The generated website includes a bunch of figures and tables, including (from top to bottom, from left to right):

- a single scenario choice, for users to choose which scenario to dive in.



- 4 figures for energy demand evolution, including households, industry, services, and mobility. unit: [GWh] (except passenger mobility [Mpkm] and freight mobility [Mtkm]). These demands are the end-use demands for a different sector.
- 4 figures for Energy consumption (GWh) by sector and resource. These figures represent the final energy consumption by sector and category. Electricity is desegregated by production source. The sectoral FECs are estimated by the assumption that consumption is proportional to the sectoral EUD shares. Concretely:
  - For Industry heat final energy consumption (excluding DHN): Industrial cogeneration high-temperature heat [GWh] + Decentralized cogeneration for low temperature [GWh] \* share of industrial low-temperature demand in all (sectors') low-temperature demand + Industrial non-cogeneration high-temperature heat [GWh] + Decentralized non-cogeneration for low temperature [GWh] \* share of industrial low-temperature demand in all (sectors') low-temperature demand. The reason for distinguishing the cogeneration and non-cogeneration is to remove the electricity in cogeneration for heat distribution.
  - For industry district heating: Industrial cogeneration LT DHN technology heat production [GWh]+ Industrial non-cogeneration LT DHN heat production [GWh] \* share of industrial low-temperature demand in all (sectors') low-temperature demand \* (1-DHN pipeline loss %).
  - For electricity: The FEC of electricity generated by PV in a sector  $s = \text{PV output [GWh]} * \text{share of EUD of sector } s \text{ among all sectors}$ . For cogeneration, a similar approach has been made as above to remove heat.

For instance, if the total annual PV power in the VD is 200 GWh, then we assume the final energy consumption in residential buildings is 80 GWh if the total electricity demand of residential buildings accounts for 40% of the electricity EUD. Details on the calculation for FEC by sector is available in the Appendix.

Hydrogen is not regarded as the final energy consumption in the model, since it serves as an energy storage medium. Here the technology ELECTRICITY implies electricity import (sum of domestic import and from abroad), started with ELECTRICITY\_, is used for supplying power, while the others, such as NG, is only for heating purpose, excluding its usage in electricity generation to avoid double counting. In addition, NG here does not include the SNG, which can be directly read from the Sankey. DHN includes geothermal heat, DHN solar thermal heat, DHN thermal plants, and DHN heat pumps. To avoid double-counting, fuel consumption in DHN is excluded from corresponding resources. The same for the following figures.

- the figure Final energy consumption, summing up all sectoral results in the above 4 figures for Energy consumption. As aforementioned, the legend begins with ELECTRICITY\_ indicates the source of the consumed electricity.
- FTE: Full-time job equivalent [people] by energy technology. This graph is generated by using the employment model proposed by [6]. Calibration work is needed.
- Energy supply by category, in total 12 graphs (6 lines \* 2 figures/line). All these graphs are animated, showing the dynamic evolution of energy technologies. Except for the last two figures on mobility with unit Mtkm and Mpkm respectively, all the other figures in the left column reflect the annual output [GWh], while the figures in the right column show the installed capacity [GW]. Here the installed capacity corresponds to the effective installed capacity  $F$ , defined in Eq. 2.

The figures are organized by category, including process heating, decentralized heating, district heating, power generation, fuel production, and mobility.

- 4 tables, elaborating the District heating share (out of total low-temperature heating supply), Train share in freight transportation, Electric vehicle share, and Public mobility share in passenger transportation. The MIN and MAX values are entered by users (see Section 4.3.1) while the RESULT is generated by the optimization algorithm.
- Resource utilization (RU), unit GWh. Different from the figure Final energy consumption [GWh], the RU englobes all utilization of resources within VD, not only final consumption. For instance, if the wood is used in gasification for SNG, then the wood is not accounted in the FEC figure, but included in the RU figure.
- Carbon emission by resource. (1) the emission from WOOD, WET\_BIOMASS, and SNG are not computed into the carbon emission; (2) the emission due to electricity import, including both domestically (ELECTRICITY\_D) and internationally (ELECTRICITY), are not accounted for in accordance to the convention by FSO (Federal Statistical Office). Please see the Carbon balance table for more detail.
- Carbon balance over years [kt-CO<sub>2</sub>], aggregated from all technologies. It encompasses: Emission (fossil + biogenic, before carbon capture), Accounted\_emission (fossil, before capture), Carbon\_capture, Carbon\_sequestration and Net emission. Here the difference between carbon capture and carbon sequestrations represents the part of CCU and the fugitive emissions in sequestration (since the sequestration mass efficiency cannot reach 100%).
- Cost breakdown [MCHF]: evolution of Annualized Investment cost (C\_inv), Operation cost (C\_op) for fuel purchasing, and Maintenance cost (C\_maint) for the whole energy system.
- TotalCost [MCHF]: evolution of system total cost (investment + maintenance + operational cost) in all scenarios defined by users.
- CO<sub>2</sub> Emission [kt]: evolution of system total net emission in all scenarios defined by users.
- Energy flow Sankey : As shown in Fig. 6, the Sankey diagram represents the optimized energy flows for the chosen year (via the blue timeline) and scenario. Each rectangular box is either a resource (inc. domestic and import), end-use demand, or technology with corresponding conversional efficiencies reflected by the ratio of outflows and inflows. The Loss includes the energy loss in the power grid and district heating network. Attention: for some technologies, the outputs are not necessarily less than the inputs, due to: (1) the units of end-use demands for passenger mobility is Mpkm and for freight mobility Mtkm other than the default GWh for energy, and kt for CO<sub>2</sub>; (2) heat pumps have a Coefficient of Performance (COP) higher than 100%.
- Carbon balance [ktCO<sub>2</sub>]: A more detailed description of the figure Carbon balance for the year chosen in the blue timeline above the Sankey. The emission ITEM includes Biogenic, Non-Biogenic, Atmosphere, and Total. Here biogenic includes wood, wetbiomass, SNG import. Non-Biogenic includes all the fossil fuels. Atmosphere implies direct air capture (DAC). In ESTP, two types of DAC exist: one is based upon high-temperature capture, noted as DAC\_HT, while the other one, DAC\_LT, is based upon low-temperature capture. All technology parameters are available in the Gitlab Energy technologies [1]. Here the accounted carbon only refers to the fossil carbon emissions, excluding biogenic sources (biomass, wet biomass, imported SNG). Carbon sequestration implies the carbon that stores underground. The net carbon emission should equal the fossil carbons minus the sequestered carbons.

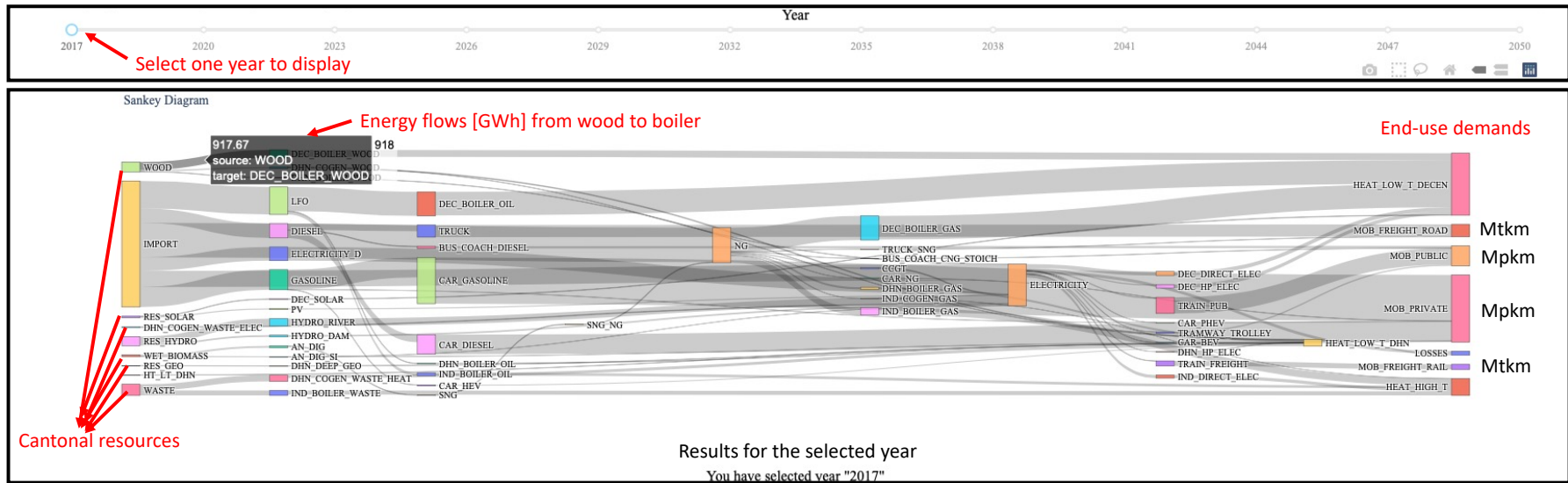


Fig. 6: Example of the Sankey diagram for the energy flows, representing the results for the year and scenario selected by the user. The unit for non-mobility flows is all GWh/year.

## 5. Summary

In this section, we summarize the major achievements and limitations of this model.

### 5.1. Major achievements

As a novel concept of model, the following achievements have been made:

- This model adapted the snapshot model to the energy transitional pathways models, allowing for process-oriented analysis than merely the objective-dominant.
- The impact of historical stocks is taken into account in energy planning, which increases the plausibility of the model, otherwise energy deficit due to the decommissioning of certain capacities might occur in the future.
- Computational efficiency: the expectation of the computational time is merely minute-level, while the majority of optimization models require hours and even days for one scenario. This allows for multi-scenarios' creation and comparison.
- The users are able to define their own roadmaps other than using pre-defined scenarios. Timeslices can be changed according to the user input. However, the increased flexibility on users' sides requires an in-depth understanding of the model and programming skills in order to handle possible numeric issues in optimization solver.
- Enrich the model by calculating the FEC and EUD in a detailed way.
- An interactive website (local API) is created for visualization of results, in terms of both single scenarios and scenarios' comparison.
- From modeling content perspective, cooling demand is integrated into the model. Waste heat utilization is improved. Building renovation is taken into account. In terms of import, hydrogen and SNG importation were added. Electricity import is divided into domestic and international. Compared to previous versions, detailed carbon flows and biomass conversion technologies have been integrated. All these improvements contribute to a better description of the real energy system.

### 5.2. Limitations

Despite a reinforced quality for projecting transitional pathways, it remains impossible to fully model the energy system due to its complexity in associated political-economical-ecological-social implications. The major limitations of ESTP are limited below:

- From the modeling perspective, this model is rich in content, and allows the concept of a circular economy. As an optimization model, it requires the users to have some optimization concepts to debug in case there are infeasible results, *e.g.* due to too strong constraints on CO<sub>2</sub> limits etc.
- The innovative modeling approach is a combination of optimization and simulation by minimization of the system cost at each time step. But it may not represent the minimal cost from the whole period (*e.g.* 2017-2050) perspective. This issue could be handled by generating a large number of scenarios (thanks to its quick computational speed) and thus obtaining the minimal possible costs. It would be more interesting to analyze the trade-offs among these scenarios. Plus, this dynamic feature helps to simulate the energy stakeholders' behaviors, thus better fitting the reality, given that the development of the energy system in the past is, in rare case, cost-optimal [11].
- The system boundary corresponds to the geography of Canton de Vaud. This applies to the energy potential estimation and demand projection. The emissions reported in the model involve only the

emissions from VD, implying the carbons that emit outside VD, *e.g.* in the mining process, in the refinery, or during transportation to VD etc., are not accounted for, in accordance with the method by Federal statistics [8]. In addition, aviation is not considered due to a non-universal convention on emission allocation.

- The sectoral FECs are estimated by the assumption that the consumption is proportional to the sectoral EUD shares. This simplification is necessary in a cantonal-level modeling scope.
- Complicated short-term behavior of power grids not modeled. Adequacy studies should follow.
- Extreme innovative technologies/applications are not included in the technology list, such as spontaneous hydrogen production, and installation of PV panels on highways. As a result, the projections are only based on our state-of-art knowledge of the energy systems. However, these technologies could be added in the model in the future when their technical-economic maturity has been proven.

## **6. Appendix**

Table 2: Python packages in installation.

Package	Version
Brotli	1.0.9
click	7.1.2
cycler	0.10.0
dash	1.16.0
dash-core-components	1.12.0
dash-html-components	1.1.1
dash-renderer	1.8.0
dash-table	4.10.1
et-xmlfile	1.0.1
Flask	1.1.2
Flask-Compress	1.5.0
freeport	0.1.9
future	0.18.2
itsdangerous	1.1.0
jdcalf	1.4.1
Jinja2	2.11.2
kiwisolver	1.2.0
lml	0.0.9
MarkupSafe	1.1.1
matplotlib	3.2.1
numpy	1.18.1
openpyxl	3.0.3
pandas	1.0.1
plotly	4.8.2
pyexcel	0.6.1
pyexcel-io	0.5.20
pyexcel-xlsx	0.5.8
pyparsing	2.4.7
pystache	0.5.4
python-dateutil	2.8.1
pytz	2019.3
retrying	1.3.3
scipy	1.4.1
six	1.14.0
texttable	1.6.2
Werkzeug	1.0.1
xlrd	1.2.0
XlsxWriter	1.2.7

## 6.1. User inputs

**End use demand inputs for reference year** In 2017\_input.xlsx, we define the end use demands (as follows) for the base year 2017, including the demands in pair (demand category, sector) with default unit GWh, except for passenger mobility Mpkm (million passenger kilometer) and freight mobility Mtkm (million tonne kilometer). These inputs are necessary as a base for the model to project future evolution. Here HEAT\_HIGH\_T denotes the process heat demands, SH implies space heating, and HW hot water. Put zero in case the demand does not exist, such as no process heating demand in transportation (HEAT\_HIGH\_T,TRANSPORTATION).

ELECTRICITY,HOUSEHOLDS  
ELECTRICITY,SERVICES  
ELECTRICITY,INDUSTRY  
ELECTRICITY,TRANSPORTATION  
LIGHTING,HOUSEHOLDS  
LIGHTING,SERVICES  
LIGHTING,INDUSTRY  
LIGHTING,TRANSPORTATION  
COOLING,HOUSEHOLDS  
COOLING,SERVICES  
COOLING,INDUSTRY  
COOLING,TRANSPORTATION  
HEAT\_HIGH\_T,HOUSEHOLDS  
HEAT\_HIGH\_T,SERVICES  
HEAT\_HIGH\_T,INDUSTRY  
HEAT\_HIGH\_T,TRANSPORTATION  
HEAT\_LOW\_T\_SH,HOUSEHOLDS  
HEAT\_LOW\_T\_SH,SERVICES  
HEAT\_LOW\_T\_SH,INDUSTRY  
HEAT\_LOW\_T\_SH,TRANSPORTATION  
HEAT\_LOW\_T\_HW,HOUSEHOLDS  
HEAT\_LOW\_T\_HW,SERVICES  
HEAT\_LOW\_T\_HW,INDUSTRY  
HEAT\_LOW\_T\_HW,TRANSPORTATION  
MOBILITY\_PASSENGER,HOUSEHOLDS  
MOBILITY\_PASSENGER,SERVICES  
MOBILITY\_PASSENGER,INDUSTRY  
MOBILITY\_PASSENGER,TRANSPORTATION  
MOBILITY\_FREIGHT,HOUSEHOLDS  
MOBILITY\_FREIGHT,SERVICES  
MOBILITY\_FREIGHT,INDUSTRY  
MOBILITY\_FREIGHT,TRANSPORTATION

## 6.2. Cost of vehicles

Vehicle type	Cost	Unit
TRAMWAY TROLLEY	625	CHF/(pkm/h)
BUS COACH DIESEL	148.1	CHF/(pkm/h)
BUS COACH HYDIESEL	163.4	CHF/(pkm/h)
BUS COACH CNG STOICH	163.4	CHF/(pkm/h)
BUS COACH FC HYBRIDH2	313.3	CHF/(pkm/h)
TRAIN PUB	564.2	CHF/(pkm/h)
CAR GASOLINE	499	CHF/(pkm/h)
CAR DIESEL	484	CHF/(pkm/h)
CAR NG	396	CHF/(pkm/h)
CAR HEV	1109	CHF/(pkm/h)
CAR PHEV	1109	CHF/(pkm/h)
CAR BEV	1001	CHF/(pkm/h)
CAR FUEL CELL	1091	CHF/(pkm/h)
TRAIN FREIGHT	104.4	CHF/(tkm/h)
TRUCK	222.2	CHF/(tkm/h)
TRUCK SNG	333.3	CHF/(tkm/h)
TRUCK FUEL CELL	387.6	CHF/(tkm/h)
TRUCK BEV	444.4	CHF/(tkm/h)

Table 3: Vehicle cost in 2017 for Switzerland. These costs are only CAPEX excluding the fuel cost. Data summarized by Jonas Schnidrig in IPESE. For instance, an electric battery car costs in average 64210 CHF/car in 2017. And the average car occupancy is 1.6 people/car from federal statistics office of Switzerland [9]. Each car is assumed to travel 30000 km/year according to [2]. By taking these values and lifetime of vehicles into account, we calculated the capex for each vehicle in terms of per kilometer or ton kilometer, and the converted it to CHF/(pkm/h) by timing 8760h for model integration assuming the mobility demand is constant across months in a year.

### 6.3. Calculation logic for FEC by sector

An example is given for the calculation of FEC of NG in industry for heating purpose. Noting that the industrial heating includes both process heating and low temperature heating (space heating and hot water), and the cogeneration provides electricity in addition to the heat, thus it is necessary to split into 4 (2 \* 2) items to calculate the FEC, represented by each line in Eq. 31-34.

In the first line (Eq. 31): Here  $P$  denotes the annual production [GWh heat] of a process technology (PT). The  $P$  times  $layers\_in\_out$  ( $lio$ ) calculates the resource utilization [GWh NG]. For cogeneration units, the total amount of NG is then distributed to heat according to the share of heat production among total (heat and electricity) production by this technology. Since NG is consumed, it is treated as a negative value for  $lio$ , thus we added a minus sign before  $lio$  to convert it to positive.

In the second line (Eq. 32): It should be noted that since the decentralized low-temperature heat (DEC\_LT) is not only for industry, it has to be distributed to the industry, Here an assumption is made by multiplying  $share[IND]$ , representing the share of EUD of low temperature heat demand in industry out of the low temperature heat demand in all sectors (Industry, residence and services), as shown in the second line.

The third and fourth lines (Eq. 33-34) are for non-cogeneration (CHP) units. No split between heat and electricity is needed.



$$FEC(IND, GAS, HEAT) = \sum_{tech \in PT \cap CHP} P(tech) * -layers\_in\_out[tech, "NG"] * \frac{heat(tech)}{heat(tech) + elec(tech)} + \quad (31)$$

$$\sum_{tech \in DEC\_LT \cap CHP} P(tech) * -layers\_in\_out[tech, "NG"] * \frac{heat(tech)}{heat(tech) + elec(tech)} * share[IND] + \quad (32)$$

$$\sum_{tech \in PT \setminus CHP} P(tech) * -layers\_in\_out[tech, "NG"] + \quad (33)$$

$$\sum_{tech \in DEC\_LT \setminus CHP} P(tech) * -layers\_in\_out[tech, "NG"] * share[IND] \quad (34)$$

However, since DHN is required as an individual FEC, it has to be treated separately as Eq. 35, taking the pipeline loss into account. Similar to low temperature decentralized heat that is not only used industry, it has to be distributed by the share[IND].

$$FEC(IND, DHN, HEAT) = \sum_{tech \in DHN \cap CHP} P(tech) * -layers\_in\_out[tech, "NG"] * share[IND] * \frac{heat(tech)}{heat(tech) + elec(tech)} * (1 - loss_{pipe}) + \sum_{tech \in DHN \setminus CHP} P(tech) * -layers\_in\_out[tech, "NG"] * share[IND] * (1 - loss_{pipe}) \quad (35)$$

Table 4: Acronym for detailed final energy consumption in the table FEC.csv. We assume the SH and HW shares in low-temperature heating demands keep the same as of 2017.

Acronym	Meaning
INDUSTRY_HIGH_T	Industry sector, high temperature heating
SERVICE_HIGH_T	Service sector, high temperature heating
INDUSTRY_DHN_SH	Industry sector, low temperature, district heating, space heating
INDUSTRY_DHN_HW	Industry sector, low temperature, district heating, hot water
SERVICE_DHN_SH	Service sector, low temperature, district heating, space heating
SERVICE_DHN_HW	Service sector, low temperature, district heating, hot water
HOUSEHOLD_DHN_SH	Residential sector, low temperature, district heating, space heating
HOUSEHOLD_DHN_HW	Residential sector, low temperature, district heating, hot water
INDUSTRY_DEC_SH	Industry sector, low temperature, decentralized heating, space heating
INDUSTRY_DEC_HW	Industry sector, low temperature, decentralized heating, hot water
SERVICE_DEC_SH	Service sector, low temperature, decentralized heating, space heating
SERVICE_DEC_HW	Service sector, low temperature, decentralized heating, hot water
HOUSEHOLD_DEC_SH	Residential sector, low temperature, decentralized heating, space heating
HOUSEHOLD_DEC_HW	Residential sector, low temperature, decentralized heating, hot water
ELEC_PRODUCTION	Electricity supply (from various sources)
MOBILITY_Passenger_Road_PUB	Mobility for Passenger, on Road, by Public vehicles
MOBILITY_Passenger_Road_PRI	Mobility for Passenger, on Road, by Private vehicles
MOBILITY_Passenger_Rail	Mobility for Passenger, by Rail
MOBILITY_Freight_Road	Mobility for Freight, by Road
MOBILITY_Freight_Rail	Mobility for Freight, by Rail

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