Assessment of the role of infrastructure in high share renewable energy systems

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Abstract:
The transition of the global energy sector from fossil-based towards a zero-carbon system is a necessity to mitigate the impacts of climate change. The ratification of both, the Paris agreement in 2015 and the European Green Deal in 2019, illustrates the political will to reach climate neutrality. Thereby, one major focus lies on the development of the power section with the aim to include a high share of renewable sources, whilst using the synergies of other energy vectors for conversion, storage, and transportation. However, a successful decarbonisation of the energy sector is only achievable if the energy policies are accepted and implemented by the corresponding actors and stakeholders. The question arises: How can the power system in symbiosis to other energy vectors safely include the required amount of renewable energies ?
The aim of this paper is to develop a Mixed Integer Linear Programming (MILP) modelling methodology, helping to answer this question. The proposed methodology allows to model the role of energy independence in future multi-energy distribution systems on different scales. On the basis of the current infrastructure, the inter-cell exchanges of the network will be categorized in terms of efficiency and capacity. The main exchanges of electricity, natural gas and hydrogen and, where appropriate, biomass and waste will also be represented. This methodology will identify how global energy system modelling can help national and international decision-makers at different levels of the society to understand and assess the impact of infrastructure on the energy system, answering the question of levels of centralization/decentralization (storage capacity, renewable production e.g) and grids capacity at various system levels depending on energy system objective functions (e.g overall investment costs, CO_2 emission targets and import/export targets).

Keywords:
Energy System, Infrastructure, Transportation, Grid, Renewable Energy, Storage, Vector

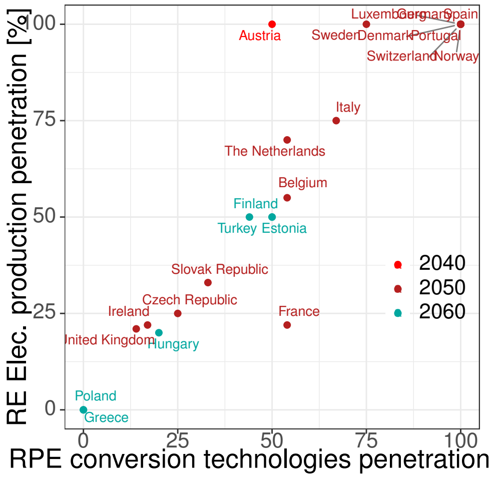
1. Introduction

1.1. Background

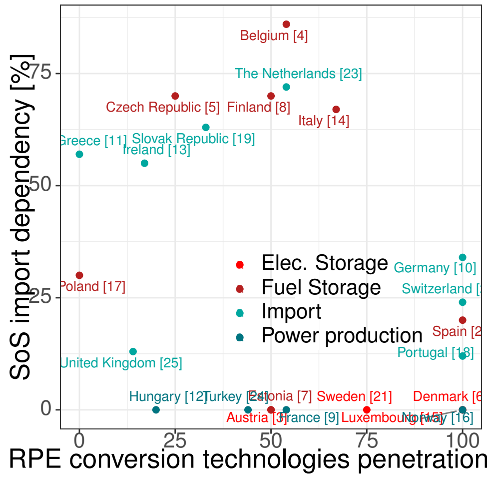
A challenge arising with the implementation of the European Green Deal is the Security of Supply (SoS), being defined at the moment as securing the Primary Energy (PE) needs of 2 weeks in Fossil Fuels (FF) stocks [1]. Switching to intermittent and decentralised Renewable Energy (RE) in future energy systems, in order to defosilise the energy system requires a new definition of SoS in terms of energy storage in case of outage, as new constraints on distribution grids and infrastructure.
European countries adopt various strategies to guarantee SoS (Fig. 1). Depending on the type of RE-strategy (Fig. 1a), the SoS strategy leads to high import needs (Fig. 1b). While countries with electrification strategies mainly rely on electricity import tend to have a lower import dependency at higher Renewable Primary Energy (RPE) shares, countries relying on combination of electricity, bio- and synthetic fuels rely on fuel storage but depend on high shares of import too. Countries with low SoS import dependencies rely on nuclear power (France, Turkey etc.) or have a high RPE potential (Sweden, Norway etc.).
Most of the countries rely on import and distribution of resources or storing of vectors. These decisions need investment in corresponding infrastructure in order to guarantee the required degree of SoS. The investment in such technologies will be translated by increased energy system costs which will be paid by the prosumer. In fact, the electric price construction is currently composed of 40% of grid costs, while for the other energy services, this factor reaches up to 35% of the final energy service price in Switzerland [2]. Integrating infrastructure in order to model the bottlenecks, the feasibility of transport and distribution, while considering the impact of the infrastructure on the energy system cost is therefore one of the key challenges.

1.2. Literature review

With the transition towards RE driven energy systems, storage of the surplus energy started being a major driver in the research. Antenucci et al. [26] combined the power system model *EMPIRE* with network simulating



(a) Energy transition



(b) Security of supply

Figure 1: Carbon neutrality policies countries overview for European countries. The abscissa depicts the share of electric RE production on the total electricity consumption.
In (a) the ordinate summarizes the specific RE penetration within the total primary energy conversion. The colors distinguish the target year reaching carbon neutrality. Poland and Greece don't have any energy transition policy taking into consideration the latter described parameters. In (b) the ordinate depicts the share import dependency for the SoS within the country energy transition strategy.

model *NSM* in order to simulate the security of supply challenges in combination to RE storage. Welsch et al. [27] focused on the optimisation of intermittent wind energy, combined with the SoS effect on storage. Another approach combining this time batteries with PV and the transmission network has been achieved by Gupta et al. [28].
Focus in the development of regional SoS models has mainly been put on the electric infrastructure and generation [29–31], while approaches to integrate several energy vectors with their infrastructure are either considering singular vectors [26] or are based on simulation models [32].
Taking into consideration other energy vectors beside electricity was done in early modelling years with [33] and [34] based on the *MARKAL* model.
Only in recent years, approaches to quit the copper-plate assumption (neglecting infrastructure and energy transport constraints) have been made, by integrating infrastructure and losses for the power system [35–38]. The application to other energy vectors has been achieved on the fossil fuels infrastructure [39] to determine the role of hydrogen in the future energy system, competing with natural gas [26, 40]. Combining different vectors with their corresponding infrastructure has been modelled by [41], focusing on the post-calculation of the energy return in investment; Li & Zheng [42] assessing the amplitude of sectors on SoS and Capros et al. [43] with the development of the *Primes* model.

1.3. Objectives and contribution

Whereas SoS needs to be redefined, recent research is focusing on existing securing infrastructure due to the transition to electrification and intermittency (Fig 1a). The target lies here on identifying bottlenecks and localizing grid enforcement points, in order to respond to the power production variation of the intermittent resources. Main research focuses on the power system, the identified gap lies in assessing this issue using additional energy vectors such as hydrogen, NG, biomass etc., and their distribution & storage infrastructure.
The novel contributions of this paper lie in:

- the characterization and definition of the grid infrastructure;
- the creation of a methodology to assess the impact of infrastructure on the energy system;
- the application of the infrastructure model to the case study of Switzerland.

2. Methodology

2.1. Grids characterization

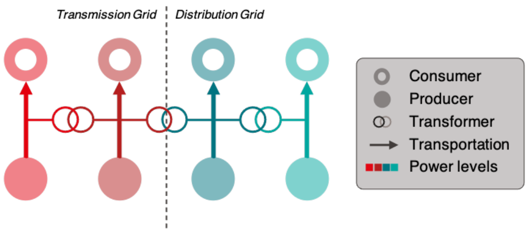


Figure 2: Grid constituting elements characterization.

Energy grids aim to transport energy vectors between producers and consumers with an intermediate possible storage actor. While the grids distinguish themselves according to the energy vector they transport, they can be characterized by common attributes: A power grid connects producers to consumers via energy vector geographic transporting lines at different power levels, being connected via transformers switching between power levels (Fig. 2). Smart grids allow to have hybrid roles of consumers and producers at the same time. While the power level is characterized by the voltage in the electric grid, gas grids are defined by the grid pressure. The analogy can be made for the transforming infrastructure, where in electric grids transformers correspond to inductors that have coupled magnetic flux and gas grid use compressors and expanders to increase and decrease the pressure level.

This study focuses on the analysis and integration of electricity, natural gas and hydrogen grids in energy systems modelling. The grid is discretized in 4 power levels: extra-high level (EHL), high power (HL), medium power (ML) and low power (LL). While the transmission grid consisting of EHL and HL aims at transporting energy vectors over long distances at national and international scale, the distribution grid allows to distribute the energy vectors at smaller geographic scales in cities or districts. Similarly to the consumers power demand, the energy conversion technologies are connected to their respective power level (Fig. 3).

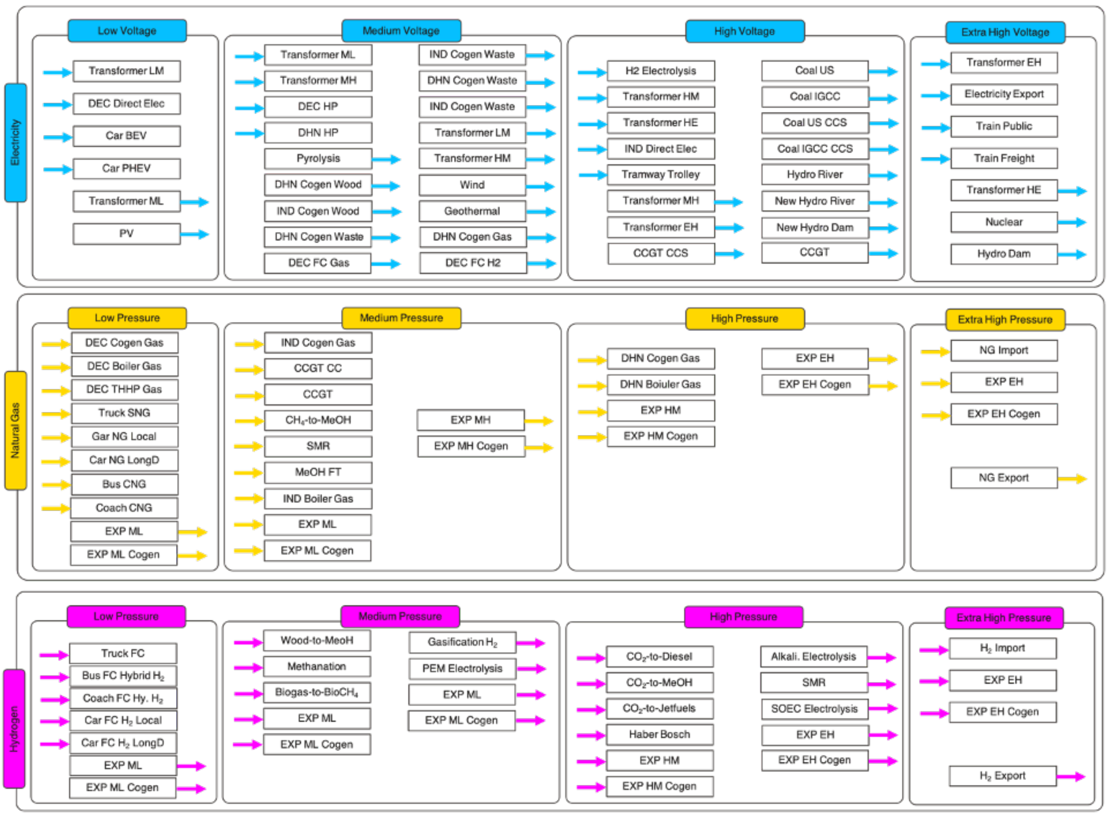


Figure 3: Energy conversion technologies categorization for electricity, natural gas and hydrogen grids.

2.2. Infrastructure

[1] Each of the technologies described in Figure 2 are characterized according to energetic (Tab. 1) and economic (Tab. 2) attributes. The thermal balance describes the heat demands or losses of the process, similar to the electric demands. The technologies are characterized by their reference size, defined as their main energy vector flow input power. The balances and efficiency are additional energy flows, losses and conversions, expressed as percentage of the main input flow. The vector efficiency is defined as the global efficiency of the technology, with the non-recoverable losses. Negative values are defined as energy needs to run the process, while positive ones are output flows which can be recovered with the respective technology configurations.

Table 1: Grid infrastructure transformer technologies energetic characterization for the three energy vectors (electricity / natural gas / hydrogen). The vector efficiency corresponds to the resource conversion efficiency to a different power level, while the thermal balance represents the heat losses or demands, similarly to the electric balance. The reference size corresponds to the typical size of the transformer technology.

Level	η_{vector} Vector efficiency [%]			η_{heat} Thermal balance [%]			$\eta_{electric}$ Electric balance [%]			Reference Size [MW]		
EHL–HL HL–EHL	98.80	95.25	98.56	1.20	-0.11 0.10	0.72 -0.69	98.80	4.86 -4.46	0.72 -0.69	1000	41.2	12.4
HL–ML ML–HL	97.35	95.60	97.96	2.65	-0.05 0.04	1.02 -0.93	97.35	4.45 -4.44	1.02 -0.96	375	29.4	8.9
ML–LL LL–ML	95.70	97.80	95.98	4.30	-0.01 0.01	2.01 -1.92	95.70	2.21 -1.99	2.01 -1.84	750	3.3	1.0

Similar to the thermal characterization, the economic characterization is based on the infrastructure technology reference size. While the investment cost of a transformer has been estimated, being mainly composed of the material costs and the production & development costs [44], the natural gas compressor and expander costs have been determined from industrially available turbines. The adaptation to the hydrogen infrastructure costs have been scaled according to the specific reference size, assuming similar operating conditions as natural gas.

Table 2: Grid infrastructure transformer technologies economic characterization for the three energy vectors (electricity / natural gas / hydrogen).

Level	Lifetime [years]			Investment costs [MCHF/GW]			Matinenance costs [MCHF/GW]		
EHL–HL HL–EHL	65	35	35	12.300	0.018 7.920	0.056 13.030	1.00	0.001 0.990	0.005 1.630
HL–ML ML–HL	70	35	35	19.800	0.020 7.270	0.068 18.450	2.50	0.002 0.910	0.005 2.360
ML–LL LL–ML	75	35	35	54.600	0.119 33.070	0.395 36.470	12.75	0.010 4.130	0.032 4.560

In addition to the transforming infrastructure, the transforming lines correspond to the highest cost withing the transportation infrastructure. The cost was estimated using existing infrastructure specific to the current energy system and distinguished according to the installation typology (air or underground) for the electric case. We assumed a similar network configuration and length for the hydrogen case. The uncertainty range of electric grid lines is issued from comparison to other similar project costs.

In order to be able to take into consideration territorial differences and production/consumption density distributions, the assessment is based on the the characterization of existing necessary infrastructure, expressed through the reference length $l_{g,r}^{ref}$. A cell r is defined in which the existing infrastructure length $l_{g,r}$ of a grid type g is known, scaled by the fraction of the infrastructure reference power limit P_g^{θ} and the maximum observed

[1] This section summarizes the main findings of the methodology described in detail available at `https://gitlab.com/jonasschnidrig/infra-documentation`.

Table 3: Grid infrastructure transportation lines economic characterization (electricity / natural gas / hydrogen).

Power level	Total Length 10^3 [km]		Power limit [MW]			Investment costs [MCHF/km GW]				Reference Length [km]	
	$l_{g,f}$		P_g^{θ}			$C_g^{inv,air}$	$C_g^{inv,underground}$			$l_{g,r}^{ref}$	
LL	130	9.7	0.3	0.47	0.21	500	1500	13.59	55.7	4.8	1.71
ML	43	4.35	30	425	132	53.3	160	0.484	1.557	159.6	51.9
HL	8.9	0.94	500	6140	1557	5.2	15.6	0.227	0.895	550.7	152.9
EHL	6.7	0.71	1700	51500	12133	3.4	10.1	0.077	0.326	1409	965.6

energy service power P_g^{max} (Eq. 1).

$$l_{g,r}^{ref} = l_{g,r} \cdot \frac{P_g^{\theta}}{P_g^{max}} \qquad \forall \quad g \in \mathcal{GRIDS},\ r \in \mathcal{REGIONS} \tag{1}$$

Applying this methodology to the case of Switzerland, we are able to determine the average length of the different infrastructure transportation lines at different levels (Tab. 3 last column).

2.3. MILP integration

Modelling infrastructure and their impact on the energy system requires a hourly basis to correctly estimate the size and operation of the transportation lines and storage technologies. The framework of *EnergyScope* developed by Moret et al. [45], Schnidrig et al. [46] and Li et al. [47] was used. The end-use energy demands were divided into heat mobility and electricity, which was on split in the present work in the four power levels. *EnergyScope* figures as energy balance between the hourly demands on one side, and the resources on the other with technologies converting resources to demands under costs and emissions. It is expressed in MILP, with the key decision variables **F** and $\mathbf{F_t}$, determining the size and the temporal use of the technologies and infrastructure respectively.

The primal objective is the total cost $\mathbf{C_{tot}}$ (Eq. 2) consisting of the sum of the technologies' ($tec \in \mathcal{TEC}$) and infrastructure grid's ($g \in \mathcal{GRIDS}$) annualized investment $\mathbf{C_{inv}}$ and maintenance $\mathbf{C_{maint}}$ (Eq. 4 & 6), as of the resources ($res \in \mathcal{RES}$) operation cost $\mathbf{C_{op}}$ (Eq. 7). The investment cost consists of the multiplication of the specific investment cost $\mathbf{c_{inv}}$ with difference of the size parameter **F** and the already installed size f_{ext} (Eq. 3). Infrastructure density and reinforcement needs are modeled using the reference length $l_{g,r}^{ref}$, where g corresponds to the infrastructure grid level. In this case study, only one region is selected, causing the region index r to drop (Eq. 5).

$$\mathbf{C_{tot}} = \sum_{tec}(\mathbf{C_{inv}}(tec) \cdot \tau(tec) + \mathbf{C_{maint}}(tec)) + \sum_{g}(\mathbf{C_{inv}}(g) \cdot \tau(g) + \mathbf{C_{maint}}(tec)) + \sum_{res} \mathbf{C_{op}}(res) \tag{2}$$

$$\mathbf{C_{inv}}(tec) = c_{inv}(tec) \cdot (\mathbf{F}(tec) - f_{ext}(tec)) \tag{3}$$

$$\mathbf{C_{maint}}(tec) = c_{maint}(tec) \cdot \mathbf{F}(tec) \tag{4}$$

$$\mathbf{C_{inv}}(g) = c_{inv}(g) \cdot (\mathbf{F}(g) - f_{ext}(g)) \cdot l_g^{ref} \tag{5}$$

$$\mathbf{C_{maint}}(g) = c_{maint}(g) \cdot \mathbf{F}(g) \cdot l_g^{ref} \tag{6}$$

$$\mathbf{C_{op}}(res) = \sum_{t} c_{op}(res) \cdot \mathbf{F_t}(res, t) \cdot t_{op}(t) \tag{7}$$

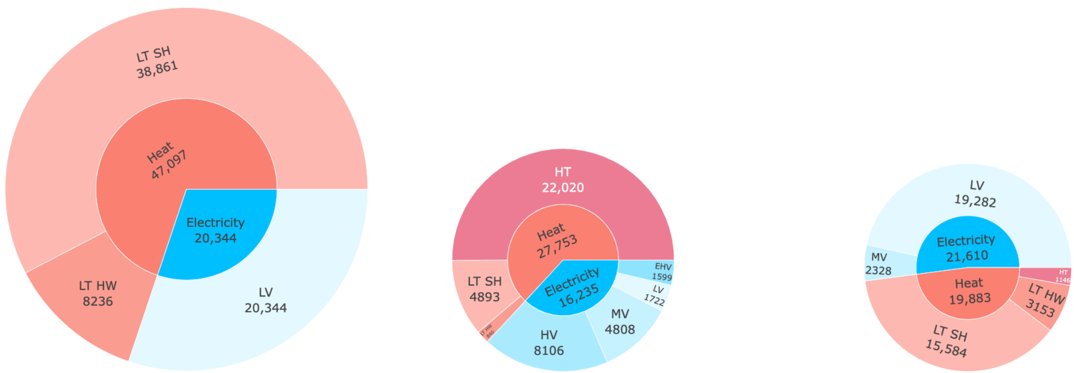
$$\forall \quad res \in \mathcal{RES},\ tec \in \mathcal{TEC},\ g \in \mathcal{GRIDS},\ t \in \mathcal{PERIODS},$$

The minimization of the total greenhouse gases emissions is the secondary objective, measured by the CO_2 equivalent **Emissions** [47]. It is modelled by considering that the layers entering the technologies contain a certain amount of CO_2, which is either emitted or absorbed by the technologies in *Energyscope*, categorizing the converted carbon dioxide in different categories $c \in \mathcal{C} - \mathcal{LAYERS}$ (captured, sequestrated, stored, emitted to atmosphere). This conversion factor η expressed in tCO_2/GWh, is valid for all time periods t (Eq. 8). Considering positive and negative emissions allows to model an emission limit ϵ (Eq. 9).

$$\textbf{Emission}(t) = \sum_{tec} \textbf{F}_\textbf{t}(tec) \cdot t_{op}(t) \cdot \eta(i,c) \quad \forall \quad tec \in \mathcal{TEC}, t \in \mathcal{PERIODS},\ c \in \mathcal{C} - \mathcal{LAYERS} \tag{8}$$

$$\sum_{t} \textbf{Emission}(t) \leq \epsilon \quad \forall \quad tec \in \mathcal{TEC}, t \in \mathcal{PERIODS} \tag{9}$$

2.4. Specific end uses demands



(a) Households (b) Industry (c) Services

Figure 4: End uses demands separation for the the direct energy demands sectors [GWh] case study Switzerland 2020. Heat demand is split in high temperature heat (HT), low temperature space heating (LT SH) and hot water (LT HW) demand. Electricity is split in the power levels extra high voltage (EHV), high voltage (HV), medium voltage (MV) and low voltage (LV). The diameter is proportional to the total energy demand of each sector.

While conventional energy system models integrate unique end uses demands, *EnergyScope* takes into consideration heat, mobility and electricity demand. In order to be aligned with the layer power separation presented in this paper, the specific electricity demand of the three direct energy end uses demand sectors (households, services, industry) has to be categorized. Switzerland in the year 2020 has been selected as proof of concept case study, assuming the historical consumption and distribution of the end uses demands. In order to fan out the specific electricity demand of each sector in the four power levels, the corresponding sub-sectors energy demand have been classified according to the voltage demand (Fig. 4). Households are assumed to have only LV electricity demand (Fig. 4a), while for industry and services, the sector characterization by the Swiss Federal Office of Statistics [48] have been used (Fig. 4b-4c)[2].

The applied methodology allowed to identify the characteristics of each energy . While industry and services have almost similar total energy demands, households sector tops the other ones by 35%. Households are characterized by a 1:3 distribution of electricity to heat demand, while being dominated by space heating and low voltage electricity requirements. The same dominance of low voltage and space heating is visible in services sector, with the difference of a higher share of electricity demands (1:1) and the appearance of some small shares of high temperature and medium voltage demands. The industry sector is dominated by high temperature for process heat (50%). The electricity demand (36%) is split between all voltage levels.

3. Results

This case study aimed to model the alternative energy system of Switzerland in the year 2020 with a "tabula rasa" approach, assuming no existing technologies or infrastructure, optimizing the economically most interesting energy system composition.

The results show a 100% renewable and independent energy system, with a high share of decentralized electricity production (Fig. 5a). The annual total cost sums up to 1498 CHF per capita for the energy system, 34% lower than the actual reference system in 2020, simulated with the same tool based on the existing structure. The infrastructure decomposition allowed to identify electric transmission as the main transportation vector,

[2]The detailed characterization of the industry sub-sectors can be accessed in the additional material `https://gitlab.com/jonasschnidrig/infra-documentation/-/blob/main/Electricity%20infrastructure/voltage_es.html`

transporting 88.6 TWh of electricity from primary energy and 37 TWh of stored or cogenerated electricity (Fig. 5b). Hydrogen is used for long distance passenger mobility (4.1 TWh), road freight transport (1.9 TWh) and storage (3 TWh) purposes (Fig. 5c). Natural gas is almost not used, except as product from wood gazification, where NG then is used as fuel for high temperature cogeneration and raw product for Fischer-Tropsch gasoline production (Fig. 5d).

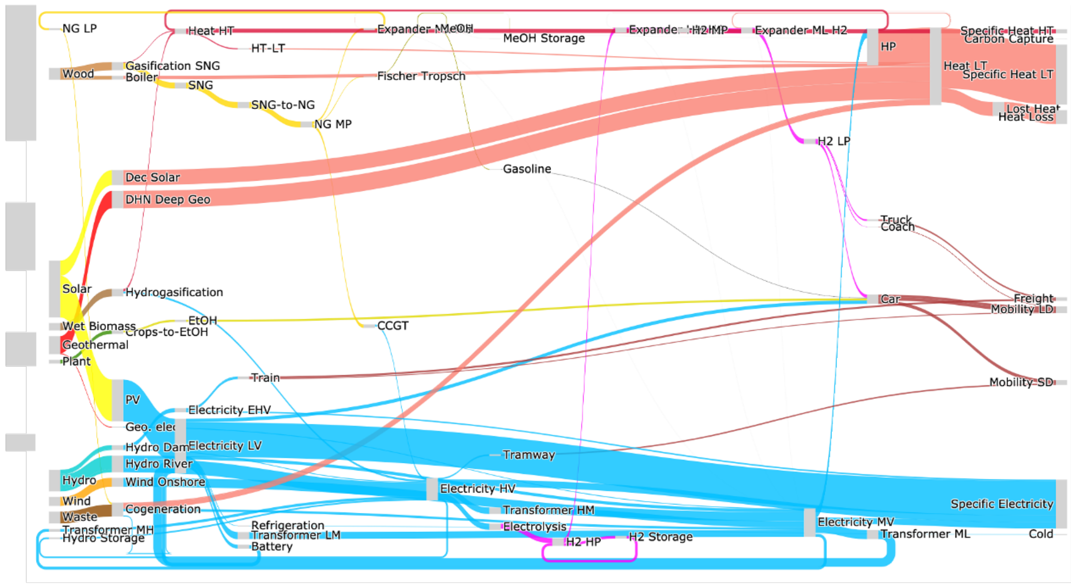
The Sankey diagrams allow to identify storage loops, being composed of electric vehicle battery (4.51 TWh), hydro dam (1.92 TWh) and hydrogen high pressure storage (3.0 TWh). The suggested solution by the model uses the possibility of vehicle-to-grid to store intra-day phase-shifts of electric consumption and production at district level. Hydro dams are used to shift the seasonal differences through long-time storage at national basis. Hydrogen complements the storage capacity with a hybrid approach consisting of mid-term storage at regional level. Hydrogen is in direct competition with regional batteries and natural gas storage. While the preference of hydrogen storage over batteries can be explained by economic reasons and by the possibility of long-term storage, the intuition of using natural gas as storage needs further clarification. Despite a higher round-trip efficiency due to lower compression needs and losses by natural gas, the necessity of installing additional technologies to convert hydrogen to natural gas are one reason of the preference of hydrogen storage over natural gas one. Another reason is the missing detail of modeling of the round-trip efficiency and the costs of the storage technology itself.

The annual infrastructure costs sum up to 420 CHF per capita corresponding to 28% of the total energy system cost (Fig. 6). This ratio remains in the same order of magnitude as the present energy system, where the electricity price is composed of one third of grid costs [2] in Switzerland. The infrastructure is dominated by the annual electric grid costs 362 CHF per capita (86% of the infrastructure costs), with negligible shares of gas infrastructure costs (7.77 CHF per capita for the hydrogen network (0.2%) and 4.41 CHF per capita for the natural gas network (0.1%)). The high share of electricity network costs can be explained by the electrification of the energy system. The infrastructure energy-specific costs of the electric grids amounts to 23.6 CHF/kWh, compared to 30.1 CHF/kWh for the hydrogen network and 39.9 CHF/kWh for the natural gas network. These differences can be explained by the different distributions of power levels of the respective grids, where the electric grid consists of all power levels on one hand and the gas networks are focused on mid and low pressure only.

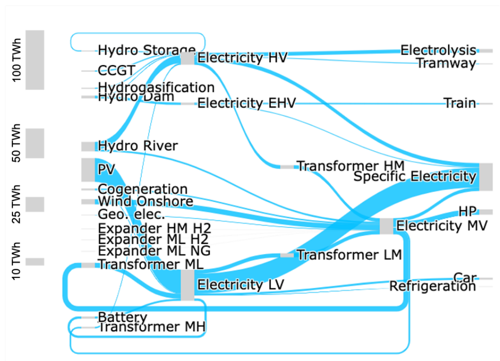
4. Conclusion

Within this paper, the grid infrastructure was characterized, allowing to be integrated in the presented methodology allowing to generate a first solution to the global energy system of Switzerland, by integrating technical and economic aspects of infrastructure in general energy systems modeling via *EnergyScope*. The results show, that the decomposition of the end uses demands in the specific power levels, does not change drastically the primary energy generation composition solution presented by conventional energy system models, but dispatches the energy vectors through alternative energy conversion paths: on one hand the short and mid term storage infrastructure shifts from battery-preferred options to power-to-gas technologies, while on the other hand mobility technologies shift towards a combination of different powering fuels instead of electric mobility only, a trend which already has been observed in similar energy system models focusing on mobility [46, 49].

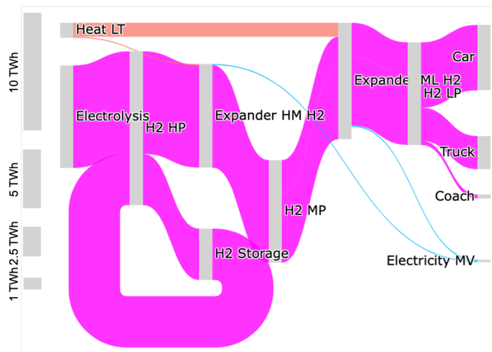
While power separation not only concerns end uses demands characterization but also regional definitions, the proposed grid characterization and separation methodology can directly be applied to regional models [50, 51], determining the grid demands and identifying grid reinforcement demands. By increasing the resolution to smaller energy hubs being inter-connected, the possible results give a better insight of the role of decentralisation of technologies, which had been fixed manually in conventional energy system models [45, 47, 52].
With the integration of energy vector transportation through corresponding infrastructure and conversion technologies, it is possible to create assessments of performance of specific energy vectors, in dependence of existing infrastructure, grid reinforcement and installation of renewable energy technologies installation.



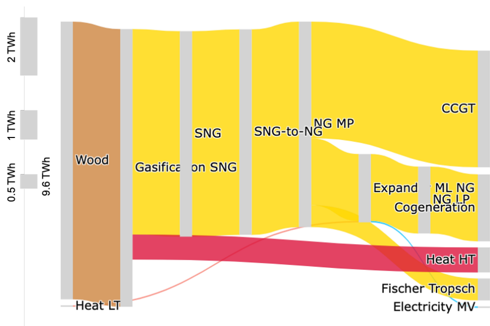
(a) Energy



(b) Electricity



(c) Hydrogen



(d) Natural Gas

Figure 5: Sankey diagram energy system Switzerland 2020. The case study corresponds to no imports, minimizing the total costs.

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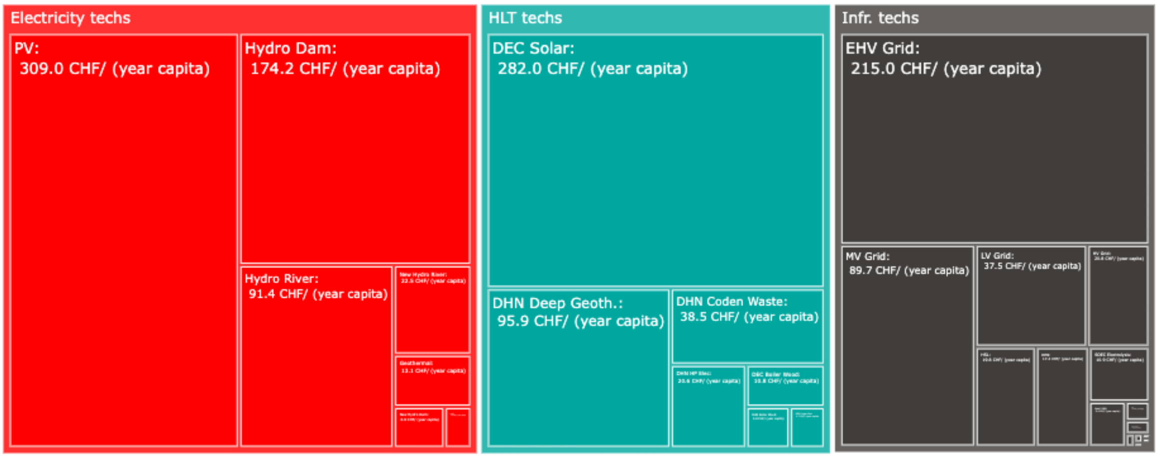

Figure 6: Treemap representation of the annual cost per capita distribution, separated in electricity, heat and infrastructure sectors.

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