Electricity-based mobility (EBM): CO2 emissions & contribution to the energy transition

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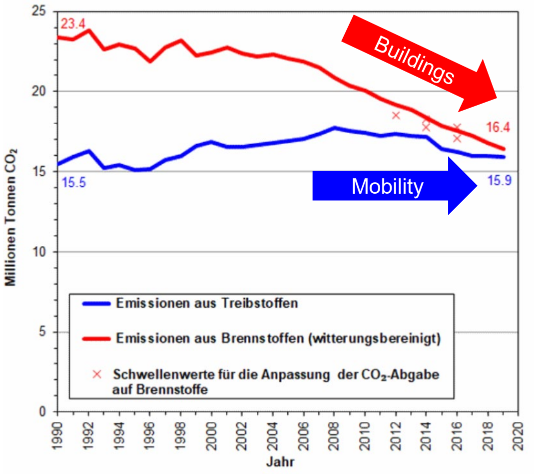
GHG emissions of mobility in CH

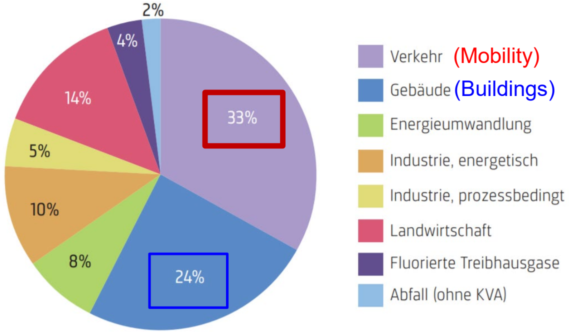
Empa
Materials Science and Technology

- Greenhouse gas emissions (GHG) = CO_2-eq
- In CH, mobility accounts for about ...
  - 15 Mt CO_2-eq / year
    - passenger cars: 75%
    - others road and rail vehicles: 25%
  - 1/3 of total Swiss GHG emissions
- No significant GHG reductions in the last decades (unlike buildings, etc.) due to …
    - lack of renewable alternatives
    - technical issues with on-board fuel storage
    - scarce recharging/refueling infrastructure
    - other reasons (sociological, economical, etc.)



GHG emissions in Switzerland, 2014

Source: BAFU, 2020



Electricity-based mobility (EBM)

- **«Electricity-based mobility» (EBM):** Alternative to fossil fuels-based mobility with «internal combustion engine vehicles» (ICEV) - if low GHG (renewable) electricity is used:
  - **Battery Electric Vehicles (BEV):**
    - Electricity → BEV
  - **Fuel Cell Electric Vehicles (FCEV-H2):**
    - Electricity → ***Electrolysis (ELYSE)*** → H2 → FCEV
  - **Synthetic Natural Gas Vehicles (SNG-V):**
    - Electricity → ***ELYSE*** → H2 → ***Methanation (METH)*** → SNG → SNG-V
- (Temporary) use of natural gas (NG) from the grid, if GHG content of electricity is higher than grid NG:
    - (NG → ***Steam Methane Reforming (SMR)*** → H2 → FCEV)
    - (NG → SNG-V)

Project «Electricity Based Mobility» (EBM)

Project-Partners: PSI, ETH zürich, EPFL, Empa

"Competence Center Energy and Mobility"
(former "SCCER")

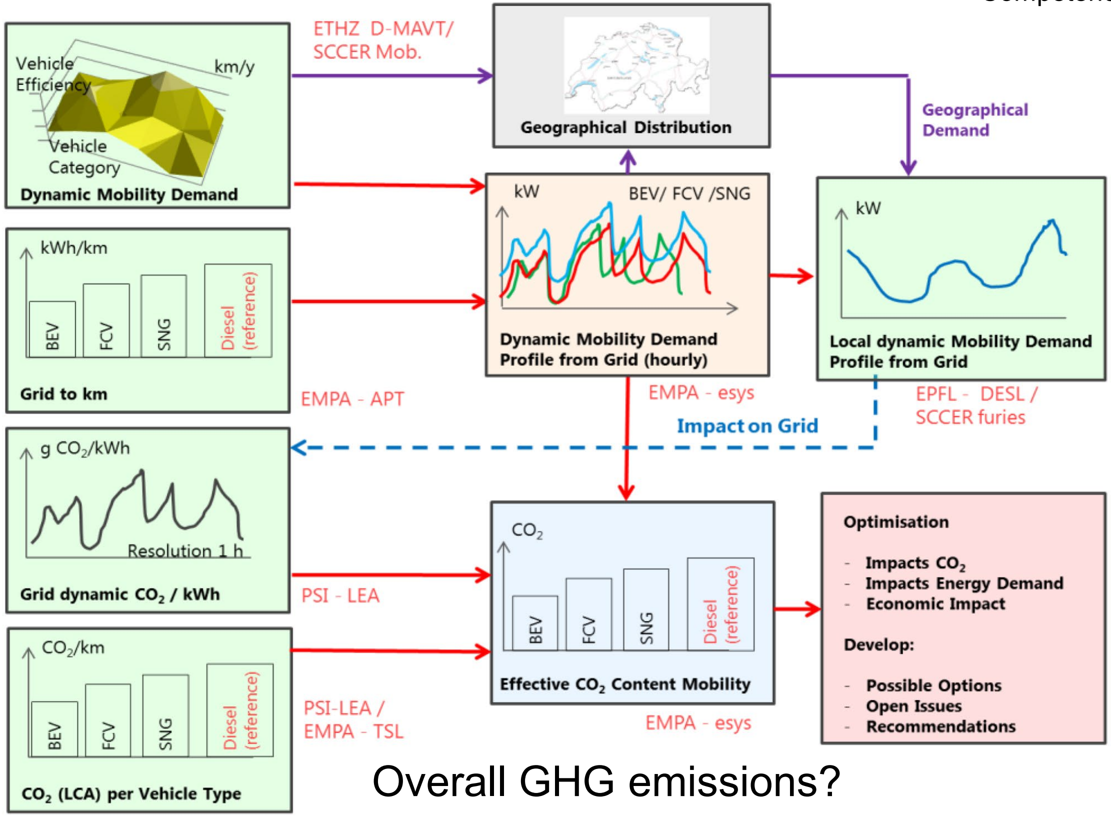
Additional electricity (natural gas) demand?

Future CH fleet?
EBM penetration?

TTW efficiencies?
(current / future)

Electricity supply?
GHG intensity?

Indirect emissions?
LCA?



Local grid aspects?

EBM:
Systemic impacts?
GHG savings?

Overall GHG emissions?

EBM characteristics

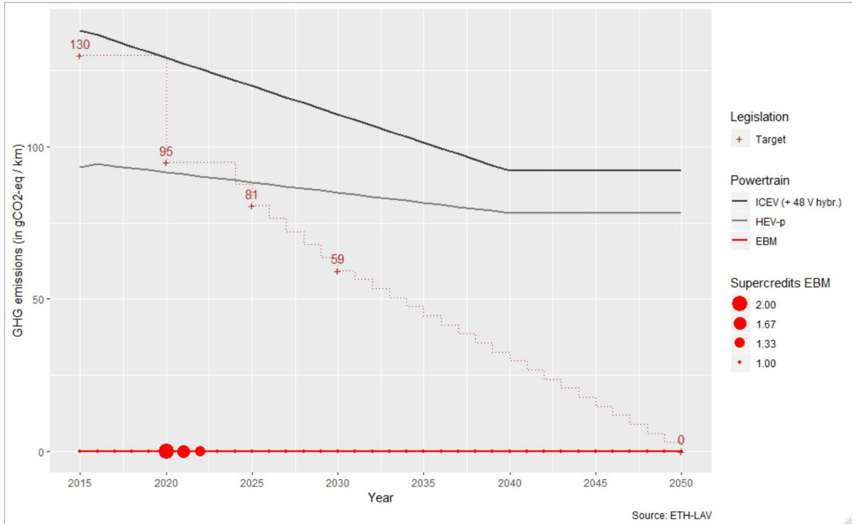
Feature	BEV	FCEV-H2	SNG-V
Fuel efficiency	Charging = 85% **Electricity-to-Tank = 85%** **Tank-to-Wheel = ~80%*** **Electricity-to-Wheel = ~70%** **+**	ELYSE = 63% *(SMR = 73%)* Compression (700 bar) = 90% Charging = 100% **Electricity-to-Tank = 57%** ***(NG-to-Tank = 66%)*** **Tank-to-Wheel = ~30%*** **Electricity-to-Wheel = ~17%** **=**	ELYSE/METH = 49% *(NG = 100%)* Compression (50 bar) = 95% Charging = 100% **Electricity-to-Tank = 47%** ***(NG-to-Tank = 95%)*** **Tank-to-Wheel = ~20%*** **Electricity-to-Wheel = ~10%** **–**
Fuel storability	**hours – days** pumped-hydro storage (PHS) and new batteries **–**	**days – weeks (– seasonal)** in specific pressurized H2 vessels (in NG grid via METH / SMR) **=**	**seasonal** in NG grid **+**

* Hänggi et al., «A review of synthetic fuels for passenger vehicles» Energy Reports 5 (2019) 555-569

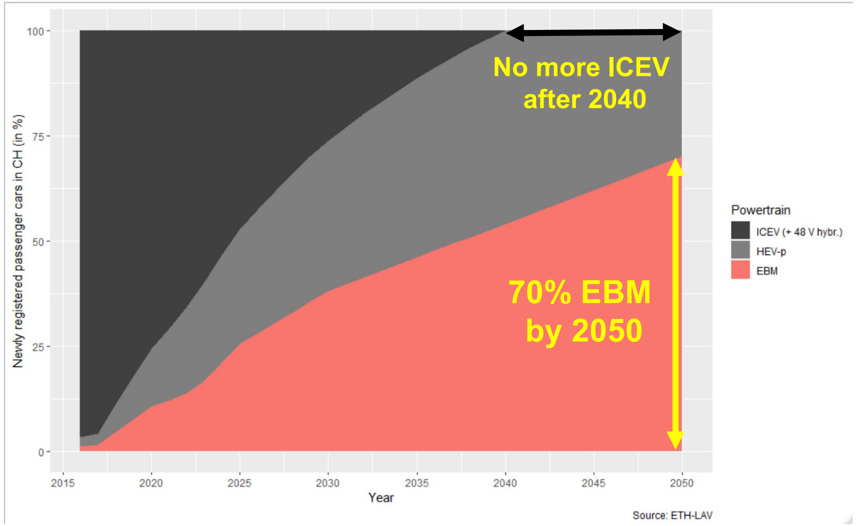
GHG reduction targets in mobility

ETH zürich
Empa Materials Science and Technology

Legislative GHG reduction targets of newly registered passenger cars (EBM = 0 gCO_2 / km + supercredits until 2022)

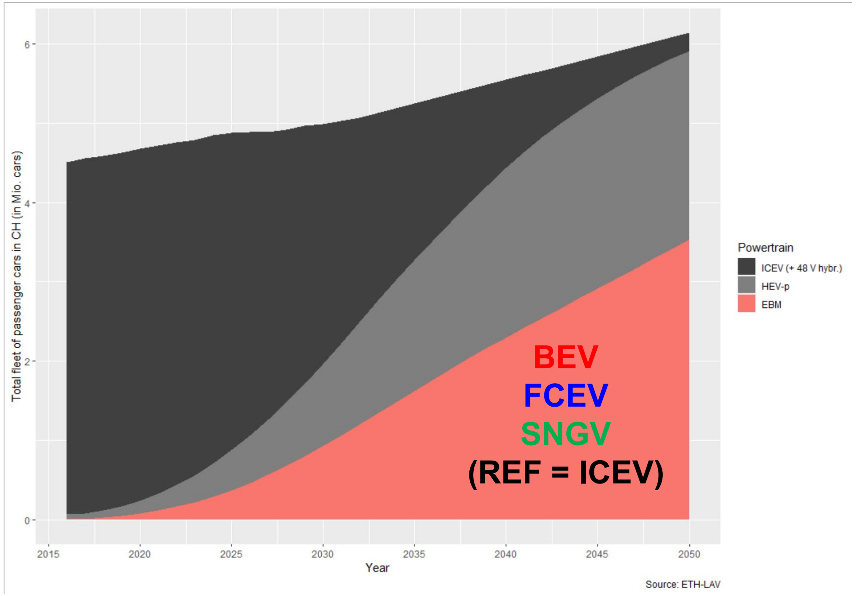


Needed share (%) of EBM powertrains in newly registered car fleet to meet legislative GHG reduction targets



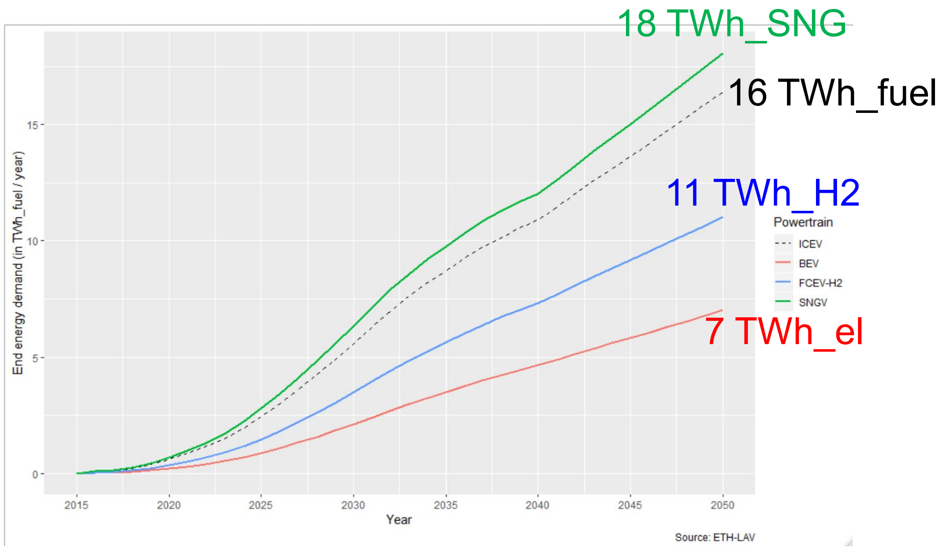
Evolution of Swiss passenger car fleet

CH passenger car fleet complying with legislative GHG targets of newly registered passenger cars*



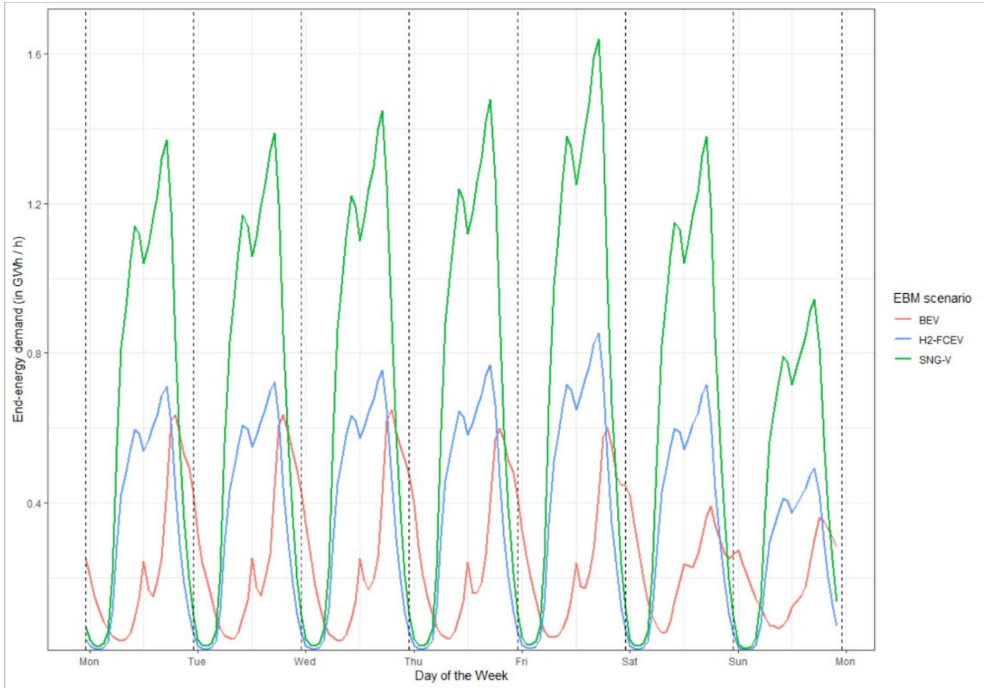
* as of 2020: < 95 gCO2-eq / km

Annual end-energy demand of EBM (+ ICEV)



Hourly charging profiles of EBM

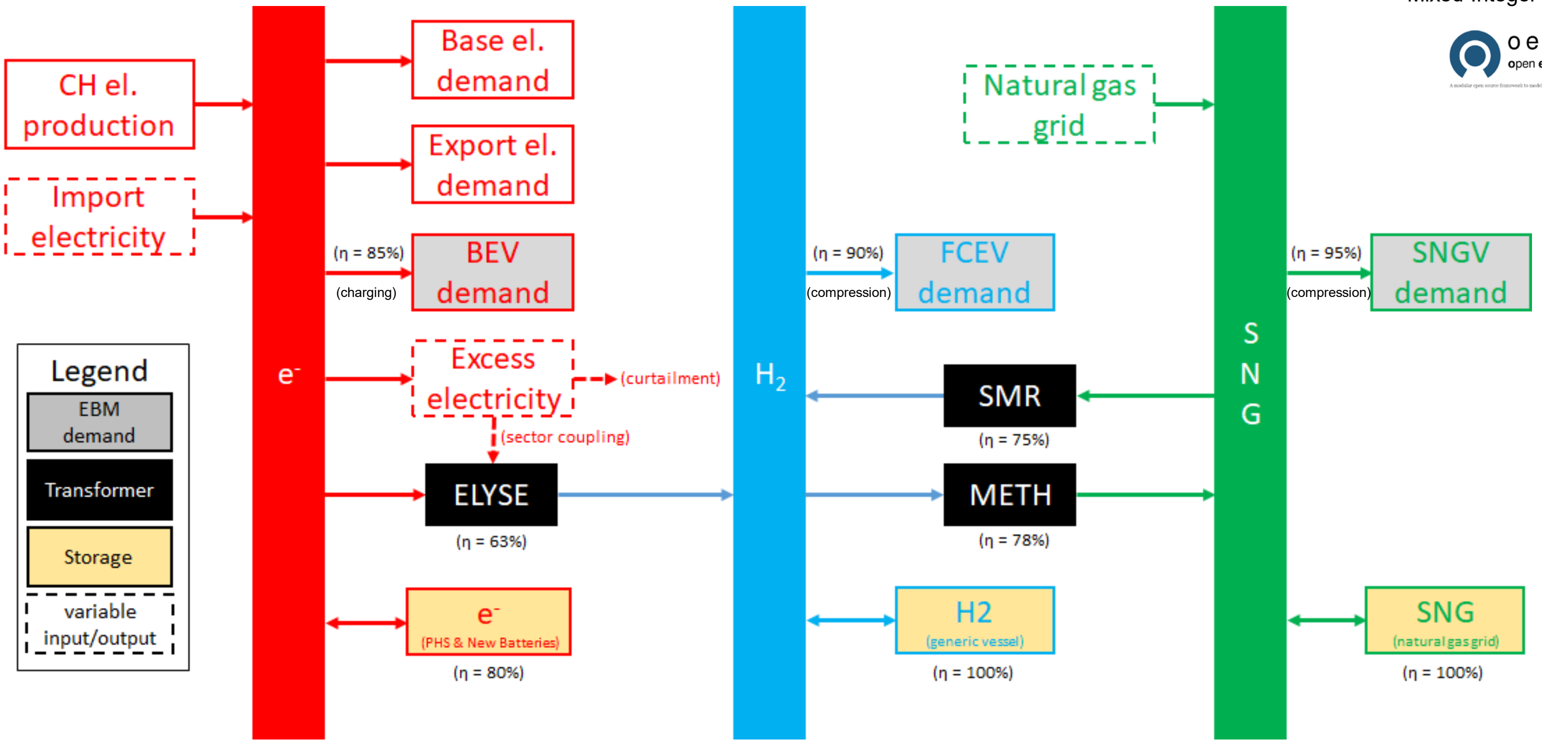
- **BEV**
  - Based on CH mobility survey «Mikrozensus» (BFS)
  - 60 kWh battery
  - Standard 230 V socket at 2.3 kW
  - Mostly “evening/night” charging (“home”)
- **FCEV / SNGV**
  - Charging like ICEV
  - From hourly and daily visits at a real refueling station (Migrol)
  - Mostly “afternoon/evening” refueling (“work”, “after-work”)



EBM Fuel Supply Chain Model

MILP* optimization model («oemof» tool) to minimize GHG emissions:

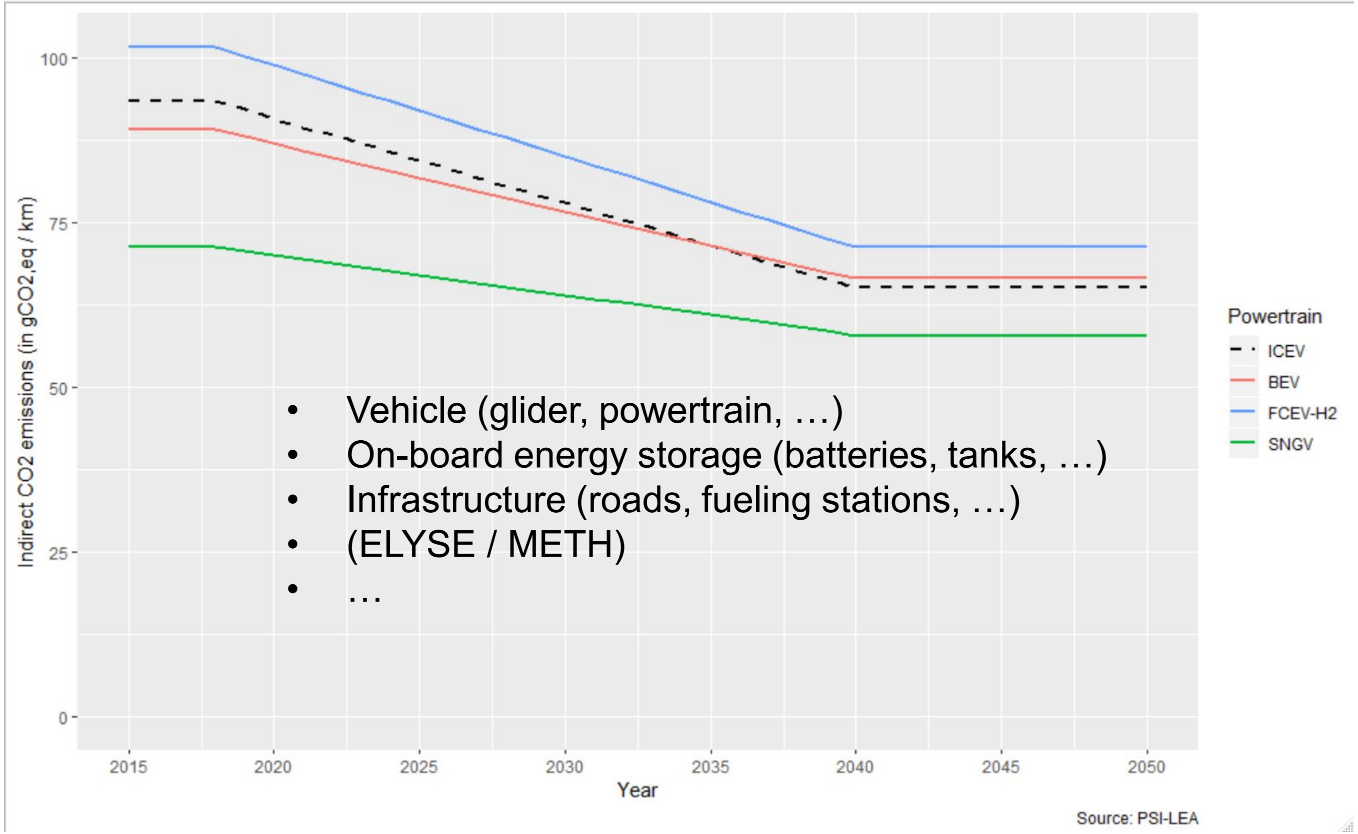
* Mixed-Integer-Linear-Programming



Modelling approach

- Hourly production and demand profiles of 2015 linearly scaled to the annual demand and production until 2050 from «EUSTEM» model (PAUL SCHERRER INSTITUT PSI).
- «Variable» nodes:
  - Import electricity (source)
  - Grid NG (source)
  - «Excess» electricity (sink)
  - Storage of electricity (pumped-hydro storage), H2 and SNG
- Domestic (Swiss) electricity generation:
  - Inflexible: Nuclear, run-of-river, PV, wind, conv.-thermal, other renewables
  - Flexible: Dam hydro storage (modelled separately with «residual load» as proxy)
- Fixed «net export» to EU (from «EUSTEM» model)
- «objective»: Minimize (life-cycle) «GHG emissions» (g CO2-eq / kWh)

Indirect («grey») emissions of EBM vehicles



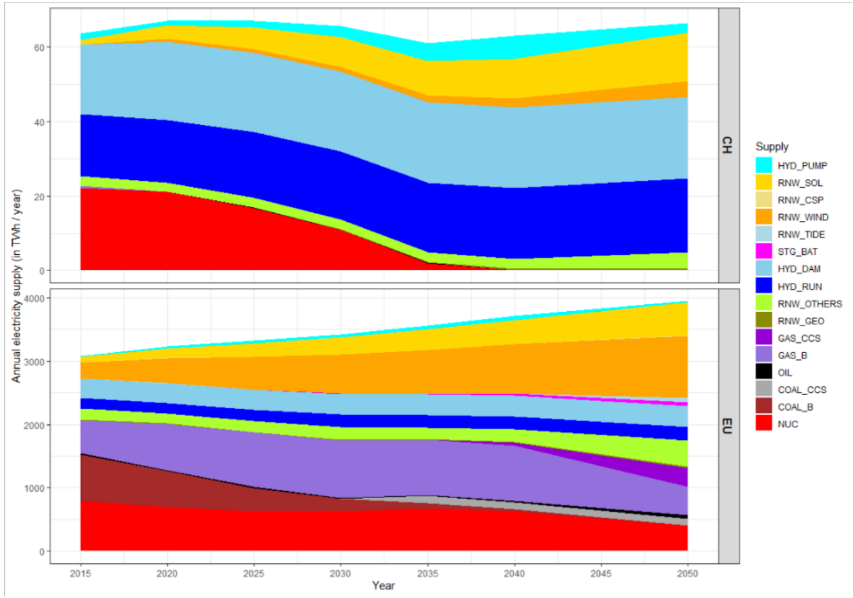
- Vehicle (glider, powertrain, …)
- On-board energy storage (batteries, tanks, …)
- Infrastructure (roads, fueling stations, …)
- (ELYSE / METH)
- …

Evolution of CH and EU electricity generation mix

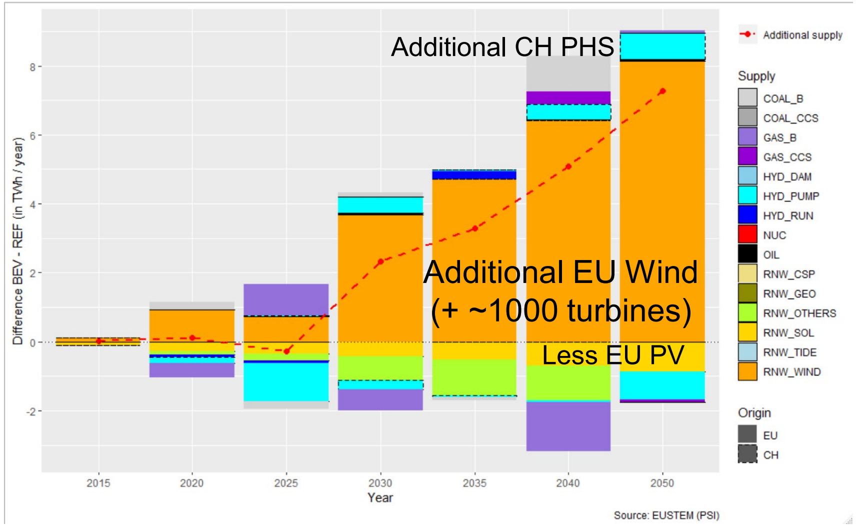
- «EUSTEM» (European Swiss TIMES electricity model):
  - Technology-rich, bottom-up, least-cost optimization model
- Supply and demand scenarios:
  - Based on actual CH and EU energy policies (e.g., nuclear/ renewable expansion, modified electricity demand, etc.)
- Import to Switzerland:
  - **Low carbon («LC»):** Based on EU target to reduct GHG emissions by 80% until 2050 compared to 1990 levels (including «Carbon Capture and Storage» (CCS) option) → less ambitious than «EU Green Deal»
  - **Combined-Cycle-Gas-Turbine („CCGT“):** Only import of CCGT electricity (“best fossil case) or new CH CCGT → no “Stromabkommen” (bilateral EU-CH electricity exchange agreement)

Evolution of CH and EU electricity generation mix

CH and EU generation mix



Marginal* generation mix with BEV



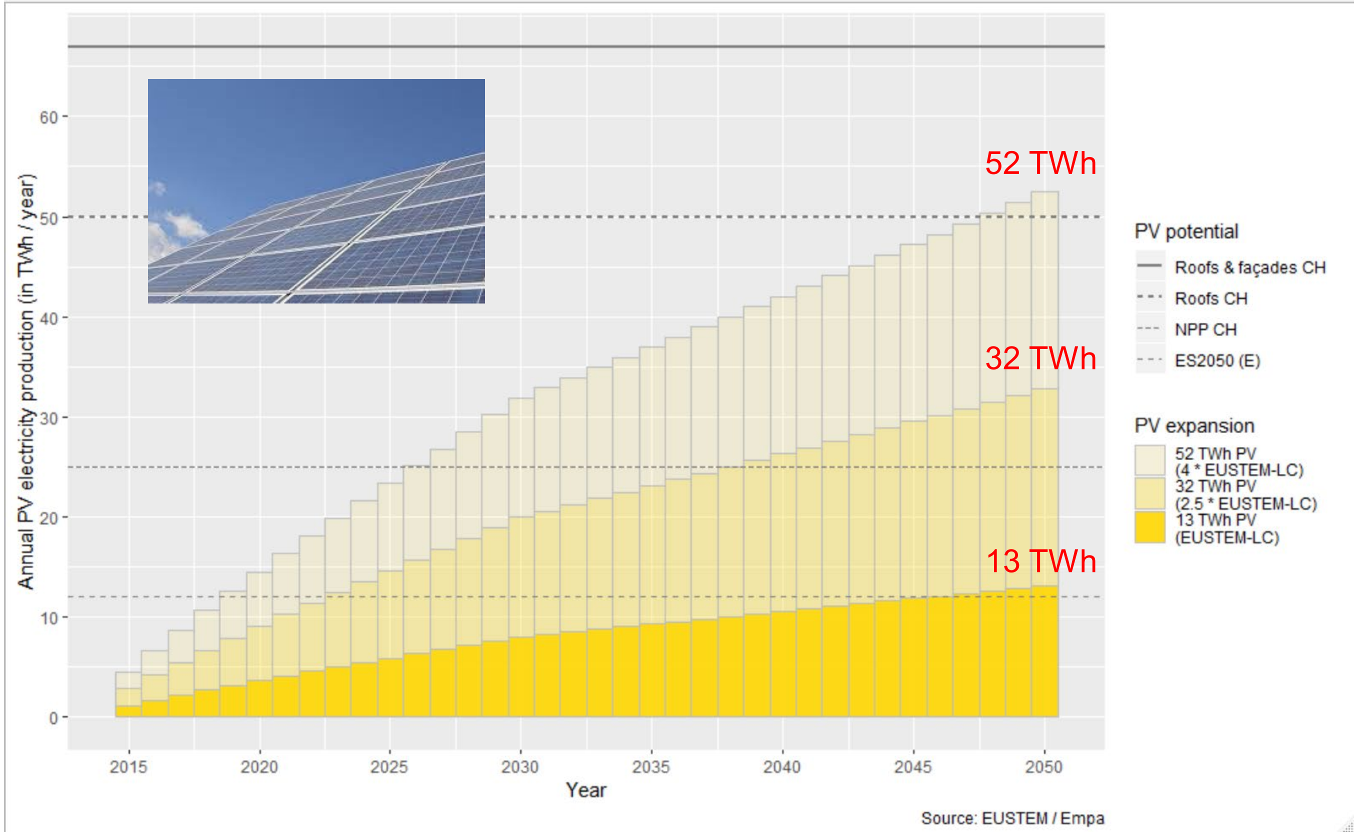
* What is added/removed compared to situation w/o BEV?

Exogenous PV expansion scenarios

- «EUSTEM-LC»: Renewable expansion in CH to substitute 24 TWh of nuclear and supply an additional 7 TWh for BEV
  - + **13.1 TWh PV** (+ 4 TWh Wind, + 2.3 TWh other RET)
  - + Rest: EU imports (~ Wind and Gas CCS)

- Two additional (exogenous) PV expansion scenarios
  - 2.5 x «EUSTEM-LC» = **32 TWh** in 2050 (= 25 TWh nuclear + 7 TWh BEV)
  - 4 x «EUSTEM-LC» = **52 TWh** in 2050 (= max. PV potential sonnendach.ch)

PV expansion scenarios



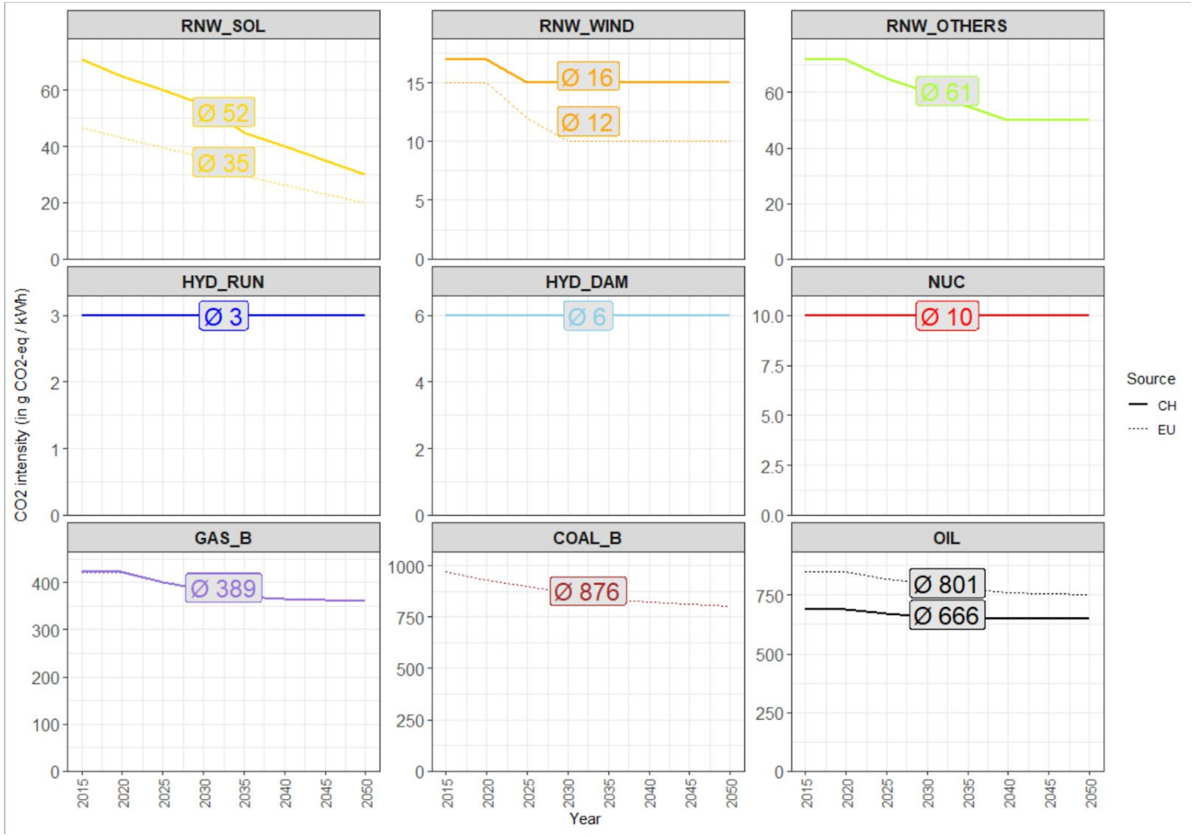
Treatment of «excess electricity»

- For *«excess electricity»* - due to a higher PV expansion - there are two (extreme) scenarios:
  - **«Curtailment»** (worst case):
    - Electricity is «lost» and its specific GHG emissions (e.g., of PV) increase
  - **«Add. SNG production»** for other energy sectors (best case):
    - Additional SNG is produced from excess electricity (via «Power-to-Gas» = ELYSE/METH) to be used in other energy sectors (e.g., long-distance and heavy-duty vehicles, process heating, chemical industry, etc.)
- In reality, (most likely) a partial curtailment will occur
- **Additional electricity exports** are not allows, as they are a-priori set by EUSTEM and it is assumed that renewable «excess electricity» occurs simultaneously throughout EU due to similar weather conditions

CO2 intensities of electricity supply

Life-cycle assessment (LCA)
GHG intensities (g CO_2-eq / kWh)

Source: **«ecoinvent» (v 3.4)**

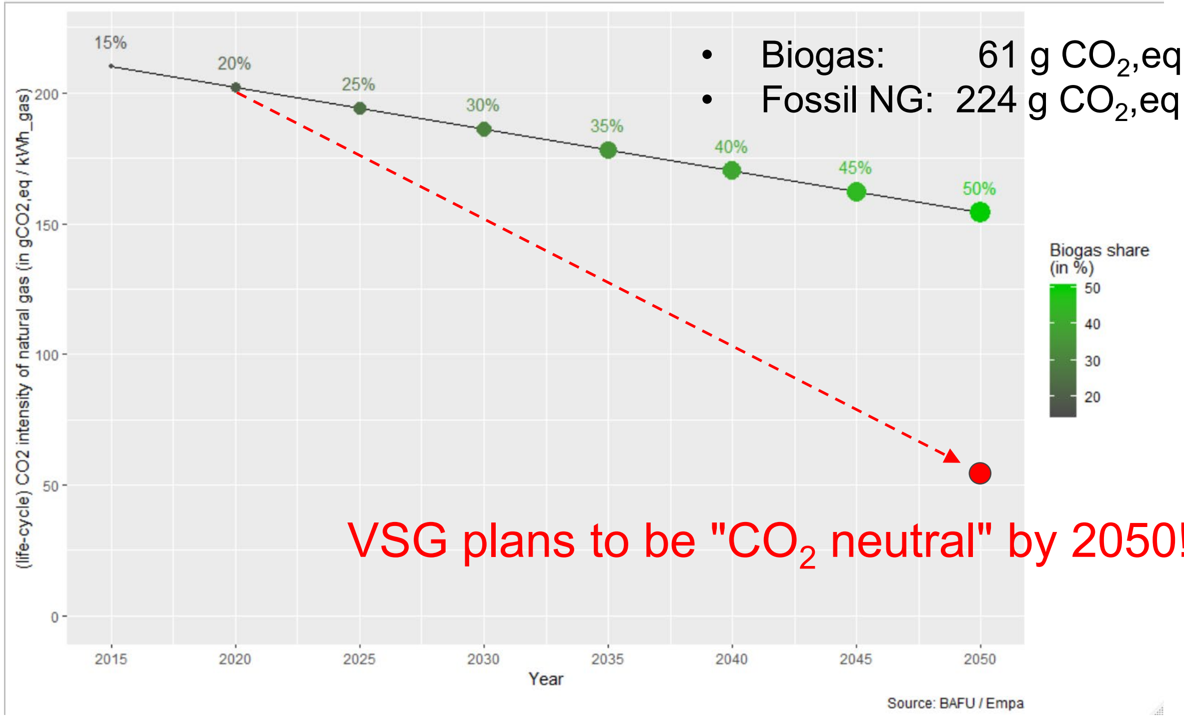


(Life-cycle) GHG content of imported electricity

Imported electricity:
- «CCGT (Gas)» (exogenous)
- «LC mix» (EUSTEM)

Domestic electricity :
- «CH mix» (EUSTEM)

Biomethane (biogas) content in NG grid



- Biogas: 61 g CO_2,eq / kWh
- Fossil NG: 224 g CO_2,eq / kWh

VSG plans to be "CO_2 neutral" by 2050!

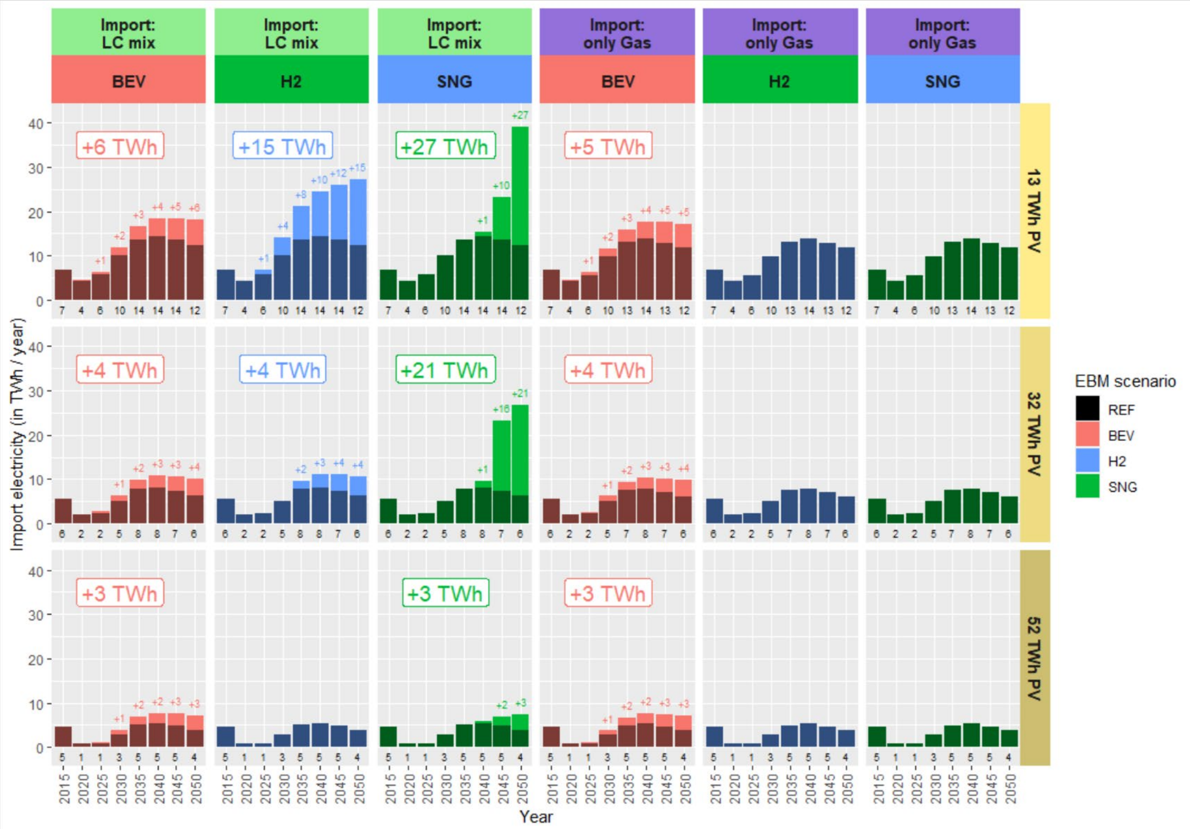
Additional (import) electricity demand

Additional import electricity needed (compared to REF):

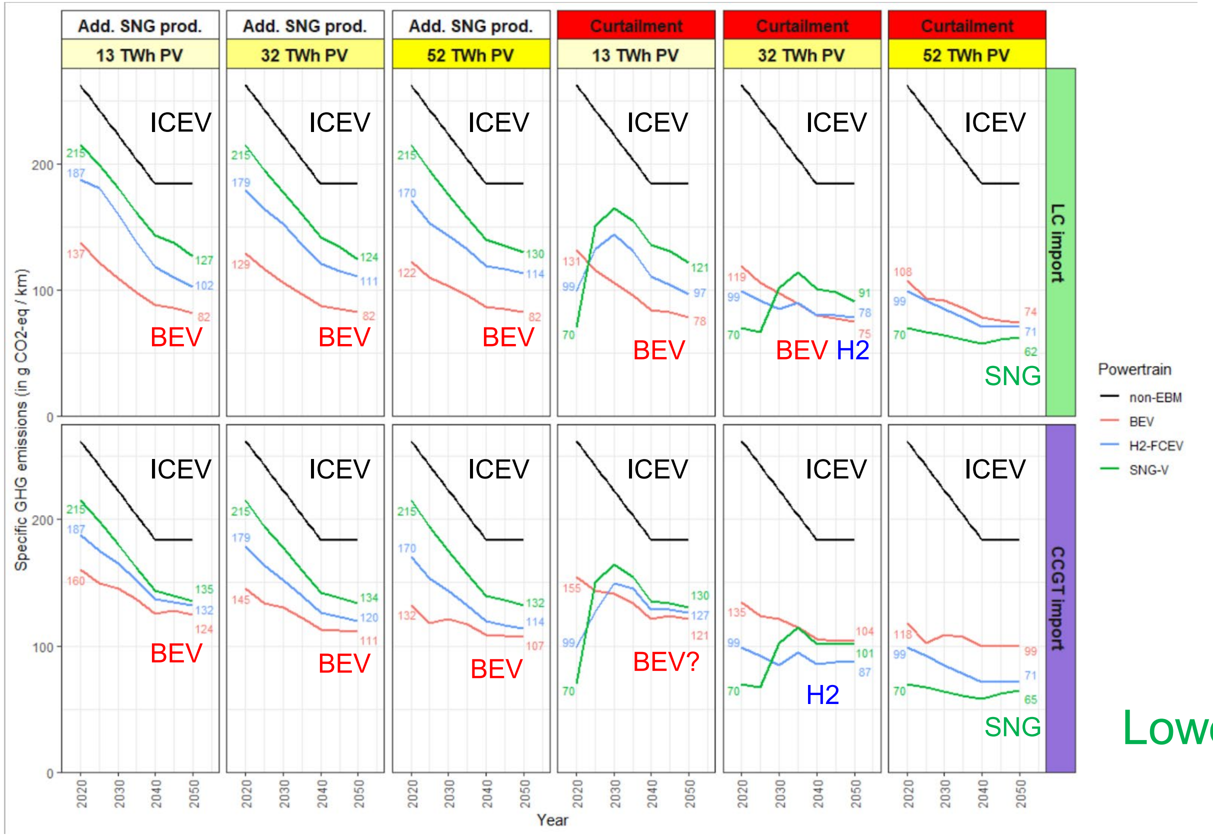
- 3 – 6 TWh (BEV)
- **0** – 15 TWh (H2-FECV)
- **0** – 27 TWh (SNG-V)

Remaining end-energy demand of EBM can be met by using:

- «excess electricity»
  - BEV → short-term storage via PHS
  - H2-FCEV / SNG-V → sector coupling and
- Grid NG (directly or via SMR)



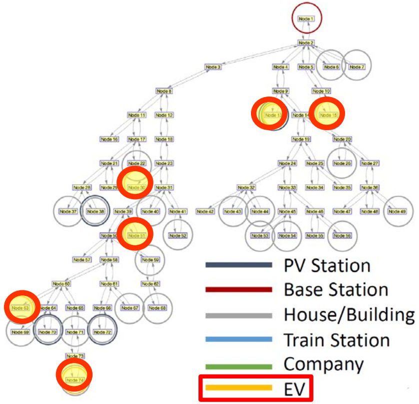
Specific GHG per km driven



Lowest overall!

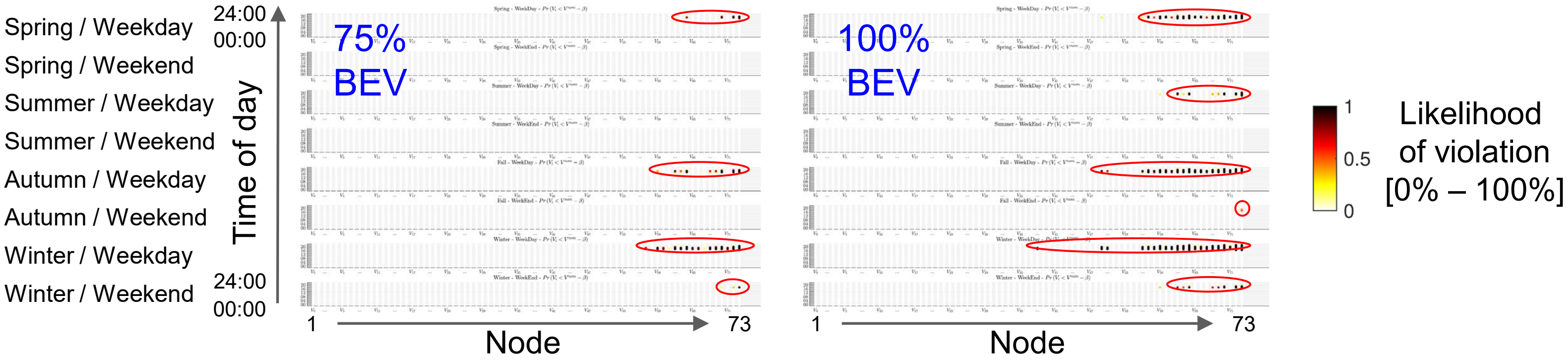
Local grid aspects

- Nodal voltage violations:
  - No violations up to 50% BEV penetration
  - Strong increase in violations until from 50% to 100% BEV penetration
  - Mitigation by load shifting (noon charging instead of evening)



(a) Network Graph with Resource Allocation.

(b) Network Map

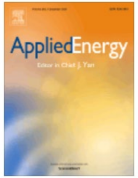


Conclusions (Take-Home-Messages)

- All EBM powertrains feature substantially **lower (life-cycle) GHG emissions** than a corresponding fossil fuels based ICEV fleet
- If all «excess» electricity can be used (e.g., with additional sector coupling / power-to-X), **BEV** are generally the most GHG-efficient powertrain
- With (partial) **curtailment** of excess electricity and a large PV expansion, the more **H2 and SNG** vehicles become equally – or even more – GHG-efficient than BEV (especially with high-carbon import electricity) due to their option …
  - … to **seasonally store** (as SNG) excess electricity (from PV in summer)
  - … to use **natural gas** (NG) form the grid (especially if it contains a large share of biomethane), when the GHG content of electricity from the grid is high
- Generally **differences** in terms of GHG reduction between EBM powertrains are small, except for **«extreme» cases** regarding PV expansion and GHG content of import electricity
- Locally, a large penetration of BEV will more likely lead to **grid failure** (current and voltage), thus in practice (without costly grid reinforcements) a **«mixed fleet»** with BEV <u>and</u> H2-FCEV / SNG-V is most likely the most sustainable option
  → need for further study with techno-economical analysis!

Questions?

Publication: *Rüdisüli et al., 2022. "Prospective life-cycle assessment of greenhouse gas emissions of electricity-based mobility options". Appl. Energy 306, 118065.* [*https://doi.org/10.1016/j.apenergy.2021.118065*](https://doi.org/10.1016/j.apenergy.2021.118065)



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