



Swiss power poles, Source: BFE

## Project report “Electricity mixes in the UVEK database (v2025)”

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## Legal note

This report is not meant to be made public as the permission for publishing any data or figures related to the raw calculation data was not completely available.

## Scope and aim

The overall aim of the project „Update of electricity mixes in the UVEK LCI database“ project is to provide a working software solution that is able to continuously update the electricity mixes in the UVEK LCI database based on a broad range of international data sources in a largely automatized way and to then perform such an update with up-to-date data. The project is split into two parts, the first of which is supposed to provide fundamentals in terms of interoperability with existingecoinvent LCI data. Furthermore, it will compare the update approach against electricity mixes using alternative approaches in order to understand the consequences of modeling choices and also to decide on the final approach. This project part with its methodology and results is described here. The second part of the project aims at the full implementation, covering several hundreds of electricity mix datasets.

## Key features

The key features of updating the Life Cycle Assessment (LCA) data in the UVEK database for electricity production and supply is a significant advancement that enhances the accuracy and relevance of environmental impact assessments. This update encompasses several critical elements: the development of a new code basis enhances the software framework's robustness and adaptability, allowing for more sophisticated analysis and modeling. Balancing extreme cases ensures that outlier scenarios are properly weighted, contributing to more reliable and representative data. The alignment and reworking of the trade model improve the accuracy of cross-border electricity flow calculations, essential for countries dependent on imported energy. Updates of technology mixes reflect the latest advancements in generation techniques, ensuring that the database accurately represents current technological capabilities and efficiencies. Lastly, the expansion of further economically relevant global countries and regional mixes offers a broader and more detailed perspective on global and regional energy dynamics, enabling stakeholders to make better-informed decisions based on comprehensive, up-to-date LCA data (for the specific regional coverage, see **table A1** in the appendix). These enhancements collectively improve the utility and precision of environmental assessments, facilitating more sustainable development in the energy sector. This includes data spanning the years 2021 to 2023, including datasets for the individual years as well.

## Previous work

The first part of this project has already dealt with establishing a mapping of electricity generation datasets between the current version of the UVEK database and the ecoinvent v3.9.1 cut-off database. Thus, the respective datasets from both databases have been extracted (in the case of the UVEK database from the Simapro dataset names of UVEK:2018 and in case of ecoinvent from the ecoeditor master data) and preprocessed to then be mapped manually against each other.

Thus, the two databases were compared against each other (analyzing the relationships on a quantitative level and identifying the reasons for the results), and the transfer of modeling principles for the recent ecoinvent database became possible. Furthermore, the results allowed for error checking, alignment in structure and coherence, while also improving on the ease of use, and the completeness of both databases. After the thorough analysis of the results, the outcomes of this project step informed the development of the updated electricity mix procedure.

The initial task of this part was the conceptual development of the updated UVEK electricity mix calculation approach. This was based on the available generation data in the database, the calculation procedures of ecoinvent v2 (as implemented in UVEK, e.g. as documented in Itten et al. (2014)), the newly developed calculation procedures for ecoinvent v3 (e.g. based on the work of Treyer and Bauer (2016)), and the experiences with the automatization of ecoinvent electricity calculations from ecoinvent v3.6. Thus, an updated calculation procedure was made explicit, so that it can then be manually applied to the case of Switzerland. This allowed to test the procedure for feasibility before creating an automatized script in a further extension of the project. The resulting electricity mix was then compared against the recently developed Swiss electricity mix for buildings from Frischknecht and Alig (2021), which not only allowed to validate the approach, but also helped to quantify the consequences of methodological differences between both approaches in terms of size. This analysis then allowed to identify possible readjustments or refinements of the initial of approach to form a solid decision basis for the following automatized implementation in extension of the project. Such electricity mix calculations for Switzerland performed before were instrumental in the development of the following procedures.

## Data

This project relied on the following key data sources:

- EIA Electricity data browser [14]
- ENTSO-E web API [13]
- BFE data specifically for Swiss biomass power generation [11]
- Plant level capacity data used for updating nuclear and hydro power technology splits [15]
- COMTRADE [16]
- Existing UVEK:2018 database datasets [10]
- IEA Extended World Energy Balances [5]
- IEA World Energy Statistics [6]
- IEA OECD - Electricity exports by destination [7]
- IEA OECD - Electricity imports by origin [8]

Additional trade data is analyzed from Frischknecht and Alig, 2021 [1], as well as further statistical data sources on electricity generation and supply, which however have not been directly used to derive that datasets, but served as validation data source. The role of each of these datasets is shown in the following table (**table 1**).

**Table 1:** Role of the different datasets for the update of UVEK mixes, distinguished by country group.

Data contribution	ENTSO-E countries	Non-ENTSO-E countries
Absolute production volumes and imports	EIA Electricity data browser [14]	EIA Electricity data browser [14]
Temporally resolved power generation and trade data	ENTSO-E web API [13]	N/A
Technology splits (CHP/non-CHP, fuels)	IEA Extended World Energy Balances [5] (equals Eurostat data)	IEA Extended World Energy Balances [5]

Technology splits (nuclear)	Plant level capacity data [15]	Plant level capacity data [15]
Technology splits (hydro power)	Plant level capacity data [15] ENTSO-E web API [13]	Plant level capacity data [15]
Technology splits (biomass Switzerland)	BFE data specifically for Swiss biomass power generation [11]	N/A
Transmission and distribution losses	EIA Electricity data browser [14]	EIA Electricity data browser [14]
Pumped hydropower losses	EIA Electricity data browser [14] IEA World Energy Statistics [6]	EIA Electricity data browser [14] IEA World Energy Statistics [6]
Trade splits by origin	ENTSO-E web API [13] IEA OECD - Electricity exports by destination [7], IEA OECD - Electricity imports by origin [8] (equals Eurostat data [18])	IEA OECD - Electricity exports by destination [7], IEA OECD - Electricity imports by origin [8] COMTRADE [16]
Dateset structure	Existing UVEK:2018 database datasets [10]	Existing UVEK:2018 database datasets [10]

Regional totals, finally, are composed based on the absolute production volumes, imports and losses provided by the EIA Electricity data browser [14].

The Swiss dataset implemented in the UVEK dataset continues to follow its existing historical approach, but for the calculation procedure established within this project, also consistently developed hourly power generation and trade data for Switzerland was needed. Thus, the established calculation procedure was extended to Switzerland, but the resulting data is only used for the Swiss contributions to foreign electricity supply. For reasons of completeness, this Swiss electricity data is also shown, even though the datasets itself is unavailable in the UVEK database and it is only indirectly is embedded in the electricity imports of other nations.

### Detailed programming methods

The calculation procedure was implemented as a set of R scripts (R version 4.3.2, 2023-10-31)<sup>1</sup> developed to generate national electricity supply and production mixes for integration into the UVEK database. Their general structure is as follows:

1. Data ingestion
2. Calculation of overall generation data
3. Trade data collection and merging
4. Net generation data calculation
5. Electricity loss calculations across voltage levels
6. Technology assignment/mapping
7. Uncertainty classification functions
8. Hourly trade calculations
9. Calculation of production mixes
10. Calculation of supply mixes

<sup>1</sup> <https://www.r-project.org/>

11. Pumped hydropower export (with updated losses)
12. Staged final ecospold file export

The scripts were developed to process multi-source datasets into standardized electricity mixes. Specifically, they extract, transform, and consolidate production and trade data from global statistical agencies. The resulting datasets allow UVEK to update its background electricity datasets and support consistent environmental accounting across regions and years.

The calculation framework is modular and consists of sequentially executed R scripts. Each script performs a discrete task in the processing chain, such as data ingestion, transformation, loss correction, or mix computation. A master script initiates their execution and ensures ordered dependency resolution.

To ensure reproducibility, the working environment is initialized from a clean state. The necessary R packages (foreign v.0.8-85, gdata v2.19.0, XML v3.99-0.16) are installed if missing and subsequently loaded. As gdata depends on Perl for Excel file parsing, a working installation of Strawberry Perl (<https://strawberryperl.com/>) or an alternative is required. All input and output files must be stored in a predefined directory structure that includes “Input”, “Output”, and “Scripts” folders. Data loading and processing are resource-intensive so a machine with ample memory is recommended, especially for the initial parsing of large CSV datasets (from IEA where unzipped data files can exceed 20 GB or more).

The scripts rely on the statistical sources listed in the section “Data” above. Mapping tables and metadata files ensure alignment between geographical and technological classifications across sources. Activity labels (for the different fuel/technology classes), geography labels (linking geography names and ISO2 codes), and technology mappings are also loaded to enable harmonization. In addition, EcoSpold XML templates are parsed to facilitate downstream integration into ecoinvent-compatible databases.

### Main methodological aspects of the implementation procedure

The main data source for the overall generation and trade data is the EIA [14] dataset, which provides not only more up-to-date data than alternative data sources (e.g. complete 2023 data at the time of calculation), but furthermore provides net electricity generation data (which reflects the data needs of the UVEK datasets), thus making conversions in this primary data source unnecessary. Supplementary data for fuel subdivision by the IEA needs such conversion due to largely providing gross generation data globally, but such values are of limited influence on the final UVEK datasets. The conversion for such cases used available data where possible or else values from [14].

More specifically, internal combustion losses are calculated by comparing gross and net generation from [6] for combustion power plants, which is there available from consistent standard energy balance methodologies. The resulting losses are applied to all gross generation datasets where they are reported in [5] in order to harmonize them with the net energy generation from [14] (as well as the direct data needs of the UVEK datasets). The conversion from energy content (TJ) to electricity (kWh) integrates both technology-specific conversion factors and loss assumptions.

When reported generation is negative (e.g. in net-consuming technologies), values are set to zero except where such entries reflect losses or trade. This prevents net energy-consuming units from distorting calculated (output) *production* mixes.

Pumped hydro power losses have previously been based on generic data without solid data basis and could now be filled with detailed consumption and production data.

Earlier electricity trade modeling in the UVEK database (and as described in the most recent version of the underlying data quality guidelines) did not yet consider the time of trading, which could (in the case of the ENTSO-E countries) now be considered based on detailed hourly electricity trade and production statistics, while total volumes (e.g. in case of minor data gaps) have been scaled to match national total values reported by the EIA [14].

Furthermore, trade data in general was covered incompletely in previous versions of the UVEK database, especially between non-OECD countries. Additional data from the UN COMTRADE database has been used to fill such gaps wherever possible.

Such gap-filling procedures prioritize trade data in non-ENTSO-E countries from IEA data sources but fall back on COMTRADE estimates when allowed. These rules are governed by an input control table (“comtrade\_trade\_allowed.csv”) that defines acceptable substitutions, considering that COMTRADE data is occasionally reported between countries that do not share a border or an electricity grid interconnector.

Swiss electricity mix data has been aligned in methodology to the neighboring countries (avoiding for example double-counting or under-counting of trade and generation data as present in previous UVEK database versions). Differences persist due to a higher level of detail in generation technologies, which has resulted in updating for example different types of biomass power generation shares directly from supplementary BFE data [11] in line with earlier versions of these datasets.

The UVEK database has limited regional coverage in terms of generation technologies, making the use of similar technologies from other regions necessary. While this procedure has been based on expert judgement in the past, this iteration of the UVEK dataset creation implements a more systematic approach based on geographical proximity, taking for example the data from neighboring countries as more systematic proxy than the previous approach of relying solely on expert judgement. In addition, this approach makes it easy to introduce new datasets without manual checking and updating of the linking, because this is now fully rule-based with the code.

Regional average electricity mixes are created to represent typical regions covered in LCA studies while also allowing to approximate regional gaps with appropriate data from a similar geographic region. Furthermore, these are available both as production as well as supply mixes and thus follow the same structure as the individual geographies. Differences between these two types of mixes are caused by the trade with outside regions, which are not covered by the production mixes but the supply mixes, but they remain of rather limited influence in the regions that are covered.

The total production volumes in the supply mixes and the production mixes may deviate from each other where different data sources contribute to them, e.g. in ENTSO-E countries, the supply mixes are primarily derived from consolidated and scaled versions of ENTSO-E and EIA data, whereas the

production mixes per country are derived from EIA data alone (without any contributions of ENTSO-E data).

### Data ingestion

Raw datasets are preprocessed once and subsequently stored in efficient “.RData” formats to improve loading times. Duplicate entries are removed (which turned out to be a specific issue with some of the IEA files at the time of downloading), key variables are coerced into numeric types, and missing data are filtered using conditional logic. Trade data from COMTRADE [16] is merged using ISO code lookups and harmonized naming conventions.

Electricity generation is aggregated into "basic production volumes" (BPVs) by technology and country. For power plants, net generation values are adjusted to account for internal conversion losses. Conversion factors are used to express all generation in kWh equivalents which is the native unit of the final UVEK datasets. The net generation data is calculated with the gross data from the OECD country statistics, with a default loss factor of 5% for thermal plants, consistent with literature on thermal inefficiencies provided by the EIA [14].

Pumped hydropower is treated distinctly to account for net losses. Net generation is supplemented by EIA loss data where available, allowing the estimation of consumption-to-generation ratios.

### Specific input data

Data for technologies used in the calculation of nuclear power and hydro power were outdated and incomplete at the time of calculation. Thus, manual calculations were used to update and supplement the technology splits in the calculation script, which follows the procedure already established for the UVEK database in [2]. Data sources were the individual power plants reported by [15] for nuclear and the European production data from [13] for hydro power, with the data in in 2023 being added up to national totals. Missing hydro power generation splits were assumed as 50:50 as was the case in older UVEK versions. There are indications that the reservoir type is more prominent in many of the regions that have no high-level reporting (based on checking some individual power plants), but this data is not sufficient to allow for a more sophisticated default estimate. Updating this assumption may be part of future work. The implemented data was as follows:

**Table 2:** Nuclear power generation splits to disaggregate to UVEK generation datasets per region.

Country	Pressure water reactor [kWh/kWh]	Boiling water reactor [kWh/kWh]
Argentina (AR)	1	0
Belgium (BE)	1	0
Brazil (BR)	1	0
Bulgaria (BG)	1	0
Canada (CA)	1	0
China (CN)	1	0
Czechia (CZ)	1	0
Finland (FI)	0.3592	0.6408

France (FR)	1	0
Germany (DE)	1	0
Hungary (HU)	1	0
India (IN)	0.9508	0.0492
Iran (IR)	1	0
Japan (JP)	1	0
Mexico (MX)	0	1
Netherlands (NL)	1	0
Pakistan (PK)	1	0
Romania (RO)	1	0
Russia (RU)	0.71609	0.28391
Slovakia (SK)	1	0
Slovenia (SI)	1	0
South Africa (ZA)	1	0
South Korea (KR)	1	0
Spain (ES)	0.8524	0.1476
Sweden (SE)	0.323	0.677
Switzerland (CH)	0.5785	0.4215
Taiwan (TW)	0.6509	0.3491
Ukraine (UA)	1	0
United Arab Emirates (AE)	1	0
United Kingdom (GB)	1	0
United States (US)	0.654	0.346

**Table 3:** Hydro power splits to disaggregate to UVEK generation datasets per region.

Country	Run-of-river [kWh/kWh]	Reservoir [kWh/kWh]
Algeria (DZ)	0.5	0.5
Argentina (AR)	0.5	0.5
Australia (AU)	0.5	0.5
Austria (AT)	0.88	0.12
Bangladesh (BD)	0.5	0.5
Belgium (BE)	1	0
Bosnia and Herzegovina (BA)	0.13	0.87
Brazil (BR)	0.5	0.5
Bulgaria (BG)	0.44	0.56
Canada (CA)	0.5	0.5
Chile (CL)	0.5	0.5
China (CN)	0.5	0.5
Colombia (CO)	0.5	0.5
Croatia (HR)	0.27	0.73
Czechia (CZ)	0.46	0.54
Denmark (DK)	1	0
Egypt (EG)	0.5	0.5
Estonia (EE)	1	0
Ethiopia (ET)	0.5	0.5

Finland (FI)	0.25	0.75
France (FR)	0.74	0.26
Germany (DE)	0.89	0.11
Greece (GR)	1	0
Hungary (HU)	0.55	0.45
Iceland (IS)	0	1
India (IN)	0.5	0.5
Indonesia (ID)	0.5	0.5
Iran (IR)	0.5	0.5
Iraq (IQ)	0.5	0.5
Ireland (IE)	1	0
Israel (IL)	0.5	0.5
Italy (IT)	0.85	0.15
Japan (JP)	0.5	0.5
Kazakhstan (KZ)	0.5	0.5
Latvia (LV)	1	0
Lithuania (LT)	1	0
Luxembourg (LU)	0.81	0.19
Malaysia (MY)	0.5	0.5
Mexico (MX)	0.5	0.5
Morocco (MA)	0.5	0.5
Netherlands (NL)	1	0
New Zealand (NZ)	0.5	0.5
Nigeria (NG)	0.5	0.5
North Macedonia (MK)	0	1
Norway (NO)	0.09	0.91
Pakistan (PK)	0.5	0.5
Peru (PE)	0.5	0.5
Philippines (PH)	0.5	0.5
Poland (PL)	0.93	0.07
Portugal (PT)	0.67	0.33
Qatar (QA)	0.5	0.5
Romania (RO)	0.61	0.39
Russia (RU)	0.75	0.25
Saudi Arabia (SA)	0.5	0.5
Serbia (RS)	0.92	0.08
Singapore (SG)	0.5	0.5
Slovakia (SK)	0.92	0.08
Slovenia (SI)	1	0
South Africa (ZA)	0.5	0.5
South Korea (KR)	0.5	0.5
Spain (ES)	0.3	0.7
Sweden (SE)	0	1
Switzerland (CH)	0.46	0.54
Taiwan (TW)	0.5	0.5
Tanzania (TZ)	0.5	0.5

Thailand (TH)	0.5	0.5
Tunisia (TN)	0.5	0.5
Turkey (TR)	0.5	0.5
Ukraine (UA)	0	1
United Arab Emirates (AE)	0.5	0.5
United Kingdom (GB)	1	0
United States (US)	0.5	0.5
Vietnam (VN)	0.5	0.5

Pumped hydro power losses have been calculated based on total 2021-2023 statistics [5, 14] as 2023 data alone was incomplete and showed some extreme outliers. These losses have been calculated from the electricity consumption per net electricity generation over these three years, which were subsequently expressed per kWh of net electricity produced. The updated values well exceed the previous default assumption of 20% losses and are:

**Table 4:** Pumped hydro power losses per geography per kWh of net electricity output.

Country	Losses (% of electricity input)
Argentina (AR)	24
Australia (AU)	27.7
Austria (AT)	30.9
Belgium (BE)	24.8
Bosnia and Herzegovina (BA)	36.6
Bulgaria (BG)	48.4
Canada (CA)	46.9
China (CN)	26.5
Croatia (HR)	28.8
Czechia (CZ)	22.9
France (FR)	26.3
Germany (DE)	34.4
Greece (GR)	30.3
Ireland (IE)	41
Italy (IT)	28.4
Japan (JP)	31.9
Lithuania (LT)	27.1
Luxembourg (LU)	26.4
Morocco (MA)	27.9
Norway (NO)	30.3
Poland (PL)	30.6
Portugal (PT)	22.3
Romania (RO)	22
Russia (RU)	26.9
Serbia (RS)	34.7
Slovakia (SK)	27.4
Slovenia (SI)	26.5
South Africa (ZA)	25.1
South Korea (KR)	23.3

Spain (ES)	26.3
Sweden (SE)	32.7
Switzerland (CH)	29.5
Taiwan (TW)	16.9
Ukraine (UA)	26.8
United Kingdom (GB)	24.2
United States (US)	20.9

## Trade matrices

Electricity trade volumes between countries are constructed using both EIA [14] and COMTRADE [16] datasets, supplemented by IEA data. Importing and exporting partners are matched via mapping tables. When data EIA or more specific national data is missing or incomplete, COMTRADE values are used conditionally, based on predefined trade allowances (national totals reported by the EIA). Intra-annual and inter-source discrepancies are reported for diagnostic purposes. In an iterative process (not visible in the R scripts), such data reporting has been used to successively fill and adjust missing data from COMTRADE where available and of major relevance due to high absolute trade flows (in case of non-OECD countries). Unrealistic COMTRADE data (between non-neighboring countries) have been eliminated manually in the data (by filtering them out, **table 5**). The trade model that was applied is model 2 from [2], consistently across all regions. In case of hourly trade calculations for the EU countries, trade model 2 was applied for each hourly time step, and then summed up over the respective investigation period.

**Table 5:** Permitted and plausible COMTRADE trade data based on neighboring regions (all other COMTRADE trade data is filtered out due to implausible minor flows in the database).

From (exporting country)	to (importing country)
Algeria (DZ)	Tunisia (TN)
Algeria (DZ)	Morocco (MA)
Argentina (AR)	Brazil (BR)
Brazil (BR)	Argentina (AR)
China (CN)	Russia (RU)
China (CN)	Vietnam (VN)
Finland (FI)	Russia (RU)
Indonesia (ID)	Malaysia (MY)
Iran (IR)	Pakistan (PK)
Iran (IR)	Pakistan (PK)
Kazakhstan (KZ)	Russia (RU)
Latvia (LV)	Russia (RU)
Lithuania (LT)	Russia (RU)
Malaysia (MY)	Indonesia (ID)
Malaysia (MY)	Thailand (TH)
Morocco (MA)	Algeria (DZ)
Norway (NO)	Russia (RU)
Pakistan (PK)	Iran (IR)
Pakistan (PK)	Iran (IR)

Russia (RU)	China (CN)
Russia (RU)	Kazakhstan (KZ)
Russia (RU)	Finland (FI)
Russia (RU)	Lithuania (LT)
Russia (RU)	Latvia (LV)
Russia (RU)	Norway (NO)
Thailand (TH)	Malaysia (MY)
Tunisia (TN)	Algeria (DZ)
Vietnam (VN)	China (CN)

## Hourly EU statistics

In case of the EU, hourly generation and trade statistics were available [13]. In a few cases, this data was available in more detailed resolution (15 minutes or 30 minutes). In such cases, higher resolution data has been aggregated to hourly resolution for consistency. As small generation units are not included in all cases, and trade data might mismatch with long-term national statistics, these values were for consistency scaled with the final values that were calculated before. For regions and fuels with unavailable temporal patterns, an even distribution of generation was assumed. This mostly relates to biomass power generation in regions that have limited generation in this field, and so the impact on the results is expected to be very limited. Wind, solar, and most types of hydro power or thermal power generation is largely derived from large-scale units, resulting in good data coverage. To some extent, the Swiss case is challenging because of smaller scale generation, but at least carbon footprints are predominantly influenced by imports from neighboring countries, which have higher data coverage, so at least carbon footprint scores are less likely to be impacted.

Pronovo data [12] was considered as alternative data source for hourly Swiss statistics. In order to assess its consistency with the other data sources, it was summed up and compared against IEA monthly generation statistics. The results showed major discrepancies that could not be reconciled. In part, it was assumed that this could be due to some Pronovo data being reported retroactively (e.g. at the end of the quarter or the reporting period). It will be up to future work to investigate this further, especially in consideration of adjusted reporting schemes or better harmonization across existing data sources, which could make such Pronovo data in a highly useful resource for improved Swiss electricity mix calculation.

After aggregation or disaggregation of all EU (and connected country) electricity generation and trade data to hourly resolution, the net hourly consumption in each region per hour was used to calculate the electricity origin per hour. This was done by calculation of the L-inverse of generation and trade matrices, and multiplication with the electricity demands, which could then be summed up over the respective reporting period (2023) to calculate the overall average electricity origin per EU country. Final kWh/kWh values were then rounded arbitrarily to six digits after the comma, implying a cut-off for very small contributions, typically from minor shares of electricity non-neighboring countries.

The underlying calculations followed this principle:

1. Set up an identity matrix  $I$  (size:  $n \times n$  with  $n = (\text{number of electricity supplying technologies} + 1) \cdot \text{number of countries}$ ).

2. Set up the technosphere matrix  $A_i$  (size:  $n \times n$ ) with electricity trade and production based on national supply data from domestic production and direct trade scaled to a total value of 1 for the time step  $i = 1$ .
3. Calculate  $I - A_i$
4. Perform the calculation of the L-inverse  $(I - A_i)^{-1} = L_i$
5. Multiply  $L_i$  with the net final electricity demand vector  $y_i$  (containing the demand of electricity per time step  $i$  in each region) to obtain the electricity supply mix  $x_i$  per region.
6. Perform the previous tasks for all  $i = 1 \dots 365 \cdot 24$  hourly time steps in the year 2023.
7. Add the supply mixes  $x_i$  for all time steps up to obtain the annual total electricity supply mix per ENTSO-E region.
8. Divide the annual total electricity supply mix by the total final demand (or supply, which should be identical) per technology in each country to obtain the respective annual shares, which can directly be implemented in the UVEK datasets (as kWh supplied per kWh consumed).

For the choice of temporally resolved electricity trade data, several options were possible. In the ENTSO-E electricity trade dataset, “Scheduled Commercial Exchanges” are the aggregated nominations the market has contracted between bidding zones (from long-term, day-ahead and intraday allocations), so they describe who is supposed to buy from whom for settlement and trade statistics. “Physical cross-border flows”, by contrast, are the metered power that actually moves across borders in real time and matter for grid operation. The two often diverge because physics doesn’t follow contracts: AC loop/transit flows, losses, outages, and TSO actions like redispatch or countertrading can shift where the electrons actually travel. In practice, use SCE when you want a clean view of cross-zone trading and net positions, and use physical flows when you care about operational loading, congestion, and where power physically goes.

Eurostat’s “trade by partner country” electricity series (e.g., “nrg\_ti\_eh”) [18] and hence also the derived IEA data [7, 8] reflect physical cross-border trade, not commercial contracts: the partner for imports is the country from which the electricity physically enters, and for exports this is the country where the electricity physically exits. If power merely transits a country, it is recorded as both an import and an export. That means these data are border-meter-oriented and can include transit. They are not based on market schedules or contractual counterparties.

Under the GHG Protocol’s Scope 2 guidance [21], the way of accounting for “physical” electricity trade corresponds to the “location-based” method. That means using the emissions of the grid where consumption occurs, which conceptually aligns with physical cross-border flows (or simply the local grid-average factor without any flow tracing). Market-based carbon accounting, by contrast, reflects emissions from contractual instruments (supplier-specific factors, power purchase agreements, guarantees of origin, or the residual mix if unspecified), so if one is allocating across borders, it would be more consistent to use “Scheduled Commercial Exchanges”, since they represent contracted trades between bidding zones. The Protocol [21] requires reporting both location-based and market-based totals.

For the modeling of the UVEK electricity mixes, a strictly location-based (physical) approach was followed. The only exceptions are the Swiss mix (which is remaining in its existing form, and follows for historical reasons a different, inconsistent approach), as well as the COMTRADE electricity trade data that was used to fill some gaps (**table 5**). The latter reflects commercial exchanges which may or may not also match the physical cross-border exchanges. Considering that better, strictly physical

electricity trade data is not available for these country pairings at a global resolution, that the alternative would have been an omission, and that these exchanges tend to have limited influence on the local mixes for the main countries such as China, India, or Russia, this is considered the best available approach.

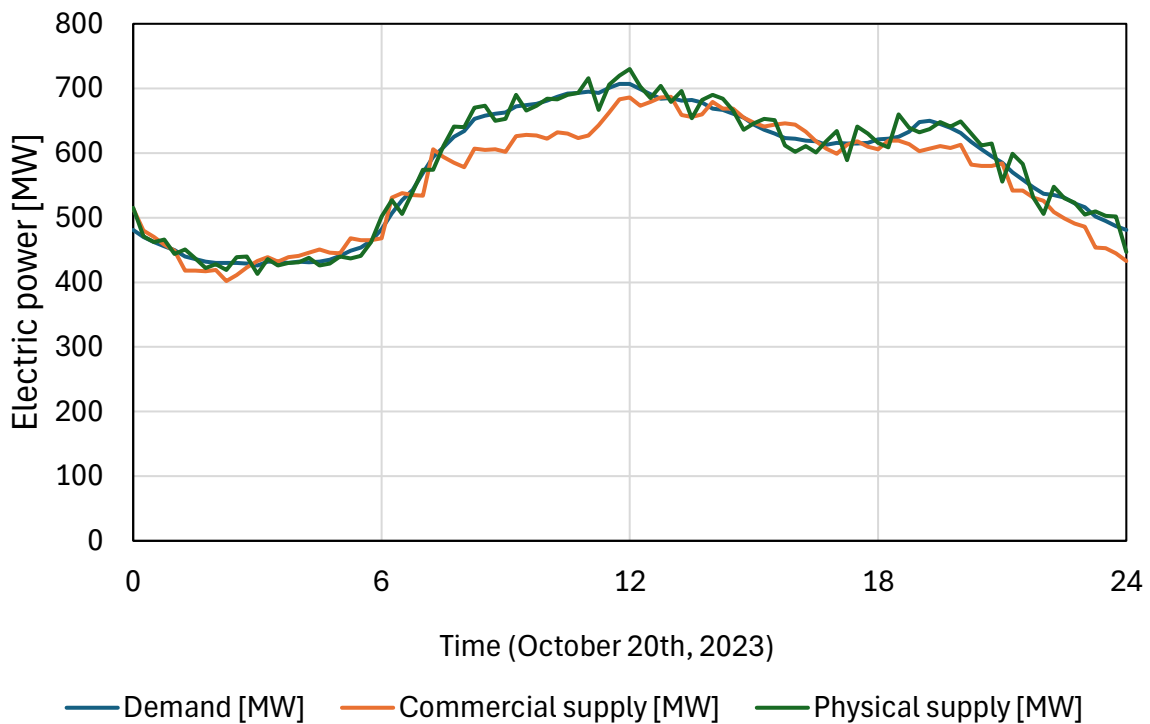
For the ENTSO-E countries, a cross check of the electricity trade data choices can be performed. The reported physical electricity imports for 2023 are visualized based on Eurostat data in **figure 1**:



**Figure 1:** Electricity imports of Luxembourg in 2023 with the width of connection representing the amount [18]. Reverse flows (exports) of electricity originating from Luxembourg are not depicted.

The main physical electricity imports of Luxembourg in 2023 come from Germany (64%) and Belgium (34%), whereas only a minor contribution comes from France (<2%) [18]. Physically, Luxembourg is reported to have two separate electricity grids, the one from Creos and the one from Sotel [19, 20]. The Creos grid is directly connected to Belgium and Germany and serves most electricity consumers in Luxembourg, while the Sotel grid is connected to France, and mainly serves the industrial sector (primarily steel-making) in Luxembourg. Both Creos and Sotel are connected with each other as well. In contrast to the national total electricity imports, ENTSO-E “scheduled commercial exchanges” trade data records only trade with Germany and is lacking both the Belgian and French data. The physical flows report both the Belgian and German contributions but lack the minor French part.

When mapping the electricity supply and demand in a temporally resolved manner based on the ENTSO-E-reported data (**figure 2**), it becomes apparent, that both the commercially scheduled as well as the physical exchanges somewhat follow the demand pattern throughout the day. At the same time, it is visible, that the cumulative physical flows match the cumulative physical demand much better, and differences are likely due to the temporal resolution difference (15 minutes for cross-border flows and hourly for demand patterns). Due to the larger mismatch between scheduled commercial exchanges and demand, a mixed calculation approach would assume that Luxembourg is undersupplied on this day in physical electricity terms, violating the principles of energy conservation. Hence, the utilization of the physical flows, despite the minor gap in French data, is considered the more suitable alternative for representing the actual physical electricity trade. In order to not neglect underreported or unreported trade, all physical flows are scaled to the annual total values, with the flows without temporal pattern available being assumed to follow a constant flow throughout the year. These are then the data points that were directly implemented in the electricity supply mix calculation via L-inverse.



**Figure 2:** Typical example for commercial and physical net electricity supply in comparison actual electricity demand (for a specific day in Luxembourg in October 2023, based on ENTSO-E data).

### Technology mapping

The technology mapping procedure (for different fuel classes) follows the intended approach that was described before [2] but generally lacked the subdivided data for full implementation. Overall production volumes from [14] have thus been subdivided by regional sub-fuel-group shares from [5]. The final technology mapping then was performed based on regional proximity where matching power generation datasets were unavailable in the UVEK database. Thus, geographical centroids from [17] were used to calculate region-by-region distances. Then, in case of a missing generation activity, the data from the nearest country with available data was used as proxy. The reasoning is that similar geographical conditions (e.g. sunshine, wind, temperatures) could also induce similar

environmental patterns in the generation activities (driven by yields, efficiencies, etc.). Uncertainty data was adjusted accordingly based on the pedigree approach, accounting for the geographical mismatch where applicable. Default technology mapping was as follows:

**Table 6:** Default technology mapping per fuel type.

Fuel type	Dataset name
biogas	Electricity, at cogen with biogas engine, allocation exergy
industrial gas	Electricity, industrial gas, at power plant
lignite	Electricity, lignite, at power plant
hard coal	Electricity, hard coal, at power plant
hydro (run-of-river)	Electricity, hydropower, at run-of-river power plant
hydro (reservoir)	Electricity, hydropower, at reservoir power plant
hydro (pumped)	Electricity, hydropower, at pumped storage power plant
municipal solid waste	Electricity from waste, at municipal waste incineration plant
natural gas	Electricity, natural gas, at power plant
nuclear (boiling water reactor)	Electricity, nuclear, at power plant boiling water reactor
nuclear (pressure water reactor)	Electricity, nuclear, at power plant pressure water reactor
distillate oil	Electricity, at cogen 300kWth, diesel, allocation exergy
residual oil	Electricity, oil, at power plant
peat	Electricity, peat, at power plant
solar PV	Electricity, production mix photovoltaic, at plant
wind	Electricity, at wind power plant
wood	Electricity, at cogen 1MWth, wood chips, allocation exergy

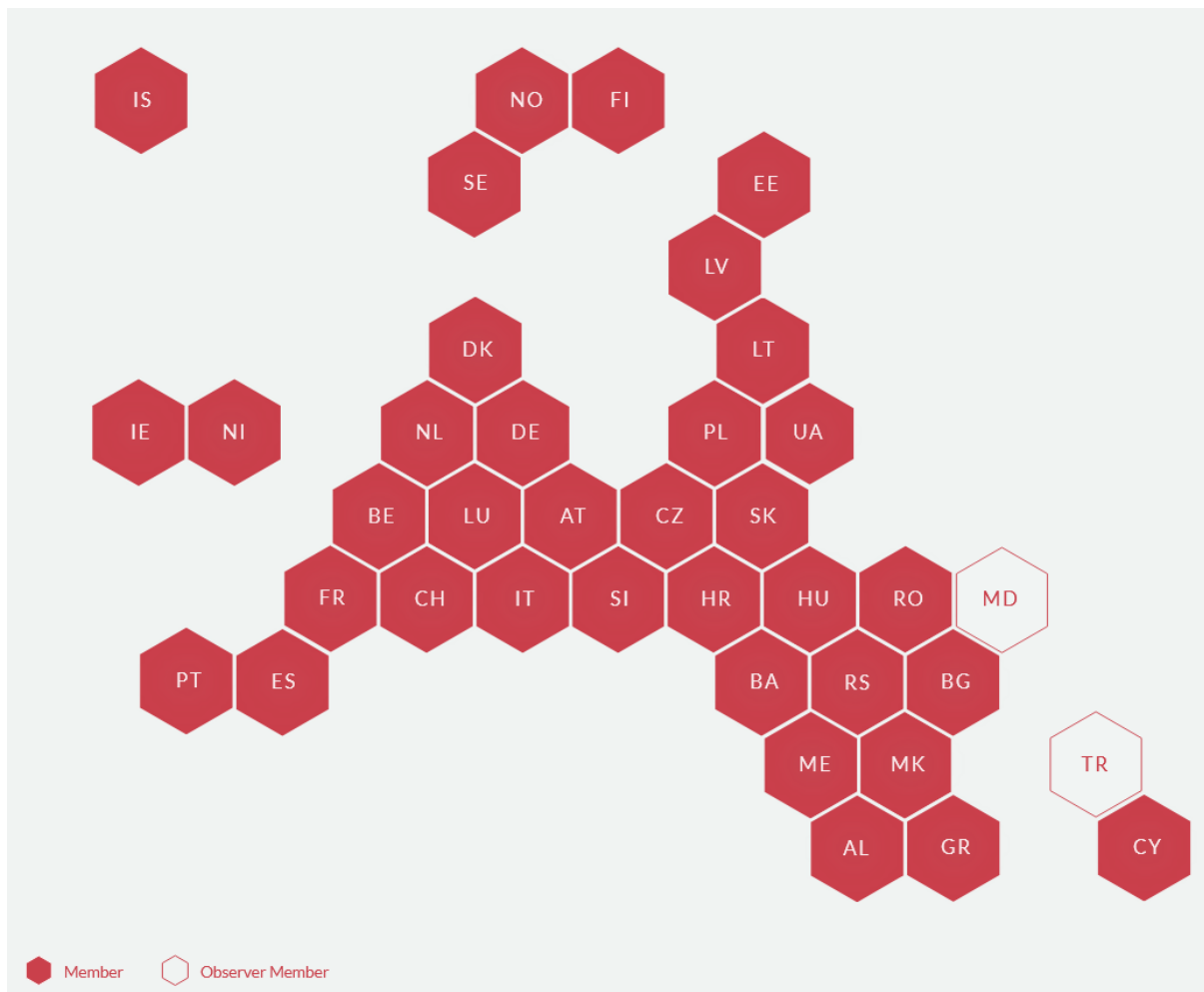
### Regional aggregation

On top of datasets for specific regions, this dataset covers also datasets for specific regions:

- RAF (Africa)
- RAS (Asia)
- RER (Europe)
- RLA (Latin America)
- RME (Middle East)
- RNA (North America)
- ENTSO-E
- GLO (Global)

Detailed connections between countries and the major regions they are part of are presented in **table A2** in the appendix. The GLO region covers all of the national regions in the UVEK database, while the ENTSO-E region covers the specific regions that are part of ENTSO-E in 2023 [16]. A part of the UK, Northern Ireland, is still part of ENTSO-E in 2024, but as it is mostly excluded, it is also not

covered by the ENTSO-E dataset in the UVEK database. In addition, a number of smaller countries (Albania, Cyprus, Montenegro) is also not covered explicitly. Iceland is part of ENTSO-E but lacks trade, so it's data coverage ultimately does not benefit from enhanced trade modeling. The ENTSO-E member countries are represented here:



**Figure 3:** ENTSO-E member countries covered in high resolution modeling in the UVEK database (excluding observer members and Albania, Cyprus, Iceland, Montenegro, Northern Ireland) [13]. These regions are also listed in **table A3** in the appendix.

In each aggregated region, national datasets are added up with their representative share in the corresponding time frame (either being the production or the supply volume), leaving out any missing datasets. Thus, implicitly, the covered nations are overrepresented in the respective regional mixes. However, the coverage of national datasets has been selected on regional representativeness on the major economies of each larger region. Thus, a major coverage within each region can be expected. Future work may expand this coverage to more complete global picture as some data is available for most countries of the world, but these may need to be balanced against the size of the UVEK database, as well as the long-lasting maintenance efforts and the user needs.

For the first time, this update provides both production as well as supply mixes for the aggregated regions. As some have trade to outside countries (no matter how small in scale this is), there will be

some differences in composition and hence also LCIA scores. For the case of ENTSO-E, for example, this might include trade with Turkey, Morocco or Russia (with the latter having ceased recently).

Furthermore, in the mixes, the Swiss supply or production mix is connected in order to avoid double-counting or not counting for some types of power generation. That is slightly inconsistent with the rest of the database, where the Swiss mix continues to follow the established approach, which has for historical reasons a different approach. At the ENTSO-E, European, or Global scale, however, the power generation contribution of Switzerland and its power consumption is so small, the influence of that inconsistency can be considered negligible (in the range of 2-3% contribution in Europe).

## Losses

The calculation of losses follows the established procedure (e.g. as written in [2]), but using updated generation and total loss data. The losses at the individual voltage levels, however, remain the same as before, especially in light of the fact that the subdivision of voltage levels in the UVEK database is somewhat arbitrary, that generation and feeding into the grid may take place at various voltage levels, and that modern grids may also include direct current (DC) voltage transmission, which was not foreseen in the original alternating current (AC) design of voltage levels. Finding a more appropriate representation of real-world conditions and balancing it with LCA user needs will be a task for future work.

Several geographies report unusually high electricity transmission and distribution losses exceeding 10% of the domestic electricity supply, whereas most other countries report losses well below 10%. Examples for that are e.g. Nigeria (18%), Pakistan (18%), Estonia 14.68%, India 19%, Argentina (24%) Egypt (29%), Ethiopia (36%) Morocco (22%) and several other geographies. Such losses may stem from electricity theft, which – in the logic of the UVEK datasets – represent also a type of electricity consumption. No detailed statistics were found related to this issue, but in order to avoid exceptionally high influences of electricity theft, a loss cut-off was set at 10% of the total domestic electricity supply, implying that the remainder is undocumented electricity consumption. Setting a 10% cut-off for electricity grid losses is reasonable because it distinguishes unavoidable technical losses from avoidable, non-technical losses such as theft and metering errors that should not be socialized through tariffs. As in most distribution systems, well-maintained technical losses - stemming from conductor resistance, transformer magnetization, and network topology - typically fall within a mid-single to high-single-digit range, a 10% cut-off serves as upper bound that allows for challenging geographies, aging assets, and peak-load conditions without embedding inefficiency.

## Detailed calculation procedure

This is the procedure implemented in the main R script (UVEK\_electricity\_mix\_script) and the related files:

1. Clean R environment
2. Install and load required R packages
3. Set directory
4. Leave year as it is (2022 is preset, but 2021, 2022, 2023 and 2021-2023 will be calculated anyway)
5. Load input data
6. Load technology split factor data
7. Load trade split factor data

8. Load transmission loss split factor data
9. Load matching tables (all data sources to intermediate format)
10. Load classification data
11. Load all relevant electricity geography regions
12. Load geography regions that should be excluded
13. Load relevant dataset names
14. Load list of names for intermediate data storage
15. Calculate internal net to gross losses of OECD thermal plants
16. Adjust OECD thermal plants losses to a minimum of 3%
17. Extract gross production volume data and fill it into intermediate format by converting it to net generation data
18. Extract pumped hydro power generation data and fill it into intermediate format by converting it to net generation data
19. Extract detailed OECD electricity import data and fill it into intermediate format where data gaps remain
20. Extract detailed OECD electricity export data and fill it into intermediate format where data gaps remain
21. Add non-OECD trade data for data gaps
22. Extract net generation data from EIA
23. Calculate full detail net generation data per year by combining all available data
24. Calculate losses and electricity consumption on all voltage levels per region as part of a multi-step process:
  - a. Calculate total net electricity generation
  - b. Calculate total electricity imports (with data)
  - c. Retrieve total electricity exports (from previous step)
  - d. Retrieve total losses
  - e. Calculate total net electricity consumption (as sum of the above)
  - f. Calculate high voltage (HV) net generation
  - g. Set medium voltage (MV) net generation to zero
  - h. Set low voltage (LV) net generation to zero
  - i. Calculate HV consumption from total consumption (based on [2])
  - j. Calculate MV consumption from total consumption (based on [2])
  - k. Calculate LV consumption from total consumption (based on [2])
  - l. Calculate HV transmission and transformation losses from total losses (based on [2])
  - m. Calculate HV-MV transformation losses from total losses (based on [2])
  - n. Calculate MV transmission losses from total losses (based on [2])
  - o. Calculate MV-LV transformation losses from total losses (based on [2])
  - p. Calculate LV transmission losses from total losses (based on [2])
  - q. Calculate HV production volume as HV generation plus imports minus exports minus HV losses
  - r. Calculate HV-MV transformation production volume as input from HV minus HV-MV transformation losses
  - s. Calculate MV production volume as input from HV-MV transformation after losses plus MV generation minus MV losses
  - t. Calculate MV-LV transformation production volume as input from MV minus MV-LV transformation losses
  - u. Calculate LV production volume as input from MV-LV transformation after losses plus LV generation minus LV losses
  - v. Calculate HV loss ratio as losses divided by production volume
  - w. Calculate HV-MV loss ratio as losses divided by production volume
  - x. Calculate MV loss ratio as losses divided by production volume

- y. Calculate MV-LV loss ratio as losses divided by production volume
- z. Calculate LV loss ratio as losses divided by production volume
- 25. Calculate distance between geographies
- 26. Fill available technologies for each region
- 27. Fill technologies as proxies based on the nearest available data in case of gaps
- 28. Add specific biomass power generation technologies for Switzerland as exception
- 29. Define uncertainty calculation function
- 30. Calculate trade data for the EU based on hourly statistics (aggregating 15 or 30 minute values to hourly values and scaling values to match national totals calculated in step 23)
- 31. Setup of final production mixes calculation and export function
- 32. Setup of final supply mixes calculation and export function (including trade datasets)
- 33. Setup of pumped hydropower calculation and export function
- 34. Run calculation and export functions to store the final results (as spold files)

### Intermediate data structures

The primary outputs include several structured data frames:

- “bpv”: A matrix containing annual or multi-year technology-specific electricity generation values per region.
- “tpil”: Internal losses for thermal power plants.
- “tv”: Electricity trade matrices indicating annual flows between importing and exporting countries.
- “bpv\_eia”: Alternative production volumes derived solely from EIA data.
- “bpv\_final”: Merged production volumes for final output (mainly from EIA data).

These data structures are used iteratively to update mixes and support uncertainty handling and technology assignment in subsequent scripts.

### Resulting spold files

The main deliverables are country-specific electricity production and supply mixes for the selected years (2021, 2022, 2023, 2021-2023). These outputs are exported in tabular form and as embedded XML strings suitable for integration into ecoinvent or other life cycle inventory system of UVEK, the UVEK database [10]. Each output spold file reflects harmonized naming conventions and includes documentation of assumptions, conversions and loss treatments. These files exceed 700 per year (with the exact number depending on the trade flow in the respective year as trade flows are covered by their own datasets). As data was generated for 2021, 2022, 2023 and 2021-2023, this amounts to more than 2800 ecospold files in total.

### Execution guide

To run the scripts:

- Install R<sup>2</sup>, a Perl environment such as “Strawberry Perl”<sup>3</sup> (under Windows) and potentially an R UI such as RStudio<sup>4</sup>
- Download raw electricity input data from the respective data sources
- Add the input files in the “input” subfolders with required data
- Make changes to technology/ trade split factors and the technology mapping (optional)
- Open the main script (“UVEK\_electricity\_mix\_script\_vx.xx.R”) in an R environment (e.g. RStudio)
- Adjust the working directory and year variable as needed in the main script.
- Run the main script or execute the source() calls in sequence.
- Import the ecospold results stored in the “Output” directory.

## Results and discussion

The results are a large number of ecospold datasets, which are created for all the different geographies covered by this update. The structure of these files is adapted from the earlier version of these files in the UVEK database, updating the documentation including the reviewer information. A notable change includes the creation of unique IDs (UUIDs) per dataset that are added to the main documentation field (“generalComment”).

The production mixes show a typical picture of electricity generation globally, with coal (mostly hard coal) still being a dominant fuel in the global economy (**figure 4**). In contrast to the earlier version of the UVEK database, which dates back more than a decade, however, the contributions of renewable energy, namely wind and solar have increased substantially, especially owing to the decline in levelized costs of electricity for these types of power generation. This is well in line with the general trends that are observed in the raw data as well as numerous other global data sources [5, 13, 14]. Regarded in many places as a “transition fuel” and being more abundantly available from the fracking in the US, natural gas also plays a major role. In that regard, it has to be kept in mind, that the consequences of the conflict between Russia and Ukraine are creating a dynamic situation that is still evolving at the time of calculation, meaning that the mixes do not represent a fully stable result in that regard. Furthermore, consequences of Covid, economic patterns and also environmental conditions (such as especially sunny, rainy or windy years) can heavily impact the composition of fuels dramatically in a country and may make the use of a more stable long-term electricity mix recommendable.

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<sup>2</sup> <https://www.r-project.org/>

<sup>3</sup> <https://strawberryperl.com/>

<sup>4</sup> <https://posit.co/download/rstudio-desktop/>

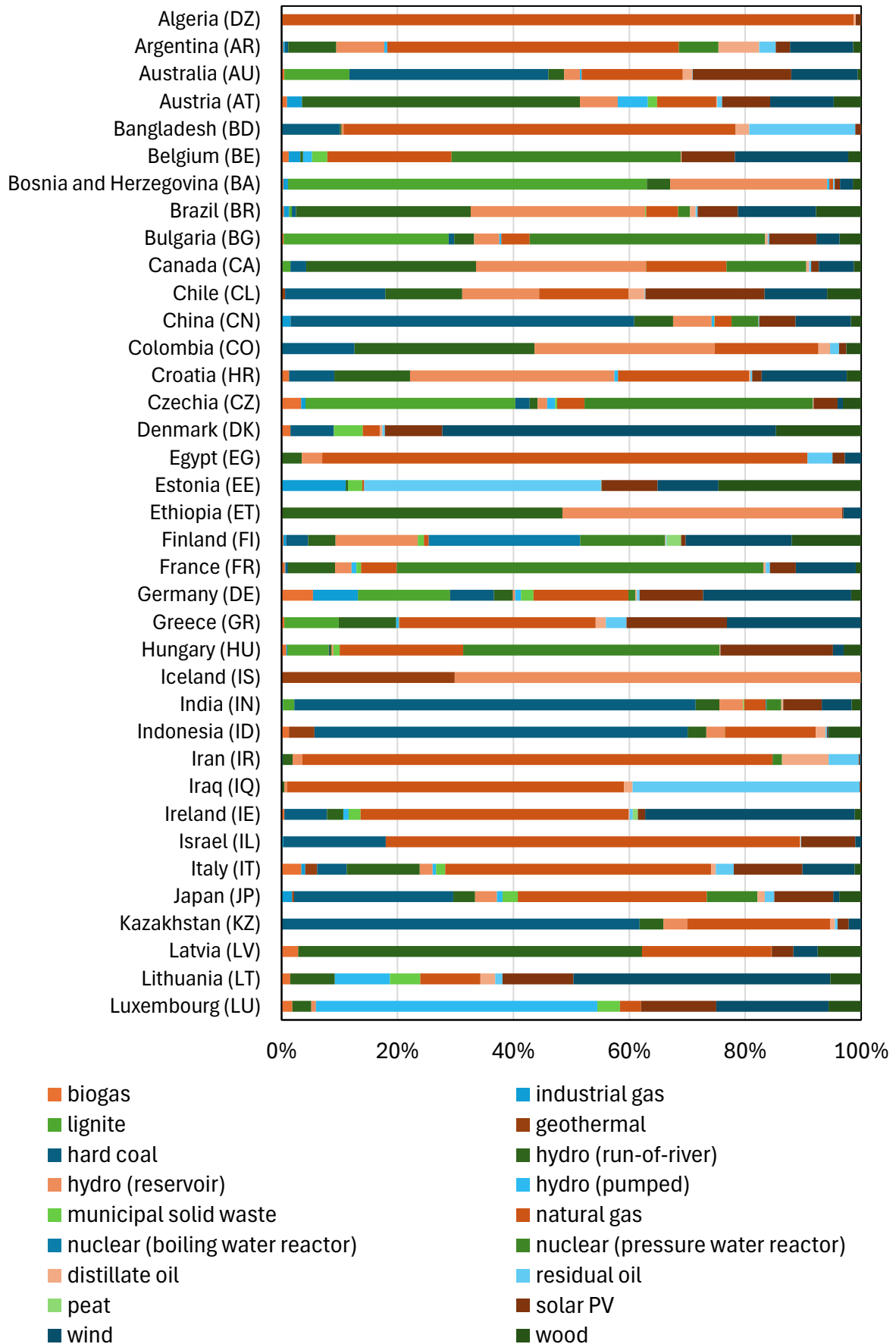
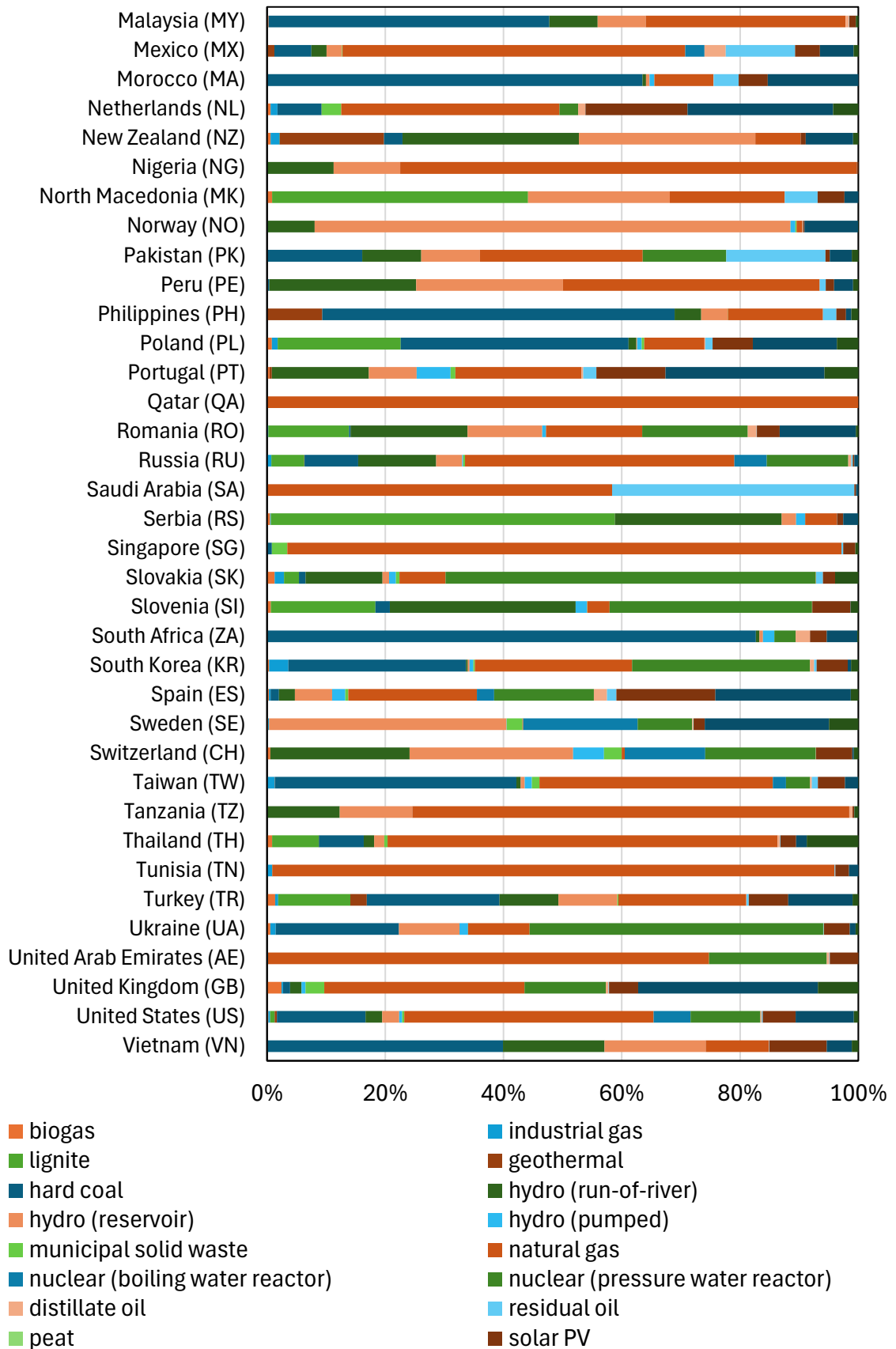


Figure 4: Production mixes calculated for the UVEK database for the year 2023.



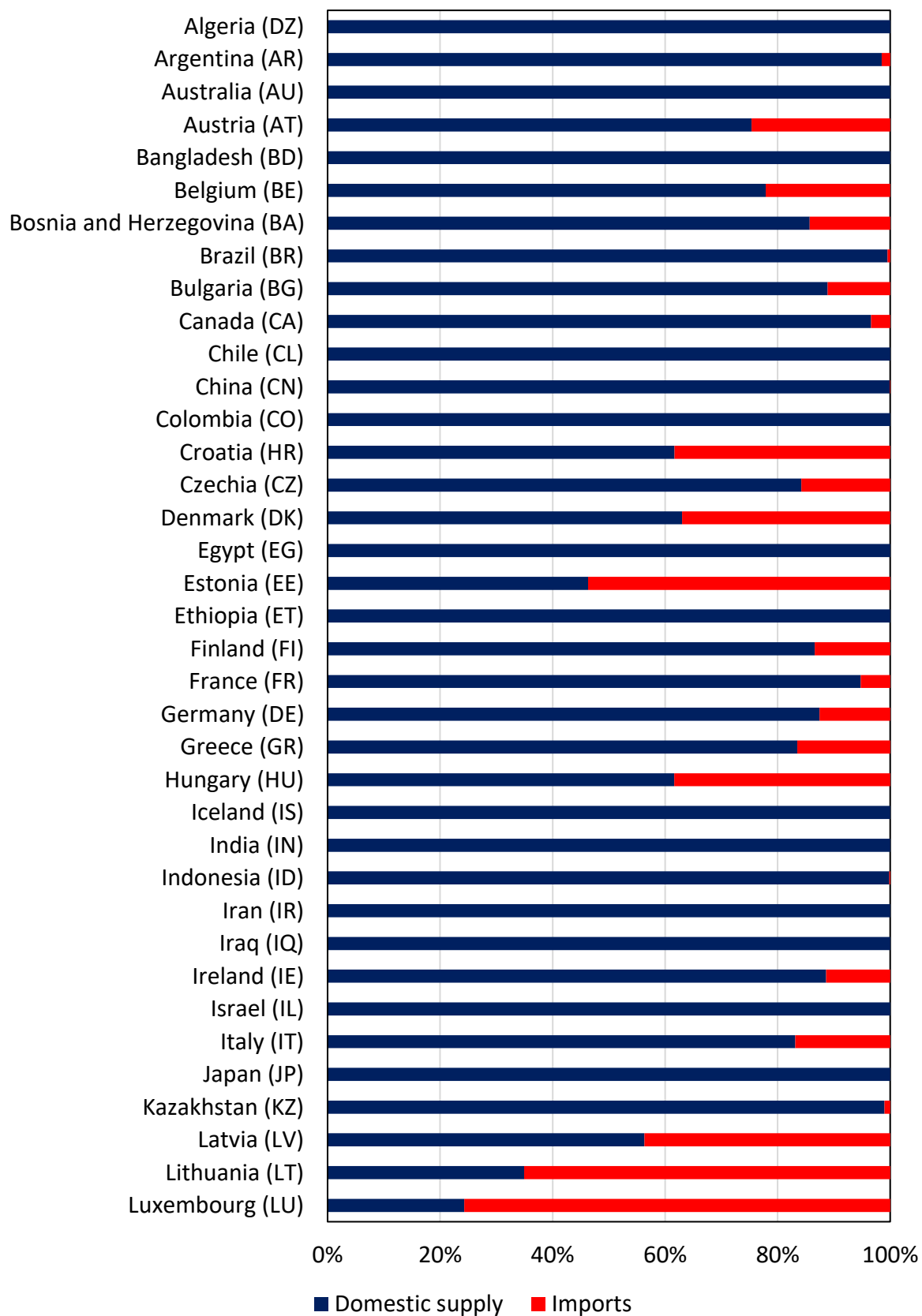
**Figure 4 (continued):** Production mixes calculated for the UVEK database for the year 2023.

In terms of electricity trade, which heavily influences certain supply mixes, there is also a varied pattern in line with published data elsewhere. Certain (especially small) countries are subject to major shares of imports (such as LU) with limited domestic production. Even Switzerland (CH), being a larger, but globally still relatively small country, receives a major share of its electricity from abroad. Besides stabilizing domestic supply and demand, this may in a larger part be for sale to Italy, but in part also for storage with pumped hydro power plants (at low costs) and later sale in times of electricity shortage (at higher prices). It is important to keep in mind, however, that the contributions of trade in the UVEK mixes can only cover the part where the producing countries are also modeled in the UVEK database. Where countries are missing, all other contributors are scaled up to not leave a gap, but the total composition can only reflect the real situation incompletely.

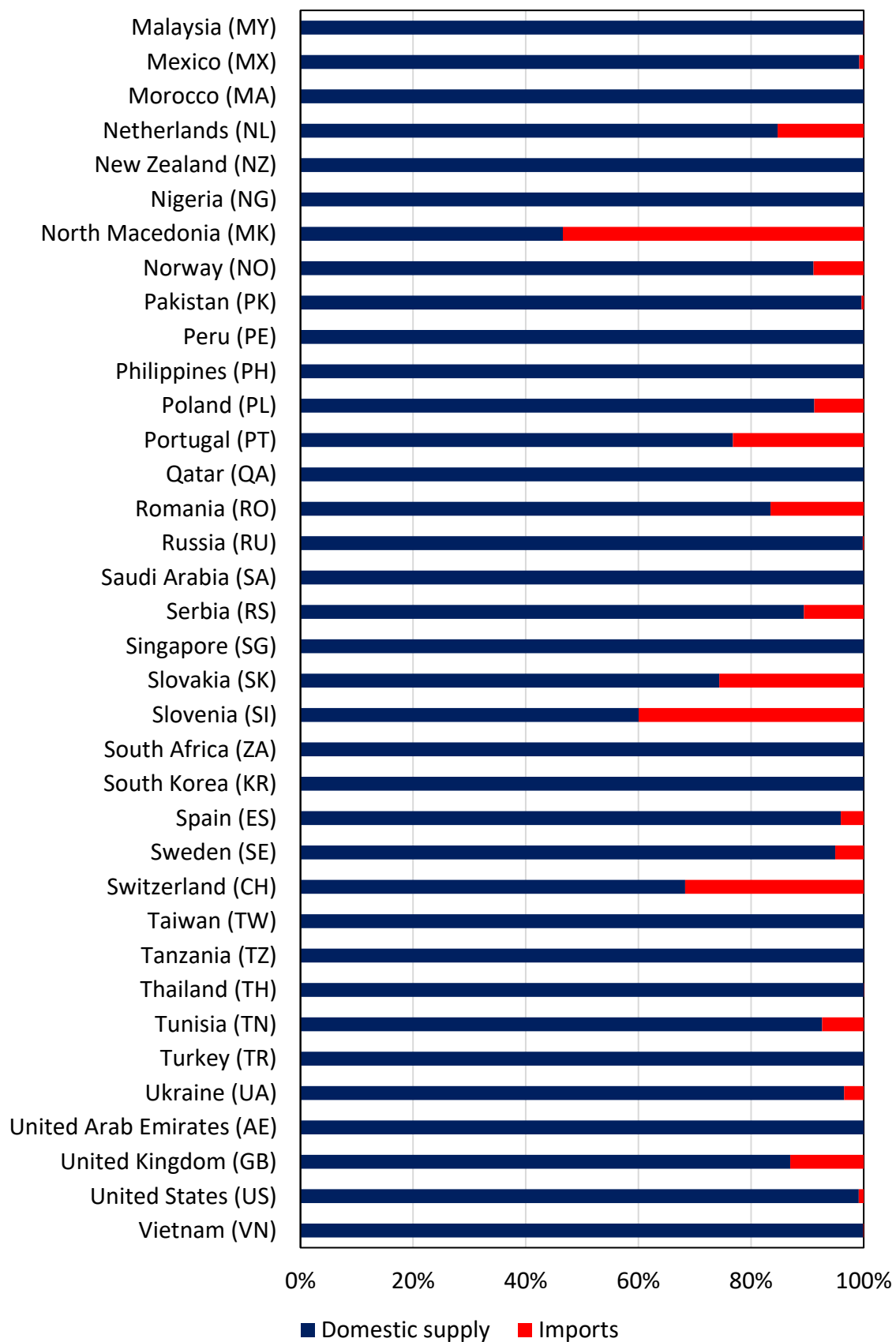
Also, the trade patterns are subject to changes in economic conditions in comparison to earlier UVEK data. The COVID-19 pandemic introduced an unprecedented short-term reduction in global electricity demand during 2020, especially in industrial and commercial sectors. Lockdowns and economic contraction led to lower fossil fuel-based generation, while the share of renewables in some countries temporarily increased due to their lower marginal operating costs and grid priority. However, investment delays and supply chain disruptions for renewable projects also temporarily hindered longer-term energy transitions. From an LCA standpoint, this temporary rebalancing altered the emission intensity of electricity mixes, requiring careful year-on-year tracking. Especially a surplus of cheap renewable electricity that is not needed domestically is likely to be reflected in increased export volumes, which can then change the supply mix composition.

The Russia-Ukraine conflict beginning in 2022 profoundly disrupted European and Eurasian electricity and energy trade. The curtailment of Russian gas exports forced many European nations to accelerate diversification strategies, including increased imports of LNG, reactivation of coal-fired plants, and rapid scaling of renewables. Cross-border electricity flows within Europe also shifted to accommodate altered supply-demand balances, with some countries becoming temporary exporters due to domestic generation advantages. These shifts require high temporal and spatial resolution in electricity modeling to capture transition-related impacts and geopolitical dependencies, and may not be considered a long-term stable result, but rather a short-lived LCI snapshot in time.

And finally, the global financial crisis with a toppling demand for various products around the world, a mismatch between expectations for the manufacturing demands, and an unprecedented overcapacity for various kinds of industrial goods resulted in a sharp downturn in electricity demand across many industrialized economies. Capital investment in new generation capacity slowed, and some planned renewable and nuclear projects were delayed or cancelled. At the same time, the crisis shifted government priorities, in some cases reinforcing subsidies as a form of economic stimulus. As a result, electricity generation and trade patterns may be distorted, including the long-term effects of an uneven recovery in low-carbon infrastructure deployment and a prolonged dependence on existing, often carbon-intensive, generation assets.

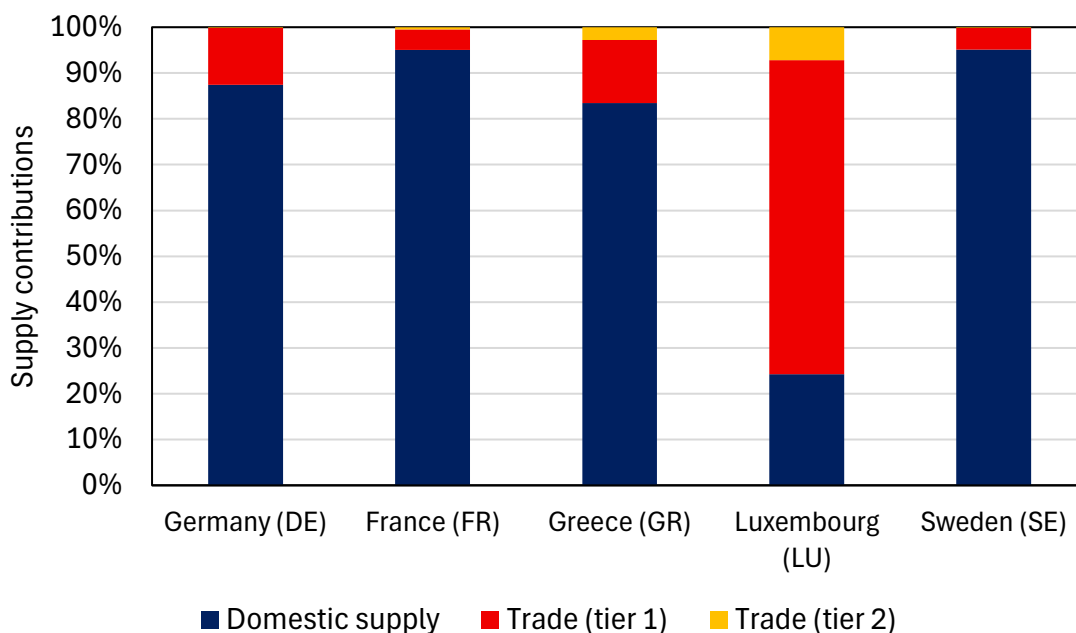


**Figure 5:** Supply mixes calculated for the UVEK database highlighting the contributions of domestic generation and import for 2023.



**Figure 5 (continued):** Supply mixes calculated for the UVEK database highlighting the contributions of domestic generation and import for 2023.

Generally, the electricity supply contributions in the more detailed electricity trade model in Europe still put strong emphasis on the immediate cross-border trade partners (**figure 6**). Even in extreme cases such as Luxembourg, where trade is the dominating source of electricity, the direct electricity makes up the clearly largest share. Hence, a meaningful representation of the direct trade partners appears to be of the highest priority, while indirect trade can play a role (e.g. when domestic supply and direct trade are largely decarbonized), but is less likely to do so.



**Figure 6:** Supply mix contributions from domestic supply in 2023 in contrast to direct electricity trade (tier 1) and indirect electricity trade (tier 2) for a few European example countries.

Preliminary LCIA results for the electricity supply mixes (as a meaningful subset of the total amount of newly created data to compare) is shown in **figures 7 and 8** for greenhouse gas emissions (IPCC GP 100a 2013) and Umweltbelastungspunkte (Ecoscarcity 2021) per kWh electricity, respectively.

Overall, the update shows clear decarbonization in comparison to the older UVEK data, exceeding some influences of the methodology. Thus, compared with the older values, most countries' climate footprints drop noticeably, especially across Europe and parts of the Americas. That pattern reflects coal retirements, more wind and solar, and cleaner gas replacing older plants, along with tighter air-pollution controls. A handful of places still look more polluting, largely where coal or oil remain central to the grid, but the scores overall have shifted downward noticeably. This matches the expectations, considering the trends in power generation deployment in these regions, but may also be influenced to some extent by the economic slowdown in these regions in recent years, destocking of manufactured goods from the COVID times, that mutes economic activities further, and the unavailability of cheap Russian natural gas in Russia, that put energy conservation measures higher up on the agenda of industries, consumers and politicians alike.

A few increases appear in already very low-carbon systems. Places dominated by hydro or geothermal edge up a little in the new dataset, not necessarily because their grids got dirtier, but

because the accounting got more sophisticated. Newer upstream data for hydropower, better splits for oil-based power generation and the overhauled trade model tend to add to impacts that earlier versions of the UVEK database treated as near-zero. In short, big drops are visible where the mix truly changed, small rises can be observed where the method has sharpened.

Eco-scarcity (UBP) and GWP usually move together (Pearson correlation coefficient  $R > 0.8$ ), but they do not tell the same story. Nuclear-heavy countries such as France come out with very low GWP yet only middling UBP, because UBP penalises non-climate burdens like uranium mining, enrichment and radioactive waste. Hydro- and wind-rich systems often score well on both (e.g. Brazil), while gas-leaning systems land in the middle on each (e.g. USA). It is also possible to see cases with moderate GWP but relatively low UBP where hydro and wind dominate and non-climate emissions are modest.

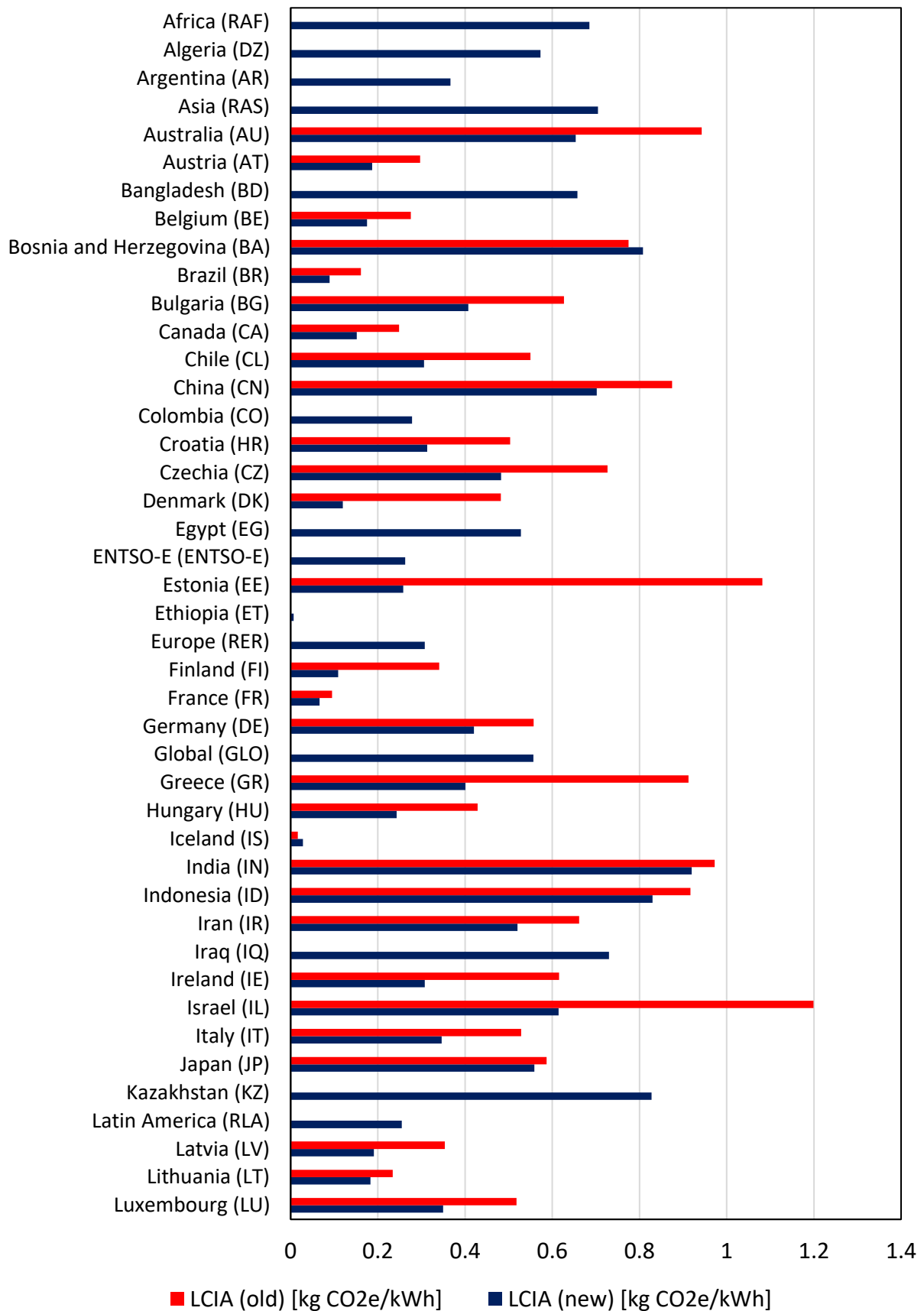
Taken together, the results look plausible. They align with well-known grid transitions over the last decade and with what would be expected when switching from coal to gas and renewables, and when refreshing life-cycle databases. The UBP method is intentionally broader and Swiss-weighted, so it will diverge from pure climate rankings in ways that make sense - especially for nuclear or resource-intensive supply chains.

Particularly strong database-wide effects could be expected from a somewhat improving environmental impact scores of the Chinese electricity mix, which is behind the consumption many types of manufactured goods that are consumed all around the world. Taking into account the high carbon footprint and UBP score of the previous datasets, however, these major improvements stay at a comparably high level, leaving much future room for environmental improvements.

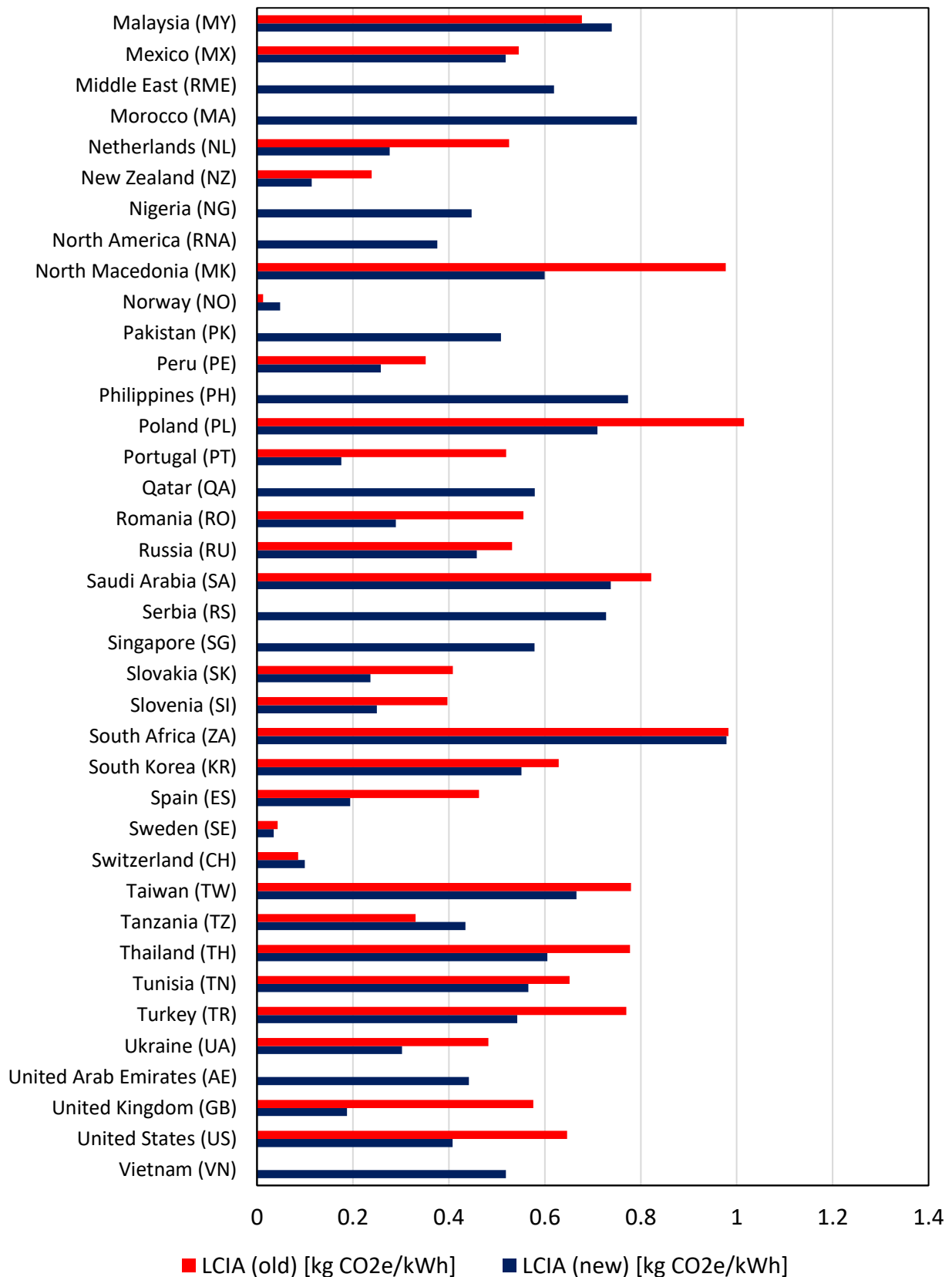
In direct comparison, some other major global countries such as the US have already reached substantially lower environmental impacts per kWh of electricity (driven in parts by the shale gas revolution and the phase-out of coal power in favor of cheap and abundant natural gas), but here, it is questionable to which extent the UVEK database with its strong focus on the European datasets is able to capture the full coverage of the emissions in the upstream supply chain.

Moreover, in comparison to some other data sources for carbon footprints, the UVEK scores remain on the higher end. In part, this is due to the more rigorous accounting for electricity trade, but potentially also a lack of combined heat and power datasets (that would exhibit lower carbon footprints per kWh of electricity generated), as well as the inclusion of upstream emissions, which are not always considered in other data sources.

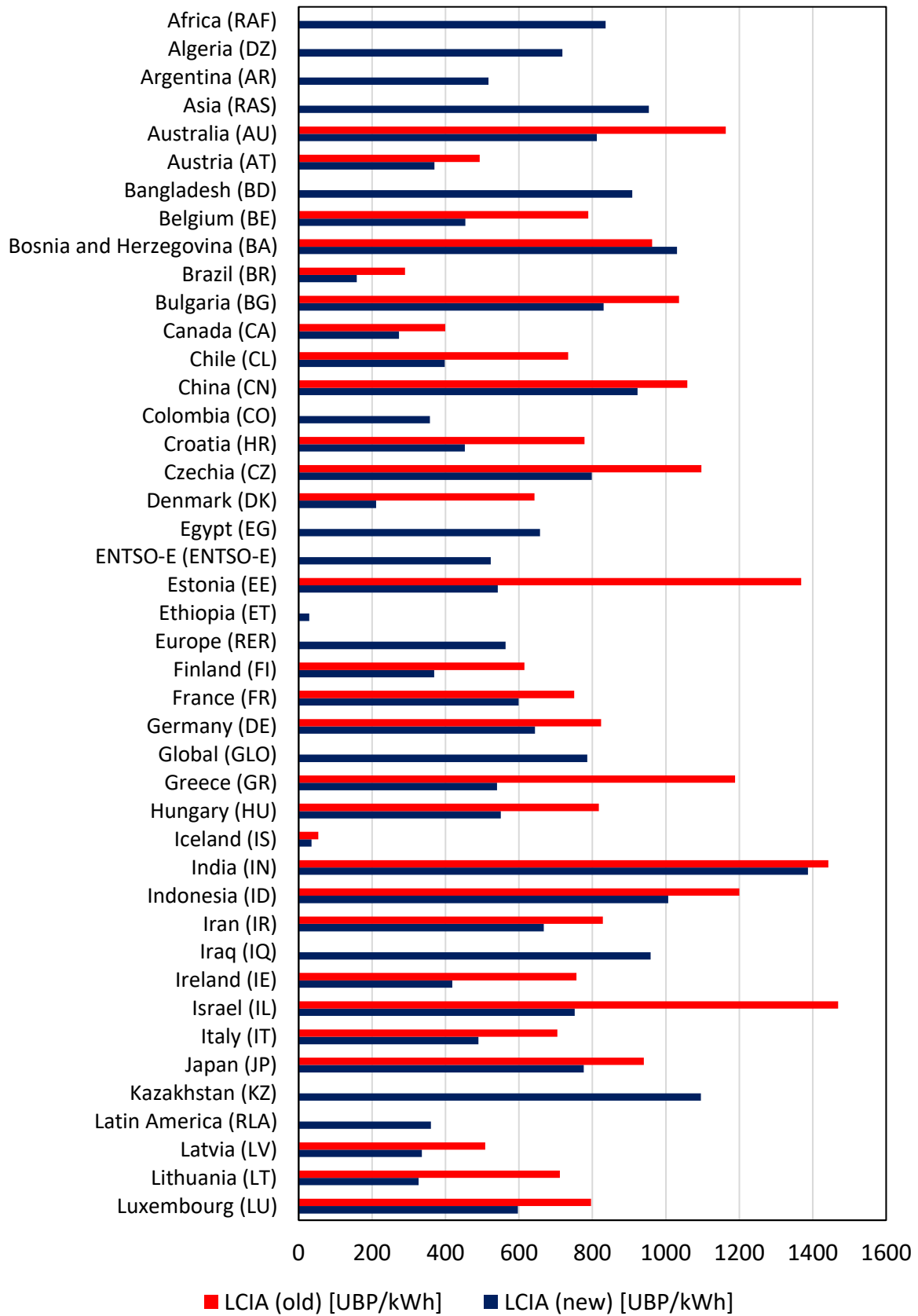
Taking these explainable differences into account, the results appear plausible, even at the lower voltage levels where the losses scale the total LCIA scores further up (not visualized in this report).



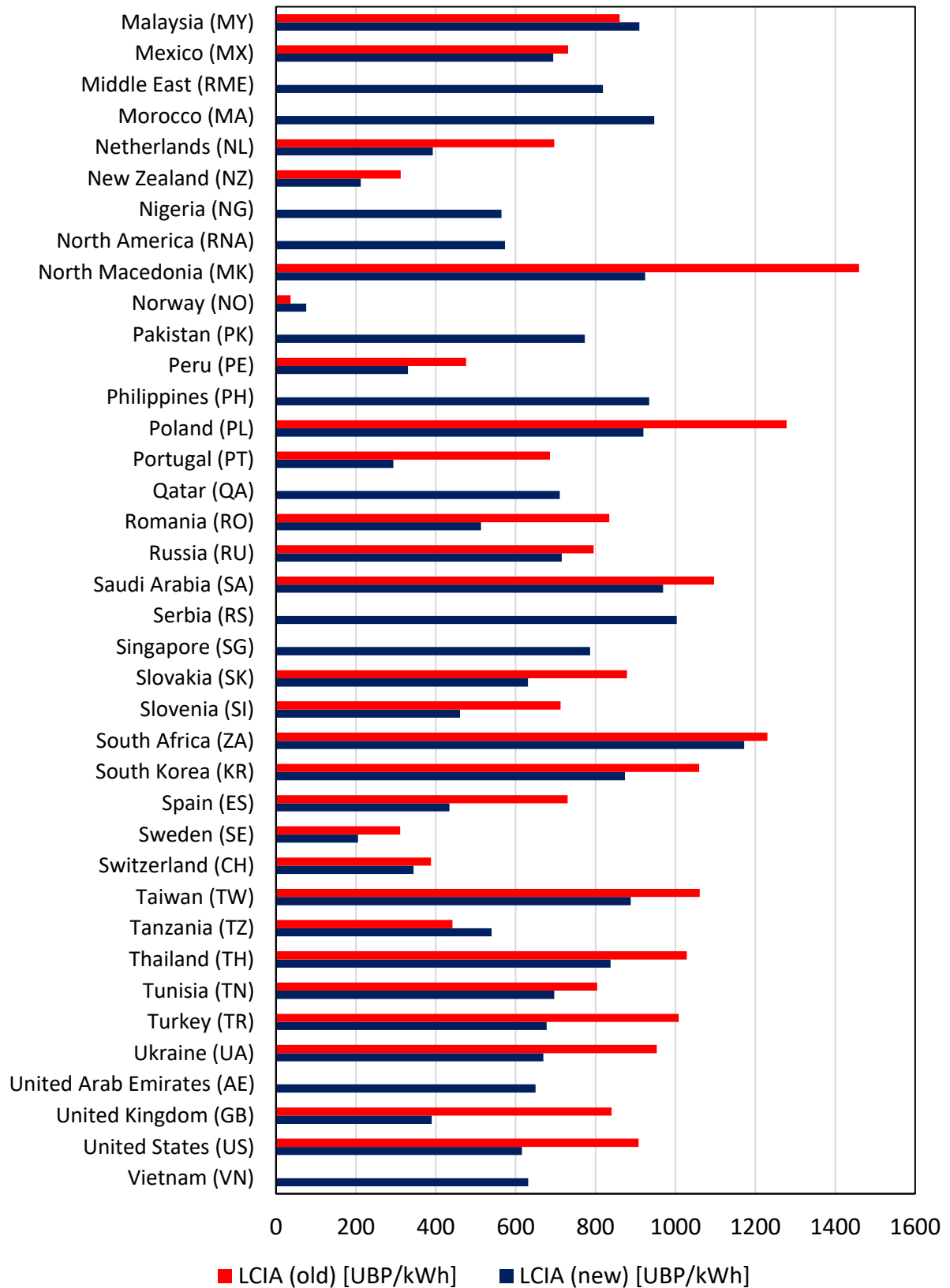
**Figure 7:** Comparison of supply mix carbon footprints per kWh electricity in the old version of the UVEK database (red) vs. the newly created datasets (blue) as calculated with IPCC 2013 GWP 100a.



**Figure 7 (continued):** Comparison of supply mix carbon footprints per kWh electricity in the old version of the UVEK database (red) vs. the newly created datasets (blue) as calculated with IPCC 2013 GWP 100a.



**Figure 8:** Comparison of supply mix ecoscarcity scores per kWh electricity in the old version of the UVEK database (red) vs. the newly created datasets (blue) as calculated with Ecological scarcity 2021.



**Figure 8 (continued):** Comparison of supply mix ecoscarcity scores per kWh electricity in the old version of the UVEK database (red) vs. the newly created datasets (blue) as calculated with Ecological scarcity 2021.

## Conclusions and outlook

The implementation of this systematic, data-driven approach to calculating national electricity mixes has enhanced the quality, transparency, and representativeness of life cycle inventories within the UVEK database. By harmonizing and merging multiple international datasets including EIA, IEA, ENTSO-E and COMTRADE and applying transparent mapping, loss correction, and uncertainty classification approaches, the resulting electricity mixes are more consistent with actual regional generation and trade patterns. This has significantly reduced the reliance on generic assumptions, which will in consequence hopefully lead to improving the environmental relevance and methodological robustness of electricity-related background data in a broad range of national and international LCA studies.

Despite these improvements, there remain areas where the current approach could be further strengthened. Key points, as in part identified and listed in this report before, include:

- Temporally highly resolved trade data has only been used for ENTSO-E countries, leaving several similar data sources globally unused.
- Electricity generation data has a broad range of gaps, including in terms of regional coverage (e.g. Asia, Middle East, South America, Africa), technology coverage (e.g. novel types of renewable power generation or battery storage), or distinction between CHP and non-CHP plants for all thermal plants as common in other LCI databases [4].
- Integration of more comprehensive temporal data especially for Switzerland, e.g. by filtering, classifying or modifying Pronovo [12] data.
- Completion of regional coverage in order to not neglect relevant contributors to regional mixes or trade.
- Making use of COMTRADE electricity trade data in a more robust way, especially when scaling this approach globally, in order to filter unrealistic data.
- Add meaningful estimates for currently non-reporting countries in terms of electricity trade, e.g. when they are not following international reporting schemes or are subject to trade embargos.
- Update the electricity mix structure (e.g. in terms of voltage levels) to better represent reality and/or increase usefulness for database users.
- Perform a comprehensive uncertainty analysis, especially for arbitrary modeling choices, e.g. when needing to decide whether to add the UK to ENTSO-E because of Northern Ireland or not.
- Updating default technology assumptions (such as 50:50 split for different types of hydro power).
- Updating the cut-off assumption of 10% for power losses due to transmission and distribution.
- Developing clean market-based electricity mixes to complement these location-based electricity mixes (in line with GHG protocol recommendations [21]).
- Waste heat generated by the various datasets were not updated as this was outside the scope of the current project and should be included in any future update.
- Despite the strength of the proximity-based technology mapping and the very good examples that exist (e.g. photovoltaic power in Vietnam is approximated with the dataset

“Electricity, production mix photovoltaic, at plant {TH}”), there are many gaps of supplying technologies and it would be good, to have at least one representative dataset per continent, which is currently not always the case.

Coverage gaps persist in certain countries and regions where reliable or granular data are unavailable or inconsistent, limiting the completeness of the global electricity model. Similarly, temporal averaging, while practical, may obscure important short-term dynamics and lead to the smoothing of critical trends, such as the uptake of intermittent renewables or the impacts of policy shocks.

To enhance future iterations, expanding the integration of new data sources could offer valuable granularity. Greater regional differentiation of production technologies would also improve representativeness. Additionally, the inclusion of more precise techno-economic and operational characteristics, such as capacity factors, grid congestion, curtailment, short-term energy storage and the share of carbon capture and storage (CCS) within highly emitting technologies, would allow the construction of LCIs that are not only geographically specific but also functionally nuanced and future-proof. These enhancements would help align the UVEK electricity data even more closely with the real-world performance of national grids, further supporting high-quality, policy-relevant LCA.

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## Appendix

**Table A1:** Regional coverage.

Geography in UVEK database
Algeria (DZ)
Argentina (AR)
Australia (AU)
Austria (AT)
Bangladesh (BD)
Belgium (BE)
Bosnia and Herzegovina (BA)
Brazil (BR)
Bulgaria (BG)
Canada (CA)
Chile (CL)
China (CN)
Colombia (CO)
Croatia (HR)
Czechia (CZ)
Denmark (DK)
Egypt (EG)
Estonia (EE)
Ethiopia (ET)
Finland (FI)
France (FR)
Germany (DE)
Greece (GR)
Hungary (HU)
Iceland (IS)
India (IN)
Indonesia (ID)
Iran (IR)
Iraq (IQ)
Ireland (IE)
Israel (IL)
Italy (IT)
Japan (JP)
Kazakhstan (KZ)
Latvia (LV)
Lithuania (LT)
Luxembourg (LU)
Malaysia (MY)
Mexico (MX)
Morocco (MA)
Netherlands (NL)

New Zealand (NZ)
Nigeria (NG)
North Macedonia (MK)
Norway (NO)
Pakistan (PK)
Peru (PE)
Philippines (PH)
Poland (PL)
Portugal (PT)
Qatar (QA)
Romania (RO)
Russia (RU)
Saudi Arabia (SA)
Serbia (RS)
Singapore (SG)
Slovakia (SK)
Slovenia (SI)
South Africa (ZA)
South Korea (KR)
Spain (ES)
Sweden (SE)
Switzerland (CH)
Taiwan (TW)
Tanzania (TZ)
Thailand (TH)
Tunisia (TN)
Turkey (TR)
Ukraine (UA)
United Arab Emirates (AE)
United Kingdom (GB)
United States (US)
Vietnam (VN)
ENTSO-E (ENTSO-E)
Africa (RAF)
Asia (RAS)
Europe (RER)
Latin America (RLA)
Middle East (RME)
North America (RNA)
Global (GLO)

**Table A2:** Regional grouping.

Region	Country
Africa (RAF)	Angola (AO)
Africa (RAF)	Benin (BJ)

Africa (RAF)	Botswana (BW)
Africa (RAF)	Democratic Republic of the Congo (CD)
Africa (RAF)	Republic of the Congo (CG)
Africa (RAF)	Ivory Coast (CI)
Africa (RAF)	Cameroon (CM)
Africa (RAF)	Algeria (DZ)
Africa (RAF)	Egypt (EG)
Africa (RAF)	Eritrea (ER)
Africa (RAF)	Ethiopia (ET)
Africa (RAF)	Gabon (GA)
Africa (RAF)	Ghana (GH)
Africa (RAF)	Kenya (KE)
Africa (RAF)	Libya (LY)
Africa (RAF)	Morocco (MA)
Africa (RAF)	Mauritius (MU)
Africa (RAF)	Mozambique (MZ)
Africa (RAF)	Namibia (NA)
Africa (RAF)	Niger (NE)
Africa (RAF)	Nigeria (NG)
Africa (RAF)	Sudan (SD)
Africa (RAF)	Senegal (SN)
Africa (RAF)	South Sudan (SS)
Africa (RAF)	Togo (TG)
Africa (RAF)	Tunisia (TN)
Africa (RAF)	Tanzania (TZ)
Africa (RAF)	South Africa (ZA)
Africa (RAF)	Zambia (ZM)
Africa (RAF)	Zimbabwe (ZW)
Asia (RAS)	Armenia (AM)
Asia (RAS)	Australia (AU)
Asia (RAS)	Azerbaijan (AZ)
Asia (RAS)	Bangladesh (BD)
Asia (RAS)	Bahrain (BH)
Asia (RAS)	Brunei (BN)
Asia (RAS)	China (CN)
Asia (RAS)	Georgia (GE)
Asia (RAS)	Hong Kong (HK)
Asia (RAS)	Indonesia (ID)
Asia (RAS)	Israel (IL)
Asia (RAS)	India (IN)
Asia (RAS)	Jordan (JO)
Asia (RAS)	Japan (JP)
Asia (RAS)	Kyrgyzstan (KG)
Asia (RAS)	Cambodia (KH)
Asia (RAS)	North Korea (KP)

Asia (RAS)	South Korea (KR)
Asia (RAS)	Kazakhstan (KZ)
Asia (RAS)	Lebanon (LB)
Asia (RAS)	Sri Lanka (LK)
Asia (RAS)	Myanmar (MM)
Asia (RAS)	Mongolia (MN)
Asia (RAS)	Malaysia (MY)
Asia (RAS)	Nepal (NP)
Asia (RAS)	New Zealand (NZ)
Asia (RAS)	Oman (OM)
Asia (RAS)	Philippines (PH)
Asia (RAS)	Pakistan (PK)
Asia (RAS)	Qatar (QA)
Asia (RAS)	Singapore (SG)
Asia (RAS)	Syria (SY)
Asia (RAS)	Thailand (TH)
Asia (RAS)	Tajikistan (TJ)
Asia (RAS)	Turkmenistan (TM)
Asia (RAS)	Turkey (TR)
Asia (RAS)	Taiwan (TW)
Asia (RAS)	Uzbekistan (UZ)
Asia (RAS)	Vietnam (VN)
Asia (RAS)	Yemen (YE)
Europe (RER)	Austria (AT)
Europe (RER)	Bosnia and Herzegovina (BA)
Europe (RER)	Belgium (BE)
Europe (RER)	Bulgaria (BG)
Europe (RER)	Belarus (BY)
Europe (RER)	Switzerland (CH)
Europe (RER)	Czechia (CZ)
Europe (RER)	Germany (DE)
Europe (RER)	Denmark (DK)
Europe (RER)	Estonia (EE)
Europe (RER)	Spain (ES)
Europe (RER)	Finland (FI)
Europe (RER)	France (FR)
Europe (RER)	United Kingdom (GB)
Europe (RER)	Gibraltar (GI)
Europe (RER)	Greece (GR)
Europe (RER)	Croatia (HR)
Europe (RER)	Hungary (HU)
Europe (RER)	Ireland (IE)
Europe (RER)	Iceland (IS)
Europe (RER)	Italy (IT)
Europe (RER)	Lithuania (LT)

Europe (RER)	Luxembourg (LU)
Europe (RER)	Latvia (LV)
Europe (RER)	Moldova (MD)
Europe (RER)	North Macedonia (MK)
Europe (RER)	Malta (MT)
Europe (RER)	Netherlands (NL)
Europe (RER)	Norway (NO)
Europe (RER)	Poland (PL)
Europe (RER)	Portugal (PT)
Europe (RER)	Romania (RO)
Europe (RER)	Serbia (RS)
Europe (RER)	Russia (RU)
Europe (RER)	Sweden (SE)
Europe (RER)	Slovenia (SI)
Europe (RER)	Slovakia (SK)
Europe (RER)	Ukraine (UA)
Europe (RER)	Kosovo (XK)
Latin America (RLA)	Argentina (AR)
Latin America (RLA)	Bolivia (BO)
Latin America (RLA)	Brazil (BR)
Latin America (RLA)	Chile (CL)
Latin America (RLA)	Colombia (CO)
Latin America (RLA)	Costa Rica (CR)
Latin America (RLA)	Cuba (CU)
Latin America (RLA)	Curacao (CW)
Latin America (RLA)	Dominican Republic (DO)
Latin America (RLA)	Ecuador (EC)
Latin America (RLA)	Guatemala (GT)
Latin America (RLA)	Honduras (HN)
Latin America (RLA)	Haiti (HT)
Latin America (RLA)	Jamaica (JM)
Latin America (RLA)	Mexico (MX)
Latin America (RLA)	Nicaragua (NI)
Latin America (RLA)	Panama (PA)
Latin America (RLA)	Peru (PE)
Latin America (RLA)	Paraguay (PY)
Latin America (RLA)	El Salvador (SV)
Latin America (RLA)	Trinidad and Tobago (TT)
Latin America (RLA)	Uruguay (UY)
Latin America (RLA)	Venezuela (VE)
Middle East (RME)	United Arab Emirates (AE)
Middle East (RME)	Iraq (IQ)
Middle East (RME)	Iran (IR)
Middle East (RME)	Kuwait (KW)
Middle East (RME)	Saudi Arabia (SA)
North America (RNA)	Canada (CA)

North America (RNA)	United States (US)
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**Table A3:** ENTSO-E geographies in the UVEK database.

ENTSO-E geography in UVEK
Austria (AT)
Belgium (BE)
Bosnia and Herzegovina (BA)
Bulgaria (BG)
Croatia (HR)
Czechia (CZ)
Denmark (DK)
Estonia (EE)
Finland (FI)
France (FR)
Germany (DE)
Greece (GR)
Hungary (HU)
Iceland (IS)
Ireland (IE)
Italy (IT)
Latvia (LV)
Lithuania (LT)
Luxembourg (LU)
Netherlands (NL)
North Macedonia (MK)
Norway (NO)
Poland (PL)
Portugal (PT)
Romania (RO)
Serbia (RS)
Slovakia (SK)
Slovenia (SI)
Spain (ES)
Sweden (SE)
Switzerland (CH)
Ukraine (UA)