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Life Cycle Assessment of GO based Electricity Mixes of European Countries 2018

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Abbreviations

AIB	Association of Issuing Bodies
a	year (annum)
CED	Cumulative energy demand
CH	Switzerland
CH_4	methane
CO_2	carbon dioxide
CO_2-eq	carbon dioxide equivalent
EAM	European attribute mix (European residual mix)
ENTSO-E	European Network of Transmission System Operators for Electricity
FOEN	Swiss Federal Office for the Environment
GO	Guarantee of Origin (deutsch: Herkunftsnachweis, HKN)
GWP	global warming potential
IEA	International Energy Agency
KBOB	Coordination Group for Construction and Property Services (German: Koordinationskonferenz der Bau- und Liegenschaftsorgane des Bundes)
kWh	Kilowatt hour
LCA	life cycle assessment
LCI	life cycle inventory analysis
MJ	Megajoule
N_2O	Nitrous Oxide
RER	Europe
SF_6	Sulfur hexafluoride
SFOE	Swiss Federal Office of Energy
UBP	eco-points (German: Umweltbelastungspunkte)
UVEK	Federal Department of the Environment, Transport, Energy and Communications (German: Eidgenössisches Departement für Umwelt, Verkehr, Energie und Kommunikation)

Summary

In this study, the life cycle inventory data of the electricity mixes of 31 European countries were compiled based on guarantee of origin (GOs) data published by the Association of Issuing Bodies (AIB 2019). The AIB publishes the composition of the electricity mixes of the individual countries on an annual basis, taking into account the traded and cancelled GOs. The annual reports on the electricity mix in individual countries, such as Austria (e-control 2019), were used to validate the statistical data published in AIB (2019). The environmental characteristics of these newly compiled electricity mixes based on GOs were compared with the environmental characteristics of the corresponding electricity mix data of the KBOB[1] life cycle assessment data DQRv2:2018 which are based on IEA statistics.

The functional unit used in the life cycle assessment of the european electricity mixes is one kilowatt hour (kWh) electricity. The life cycle assessment of the european electricity mixes includes construction, operation, dismantling and disposal of the power plants, including the production of materials required for construction, the provision of working materials and the environmental impact of operation, as well as disposal expenses, provision and disposal of fuels, including the extraction of primary energy sources (natural gas, crude oil, hard coal, uranium, wood), their refinement, as well as their conditioning and final storage, transmission and distribution to low-voltage customers, including power losses, construction expenditures, SF_6 emissions (transformers) and nitrous oxide emissions (high-voltage lines), any transport services for fuels, construction and operating materials, and waste.

The environmental impacts of the electricity mixes analysed in this study were assessed with three different impact assessment methods (ecological scarcity method 2013 according to Frischknecht and Büsser Knöpfel (2013), expressed in eco-points (UBP); cumulative energy demand (CED), which is further separated into renewable and non-renewable CED and expressed in kWh oil-eq, according to Frischknecht et al. (2015); greenhouse gas (GHG) emissions, expressed in g CO_2-eq, based on the 100 year global warming potentials (GWPs) reported by IPCC (2013)).

The environmental impacts of the European supply mixes based on GO data are shown in Tab. Z. 1. Depending on the impact indicator, the countries with the highest environmental impacts are Cyprus (UBP), Czech Republik (CED non renewable and total), and Poland (GHG). The GO supply mixes of Sweden (GHG) and Austria (CED, UBP) show the lowest environmental impacts.

The comparison of the newly compiled supply mixeswith the environmental characteristics of the corresponding previous electricity mix data of the KBOB life cycle assessment data DQRv2:2018 show generally large deviations. The environmental impacts of the

[1] KBOB: Coordination Group for Construction and Property Services (German: Koordinationskonferenz der Bau- und Liegenschaftsorgane des Bundes)

electricity supply mix based on GO data show an increase in the case of Norway, Island, Denmark (according to all three indicators), Czech Republic (non-renewable CED, overall environmental impact), Slovenia (GHG emissions, non-renewable CED), Finland and Italy (non-renewable CED) compared to the electricity mixes used in KBOB (2018). Norway, Island and Denmark export a large share of their renewable power GOs and the residual mix which compensates for these exports is mainly fossil and nuclear based. Czech Republic hardly cancels GOs and its residual mix contains a higher share of nuclear power at the expense of fossil power. Slovenia's electricity supply mix contains less and the electricity supply mix of Finland and Italy more nuclear power than the KBOB electricity mix of the respective countries. For the other countries, the assessment of the electricity supply mixes based on GO data arrives at lower environmental impacts.

Tab. Z. 1 Greenhouse gas emissions in g CO_2-eq, total and non-renewable cumulative energy demand in kWh oil-eq, overall environmental impact in UBP per kWh electricity of the supply mixes 2018 of 31 European countries based guarantee of origin data from AIB (2019).

Country	GHG (g CO_2-eq/kWh)	CED, total (kWh oil-eq/kWh)	CED, non-renewable (kWh oil-eq/kWh)	UBP (UBP/kWh)
AT	**202**	**1.80**	**0.82**	**170**
BE	**238**	**3.06**	**2.54**	**396**
BG	**650**	**3.84**	**3.57**	**723**
CH	**76**	**2.14**	**1.29**	**227**
CY	**977**	**3.57**	**3.43**	**949**
CZ	**750**	**4.00**	**3.81**	**784**
DE	**427**	**2.59**	**1.76**	**400**
DK	**634**	**3.19**	**2.89**	**576**
EE	**715**	**3.59**	**3.22**	**482**
ES	**462**	**3.05**	**2.57**	**491**
FI	**341**	**3.08**	**2.45**	**453**
FR	**89**	**3.42**	**3.16**	**475**
GB	**449**	**3.23**	**2.79**	**449**
GR	**678**	**2.88**	**2.41**	**531**
HR	**546**	**2.59**	**1.85**	**440**
HU	**460**	**3.75**	**3.46**	**614**
IE	**372**	**2.36**	**1.57**	**280**
IS	**492**	**3.04**	**2.76**	**518**
IT	**610**	**3.08**	**2.76**	**489**
LT	**279**	**2.92**	**1.30**	**292**
LU	**437**	**2.93**	**2.19**	**397**
LV	**415**	**2.78**	**1.90**	**327**
MT	**862**	**3.65**	**3.57**	**856**
NL	**405**	**2.39**	**1.70**	**312**
NO	**536**	**3.29**	**3.00**	**556**
PL	**1103**	**3.82**	**3.64**	**847**
PT	**482**	**2.57**	**1.78**	**367**
RO	**529**	**3.03**	**2.46**	**516**
SE	**37**	**2.30**	**1.35**	**243**
SI	**519**	**3.58**	**3.30**	**645**
SK	**242**	**3.24**	**2.69**	**473**

Content

1 Introduction

1.1 Status Quo and Objectives

In recent years, trading in Guarantees of Origin (GOs) has led to individual countries with a high share of renewable energy in their electricity generation, such as Norway, selling a large proportion of the GOs from their renewable electricity generation to electricity utilities abroad. This enables the power utilities, which act as buyers of these certificates, to increase the share of renewable energies in their own supply mix without having to invest directly in renewable energies. At the same time, the selling countries are reducing the share of renewable energy in their supply mix. In the case of Norway, the share of hydropower in the supply mix in 2018 was only around 35%, with hydropower accounting for about 95% of production (AIB 2019).

In this study, the life cycle inventory data of the electricity mixes of 31 European countries are compiled based on guarantee of origin data based on the latest publication of the Association of Issuing Bodies (AIB 2019). The AIB publishes the composition of the electricity supply mixes of the individual countries annually, taking into account the cancelled GOs. The annual reports on the electricity mix in individual countries, i.e. Austria (e-control 2019) and Switzerland (Pronovo 2020), are used to validate the statistical data in AIB (2019). These life cycle inventories (LCIs) are compiled in accordance with the life cycle inventory data requirements of the KBOB life cycle assessment data DQRv2:2018 (KBOB et al. 2018) and in the same structure as the electricity mix data sets contained therein (according to the system boundary "Life Cycle Assessment"). The environmental characteristics of these newly compiled electricity mixes based on GOs are compared with the environmental characteristics of the corresponding previous electricity mix data of the KBOB life cycle assessment data DQRv2:2018.

This brief report provides the essential information on how the European electricity mixes are modeled and which elements are taken into account. It quantifies greenhouse gas emissions, total environmental impact and cumulative primary energy demand (renewable and non-renewable). The background information on the electricity mixes described here is documented in various reports. The main sources of information are mentioned in the Chapters below.

1.2 Structure of the Report

The report is structured as follows: Chapter 2 describes the scope of the study including the functional unit and the system boundaries. Chapter 3 documents the different European electricity mixes and the modeling assumptions. The environmental impacts of the European electricity mixes are presented in Chapter 4. Chapter 5 discusses the comparison of the environmental impacts of the supply mixes compiled in this study with those of the correspondig electricity mix data of the KBOB LCA data DQRv2:2018 (KBOB et al. 2018). Finally, Chapter 6 discusses the data quality of the newly compiled data sets and Chapter 7 contains a discussion about the application of the GO supply mixes and conclusions.

2 Scope

2.1 Functional Unit

The functional unit used in the life cycle assessment of the european electricity mixes is one kilowatt hour (kWh) electricity, supplied in low voltage in 2018, while the official unit of traded GOs is MWh

2.2 System Boundaries

The life cycle assessment of the european electricity mixes includes

- Construction, operation, dismantling and disposal of the power plants, including the production of materials required for construction, the provision of operating resources and the environmental impact of operation, as well as disposal expenses.
- Provision and disposal of fuels, including the extraction of primary energy sources (natural gas, crude oil, hard coal, uranium, wood), their refinement, as well as their conditioning and final storage.
- transmission and distribution to low-voltage customers, including power losses, construction expenditures, SF_6 emissions (transformers) and nitrous oxide emissions (high-voltage lines).
- any transport services for fuels, construction and operating materials, and waste.

The model is structured as shown in Fig. 2.1: At the center are the electricity mix data sets, in which the respective shares of the different technologies (electricity from run-of-river power plants, from nuclear power plants, from photovoltaic plants, etc.) are queried. These technology data sets contain the expenses and pollutant emissions of the production of one kWh fed into the grid. Transmission and distribution of electricity are downstream of the electricity mix data sets.

For three voltage levels, namely high, medium and low voltage, the losses as well as the quantities of electricity transported at the corresponding voltage level are used to quantify the specific losses of each voltage level (Tab. 2.1).

The LCIs of the individual technologies are modeled on the basis of the KBOB LCA data DQRv2:2018 (KBOB et al. 2018).

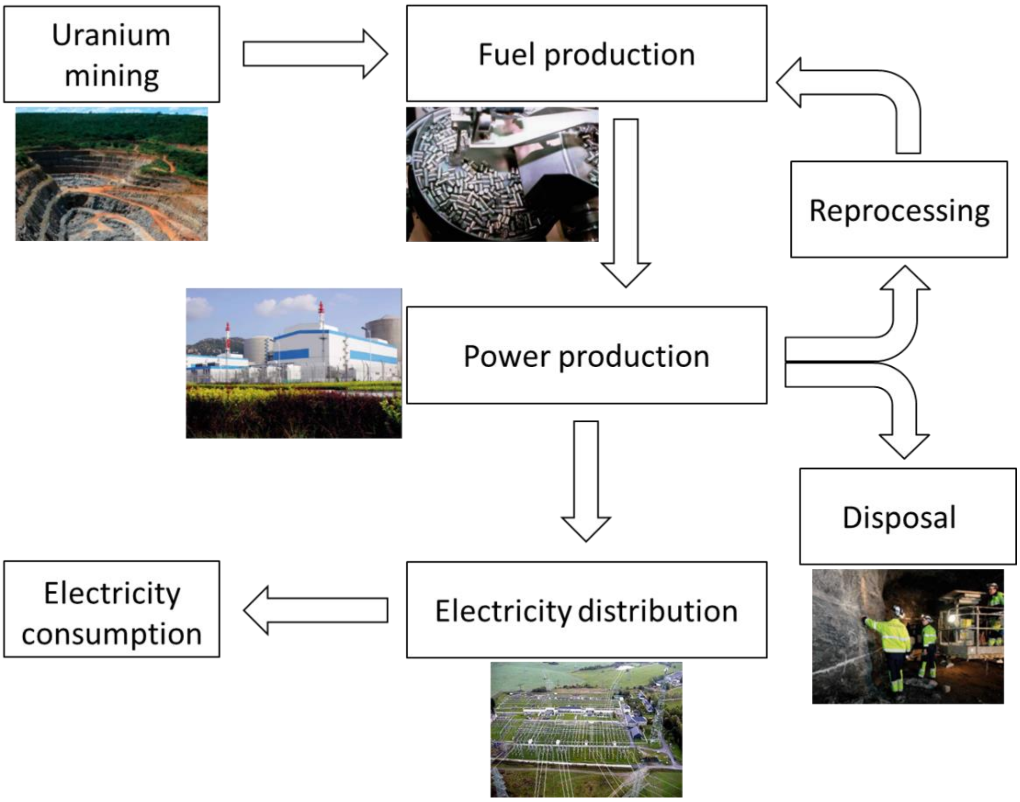

Fig. 2.1 Schematic representation of electricity supply using nuclear energy as an example. The environmental impact of electricity consumption is outside the scope of the study. the image on electricity distribution is from Siemens Energy (2014). The remaining images were taken from IAEA (2011).

Tab. 2.1 Losses in the power grid of the analysed European countries broken down into the different voltage levels and SF_6 emissions (Itten et al. 2014; Messmer & Frischknecht 2016).

Country	Code	Total Supply	Total Demand	Total Losses	Share Losses	Share Losses HV	Share Losses MV	Share Losses LV	Cumulated Losses LV	SF_6 Emission Rate	Total SF_6 Emissions	SF_6 Emissions HV	SF_6 Emissions MV	Source: Losses / SF_6 Emissions
		GWh	GWh	GWh	%	%	%	%	%	%	kg/kWh	kg/kWh	kg/kWh	
Austria	AT	64'400	61'000	3'400	5.28%	2.10%	0.73%	4.18%	7.15%	1.00	5.70E-08	5.42E-08	2.85E-09	IEA 2010 / UBA 1999
Belgium	BE	90'200	85'900	4'300	4.77%	1.89%	0.66%	3.75%	6.42%	2.10	1.20E-07	1.14E-07	5.99E-09	IEA 2010 / wie DE
Bulgaria	BG	34'600	29'900	4'700	13.58%	5.59%	1.97%	11.79%	20.37%	2.10	1.20E-07	1.14E-07	5.99E-09	IEA 2010 / wie DE
Croatia	HR	18'200	16'500	1'700	9.34%	3.78%	1.33%	7.73%	13.28%	2.10	1.20E-07	1.14E-07	5.99E-09	IEA 2010 / wie DE
Czech Republic	CZ	65'100	60'400	4'700	7.22%	2.90%	1.01%	5.84%	10.01%	2.10	1.20E-07	1.14E-07	5.99E-09	IEA 2010 / wie DE
Denmark	DK	36'700	34'300	2'400	6.54%	2.62%	0.92%	5.25%	8.99%	2.10	1.20E-07	1.14E-07	5.99E-09	IEA 2010 / wie DE
Estonia	EE	8'600	7'500	1'100	12.79%	5.25%	1.85%	11.00%	18.99%	2.10	1.20E-07	1.14E-07	5.99E-09	IEA 2010 / wie DE
Finland	FI	87'100	83'800	3'300	3.79%	1.50%	0.52%	2.95%	5.04%	2.10	1.20E-07	1.14E-07	5.99E-09	IEA 2010 / wie DE
France	FR	495'100	462'200	32'900	6.65%	2.66%	0.93%	5.34%	9.15%	0.86	4.90E-08	4.66E-08	2.45E-09	IEA 2010 / UNFCCC report FR
Germany	DE	570'900	540'800	30'100	5.27%	2.10%	0.73%	4.17%	7.14%	2.10	1.20E-07	1.14E-07	5.99E-09	IEA 2010 / UNFCCC report DE
Greece	GR	63'800	58'700	5'100	7.99%	3.22%	1.13%	6.52%	11.18%	2.10	1.20E-07	1.14E-07	5.99E-09	IEA 2010 / wie DE
Hungary	HU	41'300	37'400	3'900	9.44%	3.82%	1.34%	7.82%	13.45%	2.10	1.20E-07	1.14E-07	5.99E-09	IEA 2010 / wie DE
Iceland	IS	16'000	15'400	600	3.75%	1.48%	0.52%	2.92%	4.99%	2.10	1.20E-07	1.14E-07	5.99E-09	IEA 2010 / wie DE
Ireland	IE	28'300	26'100	2'200	7.77%	3.13%	1.10%	6.32%	10.85%	2.10	1.20E-07	1.14E-07	5.99E-09	IEA 2010 / wie DE
Italy	IT	339'500	319'100	20'400	6.01%	2.40%	0.84%	4.79%	8.21%	2.10	1.20E-07	1.14E-07	5.99E-09	IEA 2010 / wie DE
Latvia	LV	7'600	6'800	800	10.53%	4.28%	1.50%	8.82%	15.19%	2.10	1.20E-07	1.14E-07	5.99E-09	IEA 2010 / wie DE
Lithuania	LT	11'000	10'000	1'000	9.09%	3.68%	1.29%	7.50%	12.89%	2.10	1.20E-07	1.14E-07	5.99E-09	IEA 2010 / wie DE
Luxembourg	LU	6'700	6'600	100	1.49%	0.59%	0.20%	1.14%	1.94%	2.10	1.20E-07	1.14E-07	5.99E-09	IEA 2010 / wie DE
Netherlands	NL	119'200	114'500	4'700	3.94%	1.56%	0.54%	3.08%	5.26%	2.10	1.20E-07	1.14E-07	5.99E-09	IEA 2010 / wie DE
Norway	NO	125'600	115'400	10'200	8.12%	3.27%	1.15%	6.63%	11.38%	2.10	1.20E-07	1.14E-07	5.99E-09	IEA 2010 / wie DE
Poland	PL	140'400	127'700	12'700	9.05%	3.66%	1.28%	7.46%	12.82%	2.10	1.20E-07	1.14E-07	5.99E-09	IEA 2010 / wie DE
Portugal	PT	53'400	49'200	4'200	7.87%	3.16%	1.11%	6.40%	10.99%	2.10	1.20E-07	1.14E-07	5.99E-09	IEA 2010 / wie DE
Romania	RO	55'900	48'700	7'200	12.88%	5.29%	1.86%	11.09%	19.14%	2.10	1.20E-07	1.14E-07	5.99E-09	IEA 2010 / wie DE
Slovakia	SK	26'900	25'900	1'000	3.72%	1.47%	0.51%	2.90%	4.95%	2.10	1.20E-07	1.14E-07	5.99E-09	IEA 2010 / wie DE
Slovenia	SI	13'800	13'000	800	5.80%	2.31%	0.81%	4.62%	7.90%	2.10	1.20E-07	1.14E-07	5.99E-09	IEA 2010 / wie DE
Spain	ES	286'900	271'900	15'000	5.23%	2.08%	0.73%	4.14%	7.08%	2.10	1.20E-07	1.14E-07	5.99E-09	IEA 2010 / wie DE
Sweden	SE	142'500	131'500	11'000	7.72%	3.10%	1.09%	6.27%	10.76%	2.10	1.20E-07	1.14E-07	5.99E-09	IEA 2010 / wie DE
Switzerland	CH	61'814	57'494	4'320	6.99%	2.80%	0.98%	5.64%	9.66%	1.00	5.70E-08	5.42E-08	2.85E-09	BFE 2015 / THG Stat 2009
United Kingdom	GB	378'700	350'500	28'200	7.45%	2.99%	1.05%	6.03%	10.35%	2.10	1.20E-07	1.14E-07	5.99E-09	IEA 2010 / wie DE
RER	RER	3'399'514	6'928'500	228'120	6.71%	2.69%	0.94%	5.39%	9.24%	1.00	5.70E-08	5.42E-08	2.85E-09	IEA 2010 / own calculation

3 Electricity Mixes Based on Guarantees of Origin

3.1 Overview

At regular intervals, AIB publishes the composition of the electricity mixes of the individual countries, taking into account the traded and cancelled GOs. The three mixes "GO cancellations", "residual mix" and "GO total supply mix" are modeled for each country separately and described in the following sections. The annual reports on the electricity mix in individual countries such as Austria (e-control 2019) are used to validate the statistical data in AIB (2019). Based on the publication of the Association of Issuing Bodies for 2018 (AIB 2019), life cycle inventories of the electricity mixes of 31 European countries[2] were compiled using guarantee of origin data. These LCIs were prepared in accordance with the LCA data requirements of the KBOB LCA data DQRv2:2018 (KBOB et al. 2018) and in the same structure as the electricity mix data sets contained therein (according to the system boundary "Life Cycle Assessment"). Data sets from the KBOB LCA data DQRv2:2018 were used to represent the individual technologies. An overview of the used data sets is provided in Annex A. Note that most countries issue GOs only for renewable electricity and not for conventional electricity from fossil or nuclear power plants. Only Austria, Netherlands and Switzerland register electricity generation from all power plants.

3.2 Three different mixes per country

Three electricity mixes per country are presented in the following Subchapters:

- GO cancellation mix;
- residual mix;
- total supply mix;

The total supply mix is composed of the GO cancellation mix and the residual mix, the latter being used to represent the share of electricity from unknown sources. The characteristics of the three mixes are described in the respective subchapters.

3.3 GO Cancellations

"GO cancellation" is the "use" of a GO certificate and the method of assigning the attributes of that electricity to a single end user. Cancellation of a GO is the only way to remove a GO from the market and redeem its benefits, unless it expires after one year upon generation. It ensures that the certificate is not traded, transferred, sold, or used by any other end user.

[2] Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Island, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Rumania, Slovakia, Slovenia, Spain, Sweden, Switzerland, United Kingdom

The GO cancellations of the 31 European countries analyzed are shown in Tab. 3.1. The shares of "renewables unspecified" and "fossil unspecified" were allocated to the renewable and fossil technologies, respectively, according to their shares in the total. The shares of run-of-river and storage hydropower plants in "hydro & marine" were calculated according to the shares of these technologies in the EU net electricity generation in 2018 (ENTSO-E 2019).

Tab. 3.1 Shares of GO cancellations (broken down by technologies) in GO total supply mix for 31 European countries (AIB 2019). 100 % refer to the total volume of electricity supplied to a country's end users.

	Renewables								Fossil				Total
	Solar	Wind	Run of river	Reservoir (alpine region)	Reservoir (non-alpine region)	Geothermal	Biomass	Nuclear	Lignite	Hard Coal	Gas	Oil	
AT	0.00%	7.87%	33.55%	17.28%	17.28%	0.00%	1.77%	0.00%	0.00%	2.90%	18.36%	0.98%	**100.00%**
BE	0.95%	3.89%	6.37%	3.28%	3.28%	0.04%	5.37%	19.50%	0.00%	0.00%	6.88%	0.00%	**49.54%**
BG	0.00%	0.04%	0.02%	0.01%	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.08%**
CH	1.02%	0.92%	31.49%	16.22%	16.22%	0.00%	0.49%	15.99%	0.00%	0.00%	1.30%	0.00%	**83.66%**
CY	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.01%**
CZ	0.02%	0.04%	0.35%	0.18%	0.18%	0.00%	0.57%	0.00%	0.00%	0.00%	0.00%	0.00%	**1.35%**
DE	7.43%	21.04%	8.81%	4.54%	4.54%	0.30%	7.75%	0.33%	0.01%	0.01%	0.01%	0.01%	**54.76%**
DK	0.01%	14.81%	0.98%	0.51%	0.51%	0.00%	0.61%	0.00%	0.00%	0.00%	0.24%	0.00%	**17.65%**
EE	0.03%	3.45%	0.10%	0.05%	0.05%	0.00%	2.13%	0.00%	0.00%	0.00%	0.00%	0.00%	**5.81%**
ES	3.68%	13.54%	2.52%	1.30%	1.30%	0.00%	4.29%	0.00%	0.00%	0.00%	3.62%	0.27%	**30.52%**
FI	0.29%	2.70%	7.71%	3.97%	3.97%	0.00%	6.90%	0.00%	0.00%	0.00%	0.00%	0.00%	**25.55%**
FR	0.06%	0.31%	3.32%	1.71%	1.71%	0.05%	0.23%	0.00%	0.00%	0.00%	0.00%	0.00%	**7.40%**
GB	2.20%	14.04%	0.31%	0.16%	0.16%	0.00%	6.14%	0.00%	0.00%	0.00%	0.00%	0.00%	**23.02%**
GR	0.03%	0.66%	1.41%	0.73%	0.73%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	**3.56%**
HR	0.38%	7.35%	4.42%	2.28%	2.28%	0.00%	3.33%	0.00%	0.00%	0.00%	2.38%	0.00%	**22.42%**
HU	0.01%	0.29%	1.17%	0.60%	0.60%	0.00%	0.39%	0.00%	0.00%	0.00%	0.00%	0.00%	**3.07%**
IS	0.00%	0.00%	4.13%	2.13%	2.13%	11.72%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	**20.12%**
IE	1.64%	30.14%	8.21%	4.23%	4.23%	0.00%	4.43%	0.00%	0.00%	0.00%	35.11%	0.14%	**88.12%**
IT	0.10%	0.48%	5.14%	2.65%	2.65%	1.85%	2.00%	0.05%	0.00%	0.00%	0.00%	0.00%	**14.92%**
LV	0.00%	0.56%	0.15%	0.08%	0.08%	0.00%	0.17%	0.00%	0.00%	0.00%	0.00%	0.00%	**1.04%**
LT	0.09%	31.56%	1.72%	0.88%	0.88%	0.00%	28.35%	0.00%	0.00%	0.00%	0.00%	0.00%	**63.49%**
LU	1.63%	3.98%	18.89%	9.73%	9.73%	0.00%	3.25%	0.00%	0.00%	0.00%	20.22%	0.00%	**67.42%**
MT	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.00%**
NL	0.96%	30.41%	5.26%	2.71%	2.71%	0.03%	5.12%	0.00%	0.00%	0.00%	0.55%	0.00%	**47.76%**
NO	0.01%	0.87%	6.74%	3.47%	3.47%	0.58%	0.26%	0.03%	0.00%	0.00%	0.00%	0.00%	**15.45%**
PL	0.00%	1.62%	0.29%	0.15%	0.15%	0.00%	0.66%	0.00%	0.00%	0.00%	0.00%	0.00%	**2.87%**
PT	0.00%	0.00%	0.80%	0.41%	0.41%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	**1.63%**
RO	0.00%	0.11%	0.09%	0.05%	0.05%	0.00%	0.02%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.31%**
SK	0.00%	1.16%	1.23%	0.64%	0.64%	0.00%	3.83%	0.00%	0.00%	0.00%	0.00%	0.00%	**7.50%**
SI	0.98%	0.00%	6.30%	3.24%	3.24%	0.00%	2.35%	0.00%	0.00%	0.00%	0.00%	0.00%	**16.11%**
SE	0.50%	7.04%	24.93%	12.84%	12.84%	0.14%	6.73%	18.62%	0.00%	0.00%	0.23%	0.00%	**83.87%**

3.4 Residual Mixes

The residual mix of a country consists of the amount of electricity produced remaining after the cancellation of the guarantees of origin. Due to the internationality of the electricity market and the guarantee of origin system, the available residual electricity mix of the countries differs from the electricity consumption of unknown origin. Therefore, a harmonization for the whole of Europe is necessary in order to determine a correct residual mix for the different countries. This harmonization is achieved through a European residual mix (European Attribute Mix, EAM), which acts as a "balancing reservoir" of untracked electricity produced in Europe. After attribute balancing via the EAM, the volume of available generation attributes in each country's residual mix is equal to the untracked consumption in that country. This is a necessary but not sufficient prerequisite for GOs to be a credible tracking tool in the context of international trade.

The residual mixes for the 31 countries mentioned were calculated by the Association of Issuing Bodies (see AIB 2019) and are shown in Tab. 3.2. The shares of "renewables unspecified", "fossil unspecified" and "hydro & marine" were divided as described in Subchapter 3.3. Austria is the first country with a full disclosure, which results in 0 % residual mix. Countries like Sweden and Switzerland use GOs for more than 80 % of the electricity supplied to end users, whereas countries like France, Norway, Poland or United Kingdom use GOs only to a minor extent (share of residual mix between 77 % and 97 %).

Tab. 3.2 Shares of residual mix (broken down by technologies) in GO total supply mix for 31 European countries (AIB 2019; ENTSO-E 2019). 100 % refer to the total volume of electricity supplied to a country's end users.

	Renewables								Fossil				
	Solar	Wind	Run of river	Reservoir (alpine region)	Reservoir (non-alpine region)	Geothermal	Biomass	Nuclear	Lignite	Hard Coal	Gas	Oil	Total
AT	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.00%**
BE	4.16%	1.10%	0.11%	0.05%	0.05%	0.00%	1.36%	20.44%	0.00%	0.00%	23.12%	0.07%	**50.46%**
BG	3.28%	3.22%	5.86%	3.02%	3.02%	0.00%	0.70%	36.36%	39.83%	0.63%	3.99%	0.00%	**99.92%**
CH	1.34%	0.09%	0.43%	0.22%	0.22%	0.00%	0.02%	9.26%	1.09%	0.75%	2.80%	0.11%	**16.34%**
CY	3.51%	4.40%	0.00%	0.00%	0.00%	0.00%	0.76%	0.09%	0.05%	0.03%	0.06%	91.11%	**99.99%**
CZ	1.97%	0.16%	0.39%	0.20%	0.20%	0.00%	3.02%	36.44%	45.96%	4.30%	5.97%	0.04%	**98.65%**
DE	0.36%	0.00%	0.14%	0.07%	0.07%	0.00%	0.00%	8.48%	16.32%	8.83%	10.57%	0.39%	**45.24%**
DK	2.44%	1.87%	0.24%	0.12%	0.12%	0.00%	0.16%	19.12%	10.43%	27.93%	19.34%	0.58%	**82.35%**
EE	0.06%	0.00%	0.04%	0.02%	0.02%	0.00%	5.63%	0.00%	0.00%	0.00%	88.41%	0.00%	**94.19%**
ES	1.30%	1.82%	0.60%	0.31%	0.31%	0.00%	0.10%	23.55%	11.91%	5.99%	19.31%	4.27%	**69.48%**
FI	0.28%	0.28%	0.92%	0.47%	0.47%	0.00%	4.41%	33.89%	4.53%	12.62%	16.05%	0.52%	**74.45%**
FR	1.87%	5.07%	1.37%	0.71%	0.71%	0.00%	1.28%	72.93%	0.00%	1.28%	6.90%	0.48%	**92.60%**
GB	0.01%	0.02%	0.01%	0.00%	0.00%	0.00%	0.01%	23.22%	0.38%	6.01%	47.29%	0.02%	**76.98%**
GR	6.47%	13.00%	6.91%	3.56%	3.56%	0.11%	0.57%	0.00%	26.68%	1.08%	26.93%	7.59%	**96.44%**
HR	0.02%	0.21%	16.98%	8.75%	8.75%	0.00%	0.01%	1.28%	24.91%	7.79%	8.86%	0.02%	**77.58%**
HU	0.83%	1.66%	1.05%	0.54%	0.54%	0.00%	4.88%	46.83%	15.67%	6.86%	17.69%	0.37%	**96.93%**
IS	0.37%	0.70%	1.07%	0.55%	0.55%	0.46%	0.24%	28.54%	15.96%	11.01%	19.94%	0.50%	**79.88%**
IE	0.01%	2.65%	0.00%	0.00%	0.00%	0.00%	0.30%	0.00%	1.84%	2.76%	4.32%	0.01%	**11.88%**
IT	3.60%	1.22%	1.06%	0.54%	0.54%	0.15%	0.08%	9.67%	5.48%	13.35%	48.02%	1.37%	**85.08%**
LV	0.01%	1.54%	16.60%	8.55%	8.55%	0.01%	11.24%	2.78%	0.00%	2.75%	46.75%	0.18%	**98.96%**
LT	0.05%	0.07%	1.99%	1.03%	1.03%	0.01%	0.05%	3.84%	0.00%	3.70%	24.32%	0.43%	**36.51%**
LU	0.15%	0.27%	0.13%	0.07%	0.07%	0.00%	0.10%	11.15%	6.72%	4.63%	9.08%	0.21%	**32.58%**
MT	4.51%	0.33%	0.16%	0.08%	0.08%	0.00%	0.12%	14.12%	7.60%	5.24%	9.49%	58.26%	**100.00%**
NL	1.53%	0.61%	0.03%	0.02%	0.02%	0.00%	0.00%	1.74%	0.00%	9.94%	38.37%	0.00%	**52.24%**
NO	0.40%	0.72%	2.72%	1.40%	1.40%	0.00%	0.26%	28.31%	15.67%	10.81%	22.38%	0.49%	**84.55%**
PL	0.20%	2.67%	0.44%	0.23%	0.23%	0.00%	1.66%	3.06%	29.52%	48.45%	9.62%	1.06%	**97.13%**
PT	1.50%	22.56%	10.88%	5.60%	5.60%	0.00%	5.06%	0.00%	0.00%	20.48%	26.50%	0.19%	**98.37%**
RO	2.86%	10.22%	14.23%	7.33%	7.33%	0.00%	0.50%	17.34%	27.11%	2.26%	10.48%	0.01%	**99.69%**
SK	2.04%	0.07%	6.23%	3.21%	3.21%	0.00%	5.77%	50.38%	6.40%	5.35%	8.52%	1.32%	**92.50%**
SI	0.70%	0.16%	0.43%	0.22%	0.22%	0.00%	0.06%	43.26%	32.93%	2.05%	3.76%	0.09%	**83.89%**
SE	0.00%	0.68%	0.09%	0.05%	0.05%	0.00%	0.41%	13.83%	0.00%	0.59%	0.22%	0.23%	**16.13%**

3.5 GO Total Supply Mixes

The GO total supply mix represents the total consumption mix of the country, i.e., the shares of energy sources in the tracked and non-tracked part of electricity consumption. The electricity demand of supply pumps and of pumped storage power plants is assumed to be supplied by the GO total supply mix of the respective country. The share of each power plant technology in the GO total supply mix is thus increased by the share of electricity demand of supply and pumped storage pumps on 1 kWh GO total supply mix. The share of electricity demand of pumps is visible in the column "Total" of Tab. 3.3 (amount exceeding 100.0 %). Data on the electricity demand of supply and pumped storage pumps for the 31 European countries was taken from IEA (2018). If no data were available (Bulgaria, Croatia, Cyprus, Malta, Romania), the pumping electricity demand was set to zero. The GO total supply mixes of the 31 European countries are shown in Tab. 3.3. The shares of "renewables unspecified", "fossil unspecified" and "hydro & marine" were divided as described in Subchapter 3.3.

Tab. 3.3 Shares of technologies in GO total supply mix incl. pumped-storage power demand for 31 European countries (AIB 2019; ENTSO-E 2019; IEA 2018).
Values above 100 % in "Total" represent the share of electricity demand for pumping (both supply and pumped storage pumps).

	Renewables								Fossil				Total
	Solar	Wind	Run of river	Reservoir (alpine region)	Reservoir (non-alpine region)	Geothermal	Biomass	Nuclear	Lignite	Hard Coal	Gas	Oil	
AT	0.00%	8.37%	35.68%	18.38%	18.38%	0.00%	1.88%	0.00%	0.00%	3.09%	19.53%	1.04%	**106.34%**
BE	5.19%	5.06%	6.58%	3.39%	3.39%	0.04%	6.84%	40.57%	0.00%	0.00%	30.47%	0.07%	**101.60%**
BG	3.28%	3.26%	5.88%	3.03%	3.03%	0.00%	0.70%	36.36%	39.83%	0.63%	3.99%	0.00%	**100.00%**
CH	2.50%	1.07%	33.80%	17.41%	17.41%	0.00%	0.54%	26.74%	1.16%	0.80%	4.34%	0.12%	**105.87%**
CY	3.51%	4.40%	0.01%	0.00%	0.00%	0.00%	0.76%	0.09%	0.05%	0.03%	0.06%	91.11%	**100.00%**
CZ	2.03%	0.21%	0.75%	0.39%	0.39%	0.00%	3.67%	37.23%	46.95%	4.39%	6.10%	0.04%	**102.16%**
DE	7.89%	21.33%	9.07%	4.67%	4.67%	0.30%	7.86%	8.93%	16.55%	8.96%	10.72%	0.40%	**101.37%**
DK	2.44%	16.68%	1.22%	0.63%	0.63%	0.00%	0.77%	19.12%	10.43%	27.93%	19.58%	0.58%	**100.00%**
EE	0.10%	3.45%	0.14%	0.07%	0.07%	0.00%	7.76%	0.00%	0.00%	0.00%	88.41%	0.00%	**100.00%**
ES	5.04%	15.56%	3.16%	1.63%	1.63%	0.00%	4.45%	23.84%	12.06%	6.06%	23.22%	4.60%	**101.25%**
FI	0.57%	2.99%	8.63%	4.45%	4.45%	0.00%	11.31%	33.89%	4.53%	12.62%	16.05%	0.52%	**100.00%**
FR	1.96%	5.46%	4.76%	2.45%	2.45%	0.05%	1.53%	73.89%	0.00%	1.29%	6.99%	0.49%	**101.33%**
GB	2.24%	14.22%	0.33%	0.17%	0.17%	0.00%	6.22%	23.50%	0.39%	6.09%	47.86%	0.02%	**101.20%**
GR	6.51%	13.67%	8.33%	4.29%	4.29%	0.11%	0.57%	0.00%	26.73%	1.08%	26.97%	7.60%	**100.17%**
HR	0.39%	7.57%	21.41%	11.03%	11.03%	0.00%	3.34%	1.28%	24.91%	7.79%	11.24%	0.02%	**100.00%**
HU	0.84%	1.95%	2.22%	1.15%	1.15%	0.00%	5.27%	46.83%	15.67%	6.86%	17.69%	0.37%	**100.00%**
IS	0.37%	0.70%	5.20%	2.68%	2.68%	12.18%	0.24%	28.54%	15.96%	11.01%	19.94%	0.50%	**100.00%**
IE	1.65%	33.01%	8.26%	4.26%	4.26%	0.00%	4.75%	0.00%	1.85%	2.78%	39.69%	0.15%	**100.66%**
IT	3.72%	1.71%	6.24%	3.21%	3.21%	2.01%	2.09%	9.80%	5.52%	13.45%	48.36%	1.38%	**100.71%**
LV	0.01%	2.10%	16.75%	8.63%	8.63%	0.01%	11.41%	2.78%	0.00%	2.75%	46.75%	0.18%	**100.00%**
LT	0.14%	33.45%	3.92%	2.02%	2.02%	0.01%	30.03%	4.06%	0.00%	3.91%	25.72%	0.46%	**105.75%**
LU	2.21%	5.29%	23.64%	12.18%	12.18%	0.00%	4.16%	13.86%	8.35%	5.76%	36.42%	0.26%	**124.32%**
MT	4.51%	0.33%	0.16%	0.08%	0.08%	0.00%	0.12%	14.12%	7.60%	5.24%	9.49%	58.26%	**100.00%**
NL	2.49%	31.02%	5.29%	2.73%	2.73%	0.03%	5.12%	1.74%	0.00%	9.94%	38.92%	0.00%	**100.00%**
NO	0.42%	1.60%	9.52%	4.91%	4.91%	0.59%	0.52%	28.54%	15.78%	10.88%	22.54%	0.49%	**100.69%**
PL	0.20%	4.31%	0.73%	0.37%	0.37%	0.00%	2.33%	3.07%	29.63%	48.62%	9.65%	1.06%	**100.35%**
PT	1.56%	23.50%	12.16%	6.26%	6.26%	0.00%	5.27%	0.00%	0.00%	21.33%	27.60%	0.20%	**104.15%**
RO	2.86%	10.33%	14.32%	7.38%	7.38%	0.00%	0.52%	17.34%	27.11%	2.26%	10.48%	0.01%	**100.00%**
SK	2.06%	1.24%	7.56%	3.90%	3.90%	0.00%	9.73%	51.04%	6.48%	5.42%	8.63%	1.34%	**101.31%**
SI	1.71%	0.17%	6.89%	3.55%	3.55%	0.00%	2.47%	44.27%	33.71%	2.10%	3.85%	0.09%	**102.35%**
SE	0.50%	7.72%	25.03%	12.89%	12.89%	0.14%	7.14%	32.46%	0.00%	0.59%	0.45%	0.23%	**100.02%**

3.6 Comparison to National Electricity Labelling

In Austria and Switzerland, the obligation of full disclosure of electricity applies. In this subchapter, we compare the electricity mixes according to the national electricity disclosure statistics of the two countries (e-control 2019; Pronovo 2020) with the respective GO total supply mixes according to AIB (2019).

The comparison of the Swiss supply mixes (including electricity demand for pump-storage) is shown in Fig. 3.1. In the supply mix based on the Swiss electricity disclosure statistics (Pronovo 2020), the non-verifiable energy sources were divided among the technologies according to the Swiss residual mix shown in Tab. 3.2. It includes higher shares of renewable technologies compared to the AIB total supply mix (79 % compared to 73 %). In contrast, the share of non-renewable technologies, in particular nuclear energy, is higher in the AIB total supply mix (27 % compared to 22 %).

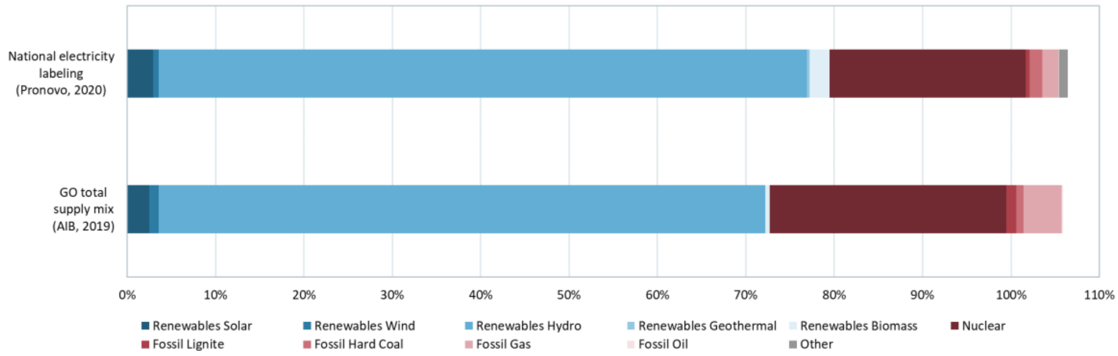

Fig. 3.1 Composition of the Swiss supply mix according to the national electricity cockpit (Pronovo 2020) and AIB (2019) in terms of technologies including the pumping energy demand.

The comparison of the Austrian supply mixes is shown in Fig. 3.2. Electricity from hydropower contributes a larger share to the supply mix according to the AIB total supply mix than according to the Austrian electricity disclosure statistics by e-control (2019). The share of non-renewable energy sources is slightly lower according to the AIB total supply mix (22.2 % compared to 23.4 %).

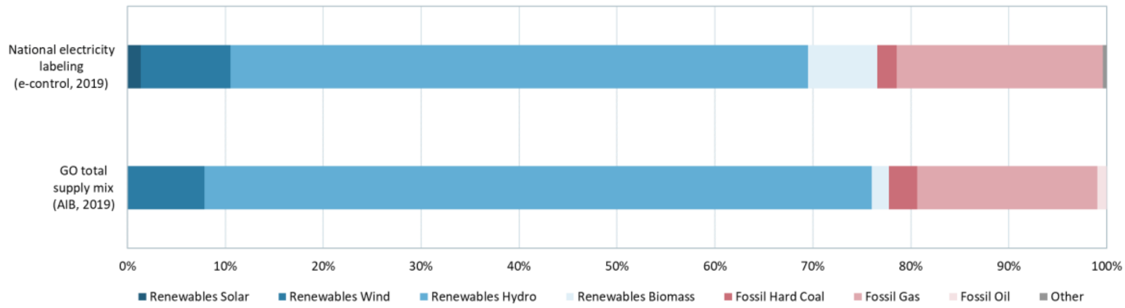

Fig. 3.2 Composition of the Austrian supply mix according to the national electricity labelling (e-control 2019) and AIB (2019) in terms of technologies.

4 Environmental impacts

4.1 Greenhouse Gas Emissions

The emissions of the GO total supply mix for each country are calculated as follows: the emissions of the GO cancellations multiplied by their share in the GO total supply mix plus the emissions of the residual mix multiplied by its share in the GO total supply mix (the respective shares can be seen in Tab. 3.1 and Tab. 3.2). The additional greenhouse gas emissions due to the pumping electricity demand are also included.

The greenhouse gas emissions (g CO_2-eq) per kWh electricity for each country's GO cancellations, residual mix and total supply mix (see Chapter 3 for a description of the three mixes) are summarized in Tab. 4.1. The greenhouse gas emissions of the residual mixes are generally considerably higher compared to those of the GO cancellations of the respective countries. The largest differences are observed in case of Cyprus, Greece, Malta, Poland.

Tab. 4.1 Greenhouse gas emissions in g CO_2-eq per kWh electricity of the GO cancellations, residual mixes and GO total supply mixes 2018 (incl. electricity demand of supply and pumped storage pumps) of the 31 analysed European countries.

Country Code	Einheit	GO cancellations	Residual mix	GO total supply mix
AT	g CO_2-eq/kWh	190	8	**202**
BE	g CO_2-eq/kWh	122	345	**238**
BG	g CO_2-eq/kWh	23	650	**650**
CH	g CO_2-eq/kWh	29	295	**76**
CY	g CO_2-eq/kWh	17	977	**977**
CZ	g CO_2-eq/kWh	37	744	**750**
DE	g CO_2-eq/kWh	33	891	**427**
DK	g CO_2-eq/kWh	34	763	**634**
EE	g CO_2-eq/kWh	41	757	**715**
ES	g CO_2-eq/kWh	125	603	**462**
FI	g CO_2-eq/kWh	31	447	**341**
FR	g CO_2-eq/kWh	18	93	**89**
GB	g CO_2-eq/kWh	38	565	**449**
GR	g CO_2-eq/kWh	21	701	**678**
HR	g CO_2-eq/kWh	108	673	**546**
HU	g CO_2-eq/kWh	27	474	**460**
IE	g CO_2-eq/kWh	316	774	**372**
IS	g CO_2-eq/kWh	21	610	**492**
IT	g CO_2-eq/kWh	26	707	**610**
LT	g CO_2-eq/kWh	42	650	**279**
LU	g CO_2-eq/kWh	223	625	**437**
LV	g CO_2-eq/kWh	30	419	**415**
MT	g CO_2-eq/kWh	17	862	**862**
NL	g CO_2-eq/kWh	35	743	**405**
NO	g CO_2-eq/kWh	21	626	**536**
PL	g CO_2-eq/kWh	33	1131	**1103**
PT	g CO_2-eq/kWh	20	470	**482**
RO	g CO_2-eq/kWh	25	531	**529**
SE	g CO_2-eq/kWh	26	89	**37**
SI	g CO_2-eq/kWh	28	600	**519**
SK	g CO_2-eq/kWh	41	255	**242**

Fig. 4.1 shows an overview of the greenhouse gas emissions of the GO total supply mixes of the countries analysed. It is divided into the contributions of the tracked part of the consumption represented by the GO cancellations, the non-tracked part of the consumption represented by the residual mix, and the electricity demand of supply and pumped storage pumps. The greenhouse gas emissions of most countries are mainly determined by the untracked part of the consumption (residual mix). The exception are some countries with a large share of tracked consumption, e.g., Austria, Luxembourg, Ireland, Sweden.

The GO total supply mix of Poland (97.13 % untracked consumption) causes the highest CO_2 emissions per kWh electricity with 1100 g CO_2-eq/kWh (to around 90 % of electricity produced with fossil fuels). The greenhouse gas emissions of the GO total supply mix of Sweden (83.87 % tracked consumption) are lowest (37 g CO_2-eq/kWh).

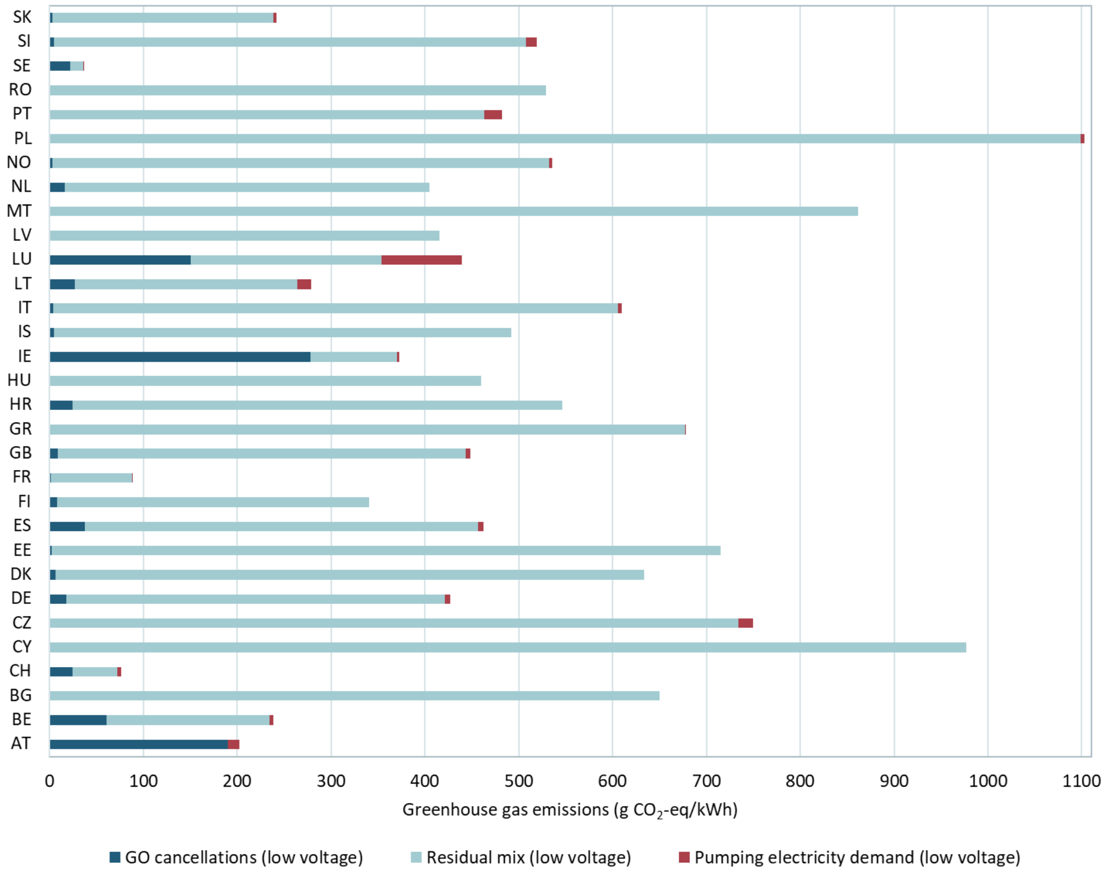

Fig. 4.1 Greenhouse gas emissions in g CO_2-eq per kWh electricity of the GO total supply mix 2018 of 31 European countries divided into the shares contributed by the GO cancellations, the residual mixes and the electricity demand of supply and pumped storage pumps.

4.2 Cumulative Energy Demand

The non-renewable cumulative energy demand (kWh oil-eq) per kWh electricity for each country's GO cancellations, residual mix and total supply mix are summarized in Tab. 4.2. The largest differences with respect to the non-renewable cumulative energy demand between GO cancellations and residual mixes of a specific country are found in the case of Cyprus, France, Malta, and Norway.

Tab. 4.2 Non-renewable cumulative energy demand in kWh oil-eq per kWh electricity of the GO cancellations, residual mixes and GO total supply mixes 2018 (incl. electricity demand of supply and pumped storage pumps) of the 31 analysed European countries.

Country Code	Einheit	GO cancellations	Residual mix	GO total supply mix
AT	kWh oil-eq/kWh	0.77	0.01	**0.82**
BE	kWh oil-eq/kWh	1.96	3.03	**2.54**
BG	kWh oil-eq/kWh	0.05	3.57	**3.57**
CH	kWh oil-eq/kWh	0.82	3.26	**1.29**
CY	kWh oil-eq/kWh	0.03	3.43	**3.43**
CZ	kWh oil-eq/kWh	0.10	3.78	**3.81**
DE	kWh oil-eq/kWh	0.11	3.70	**1.76**
DK	kWh oil-eq/kWh	0.11	3.49	**2.89**
EE	kWh oil-eq/kWh	0.12	3.41	**3.22**
ES	kWh oil-eq/kWh	0.50	3.44	**2.57**
FI	kWh oil-eq/kWh	0.08	3.26	**2.45**
FR	kWh oil-eq/kWh	0.04	3.36	**3.16**
GB	kWh oil-eq/kWh	0.11	3.55	**2.79**
GR	kWh oil-eq/kWh	0.04	2.49	**2.41**
HR	kWh oil-eq/kWh	0.43	2.25	**1.85**
HU	kWh oil-eq/kWh	0.05	3.57	**3.46**
IE	kWh oil-eq/kWh	1.39	2.78	**1.57**
IS	kWh oil-eq/kWh	0.05	3.44	**2.76**
IT	kWh oil-eq/kWh	0.07	3.21	**2.76**
LT	kWh oil-eq/kWh	0.13	3.15	**1.30**
LU	kWh oil-eq/kWh	0.96	3.42	**2.19**
LV	kWh oil-eq/kWh	0.08	1.92	**1.90**
MT	kWh oil-eq/kWh	0.03	3.57	**3.57**
NL	kWh oil-eq/kWh	0.11	3.16	**1.70**
NO	kWh oil-eq/kWh	0.04	3.51	**3.00**
PL	kWh oil-eq/kWh	0.09	3.73	**3.64**
PT	kWh oil-eq/kWh	0.03	1.73	**1.78**
RO	kWh oil-eq/kWh	0.05	2.47	**2.46**
SE	kWh oil-eq/kWh	0.92	3.60	**1.35**
SI	kWh oil-eq/kWh	0.06	3.83	**3.30**
SK	kWh oil-eq/kWh	0.12	2.87	**2.69**

Fig. 4.2 shows an overview of the non-renewable energy demand of the GO total supply mixes of the analysed countries. It is divided into the contributions of the tracked part of the consumption represented by the GO cancellations, the non-tracked part of the consumption represented by the residual mix, and the pumping electricity demand. The non-renewable energy demand of most countries is mainly determined by the untracked part of the consumption (residual mix). In the case of Austria, Belgium, Switzerland, Ireland, Luxembourg, and Sweden the contributions of the tracked consumption are also considerable.

The GO total supply mix of Czech Republic (98.65 % untracked consumption) causes the highest non-renewable energy demand (3.81 kWh oil-eq/kWh). The non-renewable energy demand of the GO total supply mix of Austria (100 % tracked consumption) is lowest (0.82 kWh oil-eq/kWh).

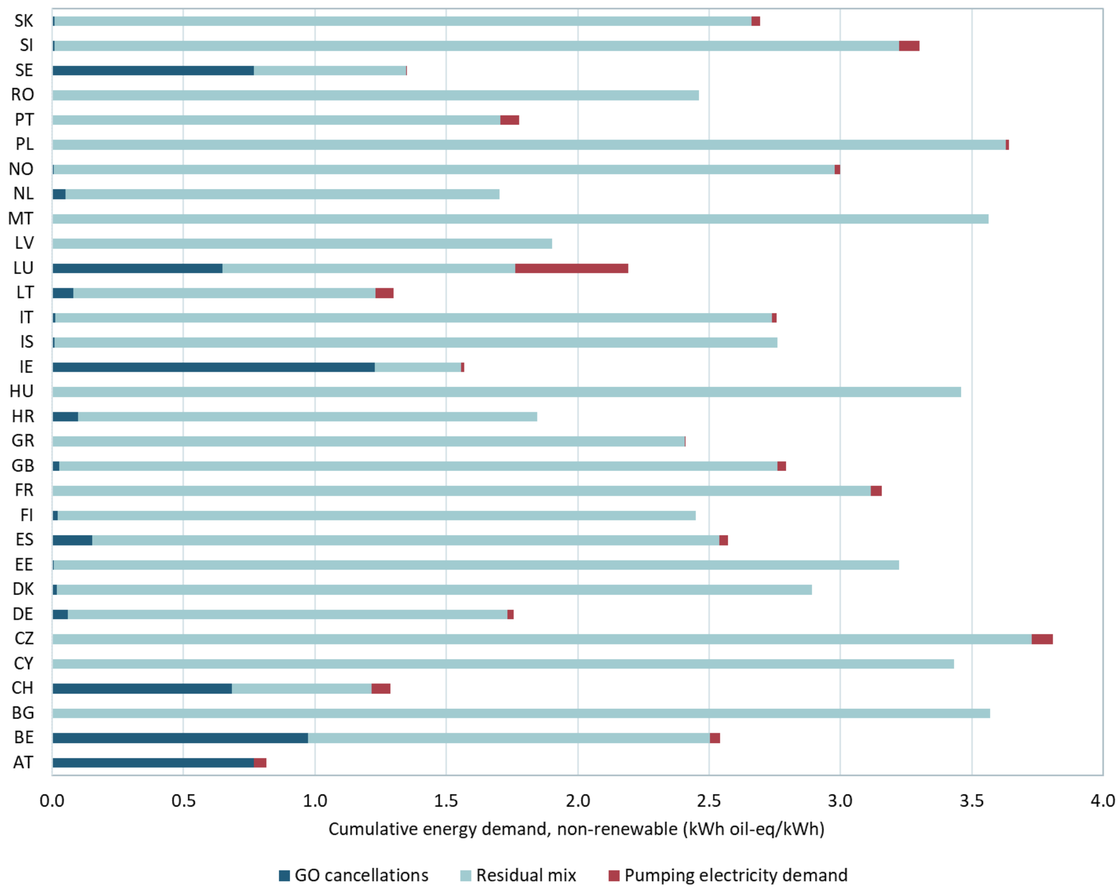

Fig. 4.2 Non-renewable cumulative energy demand in kWh oil-eq per kWh electricity of the GO total supply mix 2018 of 31 European countries divided into the shares contributed by the GO cancellations, the residual mixes and the electricity demand of supply and pumped storage pumps.

4.3 Overall Environmental Impact

The overall environmental impact (UBP) per kWh electricity for each country's GO cancellations, residual mix and total supply mix are summarized in Tab. 4.3. The largest differences with respect to the overall environmental impact between GO cancellations and residual mixes of a specific country are found in the case of Bulgaria, Cyprus, Island, Malta, and Norway.

Tab. 4.3 Overall environmental impact in UBP per kWh electricity of the GO cancellations, residual mixes and GO total supply mixes 2018 (incl. electricity demand of supply and pumped storage pumps) of the 31 analysed European countries.

Country Code	Einheit	GO cancellations	Residual mix	GO total supply mix
AT	UBP/kWh	162	32	**170**
BE	UBP/kWh	326	453	**396**
BG	UBP/kWh	57	723	**723**
CH	UBP/kWh	154	530	**227**
CY	UBP/kWh	47	949	**949**
CZ	UBP/kWh	137	777	**784**
DE	UBP/kWh	93	761	**400**
DK	UBP/kWh	71	684	**576**
EE	UBP/kWh	141	503	**482**
ES	UBP/kWh	148	634	**491**
FI	UBP/kWh	103	573	**453**
FR	UBP/kWh	55	503	**475**
GB	UBP/kWh	118	542	**449**
GR	UBP/kWh	52	547	**531**
HR	UBP/kWh	133	528	**440**
HU	UBP/kWh	78	631	**614**
IE	UBP/kWh	240	568	**280**
IS	UBP/kWh	55	635	**518**
IT	UBP/kWh	80	557	**489**
LT	UBP/kWh	150	500	**292**
LU	UBP/kWh	179	631	**397**
LV	UBP/kWh	93	330	**327**
MT	UBP/kWh	47	856	**856**
NL	UBP/kWh	83	522	**312**
NO	UBP/kWh	55	643	**556**
PL	UBP/kWh	105	866	**847**
PT	UBP/kWh	49	359	**367**
RO	UBP/kWh	68	518	**516**
SE	UBP/kWh	183	550	**243**
SI	UBP/kWh	82	736	**645**
SK	UBP/kWh	150	493	**473**

Fig. 4.3 shows an overview of the overall environmental impact of the GO total supply mixes of the analysed countries. It is divided into the contributions of the tracked part of

the consumption represented by the GO cancellations, the non-tracked part of the consumption represented by the residual mix, and the pumping electricity demand. The untracked part of the consumption (residual mix) is in the case of most countries responsible for the largest contributions to the overall environmental impacts of the GO total supply mixes. In the case of Austria, Belgium, Germany, Ireland, Lithuania, Luxembourg, Netherlands, Spain, Sweden, and Switzerland the contributions of the tracked consumption are also considerable.

The GO total supply mix of Cyprus (99.99 % untracked consumption) causes the highest overall environmental impact (949 UBP/kWh). The overall environmental impact of the GO total supply mix of Austria (100 % of tracked consumption) is lowest (170 UBP/kWh).

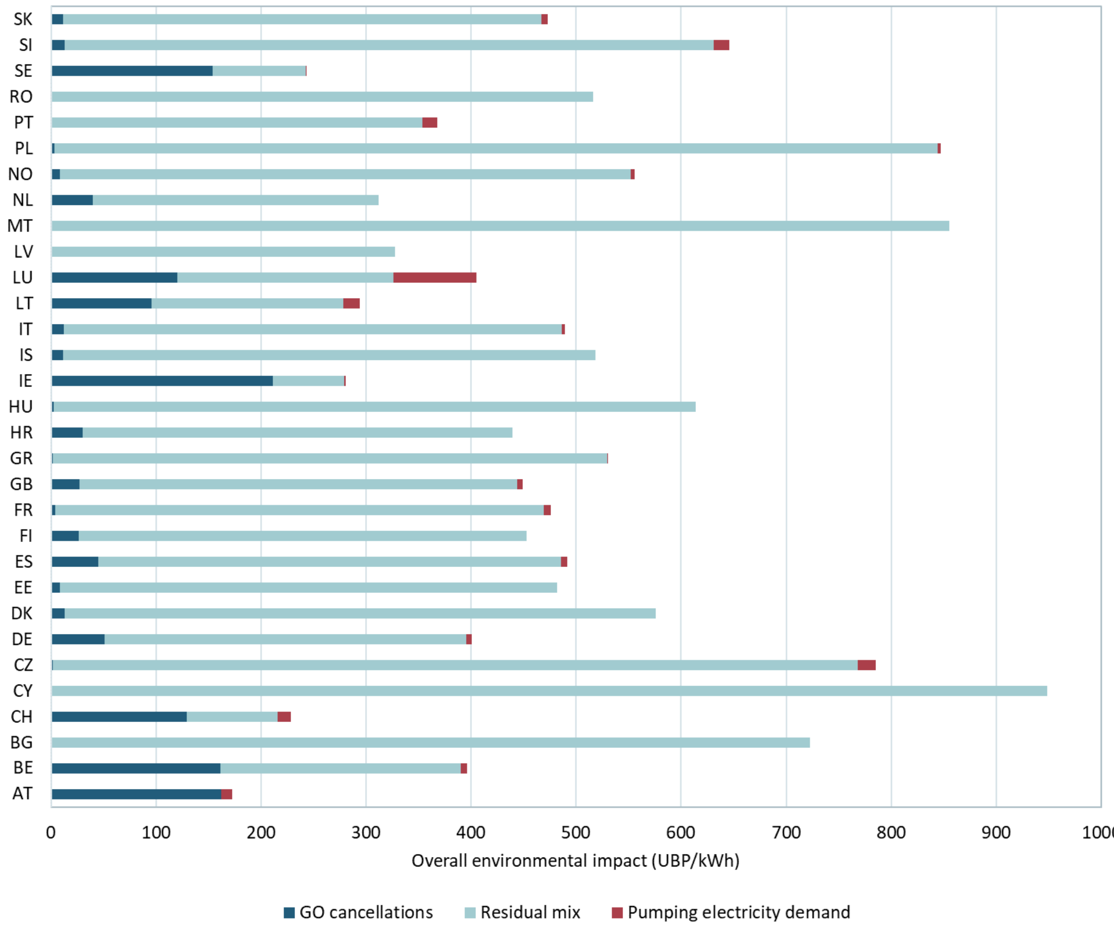

Fig. 4.3 Overall environmental impact in UBP per kWh electricity of the GO total supply mix 2018 of 31 European countries divided into the shares contributed by the GO cancellations, the residual mixes and the electricity demand of supply and pumped storage pumps.

5 Comparison to Existing Electricity Mixes

The life cycle inventory data of the country electricity mixes - with the exception of Switzerland, whose electricity mix life cycle inventories are based on production and commercial trade as described in Krebs & Frischknecht (2020) - in the UVEK life cycle inventory data set DQRv2:2018 (KBOB et al. 2018) as well as in the ecoinvent data set v3.6 (ecoinvent Centre 2019) are based on the electricity statistics of the IEA. These only take into account the physical import of electricity from neighbouring countries and accordingly do not consider economic trade of physical electricity nor trade of GOs. As the example of Norway shows, the current modelling (production plus physical imports) does not reflect the contractual agreements with GOs

In Fig. 5.1, a comparison of the greenhouse gas emissions (a), non-renewable cumulative energy demand (b), and overall environmental impact (c) of the country electricity mixes based on the electricity statistics of the IEA and based on the guarantee of origin data (AIB 2019) is shown. Generally, we see large deviations between the electricity mixes per country. The environmental impacts of the electricity supply mix based on GO data show a substantial increase in the case of Norway, Island, Denmark (according to all three indicators), Czech Republic (non-renewable CED, overall environmental impact), Slovenia (GHG emissions, non-renewable CED), Finland and Italy (non-renewable CED) compared to the electricity mixes used in KBOB et al. (2018). Norway, Island and Denmark export a large share of their renewable power GOs and the residual mix which compensates for these exports is mainly fossil and nuclear based. Czech Republic hardly cancels GOs and its residual mix contains a higher share of nuclear power at the expense of fossil power. Slovenia’s electricity supply mix contains less and the electricity supply mix of Finland and Italy more nuclear power than the KBOB electricity mix of the respective countries. For the other countries, the assessment of the electricity supply mixes based on GO data arrives at lower environmental impacts.

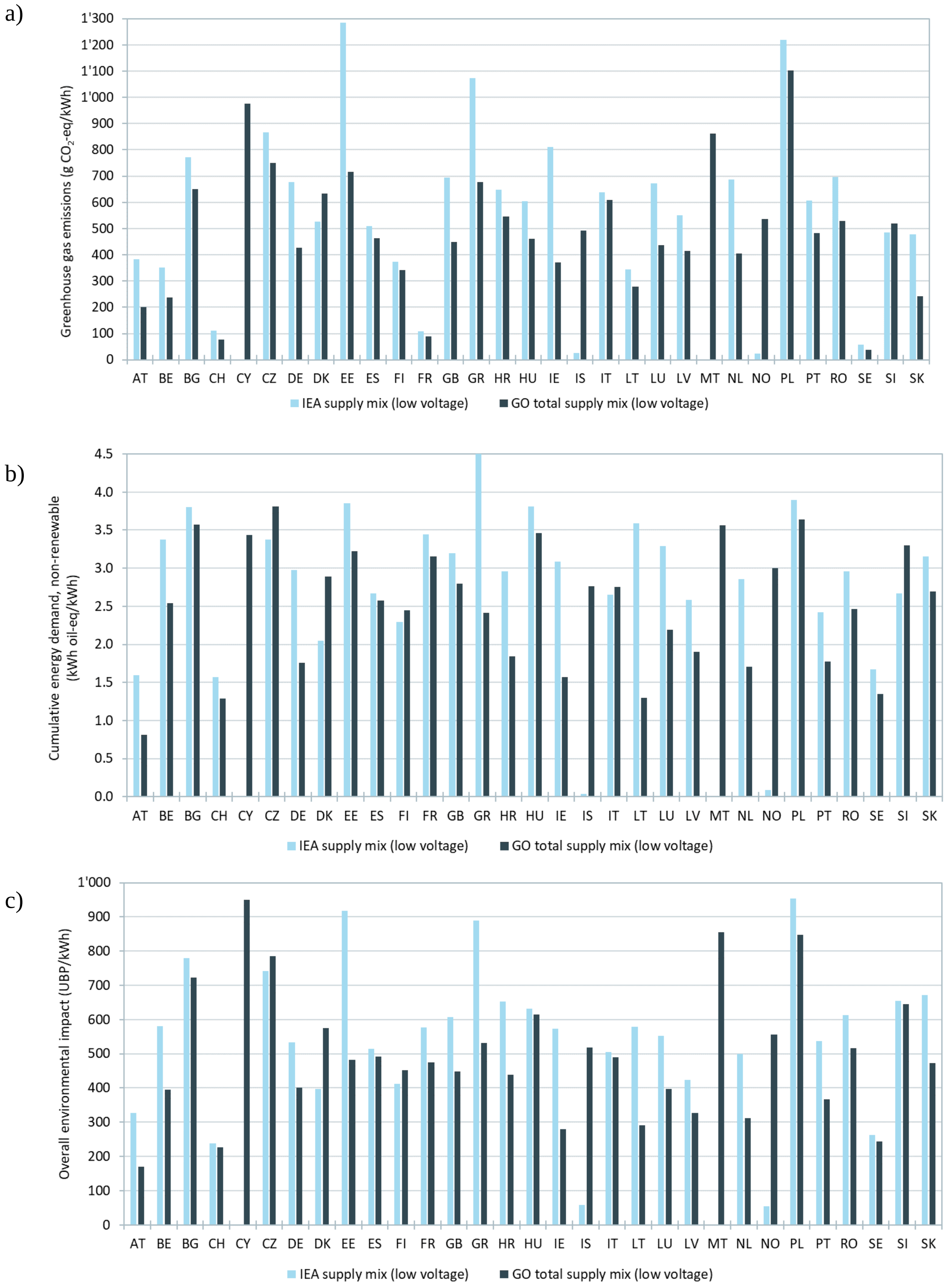

Fig. 5.1 Greenhouse gas emissions in g CO_2-eq (a), non-renewable cumulative energy demand in kWh oil-eq (b), overall environmental impact in UBP (c) per kWh electricity (at the busbar of the power plants) of the supply mixes of 31 European countries based on IEA electricity statistics (as available in UVEK LCA data DQRv2:2018; KBOB et al. 2018) and based guarantee of origin data from AIB (2019, GO total supply mix). The environmental impacts of the Swiss supply mix (UVEK 2018) were taken from an updated assessment (Krebs & Frischknecht 2020) based on production and commercial trade.

6 Data Quality

The data published by AIB allow a rather accurate modeling of the 31 European electricity mixes. This applies for the tracked (based on GO) and non-tracked part of the consumption (resdiual mix). The comparison of the electricity mixes of countries with mandatory full disclosure (Austria and Switzerland) revealed substantial differences in technology shares between the AIB data and the respective national disclosure statistics. Hence, the AIB data are a moderatly accurate approximation of the electricity quality delivered with GOs to a country's end users.

The electricity mixes based on GOs (as reported by AIB, based on the European electricity disclosure scheme) and those based on IEA data describe different reference years. The difference in environmental impacts is thus caused by the different concept (GO versus IEA) on one hand and evolution of the technology shares (e.g. increase of the share of wind power in the German electricity supply mix) on the other.

The electricity demand for pump storage was not available for some of the 31 assessed European countries.

The life cycle inventories of the power plant technologies are not up to date, with the exception of the hydropower plants and the photovoltaic plants. In particular the efficiency and emission factors of hard coal and lignite power plants should be cross-checked and updated if needed In the case of biogas power plants, a reduction in methane emissions during biogas production and a reduction in the effort required for biogas processing (for feeding into the natural gas grid) can be expected.

The life cycle inventory of geothermal electricity is approximated with data from electricity from European wind power plants. This may result in deviations in the environmental intensity of the corresponding shares in the electricity mix. However, these deviations are of minor importance, since the shares of geothermal electricity on the supply mixes are small in most cases (except Island).

7 Discussion and Conclusions

7.1 Synthesis

The national electricity mixes of 31 european countries were modelled based on information and data on the trade and cancellation of guarantees of origin. The environmental impacts per kWh GO based electricity are compared to those of the electricity mixes based on IEA statistical data. The comparison showed that countries with high shares of electricity production with renewables such as Norway, Iceland and Denmark export substantial shares of GOs to other European countries and rely on residual electricity mix qualities with high shares of nuclear and fossil electricity. In countries with significant shares of nuclear power in the production mix like Switzerland or Sweden, electricity suppliers use GO information to increase the share of renewable energy qualities in their electricity supply mix. Finally, in many countries utilities simply do not care about GOs and rely on 95 % to 100 % unknown electricity.

Guarantees of origin is a scheme used to communicate about the quality of the electricity supply mix (power plant technologies used to generate electricity) requested for renewable energies by the EU Renewable Energy directive (European Commission 2018). GOs are traded independently of purchases and sales of physical electricity.

There are two possibilities to achieve consistently modelled electricity supply mixes in LCA background databases such as the UVEK LCA data DQRv2:2018 and voluntary and regulatory LCA applications:

1. Guarantees of Origin: Full disclosure is mandatory in all countries, the electricity mix of all countries is modelled according to the GO total supply mix and relevant voluntary and mandatory LCA applications in all countries require its application in the life cycle inventories.
2. Production and commercial trade: the electricity supply mix of all countries is modelled based on the IEA electricity generation and trade statistics (or relevant regional or national statistics) and relevant voluntary and mandatory LCA applications in all countries require its application in the life cycle inventories.

The current situation with voluntary full disclosure of electricity on one hand and greenhouse gas emission accounting schemes and LCA standards such as the Greenhouse Gas Protocol (WBCSD & WRI 2015) or building LCA standards (Standards Norway 2018 and SIA 2017) which require or allow both approaches on the other is prone to double counting of renewable energy qualities.

7.2 Consequences of Using the GO Mix in Switzerland

The electricity disclosure[3] of Swiss utilities allows the accounting for foreign (renewable) guarantees of origin. The utilities need not being invested in power plants from which they purchase the GOs. They may purchase the GOs independently of the purchase of physical production of electricity. GOs purchased need simply to cover the annual amount of electricity supplied to the end users.

The Swiss energy act as well as the new energy perspectives scenarios "ZERO" (BFE (Hrsg) 2020) assume ambitious quantitative goals regarding the domestic electricity production with hydroelectric power plants and with new renewable energies. The full disclosure scheme in Switzerland primarily serves to inform end consumers about the quality of the electricity. GO electricity mixes based on (foreign) renewable energies may be used by Swiss companies to lower their corporate environmental footprints without investing domestically in renewable energies. The GO system does thus not primarily support the ambitious expansion plans for renewable energies stipulated in the Swiss

[3] www.stromkennzeichnung.ch, accessed 3.3.2021

energy policy. The purchase of European hydropower GO merely provides a renewable quality to the (nuclear) electricity produced in Switzerland.

A similar effect is observed in the building sector. The operational electricity consumption of buildings has up to now been modelled with the Swiss GO electricity mix. With increasing shares of foreign, GO based electricity from hydroelectric power plants, the environmental impacts of electricity have decreased, reducing the need for on site production of electricity with building integrated or building attached PV. However, the building sector is expected and required to play a key role in the Swiss energy strategy 2050.

The GO system with its voluntary full disclosure allows double counting, for instance in LCA for building standards or in quantifying the environmental impacts of electric cars. The norwegian standard NS3720:2018 („Method for greenhouse gas calculations for buildings") requires the use of the Norwegian production mix (2015 to 2075) or a future European electricity mix (2015-2075). As Norway sells a large amount of hydropower GO, the Norwegian hydropower is accounted for twice: in Norwegian and in Swiss building LCAs, because Switzerland has been using the average GO total supply electricity mix .

7.3 Conclusions

The assessment of national electricity supply mixes based on guarantees of origin revealed significant differences in technology mix composition and environmental impacts compared to the traditionally modelled electricity supply mixes based on IEA generation and trade statistics.

Leading background LCI databases model the electricity mixes using data from IEA electricity generation and trade statistics while organisations (companies, associations) use electricity supply mixes based on guarantees of origin in their corporate LCA. This may lead to substantial distortions and double countscounts of electricity based on renewable energies, mainly hydroelectric power plants.

In order to prevent any double counting, the LCA protocols of corporate and product LCAs should be aligned with the approach of electricity mix modelling used in the background databases. This can be achieved by two ways:

1. Model all European electricity mixes based on physical production and commercial trade (exports and imports) and limit the accounting for GOs to those, where the risk for double counting can be excluded;
2. Model all European electricity mixes with the GO information according to AIB and require the use of electricity declarations based on GO in corporate and product LCAs;

In the current state, the European GO system suffers from an incomplete coverage, with only a few countries providing full GO coverage of their electricity supply and from a lack of its consistent and mandatory application in national and international LCA standards and regulation. As long as the situation persists, it is important to critically assess possibilities for distortions when providing life cycle inventories of national electricity supply mixes, when applying LCA of national electricity supply mixes in regulation and when interpreting or comparing LCAs in which electricity consumption is expected to play an important role (mobility, housing, information and communication technologies). National electricity disclosure statistics should be used in a very restrained way in such LCAs.

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A Annex

Tab. A. 1 The data sets of each technology used in the life cycle inventories.

Technology	Used data sets of KBOB life cycle inventory DQRv2:2018 based on ecoinvent v2.2 data	Comments/Adjustments
Renewable energy		
Run of river	*electricity, hydropower, at run-of-river power plant/kWh/RER U*	
Reservoir (alpine region)	*electricity, hydropower, at reservoir power plant, alpine region/kWh/RER U*	*CO2 emissions are modeled as biogenic, according to greenhouse gas inventory modeling.*
Reservoir (non-alpine region)	*electricity, hydropower, at reservoir power plant, non alpine regions/kWh/RER U*	*CO2 emissions are modeled as biogenic, according to greenhouse gas inventory modeling.*
Solar	*electricity, production mix photovoltaic, at plant/kWh/DE U*	
Wind	*Electricity, at wind power plant/RER U*	
Biomass	*Electricity, at cogen 6400kWth, wood, emission control, allocation exergy/CH U*	
Geothermal	*Electricity, at wind power plant/RER U*	
Non-renewable energy		
Nuclear	*electricity, nuclear, at power plant/kWh/UCTE U*	
Oil	*electricity, oil, at power plant/UCTE U*	
Gas	*electricity, natural gas, at power plant/UCTE U*	
Hard coal	*Electricity, hard coal, at power plant/UCTE U*	
Lignite	*Electricity, lignite, at power plant/UCTE U*	
Power distribution (without losses)	*distribution network, electricity, low voltage/km/CH/I U*	*In addition to the production of the distribution network, the use of SF_6 and the emissions SF_6, N_2O and O_3 are considered for electricity distribution.*