The use of primary energy factors and CO_2 intensities for electricity in the European context - a systematic methodological review and critical evaluation of the contemporary literature

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Abstract

Reaching the European Union's 2030 targets for primary energy use (PE) and CO_2 emissions (CE) requires an accurate assessment of how different technologies perform on these two fronts. To calculate the PE and CE associated with the consumption of electricity (e.g. by an electric vehicle or a heat pump) conversion factors (CFs) are required, namely a primary energy factor and a CO_2 intensity factor. Previous theoretical work has shown that the calculation and use of CFs is a contentious and multifaceted issue, but a review of the actual practice in academic literature has so far been missing. 110 recent studies have been systematically reviewed across six methodological aspects, to find that 75% of the studies consider only a single country, 79% apply a purely retrospective perspective, 66% apply a yearly temporal resolution, 75% apply a purely operational (instead of a life-cycle) perspective, 85% make use of average (rather than marginal) CFs, and 77% ignore electricity imports from surrounding countries. Future research in which CFs are used should more carefully consider each of these methodological aspects and explicitly justify the choices that are being made on this front. There is also a strong need in the literature for a publicly available and methodologically transparent database of up-to-date CFs, which would not only enable more accurate and transparent PE and CE calculations, but also support the further development of building energy performance assessment methods and smart grid algorithms.

Highlights:

- Primary energy factors and CO_2 intensities are crucial but contentious parameters
- The calculation and use of these 'conversion factors' is systematically reviewed
- Across 110 recent studies, six methodological aspects are assessed
- Methodological shortcomings and other overarching challenges are identified
- A publicly available database of conversion factors would benefit future research

Keywords: conversion factor, primary energy factor, CO_2 intensity, primary energy, emissions, electricity, heat pump, electric vehicle, building energy performance, Europe

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Nomenclature

BEP	Building energy performance
CE	CO_2 emissions expressed in (kilo)grams (e.g. associated with the use of a particular appliance, building or EV)
CEN	European Committee for Standardization
CF	Conversion factor (i.e. PEF or CI)
CHP	Combined heat and power (plant)
CI	CO_2 intensity of electricity, expressed in g/kWh_E
CI_T	CO_2 intensity for a specific electricity generation technology, expressed in g/kWh_E
DHN	District heating network
EEA	European Environmental Agency
EED	Energy Efficiency Directive (of the European Union)
EIA	Energy Information Administration (of the United States)
ELCD	European Reference Life Cycle Database
ENTSO-E	European Network of Transmission System Operators for Electricity
EPBD	Energy performance of buildings Directive (of the European Union)
EU	European Union
GCB	Gas condensing boiler
GEMIS	Global Emissions Model for Integrated Systems
GHG	Greenhouse gas
GS	Geographical scope
HP	Heat pump
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change established by the UNFCCC
kWh_E	Kilowatt hour of electricity
kWh_F	Kilowatt hour of fuel as measured by the primary energy stored in its chemical bonds
kWh_P	Kilowatt hour of primary energy
LCA	Life-cycle analysis
LCP	Life-cycle perspective
MILP	Mixed integer linear programming
MPC	Model predictive control
NZEB	Nearly-zero energy building
OP	Operational perspective
PE	Primary energy (use) expressed in kWh_P (e.g. associated with a particular appliance, building or EV)
PEF	Primary energy factor for electricity, expressed in kWh_P/kWh_E
PEF_F	Primary energy factor for a specific fuel, expressed in kWh_P/kWh_F
PEF_T	Primary energy factor for a specific electricity generation technology, expressed in kWh_P/kWh_E
PPA	Power purchasing agreement
PV	(Solar) photovoltaics
PVT	Photovoltaic thermal
Ref	Reference
SGA	Smart grid algorithm
TES	Thermal energy storage
TR	Temporal resolution
TS	Temporal scope
TSO	Transmission system operator
UCED	Unit commitment economic dispatch (model)
UNFCCC	United Nations Framework Convention on Climate Change
VRES	Variable renewable energy sources (wind and solar energy)

1. Introduction

The European Union (EU) strives for sharp reductions in both its primary energy use (PE) and CO_2 emissions (CE), as formalised in the flagship 2030 policy targets and the associated legislation – including the Energy Performance of Buildings Directive (EPBD) and the Energy Efficiency Directive (EED)[1,2]. Electricity use already represents a major component of the EU's PE and CE today, and its importance is increasing due to the ongoing electrification of heating and transport services [3]. Together with the continuing increase in renewable electricity generation, this electrification is an essential element of the energy transition, which calls for an accurate evaluation of electricity consuming technologies. For example, it is important to correctly calculate the CE associated with the electricity consumption of a heat pump (HP) or electric vehicle (EV). However, such a calculation requires an estimate of the CO_2 intensity (CI) of the electricity used, expressed in gCO_2/kWh_E. Similarly, a primary energy factor (PEF), expressed in kWh_P/kWh_E, is required to assess the associated primary energy use. CIs and PEFs are called conversion factors (CFs) – respectively converting an amount of electrical energy into either an amount of CO_2 emissions or primary energy – and they are widely used in a variety of academic and applied research associated with the European energy transition[1].

When compared to fossil-fuelled technologies, the merits of electricity consuming technologies like HPs and EVs are largely dependent on CFs. In the case of EVs, some studies even claim that the assumed CFs can lead to completely opposing conclusions about the technology's merits [4,5]. In the case of HPs, an interaction exists with the coefficient of performance (COP)[6,7]. It is namely the ratio between the assumed PEF and COP which determines the degree to which the installation of a HP results in a reduction of a building's PE.

CFs also affect the evaluation of local electricity production technologies, like photovoltaic (PV) installations on the roofs of buildings. Although the EPBD has not been implemented in exactly the same way in every European country, the building energy performance regulations in certain countries (like Belgium) allow to subtract the annual PE production (electricity production multiplied with a PEF) of a PV installation from the building's overall PE use. Given the assumption that the electricity generated by the PV installation is displacing grid-electricity that would have otherwise been generated, a 'high' PEF can thus be beneficial in this case. Similarly, several studies have quantified the degree to which PV can lead to CE reductions in this way [8–10]. For example, in the case of realising a *net-zero emissions neighbourhood*, the injection of PV-electricity into the grid (and the associated CI) was found to be of crucial importance [10]. Given the importance of CFs with respect to both HPs and PV, they can also determine whether or not a building qualifies as a *nearly zero energy building* (NZEB)[11,12], or which score it achieves on its Energy Performance Certificate (EPC).

Whenever a building is heated (or cooled) using electricity consuming technologies, both CFs also affect the attractiveness of electricity-saving measures like improving thermal insulation. For a given investment cost, more CE and PE will be saved if the CFs are higher. In other words, CFs co-determine the 'abatement costs' associated with different technologies and measures. Therefore, they also co-determine the contents of the cost-optimal mix of technologies and measures to reach a certain goal. An illustrative example of this can be found in [13] – in which PEFs are used to track progress in the Spanish residential sector towards the EU 2020 goals, supporting policy makers by rating different possible actions related to energy savings and efficiency. Through such applications, CFs can also have

[1] The terms 'primary energy factor' and 'CO_2 intensity' are used inconsistently in the literature. To avoid confusion, more extensive definitions and a comparison to other uses are provided in Appendix A.

a significant market impact, as they may influence the selection of technologies receiving government support.

The importance of CFs is further illustrated by the wide variety of applications across the literature. In many cases, CFs are used in the context of retrofit scenarios – in which the PE or CE of one or several buildings needs to be calculated before and after a number of measures are taken [14–21]. In some of the other cases, CFs are used to assess the CE reduction potential of energy communities [9], to design control strategies for flexible electricity demand [22], and even to assess the benefits of electrifying offshore oil platforms [23]. Some studies use the 'official' CFs proposed by national regulations and building codes [7,11,24,25], while others use different externally-sourced CFs, or calculate CFs themselves [26–28].

The crucial observation with respect to all of the above, is that there is no consensus on how to calculate or use CFs – even though they can substantially affect the results and conclusions of studies. The European Union's EPBD mandates the use of PEFs, but fails to provide a standardised methodology to calculate them. This has led to a variety of methods being used by Member States across Europe [11,29]. Also in the academic literature, the methodologies used to calculate CFs are highly variable and subject to improvement. Moreover, across studies different kinds of CFs are used for similar applications, indicating a patchwork of ad-hoc approaches.

To improve and streamline research practices with respect to CFs in the future, a thorough analysis of how they are *currently* being calculated and used is needed. However, such an analysis has so far been missing in the literature. Previous work focusing on the methodological aspects related to CFs has remained limited to theoretical discussions, excluding a review of the choices that are actually made in contemporary research practice [30–34]. This paper aims to fill this gap by performing a first-of-its-kind stocktaking of the academic literature, specifically focussing on PEFs and CIs for electricity. A total of 110 recent academic publications are systematically reviewed, with a focus on the European context. By improving the understanding of how CFs are actually being calculated and used, current trends and shortcomings are identified, and potential avenues for improvements in future research are explored.

The contribution of this paper is organised in two parts. The first and most important part is the systematic methodological review of the literature itself. Several methodological 'aspects' can be associated with CFs, each containing a number of 'options'. For example, one aspect is a CF's temporal resolution, which has options like yearly, monthly and hourly. The combination of methodological aspects and their respective options establishes a functional taxonomy, which is used to structure the systematic review. The previous theoretical work has established a number of varying taxonomies [30–34], as have the standards developed by CEN (EN17423) and ISO (52000 series)[35–37], but they are suboptimal for the purposes of the present paper. The definition and selection of aspects was therefore determined in a bottom-up way, considering the actual methodologies being used in the literature. This resulted in a taxonomy including six methodological aspects (listed below), which are used in section 2 to evaluate each of the 110 studies included in the literature sample. More extensive explanations of the aspects and their options are provided in the respective subsections.

- Whether only one or several country-specific CFs were used (*geographical scope*)
- Whether the used CFs reflect yearly values or rather a higher *temporal resolution*
- Whether the used CFs refer to the past or the future (*temporal scope*)
- Whether or not the used CFs take into account electricity *imports from other countries*
- Whether the used CFs apply an operational or a life-cycle perspective (*assessment boundary*)
- Whether average or marginal CFs were used (*market perspective*)

Although the systematic review of section 2 already leads to a number of important insights, it does not yet provide a holistic view on the literature's calculation and use of CFs. Therefore, the second part of this paper's contribution is the discussion of a number of additional topics in section 3. These topics relate more broadly to trends, challenges and opportunities with respect to CFs as identified in the literature, namely:

- The available sources for CFs
- Transparency in the literature about the origin of CFs
- The degree to which CFs used in the literature are up-to-date
- Contrasting the use of CFs with different approaches to calculate the PE and CE for certain electrical loads, in which the electricity sector is endogenised
- The use of CFs in official calculation methods for the certification of building energy performance
- The use of CFs in the context of developing smart grid algorithms (SGAs)

The review's findings – as discussed in sections 2 and 3 – are summarised in the conclusion, in which it becomes clear that many of the issues revealed in the literature could be alleviated if a thoroughly and coherently calculated database of up-to-date CFs for all European countries would be generated and made publicly available.

2. Systematic literature review of PEF and CI methodological aspects

2.1. Literature selection process

The literature selection process was organised as follows. First of all, the studies obviously needed to make use of (or calculate) at least one PEF or CI meant to estimate the PE or CE associated with an electrical load (e.g. of an appliance, EV, building, entire neighbourhood, etc.). Studies in which *only* the PE and CE of *non*-electrical energy demands were estimated (e.g. [38,39]) are out of scope. Secondly, the literature selection was limited to studies that were published no earlier than 2017, to guarantee that the review represents the current state of play. Finally, the selection was focused on publications that relate to the European context.

It should be noted that the use of CFs is not always the core focus of each of the included studies. In fact, in many cases CFs are only mentioned briefly. However, a detailed discussion on all the other content and findings of the selected studies is out of scope for the purposes of the review.

To collect the relevant studies, the *Web of Science* search tools were extensively used, using a wide variety of "Topic" queries including "PEF", "primary energy", "CO_2", "intensity" and "electricity". Several hundred recent publications were then manually reviewed for relevance according the aforementioned selection criteria.

2.2. Overview of the literature sample

After the selection process, the final literature sample contains a total of 110 recent studies. An overview of these studies – focusing on their use of CFs – is provided in Table 1, which acts as a guide throughout the rest of the paper. For the sake of clarity, the studies in Table 1 are grouped into several categories. The first five categories of studies use CFs to calculate the PE or CE associated with buildings at various levels of analysis (from a single appliance like a HP to an entire building stock). The sixth category groups studies that are focussed on EVs, followed by a seventh category including miscellaneous PE and CE calculations. Finally, the last category groups together the studies that are purely focused on the *calculation of CFs* themselves (e.g. for particular geographical areas). These studies typically do not 'apply' the calculated CFs in a PE or CE calculation. To provide additional insight into the literature sample, Figure 1 illustrates the number of studies included in each category, Figure 2 shows how prevalent each of the methodological 'options' are (as discussed in section 2), and Figure 3 indicates how frequently CFs were calculated or used for each European country. In addition, studies that do not calculate or use CFs themselves but discuss their methodological aspects from a purely theoretical perspective are summarised in Table 2, for the sake of comparison with the present work and to demonstrate that they do not address the identified literature gap.

Table 1: Systematic review of how PEFs and CIs are calculated and applied across academic literature

Ref	PD	CF	GS	TR	TS	IP	S	DA	AB	MP	What is calculated
Single appliance level											
[40]	'18	CI	NL, UK, DE, FR	y	r, p	p	o	na	l	a	CE of a HP + PV + battery
[41]	'17	PEF	IT	y	r, p	p	h, o	'14	o	m	PE savings when replacing a GCB with a HP
[42]	'18	PEF	IT	h[1]	r	p	h	'15-'16	o	a	PE of a HP as compared to providing heating with a CHP through a DHN
[43]	'18	PEF	IT	h[2]	r	p	h	'11-'16	o	a	PE of a HP as compared to a GCB
[44]	'17	PEF	DE	h	r	p	o	na	o	a	PE of individual HPs combined with TES
[45]	'18	CI PEF	EU[3]	y	r, p	p	h, o	'12,'14	o	a	PE and CE of a HP compared to a GCB, in the context of seven European countries
[46]	'19	PEF	LU	y	r	p	o[4]	na	o	a	PE of a ventilation system
[47]	'20	CI	10[5]	y, h	r	p	h	'18	l	a	CE of HPs in 10 European countries
[48]	'19	CI	NO	h	r	c	h	'15	l	a	CE of a HP in Norway
[49]	'20	PEF	CY, GR	y	r	p	h	'17	o	a	PE of a solar-driven organic rankine cycle in two European countries
[6]	'20	CI PEF	EE, ES, FI, GR, UK	y	r	p	h	'15	o	a	PE and CE of a HP in five European countries
[25]	'19	CI PEF	GR	y	r	p	h	'05, '16[6]	o	a	PE and CE of an LED lighting system in a school building in Greece
[50]	'19	PEF	FR, RO	y	r	p	h	'16	o	a	PE savings when a PVT system is added to two residential buildings in France and Romania
[22]	'19	CI	BG, ES, DE, NL, NO	h	r	p	h	'18	o	a	CE savings of demand-side response technology in five countries
[51]	'20	CI	DE	h	r	p	h	'19	o	a, m	CE savings of industrial scale batteries at 50 small and medium size companies in Germany
[52]	'20	CI	DK	h	r	c	h	'17, '18	l	m	CE savings of a controlled HP in Denmark
Individual building level											
[53]	'18	CI PEF	SE	y	r	p	o	na	o	m	PE and CE of a multi-family building In Sweden
[14]	'17	PEF	FI	y	r	p	h	'15	o	a	PE and CE of a single apartment building in Finland

[54]	'19	PEF	IT	y	r	p	h	'15	o	a	PE of a multi-family building in Italy
[55]	'19	PEF	IT	y	r	p	h	'14	o	a	PE of a single-family building in Italy
[56]	'19	CI PEF	CZ	y	r	p	h	'08	o	a	PE and CE of a 'reference building' in Czechia
[57]	'19	CI PEF	SE	y	r	p	h	'16	l	a	PE and CE of a single-family building in Sweden
[58]	'20	CI PEF	SE	y	r	p	o	na	l	m	PE and CE of a multi-family building in Sweden
[59]	'19	PEF	IT	y	r	p	h	'14	o	a	PE of an office building in Italy
[60]	'18	CI PEF	CH	h	r	c	h	'15	l	a	PE and CE of a building in Switzerland
[61]	'18	CI	DK	h	r	c	h	'13-'16	o	a	CE of a single-family building in Denmark
[62]	'17	CI	DK	h	r	c	h	'15	o	a	CE of a single-family building in Denmark
[63]	'18	CI	ES	h	r	p	h	'16	o	a, m[7]	CE of a multi-family apartment building in Spain
[64]	'19	CI PEF	IT	y	r	p	h	u	o	a	CE of a hotel building in Italy, connected to EVs
[65]	'19	CI PEF	CH	h	r	c	h	'16-'18	l	a	PE and CE of a single-family building in Switzerland
[66]	'21	CI PEF	GR	y	r	p	h	'18	o	a	PE and CE of an office building in Greece
[67]	'21	CI PEF	ES	y	r	p	h	'13	o	a	PE and CE of a commercial center in Spain
[68]	'20	CI PEF	ES	y	r, p	p	h, o	'18	o	a	PE and CE of a single-family building in Spain
[69]	'21	PEF	IT	y	r	p	o	u	o	a	PE of a greenhouse building in Italy
[70]	'20	PEF	PL	y	r	p	o	u	o	a	PE of an advanced ventilation system for a multi-unit residential building
[71]	'20	PEF	IT	y	r	p	o	u	o	a	PE of a wine cellar in Italy
[72]	'20	CI PEF	UK	y	r	c	h	'19	l	a	PE and CE of (a multi-energy system to partially cover the energy needs of) an office building in the UK
[73]	'20	CI PEF	PL	y	r	p	h	'17	o	a	PE and CE of a nursery building in Poland
[74]	'20	CI PEF	IT	y	r	p	u	u	o	a	PE and CE of a non-residential building in Italy
[75]	'20	CI PEF	IT	y	r	p	h, u[8]	'13, u[8]	l	a	PE and CE of a 'typical' residential building in Italy
[16]	'20	PEF	IT	y	r	p	h	'14	o	a	PE of a historic museum building in Italy
[17]	'20	CI PEF	ES	y	r	p	h	'13	o	a	PE and CE of an apartment building in Spain
[7]	'20	PEF	SE	y	r	p	o	u	o	a	PE of an office building in Sweden
[18]	'20	CI	NO	y	r	p	h	'12	l	a	PE of a residential building in Norway
[76]	'19	PEF	IT	y	r	p	o	na	o	a	PE of an office building in Italy
[20]	'19	CI	EU, IT	y	r	c	h	'13	l	a	PE of a (proposed) residential building in Italy
[77]	'19	CI	DE	y	r	p	h	'13	o	a	PE of a school building in Germany
Multiple buildings level											
[15]	'19	CI	SE	y	r	p	h	'13-'15	o	a	CE of a range of Swedish buildings

[78]	'17	CI PEF	BE	h	r, p	p	h	'14-'15	o	a	CE and PE of two Belgian buildings (one terraced, one detached)
[79]	'21	CI PEF	IT	y	r	p	h	'18	o	a	PE and CE of a condominium of 87 residential buildings in Italy
[80]	'17	CI	FI	h	r	p	h[9]	'11	o	a	CE of three residential buildings and two commercial buildings in Finland
[81]	'20	CI PEF	CH	y	r	p	h[10]	'16,'18	o	a	PE and CE of several multi-family buildings in Switzerland
[82]	'20	CI	CY, ES, FR, GR, IT, PT	y	r	p	h	'16	o	a	CE of buildings in 26 Southern-European cities, spread across six countries
[19]	'20	CI PEF	ES	y	r	p	h	'13	o	a	PE and CE of a technology park in Barcelona
[11]	'19	PEF	EE, FI, NO, SE	y	r	p	h	'13, '17[11]	o	a	PE of apartments in Norway, Sweden, Finland and Estonia
[83]	'19	CI	FI	m	r, p	p	h	'11-'15	o	a	CE of several generic apartment buildings in Finland
[8]	'19	CI	DE	y	r	p	h	'17	o	a	CE of several wine producing facilities in Germany
[84]	'20	CI	SE	h	r	c	h	'19	o	m	CE of (a multi-energy system to partially cover the energy needs of) a technology campus in Sweden
[85]	'20	CI	FI	m	r	p	h	'11-'15	o	a	CE of (a DH system to serve the heating needs of) a cluster of four residential buildings in Finland
[86]	'21	CI	EU, NO	y, h	r	c	h, o	'16	o	a, m	CE of a neighbourhood in Norway
[10]	'21	CI	EU, NO	y	p	p	o	na	l	a	CE of a neighbourhood in Norway
[87]	'19	CI	EU, NO	y	p	p	o	na	l	a	CE of a neighbourhood in Norway
[12]	'19	PEF	ES	y	r	p	h	na	l	a	PE of multi-family buildings in several climate zones in Spain
[21]	'21	PEF	ES	y	r	p	h	na	l	a	PE of multi-family buildings in several climate zones in Spain
Municipality level											
[88]	'19	CI	HR	y	r	p	h	'16	o	a	CE of the city of Zagreb
[89]	'18	CI	IT	y	r	p	h	'11	o	a	CE of 16 municipalities in Italy
[90]	'19	CI	IT	y	r	p	h	'16	o	a	CE of the municipality of Évora
[91]	'18	CI	IT	y	r	p	h	'06,'08	o, l	a	CE of the municipality of Licata
[92]	'20	CI	IT	y	r	p	u	u	o	a	CE of small districts in Naples and Turin
[93]	'20	CI PEF	IT	y	r	p	h	u	o	a	PE and CE of (a multi-energy system to partially cover the energy needs of) a district in Naples
[94]	'20	PEF	IT	y	r	p	h	'14	o	a	PE of a district in Milan
[24]	'19	CI PEF	AT	y	r	p	h	u	o	a	PE and CE of (a multi-energy system to partially cover the energy needs of) a district in Vienna
[9]	'19	CI	8[12]	h	r	c	h	'17	o	a	CE of energy communities in eight European countries
[95]	'20	CI	DE	y, h	r, p	p, c	h, o	'18	o	a	CE of a district heating system for the city of Heide
[13]	'18	PEF	ES	y	r	c	h	'91-'13	o	a	PE of the autonomous community La Rioja
Building stock level											
[96]	'19	PEF	DK	y	p	p	o	na	o	a	PE of the 2050 Danish building stock
[97]	'19	CI	28[13]	y	r	p	h	'12	o	a	CE of various national building stocks in 2012 and 2030

[98]	‘18	CI	DE, ES, FR, SE, UK	y	r, p	p	h	’09-‘12	o	a	CE of a representative building stocks for five European countries
[99]	‘18	CI PEF	CH	y	r	p	h	‘15	l	a	CE and PE of a synthetic building stock representing Switzerland
[100]	‘21	CI	28[13]	y	r	p	h	‘15	o	a, m	CE of heating electrification in 28 European countries
Electric vehicles											
[101]	‘19	CI	DE	h[14]	r, p	p	h, o	‘16	l	a	CE of electric busses in Germany
[5]	‘18	CI	EU, 28[13]	y	r	c	h	‘13	l	a	CE of EVs in 28 European countries
[102]	‘17	CI	DE, FR	h	r	p	h	‘13	o	a	CE of EVs in France and Germany
[103]	‘18	CI	CZ, PL, o	y	r, p	p	h	‘15	l	a	CE of EVs in Poland and Czechia
[104]	‘18	CI	SI	y	r	p	h	’09-‘14	o	a	CE of EVs in Slovenia
[105]	‘20	CI	IT	y	r	p	h, o	‘14	o	a, t	CE of EVs in Italy
[106]	‘20	CI PEF	EU	y	r, p	p	h, o	’18, ‘19	o	a	PE and CE of EVs in Europe (as a whole)
[107]	‘19	CI	ES	h[15]	r, p	p	h, o	‘17	o	a	CE of electric busses in Spain
[108]	‘20	CI	EU	y	p	p	o	na	o	a	CE of EVs in Europe in the year 2050
[109]	‘20	CI	UK	y	r	p	h	‘17	o	a	CE of EVs in the UK
[110]	‘20	CI	ES	y	r, p	p	h, o	‘16	o	a	CE of EVs in Spain
[111]	‘20	CI	EU	y	r, p	p	h, o	‘17	o	a	CE of EVs in Europe
[112]	‘20	CI	PL	y	r	p	h, o	‘18	o	a, t	CE of EVs in Poland
[113]	‘20	CI	UK	h[16]	r	c	h	’18, ’19	o	a	CE of EVs in the UK
[114]	‘21	CI	DE	h	r	p	h	‘17	o	m	CE of EVs in Germany
Other PE and CE calculations											
[115]	‘21	CI	UK	h[16]	r	c[17]	h	‘19	o	m	Calculation of marginal CIs for the UK, to assess the CE-impact of storage operation
[116]	‘20	CI	GR	y	r	c	h	‘14	o	a	CE of a highway in Greece
[117]	‘20	CI	EU	y	r, p	p	h, o	‘15	o	a	CE savings when electrifying European industry
[23]	‘19	CI	EU, NO	y	p	p, c	o	na	o	a, m	CE savings when electrifying offshore oil platforms
Calculation, analysis and forecasting of CFs themselves (without a concrete PE or CE calculation)											
[26]	‘18	CI PEF	IT	h	r	p	h	’12-‘17	o	a	Calculation and analysis of hourly PEFs and CIs, based on historical data from the Italian TSO
[118]	‘17	PEF	SE, EU	y	r	p	h	‘14	l	a	Novel calculation of the PEF_T of nuclear, and its impact on the Swedish and European PEF
[27]	‘19	CI PEF	IT	h	r	p	h	’16,’17	o	a	Calculation of hourly PEF and CI
[28]	‘18	CI PEF	CH	h	r	c	h	‘15	l	a	Calculation and analysis of hourly PEFs and CIs for Switzerland
[119]	‘18	CI	DK, NO, SE	h	r	c	h	‘16	l	a	Calculation of hourly CIs for Denmark, Norway and Sweden
[120]	‘19	CI	6[18]	h	r	c	h	‘15	l	a	Calculation of hourly CIs for six Northern-European countries
[121]	‘18	CI	FR	h	r	c	h	’12-‘14	l	a	Calculation of hourly CIs for France
[122]	‘19	CI	28[13]	h	r	c	h	‘17	l	a	Calculation and analysis of hourly CIs for 28 European countries
[123]	‘20	CI	DK	h	p	c	o	na	o	m	Short-term forecasting technique for marginal CIs

[124]	'20	CI	IT, UK[16]	h	p	p	h	'17, '18	o	m	Statistical technique to calculate marginal CIs
[125]	'21	CI	DE, DK, FR, NO, PL	h	p	c	h	'18, '19	o	a	Short-term forecasting technique for average CIs

Note: **Ref** = reference, **PD** = publication date **CF** = conversion factor used, **GS** = geographical scope of the CF (code of geographical areas like countries or the entire European area, the number of countries (further referenced below), or another approach), **TR** = temporal resolution (yearly, monthly or hourly), **TS** = temporal scope (is the CF calculated retrospectively or prospectively), **IP** = import perspective (production or consumption perspective on the CFs, cf. section 2.8), **DA** = data age (historical year on which the CF is based), **S** = CF source (is the CF purely based on historical data or on another approach), **AB** = assessment boundary (is the CF calculated from an operational or a life-cycle perspective), **MP** = market perspective (is the CF calculated as an average, a marginal value, or is a specific technology assumed). Notation "**na**" in any aspect column indicates 'not applicable', while notation "**u**" indicates 'unclear'. Table contents are limited to the PE and CE calculations associated with electrical loads in each study, ignoring other content and contributions. For supplementary notes on some of the studies included in Table 1, see Appendix B.

[1]: PEF calculation is only partially based on hourly historical data. Yearly values are used for all thermoelectric technologies.
[2]: Same 'partially hourly' approach as [3] with respect to PEF calculation.
[3]: Building characteristics are adapted to the typical circumstances in each of the seven countries (DE, FI, GR, IT, NL, SE, and UK) but European average CI and PEF values used for each case.
[4]: PEF simply assumed by authors to be 2.7, without providing a source.
[5]: The included countries are AT, CH, DE, DK, FR, IE, IT, NL, PL and UK.
[6]: The CI refers to 2005, while the PEF refers to 2016.
[7]: CIs are calculated from a marginal perspective, while PEFs are calculated from an average perspective.
[8]: The CI refers to 2013, while it is unclear what the source or reference year is for the PEF.
[9]: Hourly CIs are partially based on historical electricity production data for renewables and nuclear. The electricity generation by technologies for which data was not available is estimated with a capacity and dispatch optimisation model to cover the residual demand.
[10]: The CI refers to 2018, while the PEF refers to 2016.
[11]: The PEFs for Norway, Sweden and Finland refer to 2017, while the PEF for Estonia refers to 2013.
[12]: The countries included in the analysis are AT, BE, FR, DE, IT, NL, PT and ES.
[13]: The 28 EU Member States before Brexit.
[14]: CI in 2016 is calculated on the basis of quarter-hourly historical data from a German TSO. CE in future years (2017-2028) are calculated on the basis of yearly average CIs out of a German governmental report which made a rudimentary projection of CIs.
[15]: Hourly CIs are calculated on the basis of historical data for the year 2017. For future years up to 2030, yearly CIs are considered.
[16]: The actual temporal resolution is half-hourly
[17]: The consumption-based perspective focusses on flows within the UK, between several sub-national regions.
[18]: The countries for which CIs are calculated are DE, DK, FI, NL, NO and SE.

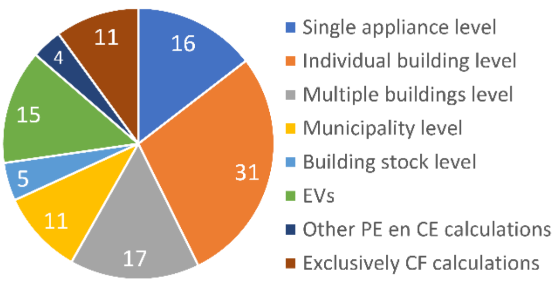

Figure 1: Number of studies per category in the literature sample

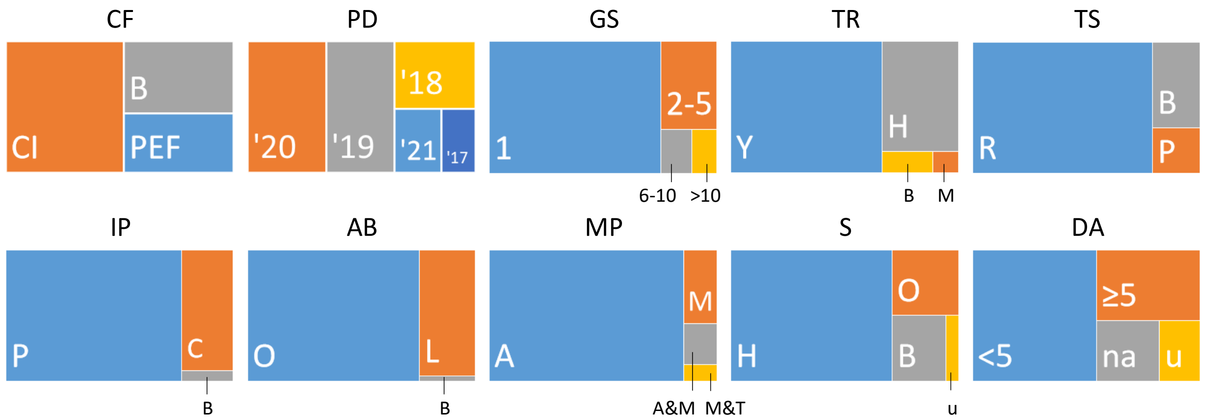

Figure 2: Distributions of methodological aspects in the literature sample

Note: for abbreviations, see Table 1. **GS** is shown here as the number of geographical areas considered. **DA** is shown here as the number of years between the publication date and the historical year to which the conversion factor(s) used in the study refers. **B** stands for both.

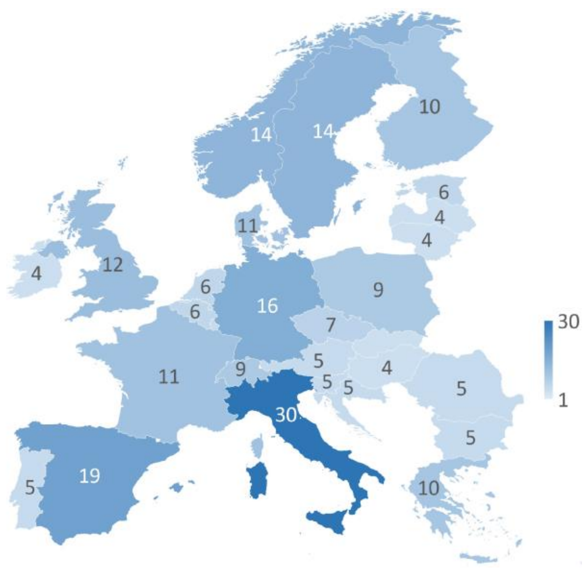

Figure 3: Geographical distribution of CFs calculated or used in the literature sample

Table 2: Other references discussing CF methodological aspects

Ref	PD	CF	Goal of Ref	Note
[30]	'16	PEF	Fraunhofer study procured by the European Commission to review PEF, PEF_T and PEF_F calculation methods	Detailed discussion of all possible PEF calculation methodologies with respect to PEF_T calculations for various technologies, GS, TR, TS, IP, S, AB and MP. *Not* a review of academic literature.
[31]	'19	PEF	Overview of PEF, PEF_T and PEF_F calculation methods of the IPCC, IEA, EIA and European legislative framework (EED and EPBD)	Stresses the fact that there are technical, political and economic dimensions to PEFs, which explains the current absence of a consensus on calculation methods. *Not* a review of academic literature.
[32]	'17	PEF	Evaluation of the use of PEFs at various TRs	Also investigates various methodological options for the application of PEFs on a building's own production – and injection into the grid – of solar power.

[33] '18	CI PEF	Overview of PEF and CI calculation methods	Specifically focusses on the aspects of temporal resolution and the choice between an average or marginal market perspective.
[34] '18	PEF	Calculation of PEF_T values for various technologies	Uncertainties about the input parameters in each PEF_T calculation (e.g. power plant thermal efficiencies etc.) are used to generate a *spread* of possible PEF_T values for each technology.
[29] '19	PEF	Calculation of PEF_T values for wind	Shows that not only a PEF_T value of 0 or 1 is possible for electricity from wind power, but also various other options, based on a range of methodologies considering different life-cycle aspects

Note: for abbreviations, see Table 1.

2.3. Geographical scope

In the literature sample, 83 out of the 110 studies (75%) use CFs representing only a single country. Most of them effectively ignore the fact that CFs are geographically variable and that their PE and CE results may therefore be highly specific to the single country they consider. This stands in sharp contrast with the fact that many studies explicitly mention the importance of considering the geographical variability of CFs (e.g. [5,11,41,43,47,120,126]). However, it should be noted that some of those studies only do so to acknowledge the fact that their use of only a single country's CFs forms an important limitation of the presented work. For example, in [43] the PE associated with a HP is calculated, and it is concluded that the results are highly sensitive to the assumed PEF. The authors then call for *future* research to replicate their analysis within the context of other countries – using a variety of geographically diverse PEFs.

To illustrate the diversity of national CIs across Europe, Table 3 presents the values calculated by Eurostat for the year 2019 [127]. A similar comprehensive overview of up-to-date national PEF values for European countries is currently unavailable, as discussed later. However, the literature sample indicates a significant geographical variability here as well, ranging from values of 1.4 and 1.6 that are used for Norway [11] and Sweden [57], to values of 2.5 and 2.7 that are used for The United Kingdom [72] and Luxembourg [46]. In twelve of the studies in the literature sample, CFs are used for Europe as a whole (cf. Table 1). Using European instead of national CFs has been shown to affect results [86], but the exact impact may differ from country to country.

Table 3: Overview of national CO_2 intensities (CIs) for European countries in 2019

Country	CI (g/kWh)
Austria	91
Belgium	167
Bulgaria	421
Croatia	145
Czechia	431
Denmark	126
Estonia	891
Finland	86
France	52
Germany	338
Greece	598
Hungary	212
Ireland	316
Italy	233

Latvia	117
Lithuania	22
Luxembourg	74
Netherlands	390
Norway	19
Poland	719
Portugal	244
Romania	293
Slovenia	231
Spain	207
Sweden	8
United Kingdom	228

Source: [127]. These are average values from a life-cycle perspective, which do not take into account imports (cf. sections 2.6, 2.7 and 2.8).

In the minority of studies actually using geographically diverse CFs, the value of doing so is confirmed across a range of applications. For example a number of studies show the importance of carefully considering CFs in the context of EVs. In [5], the CE associated with EVs is estimated using CIs for 28 European countries, showing a CE below 50 $gCO2_{EQ}$/km in some countries (FI, FR, SE) and up to approximately 200 $gCO2_{EQ}$/km in other countries (EE, LT, PL). Similarly, [106] considers the PE of EVs across Europe, Japan and the United States, and finds that the (generally) higher conversion efficiency of electricity production in Europe leads to a comparatively lower PE.

The importance of the geographic variability of CFs is demonstrated outside of the EV context as well. In [11], the PEFs of four Northern-European countries are used to assess renovation strategies for apartments. It was found that PEFs have an important impact on whether or not identical apartments in the different countries qualify as NZEBs. In [9], the CE reduction potential of energy communities is analysed, using CIs for eight European countries. The study finds that the benefits of intelligently controlling HPs, PV and energy storage across an energy community can be largely dependent on the CI of the considered country. Along the same lines, [22] finds that country-specific CIs have an important influence on the benefits of dispatching flexible electricity demand during peak hours.

By considering CFs for a range of different countries within a single study, a coherent comparison can be made of PE or CE results – showing how they can vary, depending on the constitution of the country-specific electricity mix. In contrast, comparing results for different countries across multiple studies (e.g. each considering the CE of EVs for a single country) can be problematic, because the used CFs may be based on a different historical year or vary in terms of their methodological characteristics.

The fact that – so far – most studies have failed to use geographically diverse CFs can be justified to a certain degree. Currently, authors are burdened with a significant amount of additional effort if they want to take geographical variability into account, because a public database of up-to-date CFs of European countries – estimated using a rigorous and transparent methodology – is currently unavailable (cf. section 3.1). Moreover, the varying weather conditions in different countries do not only affect the CFs but may also affect other aspects of the study, such as the electricity demands (e.g. for heating or cooling a building). Whenever the use of geographically varying CFs is not feasible, a sensitivity analysis of the CFs can be advised.

2.4. Temporal scope

87 out of the 110 studies (79%) perform PE and CE calculations that are purely *retrospective* in nature. Whenever this is the case, the results of a study are at risk of quickly becoming outdated, given the fact that CFs are continually changing due to the evolving electricity mix – as frequently mentioned across the literature [31,41,43,44,78,128]. Therefore, many studies recognise the value of taking the future evolution of the electricity mix into account, and use *prospective* CFs instead. The main reason why prospective CFs are expected to differ from retrospective CFs is the ongoing energy transition, whereby the penetration of renewable electricity generators is increasing all across Europe [41,43,44] and policy-driven phase-outs of nuclear and coal technologies are taking place in certain countries. Prospective CFs are typically calculated by simulating (scenarios for) the future electricity system using a model-based approach [51].

Prospective CFs are valuable across a range of applications. For example, they allow for future changes in the electricity mix to be taken into account when calculating the CE associated with charging EVs. Throughout an EV's operational lifetime, the CI associated with charging is likely to decrease, leading to a lower amount of CE compared to a situation in which a constant (historical) CI is assumed [129]. Similarly, neglecting the expected decrease in the future PEF can lead to a significant overestimation of the PE associated with HPs [31,44].

Still, a number of studies explicitly consider the long-term future in their PE and CE calculations, and assume (implicitly) that the applied CFs – which are based on historical data – will remain constant over time. For example, [54] uses a constant PEF in the context of finding the optimal design for a multi-family building in Italy, explicitly considering a period up to 2045. In [97], the CE of national building stocks is calculated for the year 2030, using a CI based on the year 2012. Similarly, [98] even assumes a constant CI while calculating the CE of building stocks up to the year 2050. There are several more examples of studies that consider the future while assuming constant CFs that are based on historical data for the assessment of apartment buildings [83], office buildings [66], technology parks [19] and EVs [109].

Forecasting the future evolution of the electricity mix and translating it into prospective CFs can be a challenging exercise, which explains the frequent use of simplified approaches across the literature. Some studies simply make a few high-level assumptions about the future penetration of renewable technologies [41,78,106], consider the projected electricity mix in governmental policies [110], or refer to other high-level scenario projections [108,111]. Others linearly extrapolate CFs, from a known historical value towards an expected future value (e.g. 0 gCO_2/kWh in the year 2050)[40].

2.5. Temporal resolution

73 out of the 110 studies (66%) exclusively make use of CFs with a yearly temporal resolution, ignoring temporal variations at the seasonal, monthly and even the hourly level. This stands in contrast with the fact that the importance of higher temporal resolutions is continually stressed in the literature – namely in the two studies using monthly CFs and the 35 studies using hourly CFs (cf. Table 1). For example, in [83] CIs with a monthly temporal resolution are used to devise optimal renovation measures for Finnish apartment buildings, while hourly CIs are used in [22,125] to calculate the CE savings made possible by dispatching flexible loads. Elsewhere, hourly CIs are used to better calculate (and to help minimise) the CE related to HPs [52,95] and EVs [113].

PE and CE calculations using a higher temporal resolution generate a *more accurate* result. In fact, many studies have purposefully sought and found differences between what may be called the 'yearly' and 'hourly method' [27,42–44,47,65,80,130]. For example, in [47] the difference between the outcomes of the yearly and hourly methods is analysed in the context of calculating the CE associated with HPs in ten European countries, showing that the temporal resolution of the CI can make a difference of 5% to 10%. Similarly, in [80] the CE of two residential buildings is calculated using yearly and hourly methods, finding a difference of up to 6%.

Deviations between yearly and hourly methods are not only important for the sake of accuracy in and of itself – they can also affect comparisons between the merits of different technologies. For example, in [43] HPs and gas condensing boilers (GCBs) are compared, and it is found that HPs result in significant PE savings compared to GCBs, but that the yearly method underestimates these savings by 8% when compared to the hourly method. Moreover, hourly values are expected to become all the more important to consider in the future, as their volatility increases due to the growing penetration of variable renewable energy sources (VRES)[27,33,40,43,48].

An important barrier to the use of hourly CFs is the fact that they are not generally available. The Danish Transmission System Operator (TSO) Energinet and the French TSO RTE actively publish hourly CIs – triggering analyses that make use of them [61,62,131] – but hourly CFs remain unavailable for other European countries. This forces researchers to calculate hourly CFs themselves, on the basis of historical electricity production data (e.g. [26–28,119–121]). When *prospective* hourly values are required, historical data cannot be used. In this case, the advanced methodologies required to calculate the necessary values can further impede the stated research goals – as demonstrated in [86].

2.6. Assessment boundary

83 out of the 110 studies (75%) consider CFs from a purely *operational perspective* (OP). This means that the CFs only include the PE and CE that is directly associated with the production of electricity. In principle, it is then possible for certain technologies to have a PEF_T of 0 kWh_P/kWh_E (wind, solar and hydro) or a CI_T of 0 g/kWh_E (all renewables and nuclear) – as explained in Appendix A. When an OP is used, the only thing that is potentially considered in addition to the generation of electricity itself, is its transportation from producer to consumer and the associated grid losses.

The alternative for an OP is a *life-cycle perspective* (LCP), which includes the PE and CE associated with the entire life-cycle of the power plants (construction, maintenance, deconstruction) and fuels (extraction, processing and transport). A LCP implies that PEF_T and CI_T values can no longer be zero, because a certain amount of PE and CE will always be associated with the non-operational aspects like construction.

LCP CFs are typically used in life-cycle analyses (LCAs), in which the entire life-cycle of buildings (e.g. [18,20]) or EVs (e.g. [5,101,103]) is taken into account, instead of only the operational impact. It then makes sense to apply LCP CFs to calculate the PE and CE associated with the operational electricity consumption to avoid methodological inconsistencies. Furthermore, LCP CFs are valuable as they provide a more holistic insight in the PE or CE related to various energy technologies used in the electricity mix.

Assumptions about CFs can be highly important in LCAs, because they co-determine the ratio between operational and embodied PE and CE. This ratio is a crucial output variable of LCAs, because a high share of embodied PE and CE is what confirms the added value of considering the non-operational aspects. In many of the LCA-related studies included in the literature sample, not only the importance of CFs is stressed, but also specifically the value of using *prospective* CFs (cf. section 2.4) and CFs with higher-than-yearly temporal resolutions (cf. section 2.5). For example, in [9] the CE associated with 'energy communities' is calculated across the life-cycle, and it is shown that both the seasonal dynamics and long-term evolution of the assumed CIs have a significant impact on the results for the operational CE.

2.7. Market perspective

94 out of the 110 studies (85%) make use of average CFs, which consider the entire mix of electricity generation from different technologies during a given period (e.g. a particular year or hour). An average CF is calculated as a weighted average, multiplying the electricity production by each technology (coal, wind, nuclear, etc.) with its respective PEF_T or CI_T value and dividing by the total aggregated electricity production.

The main alternative to using average CFs is using marginal CFs, which only consider the marginal electricity producer during a given timestep. This is the powerplant that would change its electricity production in response to an incremental change in electricity demand. A marginal CF does not need to be 'calculated', in the sense that it is simply equal to the PEF_T or CI_T of the marginal producer itself. However, it can be challenging to identify the marginal producer on the basis of historical electricity production data [51,124], and state-of-the-art techniques are required to generate short-term forecasts of marginal CFs [114,123]. As observed by [114], there is no directly observable 'ground truth data' with respect to marginal CFs, which means that statistically estimated values are sensitive to the applied assumptions. It can therefore be difficult to estimate marginal CFs with a high level of accuracy [115].

The choice between using average or marginal CFs can have a considerable impact on the outcome of PE and CE calculations [4,33,86,100,102], leading to intense debates about which kind of CF is most appropriate. The analysis of the literature sample indicates that this methodological choice is largely dependent on the application – although there is not always a consensus about which kind of CF should be used in which application. As explained by [115], marginal CFs are typically used to calculate the impact of intervening in the electricity system – for example by deploying an energy storage technology that withdraws and injects electricity from the grid. Using average CFs in this case would assume that all electricity generators respond to a change in grid load – potentially leading to an underestimation of the change in CO_2 emissions (as also noted by [51,124]). Therefore, some of the studies in which methods are developed to minimise the CE associated with HPs and EVs through demand side interventions use marginal CFs [52,114]. In [114], it is shown that using average CIs for these kinds of applications may even inadvertently lead to *increasing* CO_2 emissions.

Still, there is no consensus on whether marginal CFs should always be used in these cases. A significant amount of studies in the literature sample uses average CFs even though the impacts of demand side interventions are being evaluated [61,62,64,78,97,119–121]. In [119,120], the reasoning behind this is the fact that the interventions are evaluated within a framework which itself uses average CFs. The impact of a HP's demand response capability is evaluated using traditional BEP calculation methods, arguing that this is in line with the EPBD.

The *traditional* use-case for average CFs is any kind of PE or CE *accounting method,* that is meant to be applicable to all 'users' (e.g. *all* buildings or *all* EVs). Not only is it not feasible to consider all users as marginal, but even applying marginal CFs to *part of* the users can be problematic when 'accounting' PE or CE – because it implies that a lower-than-average CF needs to be calculated and applied to the other users. Otherwise the total amount of attributed PE or CE would no longer be correct. For this reason, [86] argues against the use of marginal CFs in the context of calculating the CE for a (new) neighbourhood, stating that any particular building should not be handled differently from all the rest (i.e. as the 'marginal building'). However, [86] *does* approve of using marginal CFs to calculate the PE-savings realised though PV grid-injection.

Given the fact that – in practice – buildings are subject to regulatory BEP calculation methods (e.g. to produce official EPCs), average CFs are also typically used in academic studies focussing on optimal building design [11,21]. Moreover, average CFs are dominantly used in the context of LCAs, both for buildings and other applications like EVs. In the literature sample, only two of the 27 studies that apply a LCP use marginal CFs [52,58]. Recently, a tool has been developed to aid researchers in their choice between average and marginal CFs [132], but the debate about which kind of CF to use for certain applications could remain unresolved for years to come.

Finally, it should be noted that it is sometimes claimed that average CFs are easier to calculate than marginal CFs [119,120]. However, in the complex reality of Europe's increasingly interconnected electricity grid, the calculation of both average and marginal CFs has become a highly non-trivial task – as discussed in the next section.

2.8. Import perspective

85 out of the 110 studies in the literature sample (77%) use CFs that only consider the electricity production within the country (or countries) they focus on. In line with [122], this can be called a *production perspective*. It ignores the fact that a country may be a significant (net-)importer of electricity that is generated abroad, which can affect CFs. For example, the average CI of Austrian electricity production (for the year 2017) has been estimated to be as low as 136 gCO_2/kWh, but the substantial imports from Czechia and Poland increase the CI of electricity consumed in Austria by 82% (to 248 gCO_2/kWh)[122].These kinds of effects are important to consider, as many European countries import a significant amount of the electricity they consume – especially at sub-yearly temporal resolutions (e.g. during specific months or hours)[133,134]. The alternative to a production perspective is a *consumption perspective*, whereby imports are no longer ignored. Using CFs that apply a consumption perspective may become increasingly important in the future, as the European electricity system becomes increasingly well interconnected. It has been recognised that failing to consider imports can lead to "significant distortions" [30], a notion that is echoed in many studies [5,42,47,57,62,65,119–122,135]. However, calculating CFs from a consumption perspective presents a considerable challenge – especially if hourly variations in the flows across the entire European network are considered.

Several approaches to take imports into account are found in the literature sample, ranging from highly simplified ones to the more complex state-of-the-art. The simplest approach is to assume constant CIs for the electricity that is imported from neighbouring countries, ignoring temporal fluctuations. For example, in [61,62] Danish imports from Germany are *always* attributed a CI of 415 g/kWh_E. This approach is also used in [113,116], in the context of estimating the CE associated with charging EVs in the UK. In a somewhat more advanced variety of this approach, hourly CIs are calculated for the countries being imported from [65,121]. Another simplified approach is to use empirically observed electricity market prices to identify the marginal electricity generator, which may be located in another country [136]. However, this approach can only be used to estimate marginal (as opposed to average) CFs from a consumption perspective.

The state-of-the-art methods for taking into account imports consider the complex flows across the entire European network as a whole, instead of imposing an arbitrary geographical boundary around countries. In [119,120], a technique based on multi-regional input-output models is used, which are widely applied in economics. The technique assumes a balance between the sum of electricity production and imports on the one hand, and the sum of electricity consumption and exports on the other - which is respected in every country node and timestep. A similar method called 'flow tracing' is developed in [122], and applied on historical data to calculate the difference between CFs from a production and consumption perspective for 27 European countries. For every historical hour, the CIs of each country are considered as vectors in a linear equation system, which can subsequently be solved – generating hourly CIs that take into account all flows across the European network.

3. Discussion

3.1. Available sources of conversion factors

The fact that most of the studies in the literature sample calculate CFs themselves can be explained by the fact that the externally available CFs are subject to a number of limitations. Table 4 provides a brief overview of these available sources. In addition to the sources presented in this table, a number of studies in the literature sample use CFs that are found in national building codes and regulations [7,11,24,25].

Table 4: Available sources of CFs

Source	CF	GS	TR	IP	AB	Ref	Limitations
IPCC	CI	EU 28	y	p	o,l	[91]	Outdated (due to the slow publication cycle) Highest temporal resolution is yearly Does not consider imports
GEMIS	PEF CI	EU 28	y	p	o	[137]	Outdated (based on EUROSTAT data 2010-2013) Highest temporal resolution is yearly Does not consider imports
EU JRC	CI	EU 28	y	p	o,l	[138] [139]	Outdated (latest version published in 2017, refers to historical data from 2001-2013) Highest temporal resolution is yearly Does not consider imports
IEA	CI	EU 28	y	p	o	[140]	Not publicly available Simplified aggregations of certain technologies Highest temporal resolution is yearly Does not consider imports
EnergiNet	CI	DK	h	c	o	[141]	Only for Denmark Simplified assumptions for CI of imports
RTE	CI	FR	h	p	o	[142]	Only for France Does not consider imports
Tomorrow	CI	EU 28	h	c	l	[143]	Historical dataset (since 2016) not publicly available, only the real-time values can be viewed
Ecoinvent	na	na	na	na	na	[144]	Only provides PEF_T and CI_T values for electricity generation technologies, not CFs for particular geographical areas
ENTSO-E	na	EU 28	h	na	na	[145]	Only provides historical electricity production data for each electricity generation technology (on the basis of which CFs for particular countries can be calculated).

Some technologies with different PEF_T and CI_T values are aggregated (e.g. 'gas'), limiting the accuracy of CFs calculated on the basis of this data source.

Note: **CF** = conversion factor used, **GS** = geographical scope of the CF (code of geographical areas like countries or the entire European area), **TR** = temporal resolution (yearly or hourly), **IP** = import perspective (production or consumption perspective on the CFs), **AB** = assessment boundary (is the CF calculated from an operational or a life-cycle perspective). Temporal scope and market perspective are not included in this table because all sources are retrospective and contain only average values. **Na** = not applicable.

The overview in Table 4 shows that – generally speaking – up-to-date, rigorously and transparently calculated CFs are not sufficiently available. This is problematic, because CFs are essential inputs for many kinds of academic and non-academic applications. The review of the literature sample also indicates that this is a widely recognised problem. Across a wide range of studies that use CFs for a variety of applications, the unavailability of a satisfactory database of CFs is frequently mentioned as an important research barrier [6,10,11,25,62,63,107,120,122,146]. For example in the areas of heating electrification [6], transport electrification [107] and zero emission neighbourhoods [86,87].

An ideal conversion factor database would help alleviate many of the issues raised in section 2, namely:

- The use of CFs for only a single country, whenever the analysis perfectly allows for (and would benefit from) the use of several geographically diverse CFs
- The use of retrospective CFs, whenever the analysis would benefit from using prospective CFs
- The use of yearly CFs, whenever higher temporal resolutions would benefit the analysis
- The use of purely operational CFs, whenever life-cycle CFs are more appropriate
- The use of CFs which ignore electricity imports from other countries

A few studies have focused on calculating CFs (as shown in Table 1), but they do not meaningfully expand upon the sources shown in Table 4 because they have not made their results publicly available. The exception to this is [147], but its database of calculated CFs is limited to values for Switzerland, and is based on the outdated reference year 2015. Generating and publishing an up-to-date database of CFs for all European countries would present a considerable modelling challenge, especially if it were to include both average and hourly CFs that take into account imports and project into the future. Ideally, a public database of prospective CFs for all European countries would be based on the best available scenarios and state-of-the-art simulation approaches. For example, by deploying a European electricity system model based on ENTSO-E's TYNDP 2020 scenarios [148].

3.2. Transparency in conversion factor calculations

The literature sample indicates that full transparency about the calculation procedure behind the used CFs is unfortunately rare. In many studies, transparency is found to be weak or even completely lacking. For example, in many cases the value of the assumed CFs is simply mentioned, without providing any information about where the value comes from or how it was calculated [46,57,69,70,75,92,93]. Not even the assumed value of the used CFs is always provided [149].

Weak transparency is also common in studies that are performed in a governmental context. National and local governments often employ ad-hoc methodologies to calculate CFs – which are then used to measure progress towards policy goals of reducing the PE or CE of a country, city or municipality by a certain amount [29,31,98]. As noted by [150], the CIs used by municipalities in the context of the *Covenant of Mayors* programme are also often *self-declared*. Others explicitly use CIs from one of the sources mentioned in Table 4, which are often severely outdated and lacking in terms of transparency about the applied calculation methods [150,151].

Overall, it is clear that there is a strong need for CF calculation methods to be harmonised across Europe, as also stressed by [29]. The CEN has developed a standardised protocol to calculate CFs [36,37], but it leaves open all of the methodological 'options' that are discussed in section 2 to its users. At best, this standard will help improve the transparency of CF calculations and increase the degree to which various methodological aspects are actively considered, but it is unlikely to lead to a significant harmonisation. A widely used conversion factor database *could* contribute towards that goal, if the included CFs are not only calculated in a *transparent* way, but also in a *harmonised* way (i.e. across the included European countries). If several future studies used the same coherently calculated values from such a database, their PE and CE results could be more easily compared. Moreover, if the database would include several kinds of CFs (e.g. average, marginal, operational and life-cycle CFs), it could also be used for a wide range of applications.

3.3. The limitation of using historical data to calculate conversion factors

Most studies in the literature sample make use of historical electricity production data to calculate CFs – namely 78 out of the 110 studies (71%). As shown in Table 1, 13 studies base their CFs on historical data referring to electricity production that took place four years before they were published. A further 27 studies make use of data that is five or more years older than the publications themselves, which is 35% of all studies that make use of CFs based on historical data. Notably, three of those studies make use of data that is even ten or more years older [56,91]. In other words, the PE and CE results in many studies are immediately outdated upon publication. This is another problem that can be attributed to the unavailability of an up-to-date and comprehensive database of CFs for all European countries, and one that could especially be addressed if an available database would also include prospective values. The only case in which the use of historical data that is five or more years older is perfectly appropriate, is when it is explicitly the goal to calculate the PE or CE for a specific range of historical years. For example in [13], where PEFs are used to track progress in the Spanish residential sector between 1991 and 2013.

3.4. Endogenous conversion factors

All the studies presented in Table 1 use exogenous CFs. This means that the CFs they use are assumed to remain unaffected by the consumption of electricity that is being considered. This is an obvious methodological choice in most cases, namely when the PE or CE related to an individual appliance, building or EV is calculated. Given the fact that it is reasonable to assume that the examined electrical loads do not meaningfully affect the large-scale electricity system, this kind of calculation presents an 'ideal use-case' for exogenous CFs. For other kinds of calculations – in which the PE or CE is calculated for electrical loads on a much larger scale – exogenous CFs may still be used, but the methodological choice of doing so is more debatable. For example, when instead of considering an individual HP, renovation measure or EV, their large-scale *roll-out* at the societal level is considered. These kinds of *'roll-outs'* – as they are henceforth referred to – are also studied widely in the literature (e.g. [100,106,108,126,152–158]).

If roll-outs cause a significant change to the societal electricity demand, the electricity system (i.e. the supply side) will have to adapt. Instead of using exogenous CFs, it may then be desirable to endogenously model the electricity system as part of studying the roll-out's impacts. For the sake of a clear taxonomy, this can be labelled as "using endogenous CFs". The studies that do this are not included in Table 1 or in the systematic review of section 2, given the fact that the PE and CE of the electricity system are calculated directly and CFs are no longer used explicitly.

It is challenging to endogenise the electricity system in a way that fully captures the interactions between the supply and demand sides, especially while keeping the integrated model computationally manageable. Therefore, both the demand and supply sides are often represented in a highly simplified way, leading to a number of limitations. On the supply-side, the electricity system is usually represented in a rudimentary way, at least compared to state-of-the-art electricity system models [153–155]. For example, by (sharply) reducing the number of electricity generation technologies and included countries – simplifying or even ignoring imports from the surrounding area. On the demand-side, simplifications are typically made to the representation of the electrical loads that are being considered. For example, when a large-scale roll-out of HPs is being studied, the hourly space heating demands of the entire building stock may simply be based on heating degree data, ignoring the complexity related to building physics and real-world heating behaviour [158]. Similarly, studies that endogenise the electricity sector to estimate the CE-impact of EV roll-outs may rely on a simplification of driving and charging behaviour [159,160]. Even though the endogenisation is meant to improve the understanding of a roll-out's impacts in terms of PE and CE, these kinds of simplifications can potentially counteract (some of) the expected gains in the accuracy of the calculations.

Moreover, it should be noted that – even though the electricity sector is endogenised and the additional demand associated with the roll-out is considered – other changes in electricity demand typically remain out of scope. For example, while a change in the electricity sector's PE or CE may be studied as a result of an EV roll-out, the impacts of electrification in the heating and industrial sectors – which may very well impact the same electricity system during the future period that is being studied – could still be ignored [159,160]. Such a partial analysis may invalidate claims about how the electricity supply side would respond to the analysed roll-out, as the dynamics of that response may be different in practice due to the simultaneous electrification of other sectors.

Given all of these drawbacks of endogenised approaches, many studies in the literature sample choose to apply exogenous CFs, even when large-scale roll-outs are being considered [96–100,106,108–110,113,117]. In these studies, the use of exogenous CFs allows for other modelling aspects (on the demand side) to receive a greater amount of attention. For example, studies focussing on the PE-savings realised by rolling out certain building renovation measures at scale can choose to focus their efforts on a more realistic BEP model – by including a multi-zonal heating representation, behavioural aspects like rebound effects, or a more detailed representation of technical installations like HPs. Similarly, a study focussing on the CE associated with a large-scale EV roll-out can resort to using exogenous CFs in order to pay greater attention to aspects like driving behaviour [109]. The consideration of other aspects can be 'crowding out' the endogenisation of the electricity system from a methodological point of view, but their net benefit may still be positive. Choosing for exogenous CFs in the context of analysing roll-outs can therefore be entirely legitimate.

3.5. PEFs in the context of official BEP assessments

In addition to the overarching methodological discussion of the previous subsections, it is important to shed a light on two crucial conversion factor applications, namely official building energy performance assessments (discussed in this subsection) and smart grid algorithms (discussed in the next subsection).

Across Europe, PEFs are used in the calculation methods for official BEP assessments, for example when producing EPCs that are used to inform owners and potential buyers about a building's energy performance. The PEF's value co-determines how buildings – as well as the associated technologies and policies – are evaluated. Therefore, it has been the subject of considerable debate.

The 2012 Energy Efficiency Directive (EED) proposed a European PEF of 2.5, based on an assumed 40% average thermal efficiency in the European electricity system [161]. In 2016, the European Commission procured a study to evaluate the PEF, which concluded that the value should be updated (lowered) to better reflect the current state of the European system – which is seeing a continually increasing share of renewable electricity generation [30]. The 2018 revision of the EED confirmed this by stating that the PEF "should be reviewed", although a new value was not proposed in the Directive itself. Therefore, the outdated value of 2.5 is still being widely used today. This PEF is purely retrospective in nature, applies a yearly temporal resolution, and applies an operational perspective (cf. section 2).

Ideally, Member States would adopt national PEF values that are up-to-date and better reflect national circumstances than a European average. They are allowed to do so, but they are unfortunately not obliged to be transparent or to use a particular methodology [29,161]. Therefore, it is unclear how the various national values that are already in use across Europe were calculated, and whether or not they can be mutually compared in a consistent manner [31].

Potentially, the adoption of the recently released CEN standard EN17423 will help alleviate this problem [36,37], although many methodological choices are left to the user. This means that Member States using it would not necessarily calculate CFs in exactly the same way. Ideally, Member States would carefully consider the drawbacks and benefits of the different methodological options (cf. section 2). This could result in a more widespread use of higher temporal resolutions, prospective PEFs, and PEFs which take into account imports – positively affecting official BEP assessments (like EPCs). Adopting such PEFs in official BEP assessments is entirely feasible in principle, although an official institution (e.g. the European Commission) would need to deploy its modelling tools (e.g. PRIMES and METIS)[162,163] to calculate these PEFs in the first place, and provide them to the Member States. In the meantime, the academic publication of a database containing prospective and hourly PEFs could facilitate an improved understanding of precisely how they would affect EPCs in various countries – each containing different kinds of buildings and local climates.

Prospective PEFs would enable the PE associated with a particular building to be projected for a period of 10 or 20 years. This would better approximate the PE that should actually be expected from a building in the foreseeable future (i.e. across its lifetime), compared to the current (implicit) assumption that the PEF will remain constant over time. It is possible that a building that does not reach a regulatory PE target (e.g. NZEB) under a constant (retrospective) PEF, *does* reach the same target when a prospective PEF is used [11]. Moreover, prospective PEFs can reveal that certain technologies are more beneficial in the longer term (e.g. because a HP benefits from improvements in the electricity mix, unlike GCBs)[128]. Meanwhile, hourly PEFs could better take into account the PE associated with temporal fluctuations in a building's electricity demand. This may be especially useful when a building's hourly electricity demand fluctuates heavily, for example when a HP is combined with PV. EPCs that take these kinds of methodological improvements into account may present a more accurate picture.

3.6. Conversion factors in the context of developing smart grid algorithms

Another application of CFs is the development of smart grid algorithms (SGAs), which is a generic term used here for the sake of clarity and conciseness. SGAs can be defined as techniques to optimally schedule electrical loads from individual appliances, buildings or EVs. Traditional research challenges in the development of SGAs include dealing with uncertainty and combining different optimisation objectives. In the literature sample, it is found that many studies can be associated with SGA-development in one way or the other [44,48,60–62,78,80,120,164]. Each of these studies explicitly uses either PEFs or CIs as (one of the) control signal(s) in their SGAs. By helping to reduce the PE and CE associated with various electrical loads, SGAs can make an important contribution to the realisation of the European climate and energy policy goals.

CFs that are both prospective and have an hourly temporal resolution are *especially* useful in the context of SGAs. The increasing volatility of hourly CFs as a result of the future increase in the VRES penetration can have a substantial effect on the PE and CE reductions that can be achieved with SGAs [48]. Projecting the future profiles of hourly CFs in every European country would therefore enable an assessment of the future performance of SGAs all across the continent. However, a database containing such profiles has so far remained unavailable – as previously explained. Therefore, current studies using hourly CFs in the context of SGA-development have remained limited to retrospective values based on historical data. For example, to assess the CO_2 emissions that can be avoided by intelligently scheduling HPs [61,62,100,131], EVs [114], stationary battery storage [51,165], or simply a generic demand response technology [22,125]. Each of these studies has gone through the effort of calculating hourly CIs themselves, using a variety of approaches. Other studies simply mention the fact that the unavailability of the appropriate (hourly) CFs forms an obstacle to the further development of SGAs [26,119,120].

In practice, the concrete implementation of SGAs – e.g. in the form of algorithms for HPs or EVs to minimise their PE or CE through the intelligent scheduling of their electrical loads – will eventually require short-term forecasts of CFs to become available. Producing these forecasts lies entirely within the realm of possibility, since ENTSO-E already continuously produces 72h forecasts of the hourly electricity production across Europe, as noted by [119,120]. Moreover, a number of forecasting methods have already been developed in the recent literature – both for average and marginal CFs [52,123,125].

4. Conclusion

PEFs and CIs for electricity play an important role in the context of the European energy transition and the associated policy goals with respect to reducing the EU's PE and CE. These conversion factors help track progress towards the policy goals, and they enable comparisons between different technologies and measures that can play a role in reaching them. More specifically, they co-determine the PE and CE that should be associated with individual appliances like heat pumps, entire buildings (e.g. before and after renovation measures) and EVs. As heating and transport services continue to be electrified, the importance of these conversion factors will only increase in the coming decades. To better understand the ongoing energy transition and to support future policies aimed at accelerating it, PEFs and CIs therefore need to be carefully assessed.

In this context, a first of its kind 'systematic review' of how CFs are actually calculated and used in recent academic literature was performed. For each of the 110 studies included in the literature sample, six methodological aspects concerning CFs were evaluated, leading to the following findings.

For four of the methodological aspects, it is found that a majority of studies chooses for what is arguably an inferior approach (Figure 1). Namely, to only consider the CF of a single country (75%), to apply a purely retrospective perspective (79%), in which case, historical data that is five or more years old is often used (35%), to apply a yearly temporal resolution (66%), and to ignore electricity imports from other countries (77%). This stands in contrast to the fact that many studies across the literature sample have shown that considering the spatiotemporal variability of CFs (including in the foreseeable future) and considering imports can all have an important added value when calculating the PE or CE associated with a particular load. For example, calculations of the current PE and CE associated with HPs and EVs can benefit from a consideration of CFs for different European countries, as well as from CFs with an hourly temporal resolution. More accurate assessments that also shed a light on cross-country differences improve the understanding of the merits of different technologies and thereby contribute to policies aimed at reaching certain PE or CE goals.

Calculating CFs for a large number of European countries and simultaneously taking into account imports forms a considerable modelling challenge, although the required techniques including 'flow tracing' have recently been developed in the literature. However, these techniques have only been used scarcely so far, and the existing applications have remained limited to the calculation of retrospective CFs. Prospective CFs could provide a particularly significant added value, because they allow PE and CE calculations to take into account future developments in the electricity mix. For example, when calculating the expected CE of a particular HP or EV across the coming ten years. Moreover, if prospective CFs also have a high temporal resolution, then the expected trends in the seasonal and hourly variability of the electricity mix can also be taken into account, further improving PE and CE calculations.

It is also found that most studies use average CFs (85%) as opposed to marginal CFs, and apply an operational rather than a life-cycle perspective (75%). The debate between average and marginal CFs is still ongoing. With respect to the use of CFs that apply an operational versus a life-cycle perspective, the dominant use of the former can simply be seen as a matter of scope. Most studies do not yet apply a life-cycle perspective because of the additional effort and assumptions that are often required to do so. In any case, future research in which the PE or CE of any electrical load is calculated should not only consider the choice between average and marginal CFs, or between operational and life-cycle CFs, but *each* of the methodological aspects that are dealt with in the present review. All options with respect to CFs should be carefully considered, and choices should be clearly explained. In the present review, it is found that such transparency about CFs is unfortunately still missing in many recent studies.

A few of the studies in the literature sample have focused exclusively on the calculation of CFs itself. However, none of them have made their calculated CFs publicly available (with the exception of a single study which calculated CFs for Switzerland in the year 2015). A number of sources for PEFs and CIs are publicly available, but each of them is either severely limited geographically (e.g. the Danish TSO's publication of hourly CIs) or heavily outdated (e.g. the IPCC, GEMIS and EU JRC databases). Moreover, none of them take future evolutions in the electricity mix into account.

An ideal database would contain CFs that have each of the desirable characteristics described above, and are calculated in a coherent and transparent manner. This would be valuable for a number of reasons. First of all, such a database would substantially support future calculations of the PE and CE associated with individual electrical energy demands. Secondly, the CFs could be used to calculate the

PE and CE associated with large-scale roll-outs of HPs or EVs, as demonstrated by several studies included in the review. Third, it would allow for a critical evaluation of the regulatory CFs that are currently used in official BEP assessments across Europe (e.g. in the context of generating EPCs). Fourth, it would allow for a meaningful *comparison* of CFs across European countries, in terms of yearly averages, seasonal dynamics, hourly volatilities and the degree to which CFs are co-determined by imports –both now and in the foreseeable future. Finally, such a database would also support the process of developing *new* BEP assessment methods and SGAs, which can contribute to the European energy and climate policy goals as mentioned by several of the reviewed studies. Nonetheless, such a database remains unavailable at the time of writing – hindering progress towards alleviating the current literature's methodological issues with respect to CFs, as they have been explained in this review.

As noted by the landmark study procured by the European Commission in 2016, generating this type of database would require "very complex power sector model calculations which […] would have to be carried out using a highly detailed European model." [30, p. 39]. Given the strong need in the literature, the authors are currently developing such a model that will be used to generate the desired database, so it can be analysed and made publicly available for future applications in which CFs are used.

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6. Appendices

Appendix A: Differentiating different kinds of conversion factors

In this paper, the term 'primary energy factor' is used as a synonym for what is sometimes more specifically called the 'primary energy factor for electricity'. For every unit of grid-electricity consumed by an appliance, building or EV, it indicates the amount of associated PE taking place in the electricity system. It should therefore be distinguished from the primary energy factors associated with specific electricity generation technologies, which are called "PEF_T" values in this paper. For example, electricity from a nuclear power plant may have a PEF_T of 3 kWh_P/kWh_E, and electricity from renewable technologies like wind and solar may have a PEF_T value of 0 or 1 kWh_P/kWh_E [30]. Furthermore, primary energy factors can also be defined for specific *fuels*, denoted here as PEF_F. A fuel like natural gas can have a PEF_F higher than 1 kWh_P/kWh_F (primary energy per kWh of fuel, measured as the energy stored in the fuel's chemical bonds) if life-cycle aspects are considered. For example, the PE associated with fuel extraction, processing and transport.

With respect to CIs, a distinction can be made between conversion factors considering the emissions of several greenhouse gases (GHGs) and expressing them together in terms of CO_2 *equivalents* (e.g. as used in [18,75,115]), and conversion factors considering CO_2 emissions alone (e.g. as used in [25,102,108]). When conversion factors for CO_2 *equivalents* are used, authors rarely discuss the specific GHGs that are being considered. These two varieties of emissions-related conversion factors are both denominated as "CI" in the present paper. Not only for the sake of conciseness, but also because differentiating between the two throughout the presented literature review is considered out of scope. The expression "CE" is thus used interchangeably as well, referring both to CO_2 emissions and CO_2 equivalent emissions, depending on the publication being discussed.

Appendix B: Supplementary information accompanying the literature sample

Table B.1: Supplementary information about the studies included in the literature sample

Ref	Note
Single appliance level	
[40]	Yearly average CI calculated by linearly extrapolating from the latest available historical value of each of the four countries, down to zero in the year 2050. Finds that the battery can increase PV self-consumption and reduce both the CE and peak demand associated with the HP.
[41]	'Current' PEF calculated on the basis of historical data (2014). 'Future' PEF calculated by adjusting wind and solar capacities to the values found in external scenarios (from ENTSO-E) and performing a simplistic estimation of the capacity factor of other technologies, given those renewable capacities. PE savings are estimated on the basis of changes in the consumption of gas in (a) buildings and (b) the electricity system.
[42]	Assumes both a PEF_T of 0 and 1 for VRES (calculating PE in each case).
[44]	Also performs an integrated analysis at the national level (i.e. taking into account the impact on PEF if there would be many such HP + TES installations). The same endogenously calculated PEF is used in the analysis at the individual appliance level.
[45]	CI value is based on historical data (EEA calculation for the year 2014). Several PEFs are used; the traditional European average value of 2.5 established in the 2012 EED, the 2.0 'updated' value proposed by [30] and a value of 1.8 which is assumed to be a good estimate of the future PEF.
[47]	Purpose of the study is to identify the difference in results when hourly CIs are used instead of yearly CIs.
[48]	Operation of the HP is optimised to minimise CE on an annual basis, by using the hourly CI as a control signal. The CI calculation method is analogous to the one used in [119,120].
[50]	PEF is derived from the average (estimated) conversion efficiency of electricity generation in France and Romania (respectively), based on historical data from the European Environmental Agency
Individual building level	
[53]	Potential renovation scenarios for a particular building are simulated. For each scenario, PE and CE related to the building's electricity demand is calculated. PEF and CI are 'calculated' by assuming that a coal plant is always marginal in Sweden, and that coal plants have a thermal efficiency of 35%.
[14]	PE and CE calculated for a variety of renovation scenarios for the building in question. PEF values based on a governmental report, the values of which are based on historical data. The building is thought to be representative of many such typical apartment buildings across Finland and comparable geographies.
[54]	Building design is optimised on the basis of both costs and achieved PE. The building contains a HP for both heating and cooling. PEF provided in Italian regulation is used, which is based on historical data.
[55]	Nearly identical analysis as [54]. Building design is optimised on the basis of both costs and achieved PE. The building contains a HP for both heating and cooling. PEF provided in Italian regulation is used, which is based on historical data (one year older data than [54]).
[56]	Many renovation scenarios are simulated, including scenarios with HPs. PEF and CI are taken from a 'Czech GEMIS database' which is based on historical data. As a sensitivity, PEF and CI values are increased and decreased by 10%, 20% and 30%. In the scenarios containing a HP, this generates '*substantially different results*'.
[57]	The building only consumes electricity. It is heated with a HP. Full LCA, considering not only the electricity consumption of the building, but also its embodied energy and emissions.
[58]	The building is connected to a DHN, so the electricity consumption for which the PE and CE are calculated is non-heating related (e.g. ventilation). PEF and CI are set to the PEF_T and CI_T of a coal power plant, which is assumed to always be the marginal plant in the Swedish system. As a sensitivity, the values are changed to the PEF_T and CI_T of a gas power plant, which is assumed to always be the marginal plant in the future Swedish system.

[59]	Analysis of a retrofit scenario which reduces the buildings' PE to the NZEB level. Italian national PEF is taken from an Italian Ministerial Decree, which is based on historical data.
[60]	The authors use PEF and CI values based on historical data, calculated by [28]. The building's battery system uses the hourly CI values to minimise the buildings' CI.
[61]	CE of the building is minimised though MPC that uses the hourly CI signal published by the Danish TSO EnergiNet.
[62]	Similar to [61], with the difference that the historical data for the year 2015 is used.
[63]	The buildings' HP is used both for heating and cooling. MPC is used to minimise CE.
[64]	Hourly simulation explores opportunities for EVs to reduce the buildings' CE and PE, but yearly average CI and PEF are used. Building CE and PE are reduced by increasing the self-consumption of its locally produced solar energy. EV CE and PE are reduced by being (partially) charged with the buildings' solar energy.
[65]	PEFs are separately calculated considering only the renewable electricity generation, or only the non-renewable electricity generation. The building only consumes electricity and is equipped with a HP and a PV installation.
[66]	Hybrid energy system considered for the office building, combining renewables and hydrogen. The LCA considers a period of 20 years, during which the PEF and CI are assumed to remain constant.
[67]	Hybrid energy system considered for the commercial center, combining solar and biomass technologies.
[68]	PEF and CI values also calculated for 2030, considering the electricity mix evolution according to government plans.
[72]	The building is meant to be a 'representative' office building. The multi-energy system includes solar, wind and combined heat-and power technologies, but grid-electricity is still used as well (i.e. it is not an off-grid system).
[76]	The PE is calculated before and after the implementation of a trigeneration system.
Multiple buildings level	
[15]	Building samples are representative for the analysed Swedish cities. Three CI values are calculated and applied, each representing the 'the average CI in Nordic countries' in a different historical year.
[78]	Hourly CIs and PEFs calculated on the basis of historical data from the Belgian TSO Elia. One building is heated with traditional electrical resistance heating, the other with a heat pump. Both make use of the TES capacity of their floor heating systems. In separate simulations, the CE and PE of both buildings is minimised through MPC that uses the hourly CIs and PEFs. Stylised prospective PEFs and CIs are calculated by extrapolating VRES production to 40% of demand.
[79]	Not only the buildings are considered, but also mobility (including EVs).
[81]	The paper's goal is to estimate the potential of thermal energy storage to reduce emissions.
[82]	CE reduction potential of a novel insulation technique whereby façades are wrapped with membranes
Municipality level	
[88]	The calculation uses a Croatian national CI based on historical data, found in a report from the Croatian Ministry Of Environment And Energy.
[89]	The calculation uses an Italian national CI based on historical data, found in a report from the Italian Ministry of Environment.
[90]	The calculation uses an Italian national CI based on historical data, found in a report from the 'National Emission Inventories'.
[91]	The CE calculation is performed both with the Italian national CI and a local CI for Sicily, to compare the results. Calculations are performed both from an operational and a life-cycle perspective. The operational national value is sourced from the IPCC (based on historical data, 2006). The life-cycle national value is sourced from the ELCD (based on historical data, 2008).
[80]	Hourly CIs are *partially* based on historical electricity production data for renewables and nuclear. The electricity generation by technologies for which data was not available is estimated with a capacity and dispatch optimisation model to cover the residual demand.
[95]	CIs are calculated in three ways. First, CIs for Germany are calculated for 2018 on the basis of historical data, applying a production perspective. Second, CIs are calculated for Germany in the year 2030 and 2050 by using an electricity system model, considering neighbouring countries and applying a consumption perspective. Finally, CIs are calculated for the city of Heide itself, taking into account surpluses in locally generated renewable electricity.
Building stock level	

[96] The Danish 2050 electricity system is simulated in the energy-system tool EnergyPlan. PEFs are calculated based on the results from EnergyPlan. Biomass is assumed to have a PEF_T of 1, while all other electricity generation technologies in the 2050 system (i.e. other renewables) have an assumed PEF_T of 0, resulting in a PEF of 0.2.

[97] External scenarios used to project the future evolution of the various building stocks. Scenarios include varying levels of heat supply electrification. National CI values are calculated on the basis of historical data and *are assumed to remain constant* in the future scenarios considering the year 2030.

[98] The impact of various renovation measures on building stock CE is calculated. Renovations take place on t_0 and CE is calculated for a number of years into the future. CIs are sourced from government reports, which are based on historical data. The historical year on which the CIs are based varies from country to country (depending on the report used). CIs are assumed to remain constant across the future years considered (2030 and 2050).

[99] CIs and PEFs are sourced from an external report, the values of which are based on historical data. The synthetic building stock is meant to represent Switzerland in the year 2015.

Electric vehicles

[5] Yearly average CI per country based on IEA historical data. This is combined with ENTSO-E historical data to take into account imports.

[102] CI calculation is based on historical data from grid operators in France and Germany.

[103] CIs for both Poland and Czechia are taken from IEA reports that estimate the electricity production mix on a yearly basis from 2015 up to 2050 (in 5 year steps). On top of this, one LCA is also performed with the assumption that EVs can be fully charged by renewables only, enabled by a smart grid environment.

[105] The CE of EVs is calculated in two ways. Once assuming that the EVs are charged with specific electricity generation technologies (e.g. “gas”, “coal”, etc.), and once assuming the average CI of electricity in Europe.

[106] EV roll-outs in the United States and Japan are also analysed.

Calculation, analysis and forecasting of CFs themselves (without a concrete PE or CE calculation)

[26] The used hourly historical data problematically aggregates various thermal electricity generation technologies. To deal with this, available *yearly average* data are used to disaggregate the hourly data into a more detailed mix of technologies. This approach is pragmatic but not does not produce ideal data to accurately calculate PEFs or CIs. Moreover, their disaggregation still leaves ‘gas’ as a single generic technology. I.e. it makes no distinction between peak (OCGT) and non-peak (CCGT) gas power plants, which have a different thermal efficiency and thus a different CI_T and PEF_T.

[118] Authors claim that the PEF_T for electricity from nuclear power plants should be as high as 60 kWh_P/kWh_E, if the remaining PE in nuclear waste is taken into account. Based on historical data, this would increase Swedish PEF from 1.8 to 25.5 kWh_P/kWh_E and European PEF from 2.5 to 18 kWh_P/kWh_E.

[28] Renewable and non-renewable PEFs are separately calculated.

[119] The study includes a brief discussion about the potential for smart buildings to make use of hourly CI signals.

[120] The study includes a limited application of the hourly CIs on a Norwegian single-family building.

[121] The study includes a rudimentary estimation of how much CE could be reduced when a theoretical load consumes 1kWh every day during the hour with the lowest CI.

7. References

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