Journal of Cleaner Production 266 (2020) 121883

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Assessing domestic environmental impacts through LCA using data from the scientific literature

Christian Spreafico , Davide Russo *

DIGIP Department, University of Bergamo, V.le Marconi 5, 24044, Dalmine, Bergamo, Italy

A R T I C L E I N F O

Article history:
Received 31 January 2020
Received in revised form
21 April 2020
Accepted 23 April 2020
Available online 29 April 2020

Handling editor: CWEID- Li

Keywords:
Household carbon footprint
Appliances carbon footprint
Environmental impact
Life cycle assessment (LCA)

A B S T R A C T

The aim of this paper is to provide an overview about the distribution of the environmental impacts arising from different domestic functions (i.e. storing and preparing food, washing dishes, watching television, reading, personal cleaning, washing, drying and ironing clothes, home cleaning, heating, cooling, lighting and mobility) typically performed within a common family home. The method has general validity but for reasons related to the availability of data in the literature it has been applied by way of example only in three EU countries: Italy, Germany and France. The study was performed by using Life Cycle Assessment (LCA) in accordance with international standard ISO 14067 for determining the carbon footprint of different alternative domestic components, mainly appliances, for each function, by exclusively exploiting data from scientific literature. The functional unit is defined comprising all most common referred domestic activities of a family of three members within a house of 100 m2. The study identified an optimal configuration and a worse one of the domestic components in terms of carbon footprint, showing how a wise choice of these can greatly affect the overall impact by reducing it compared to the worst by more than 22% in Italy, 45% in Germany and 56% in France. The average impacts between the optimal and the worst configurations of Germany are higher than Italy (+27%) and France (+44%). Considering the impacts among the domestic functions in the average configuration, mobility was the most impactful in all the three countries (35–48%), followed by heating (17–26%), personal cleaning (10–13%) and washing dishes (8–13%), while cooling is consistent only in Italy (13%), against 5% in Germany and 2% in France. The study also allowed to identify some generic criteria for defining the optimal configuration: the increasing in energy efficiency, the choice of the least impacting energy source depending on the geographical location, ensuring water savings and the early replacement of older domestic components. Finally, by comparing some common measures for improving the domestic sustainability, these criteria proved to be more effective than solar systems and improved electricity mix. The provided outcomes may be used by manufacturers for improving their product in a more sustainable way as well as by legislator and end user, respectively for boosting and choosing the greener domestic components.

© 2020 Elsevier Ltd. All rights reserved.

1. Introduction

Globally, household consumptions are estimated to contribute to more than 60% of global greenhouse gas emissions and between 50% and 80% of total land, material and water use, which footprints are unevenly distributed across regions and with wealthier countries generating the most significant impacts per capita (Ivanova et al., 2016). The emissions are equally divided between food production and structural aspects, where appliances and other domestic plants, during their entire lifecycle, count for 30% of these latter (Hoxha and Jusselme, 2017). This amount is mainly due to their high energy consumption during their use phase, which represents the main problem that producers have not been able to resolve, despite the many efforts spent to increase energy efficiency (Rodrigues et al., 2017). In addition, it will further increase in the next future up to double or triple by 2050 because of the constant population growth, the increasing in their diffusion and use frequency, the use of highly polluting and unhealthy traditional solid fuels for household cooking and heating in response to the lack of access to adequate housing and electricity (Ürge-Vorsatz et al.,

* Corresponding author.
E-mail addresses: christian.spreafico@unibg.it (C. Spreafico), davide.russo@unibg.it (D. Russo).

https://doi.org/10.1016/j.jclepro.2020.121883
0959-6526/© 2020 Elsevier Ltd. All rights reserved.

Abbreviations

ASI	Annual Solar Irradiation
CDD, HDD	Cooling/Heating degree days
DE	Germany
ES	Electric Scooter
EC	Electric Car
ECC, GCC	Electric/Natural gas (methane) Coefficient of Conversion
EU	European Union
EWH, GWH	Water heather alimented by electricity of natural gas (methane)
FR	France
Gas hob	Cooker plate alimented by natural gas (methane)
ICS	Internal Combustion Scooter
ICC	Internal Combustion Car
Induction hob	Cooker plate alimented by electricity exploiting induction principle
IT	Italy
LED TV 43 inches	Light Emitting Diode Television
PBT	Pay Back Time
PV	Photovoltaic
TD	Tumble Dryer
WM	Washing machine

2015) and, scarce use of renewable sources and the short-sighted attention to technologies for carbon sequestration, typically too conditioned by economic factors (Maroušek et al., 2019a). Other environmental impacts will arise from their increased request of water consumption (Maroušek et al., 2019b) and the exploitation of agricultural land (Judit et al., 2017) since their sustainable management is in stark contrast to their cost-effectiveness.

For some years now, both legislators and manufacturers have been paying particular attention in monitoring and reducing the environmental impacts of household appliances, especially by increasing energy efficiency and, secondly, by using more sustainable materials and waste management procedures (Scur and Barbosa, 2017). In addition, the promoted measures about impacts reduction, have made sustainability a requirement of primary importance in the appliances development, by increasing the manufacturers competitiveness even to the point of making it an objective to be achieved in order to guarantee their survival (Dechezleprêtre and Sato, 2017). However, the goal of environmental sustainability must be clearly defined and faces in order not to incur benefits only in the facade that do not have real positive effects on the environment. Mardoyan and Braun (2015) showed how, sometimes, current politics of higher donations are addressed in the opposite way compared to the reduction of impacts, e.g. in the case of biofuels.

In this order of things, the objective measurement of environmental impacts plays a role of primary importance.

Among the supporting approaches, the Life Cycle Assessment (LCA) methodology is unanimously considered one of the most useful for quantitatively evaluating the sustainability of the current technologies, to critically discuss the choices to implement during eco-design and to evaluate the environmental performances of the new developed technologies (Hauschild et al., 2018). In extreme synthesis, it consists of four main steps that, according to ISO (2011), aim to: (i) define the goal and scope of the study, or the identification of the technical system to be measured, the operative scenario, the motivation for performing the assessment and all the requirement for performing it; (ii) collect all the sources of impacts, i.e. system parts and lifecycle phases; (iii) assess the impacts according to environmental indicators and (iv) interpret the results.

LCA literature about domestic impacts is dispersed in heterogeneous way in form of periodicals, book chapters, conference proceedings, patents, normative, and company reports, about a myriad of applications. A substantial number of studies provided the analysis of single household appliances and plants, e.g. cooking hob (Favi et al., 2018), oven (Landi et al., 2019), refrigerator (Monfared et al., 2014), boiler (Vignali, 2017), vacuum cleaner (Gallego-Schmid et al., 2016), dishwasher (Laicane et al., 2015), washing machine (Yuan et al., 2016), etc., by referring to restricted scenarios of application in geographical and usage terms, and by assessing the impacts through a bottom-up approach with which the contributions of the constituting parts are calculated and then composed to obtain the total value. Other studies (e.g. Makonin et al., 2016; Roux et al., 2016) provided instead top-bottom approaches for assessing the impacts arising from the overall energy consumption of an entire house that is modelled as a black-box and allocate them among the various functions.

Analyzing these contributions, the complexity of the topic clearly emerges, due to the presence of many different aspects to be considered for each domestic component in order to calculate the impacts (e.g. model, size, energy consumption, required maintenance) and their relations with the parameters of the operative scenarios (e.g. geographical locations, climatic factors, use modalities). The climatic factor strongly affects, through the degree days (Heating Degree Days – HDD, Cooling Degree Days CDD), the impacts arising from the use phase of heating and cooling, which are highly variable both in relation to the geographical location and the time period, with an unpredictable trend of this latter (De Almeida et al., 2011). In addition, their consumptions are also influenced by the solar irradiation or the spatial orientation of the home and the type of insulation. The different modalities of electricity production, i.e. electricity mix, and their distribution networks directly affect the impacts of the energy consumptions. They typically change on a regional scale or also for single cities, as well as by time, with the updating of the systems over the long term or daily switching with the distributed energy systems (Roux et al., 2016). The availability of energy sources and natural resources can influence the choice of appliances and so the impacts of their function, e.g. in several mountainous regions of Italy, where the methane gas network is not very widespread, many users adopt different more impactful alternatives such as oil boilers and wood stoves (Casasso et al., 2019). In addition, the geographical location has a considerable impact on the transportation phase of the appliances from the production site to the place of installation. The deriving impacts depends by the weight of the appliances in addition to the distance, the types of used vehicles and the characteristics of the route which in turn influence the choice of the means of transport and its consumption (Arduin et al., 2018). Also, ethnographic factors, i.e. collective or individual habits and ecological conscience, should be considered since they affect the impacts by means of the choice of the different appliances on the basis of personal preferences (Park et al., 2017) and the way they are utilized (Ross and Cheah, 2017). In particular this latter was estimated to be related to gender and age of the utilizer, especially in countries with strong industrial growth (Zhang et al., 2017).

All these parameters and their relationships mean that the overall estimate of domestic impacts cannot be simply obtained with a simple arithmetic sum of the contributions of individual household appliances, but a comparison involving a well-defined baseline scenario is necessary. However, despite the large number of contributions, this kind of approach is still missing in literature.

To achieve this goal, this paper analyzed all domestic components into a unique study based on LCA methodology, limited to the carbon footprint identification, considering an extensive and referable functional unit and a well-defined operative scenario about three EU reference countries: Italy (IT), Germany (DE) and France (FR). In addition, in order to not replicate from scratch the analysis of all the involved domestic components, it was decided to exploit as much as possible all reliable sources from scientific literature and to relate their outcomes according to the specific objectives of this study.

In particular, this study wants to verify the following hypotheses.

HP.1: In what way, the geographical location affects the impacts? With this hypothesis, we want to investigate the role of those parameters outside the boundaries of the study, i.e. energy infrastructure and climatic factors, and their comparisons in different countries. Its answer could help those who deal with energy distribution to frame the link between the type of infrastructure and domestic impacts, net of the unpredictability of the climate factor.

HP.2: Can a proper selection of the domestic components reduce the impacts? In this case, we want to quantify how much it is possible to reduce the domestic impacts by simply selecting different domestic components in order to stimulate legislators, producers and consumers to pay more attention about environment during the promotion, production and purchase of appliances.

HP.3: Do generalized criteria of selection of the appliances minimizing the overall carbon footprint exist? With this hypothesis, we want to enrich the provided suggestions to all the figures mentioned in the previous hypothesis by providing a set of indicators to guide their decisions according to the different operating scenarios.

HP.4: Can common improvements about energy management, ecological user behaviour and improved insulations, reduce the impacts? In this case we want to assess if some improvements can ameliorate the situation in comparison with the possible advantages arising from the selection of the domestic components. The comparison could be useful to support the decisions making of legislators and users regarding the strategies to be implemented to reduce the impacts.

2. Methodology

In this study, LCA methodology for assessing the impacts was strictly followed in accordance with ISO 14067 (ISO, 2011) standard, which specifies principles, requirements and guidelines for the quantification and communication of the Carbon Footprint of products, which involves the international standards on the evaluation of the LCA: ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b).

In the following, the performed activities for each step of the methodology are briefly presented.

In the first step, the objective of the study was reformulated by identifying the domestic components to be considered, establishing which phases of their life cycle and defining the geographical reference scenario. Then, the models and the main features of each domestic component were selected and the functional unit was defined, in order to provide a reference unit, for which the inventory data are normalized (ISO, 2006a) and facilitating the comparison of alternative products and services (ISO, 2006b). The criteria for collecting data and methods for the analysis were investigated and the system boundaries were defined. Finally, the all the limitations arising from the choice made during these tasks have been discussed in relation to the parameters prescribed by the normative about data quality.

During the inventory analysis, all the data and the methods to calculate the environmental impacts have been collected in order to quantify the environmental impacts associated with the system to be evaluated by means of a mass and energy balance (ISO, 2006b) and in accordance with the criteria for the selection of the sources, established during the first step.

In the impact assessment, the collected data and methods were used to evaluate the potential environmental impacts of the system, by limiting the procedure to the limiting the procedure to the Global Warming Potential indicator − (CO_2 eq.).

Within the interpretation of the results, all of the outcomes have been expressed by using the same mentioned environmental indicator in order to allow the comparison and the composition of the different functions and domestic components in a homogenous way. Their completeness, consistency, robustness was discussed in detail and the significant points and recommendations were presented for the intended audience.

In the following, each step is presented in detail.

3. Goal and scope reformulation

The goal and scope of the study were reformulated by defining the most common domestic functions performed by an average family in three countries in European Union (EU) and in referring with the generic house features the constituting domestic components.

The selected functions are: preparing food (storing, cooking, heating, making coffee and tea, washing dishes), living (watching television and reading), personal cleaning, washing clothes (washing, drying, ironing) and home cleaning, heating, cooling, lighting and mobility. The considered house has a one-floor layout with the recent building features of the last 20 years. The complete set of domestic components include: refrigerator, gas-alimented/induction hob, gas/electric-alimented and microwave (MW) oven, automatic coffee machine, kettle for tea, dishwasher, gas/electric water heater (WH), used both for hand washing dishes and personal cleaning, one television, paper books and e-readers, conventional and pulsator washing machine (WM), conventional and heat-pump tumble dryer (TD), ironing, vacuum cleaner, conventional/condensing gas boiler, oil boiler, wood stove, air conditioner, lighting plant, electric car (EC) and internal combustion car (ICC), electric scooter (ES) and internal combustion scooter (ICS). Finally, it was decided to use the national average data about the climatic factors and the features of the infrastructures for energy generation and distribution in the three considered countries.

All the choices performed in this phase aim to represent the selected scenario in a statistically representative way. Overall, Italy, Germany and France comprise almost half of the EU's inhabitants. The climate situation of the three states is sufficiently representative to describe most of the European reference climate in terms of climatic zones, rainfall and solar insulation (EU Eurostat, 2019). The features of the energy infrastructure (i.e. electricity mix) are common in large part of the continent, with a few exceptions only in Eastern Europe (European Environment Agency, 2016). The kinds and models of the considered domestic components are included within the common basket of the specific EU representative products (EC-JRC, 2012).

3.1. Domestic components description

All the considered domestic components for defining the product system have been classified according to the achieved domestic functions and their models and features were selected from a scientific literature.

Inside the kitchen, for storing food, two refrigerators have been compared. Both are of the single door layout, with energy class of A+ and with an internal volume of about 200 L. One is produced in Europe (Monfared et al., 2014) while the other in China (Xiao et al., 2015). For cooking food, a four-burner gas hob (Favi et al., 2018) and two similar four-plate induction hobs (Favi et al., 2018; Rodrigues et al., 2017) have been considered. For heating food, a 64 L gas-alimented oven, with energy class of A has been compared with a 68 L electric-alimented oven, with energy class of A+, both described by Landi et al. (2019), and with a microwave oven having a rating of 1150 W and a capacity of 17 L (Gallego-Schmid et al., 2018a). The two automatic coffee machines described by Brommer et al. (2011) and the two kettles of Gallego-Schmid et al. (2018b) have been respectively compared for making coffee and tea. Four models of familiar dishwasher from Laicane et al. (2015) and Santori et al. (2013) have been compared with hand washing method described by Stamminger (2011) for washing dishes.

For the functions of the living room, a 43-inch LED TV was selected from LG (2016), and three e-readers from Moberg et al. (2010) were compared to paper books of 500 g with 300 pages, which data about the impacts of production and disposal are described in Brommer et al. (2011), Weber and Matthews (2008) and Piroozfar et al. (2016).

The impacts from the bathroom were determined by the comparing a gas-alimented WH and an electric-alimented WH, both described in Piroozfar et al. (2016) and used for heating the water of the bathtub or the shower.

For the laundry and home cleanings, a conventional WM, with horizontal-axis layout, rated capacity of 6–8 kg and washing power of 190–230 W (Yuan et al., 2016; Laicane et al., 2015) was compared to a pulsator model of the same size (Yuan et al., 2016) for washing clothes. A conventional and a heat-pump TD of the same load capacity, both described by Yuan et al. (2016) were compared for drying clothes. Finally, the ironing described by Krasny et al. (2017) and the vacuum cleaner from Gallego-Schmid et al. (2016) were considered for ironing clothes and cleaning.

The impacts of heating was estimated by comparing a conventional gas boiler with a max power of 24 kW, a condensing gas boiler with of the same size, both described by Vignali (2017), an oil boiler (Casasso et al., 2019), a wood stove and a fireplace (Quintero et al., 2019). Two models of common domestic air conditioner for apartments (Ross and Cheah, 2017; Dechezleprêtre and Sato, 2017) were compared for estimating the impacts of cooling. While for the lighting function, the common residential lighting plant with multiple light points from De Almeida et al. (2011) was selected.

Finally, for assessing the impacts of the mobility, two kinds of electric and internal combustion engine cars and scoters have been compared. The EC has a total weight of 1479 kg and an electric consumption of 19 kWh/100 kg, while the ICC has a total weight of 1059 kg and a fuel consumption of 6.83 kg/100 kg and a cubic capacity of 1.4 L. Both the models are described in Gallego-Schmid et al. (2016). The ES (Hollingsworth et al., 2019) is one of those commonly urban mopeds used in urban centers, while the ICS has a 0.5 L 4-strokes engine (Leuenberger and Frischknecht, 2010).

The map shown in Fig. 1 reports all the collected domestic components within the product system of the study and it organizes them according to the selected domestic functions.

3.2. Functional unit

The definition of the functional unit was one of the most complex parts of this study since it required to collect data from very heterogeneous sources in referring to a unique reference scenario. The time horizon of the analysis was arbitrarily normalized to 1 reference year, while the features of the house structure and its occupants represent the averages situation in the European Union (EU-SILC, 2016). The considered home has a one-story layout with an internal surface of 100 m^2, the internal height of 3 m, the external parameter of 40 m, opened on the four sides and 6 windows of 0.9 m $\times$ 1.4 m size. The number of occupants was instead assumed equal to three, since is the minimum integer number for describing a family, having an average size of 2.3 people in EU. Other specific parameters of the functional unit for each function are reported in Table 1 along with their sources.

3.3. Selection of the sources

For what concerns the selection of the sources, all the considered data and methods have been carefully collected, considering reliable sources from the scientific literature, with two exceptions to compensate for the lack of data. All documents have been selected from Google Scholar database, by using queries containing terms about environmental impact assessment (e.g. “lifecycle assessment”, “LCA”, “eco-assessment”, “green-assessment”, “eco-evaluation”, etc.), energy consumption and the domestic components names. Almost all the documents are valuable articles from international journals. All of them contain numerical values about environmental impacts and energy consumptions for which their authors explicitly declared the adherence to reality and the use of replicable procedures of updated methods (e.g. Midpoint ReCiPe model), calculation tools (e.g. SimaPro 8.05.13, GaBi v6.5) and reliable databases (e.g. Ecoinvent). In addition, in order to take into account only updated data, for better representing the continuous updating about the domestic components, especially for what concern the efficiency improvement, only documents from the last ten years have been considering, by privileging, among them, those from the last five. Finally, in order to ensure the adherence with the geographical context of application, the great part of the selected documents present referable date for the considered countries in terms of climatic features, local limitations, energy infrastructures and user habits in relation to ethnographic factors. Only some documents from other countries (e.g. China) have been considered by exclusively collecting those also referable to the considered scenario (e.g. appliances sold in EU).

3.4. System boundaries definition

The system boundaries are defined considering the current geographical, social and cultural conditions in Italy, Germany and France.

The material extraction and the manufacturing phases of all the domestic components were included in the study because the scope of the study is from “cradle to grave” and they can be significantly different between the alternative domestic components carrying out the same function and consequently they are fundamentals to compare them.

Transportation of raw materials from extraction points to manufacturing sites was excluded from the study because, for appliances, its impacts can be considered neglected in comparison to the overall impacts was excluded from the analysis (Elduque et al., 2014). Transportation related to distribution was excluded too, in order not to distort the overall comparison between alternative domestic components that are produced in different places and due to the variability over time of the location of the production sites.

The use phase has been included in the LCA because the impacts arising from this phase because, for appliances, it is usually estimated as the most impactful phase during the lifecycle. Natural gas is supplied in the three national networks of Italy, Germany and France from abroad Russia, Libya, Algeria, the Netherlands and Norway, the same is for oil, while wood is commonly collected from the inside with similar processes in each country. Electricity has instead a characteristic upstream depending on the national electricity mixes, which are considerably different in the three countries. Among them, France has the more favorable index for the

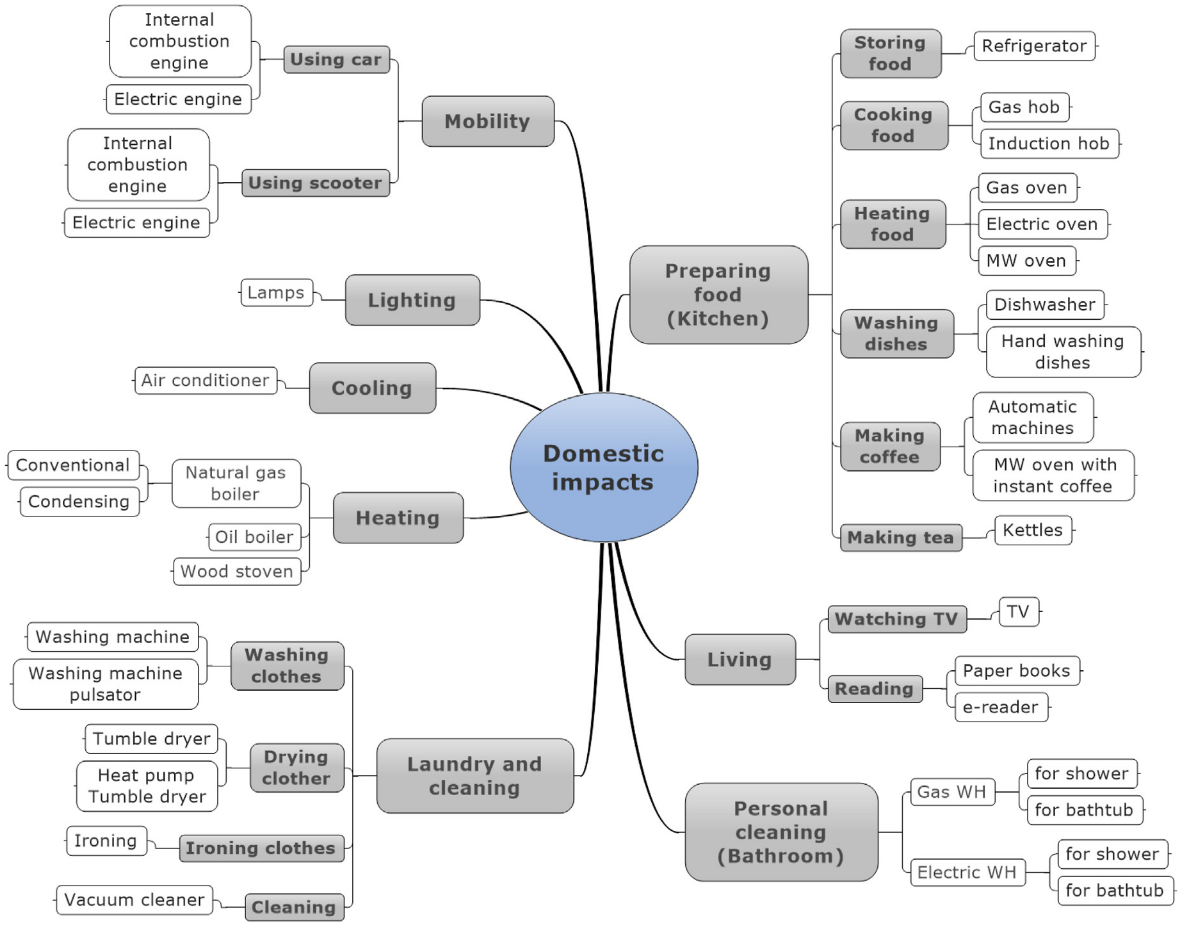

Fig. 1. Classification of the considered functions (in grey) and domestic components (white).

Table 1
Specific parameters of the functional unit and their sources.

Function	Parameter	Value	Sources
Cooking food	Meals per year per person	200 pasta, 200 tomato sauce, 200 vegetables, 200 omelettes	Favi et al. (2018)
Heating food	Meals per year per person	60 chilled meals, 60 frozen meals, 60 home-made meals	Landi et al. (2019)
Making coffee	Number of cups per year per person	300	Brommer et al. (2011)
	Coffee mass per cup	7 g	Brommer et al. (2011)
	Cup volume	0.125 l	Brommer et al. (2011)
Heating tea	Number of cups per year per person	365	Considering 1 couple per day per person
	Cup volume	0.25 l	Gallego-Schmid et al. (2018b)
Washing dishes	Uses per year per person	280	European Commission (2010)
Watching television	Use per year on-mode	1342 + 7419 (stand-by) hours/year	Austin et al. (2015)
Reading	Number of new books acquired per year per family	18	Moberg et al. (2010)
	Annual use per person of e-reader	182.5 h/year	Moberg et al. (2010)
	Number of e-readers per family	3	Assumption
Personal cleaning	Uses per year per person	300	Piroozfar et al. (2016)
	Time per shower	7 min	Piroozfar et al. (2016)
	Water temperature	37 °C (hot), 15 °C (cold)	Piroozfar et al. (2016)
	Uses per year per person of bathtub (in alternative to shower)	300	Equal to shower
	Bathtub volume	100 l	Assumption
Washing clothes	Uses per year	80.6 (IT), 85.5 (DE), 72.8 (FR)	Average between Schmitz and Stamminger (2014) and Presutto et al. (2007)
Domestic cleaning	Uses per year	0.57 h/m^2 year	European Commission (2013)
Using car	Annual distance	12000 km/year	Gallego-Schmid et al. (2016)
Using scooter	Annual distance	2270 km/year	Lesteven and Leurent (2016)

environmental impacts, which is characterized by massive use of nuclear and renewable energy, leading to very restricted carbon footprint for each electric kWh produced. In addition, all consumable materials both for use (e.g. car batteries) and maintenance (e.g. lubricants) were considered. For what concern the use of the water, only the energy required for heating it was counted, while that required for transportation was excluded from the study. Food, furnishes, soap and shampoo, clothes and detergents have not been considered as part of the life cycle inventory because their impacts are independent from the different alternative domestic components and they do not influence their comparison.

The end-of-life phase has been included in the LCA, collecting for each domestic component the impacts from literature about the 100:0 approach (Allacker et al., 2017), in which the recycling of scraps generated by the production system are not part of the product system with no credits for the subsequent recycling.

Fig. 2 graphically summarizes the system boundaries:

3.5. Impact calculation procedure

The impact calculation was performed for each domestic component following a rigorous procedure articulated through the following steps: (1) Collecting the life cycle carbon footprint arising from the masses of the materials and the used energy, from the selected sources. (2) Normalizing the impacts of material extraction, manufacturing and end-of-life phases over the 1-year period. (3) Normalizing the impacts of the use phase according to the reference parameters of the functional unit, the climatic factors of each country and the specific national impact coefficients about the electricity mixes and fossil fuels distribution networks.

3.6. Identification of the limitations

Depending on all the methodological choices described so far in this section, this study presents some limitations. They can be described in relation to the prescribed criteria about data quality according to ISO 14067 (ISO, 2014).

The time-related coverage of the study is quite restricted, since all the considered domestic components along with the sources describing them are recent. This choice was made in order to represent the current situation in a significant way, since the appliances are characterized by a great variability in terms of energy performances. For the same reason, if the evolution of the appliances will follow the same trend of the last period, this study will gradually lose significance over the next years.

The geographical coverage of the study is limited to the considered countries and it is not representative of many other areas in the world (e.g. Africa, Sud America, India) for climatic features and availability of energetical and economical resources, which strictly affect the impacts of the appliances (e.g. Cao et al., 2016; Götz and Tholen, 2016). In addition, the offered perspective within the countries is narrow because the represented situations are leveled on national average values, without explaining the differences between the constitutive regions. In particular, these latter can manifest both in terms of different impacts arising from the same domestic components (e.g. boilers - Vignali, 2017) and in the selection of their selection, e.g. in Aosta Valley (Italy), the scarce availability of natural gas leaded to a reduction of gas boilers below 10%, compared to 80% of the national average (Casasso et al., 2019).

The completeness of the study is also limited by perspective provided about the ethnographic habits of the considered populations. Italians, Germans and French are quite similar in uses and

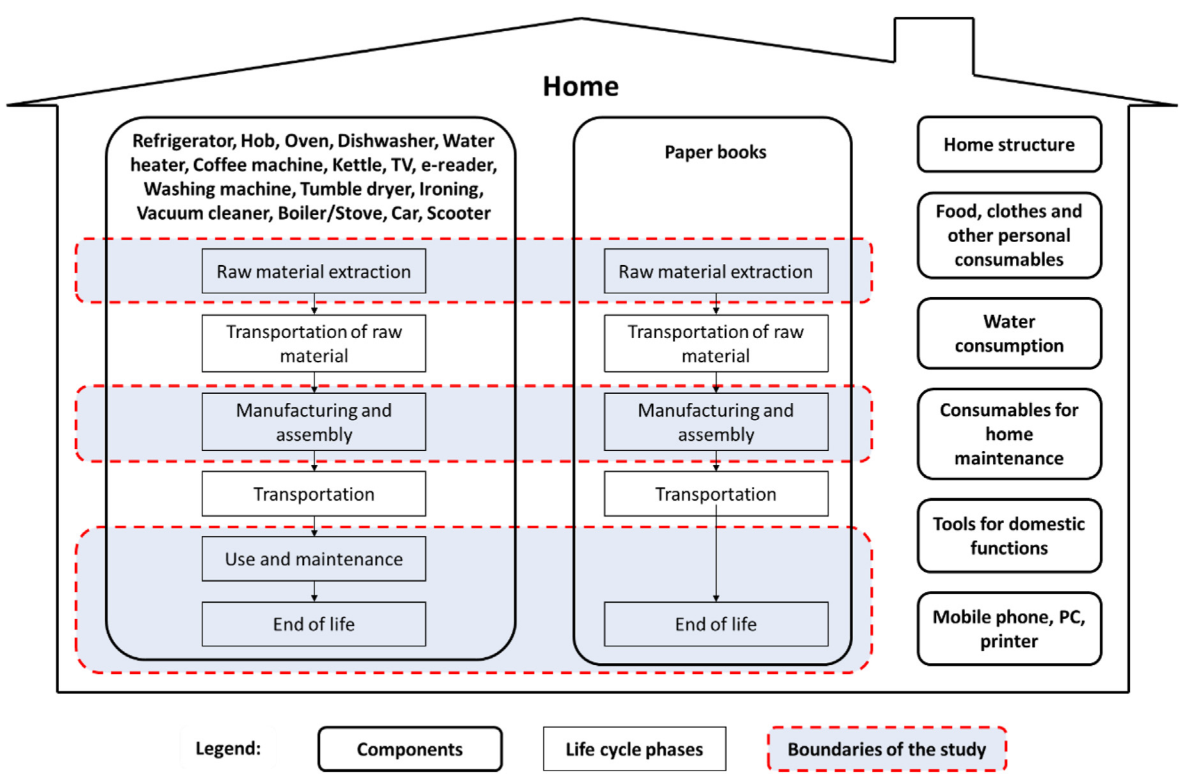

Fig. 2. Representation of the system boundaries. The considered items are included within the squares with the dashed red lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

customs and therefore also in the selection of the appliances and their methods of use. Only standard user behaviors were selected, without investigating the role of different ecological awareness on the impacts, as in the studies of Stamminger (2011) and Page (2019).

The technology coverage is affected by the selection of those most common domestic components available on European market and for each domestic component, only a restricted number of models were analyzed to exploit only those considered sources instead of enlarging the pool of document to all the pertinent contributions even if of lesser scientific quality.

On the contrary, such a rigorous work of selection of the sources, both for extracting data about the appliances and for defining the functional unit in a strictly standardized way, do not limit the precision of the results, the uncertainty of the information, the reproducibility and the consistency of the study, according to the parameters described by the reference normative.

4. Inventory data

Comparing to traditional LCA studies, in this case, Inventory data phase was significantly less onerous since it was not necessary to promptly analyze all the constituent parts or carry out experimental campaigns to determine their impacts. All the data about the environmental impacts arising from the raw material extraction, manufacturing and end-of-life phases were directly extracted from literature, while those of the use phase of all the domestic components are instead mainly based on the energy consumptions. Where these latter were firstly extrapolated from literature by normalizing them with respect to their functional unit and then referred to the scenarios considered in this study.

The parameters of the defined functional unit were used for determining the energy consumption during use, while its multiplication by the coefficients of conversion of natural gas and electricity expressing the national averages specific environmental impacts of 1 kWh of used energy in each country. In the specific cases of the boilers and the air conditioner, also the Annual Solar Irradiation (ASI) indexes and the HDD (for the boilers) or CDD (for the air conditioner) were considered to define the energy volume. Finally, the flow of natural gas within the distribution system and the flow of sanitary water were respectively esteemed equal to 2 m^3/h and 12 L/min, (Piroozfar et al., 2016).

The considered geographical parameters and their values are reported in Table 2.

5. Results and discussion

In this section, the outcomes are presented and discussed in a structured way by introducing the significant points in respect with the goal and scope definition and in an ordinated sequence, as prescribed by the reference normative. This approach was selected since it allows the readers to gradually learn the results, deepening their causes and limitations and focusing on the crucial ones (ISO, 2006a). First, we reported the overall impacts in the three countries. Then, a deeper analysis focused on the comparison of the impacts arising from the domestic functions is presented. In the last part we also compared alternative domestic components within a same function. In order to verify the completeness and the consistency of the study and for allowing the readers to reaching their own conclusions in accordance with the goal and the scope, the main limitations of each result are discussed in detail, completing the list of theoretical limitations of the methodology (see Section 3). For quantifying the relevance of the study, a sensitivity analysis was introduced. It evaluates the robustness of the results and identifies how much the uncertainty related to the most significant data inputs from the functional unit and the geographical features affects the environmental impacts. Finally, for suggesting some possible measures of interventions, some common improvements about energy management are presented and discussed in relation to the considered scenarios. In order to draw the key conclusions and make recommendations for the audience, all the results are also discussed in comparisons with other previous studies on the argument, by presenting their main differences, along with economical, regulatory and social considerations.

5.1. Baseline scenario

The achieved results about the impacts of the domestic components, expressed in kg CO_2 eq. and normalized for 1 year, are numerically reported in Table 1 of the Appendix, and summarized at macro level in Fig. 3.

This latter shows the overall domestic impacts in the three countries (Italy, Germany and France), according to three different configurations for sustainability (Average, Optimal and Worst) and with the classification of the functions (Preparing food, Living, Personal cleaning, Laundry and Home cleaning, Heating, Cooling, Lighting, Mobility). Where the optimal and the worst configurations were obtained by composing the least and the most impactful domestic component for each function, while the average configuration results from the arithmetic mean between the two. This representation of Fig. 3 was selected since it allows the readers to compare the contribution of each function within the generation of the overall impacts in the three countries and to apprehend its variability depending on the choices of the alternative domestic components ensuring it.

The achieved results show that the overall domestic impacts, resulting from the composition of all the appliances considered in this study, are equal to 6655 $\pm$ 22% (IT), 8162 $\pm$ 28% (DE) and 5635 $\pm$ 40% (FR) kg CO_2 eq., referring to the average configurations and their percentage variations with the optimal and the worst ones.

The first key observation deals with marked difference of the overall impacts between the various states, where the German house has a significantly higher carbon footprint than the Italian (+23% in the average configuration) and the French (+31%) ones. This difference is mainly due to the different climatic features (i.e. HDD, CDD and ASI) of the countries and by the energy generation and distribution networks (i.e. electricity mix), which directly affect the impacts of the single domestic components. Analyzing the influence factors of HDD, CDD and electricity mix, emerged that they

Table 2
Considered data and sources about the geographical features of the considered countries.

	Italy	Germany	France	Sources
Annual Heating Degree Days (HDD)	1762	2890	2184	EU Eurostat (2019) - average data between 2009 and 2018
Annual Cooling Degree Days (CDD)	243	25	60	EU Eurostat (2019) - average data between 2009 and 2018
Annual Solar Irradiation (ASI)	1700 kWh/m^2 year	1190kWh/m^2 year	1500 kWh/m^2 year	Urraca et al. (2018)
Gas Coefficient of Conversion	0.245 kg CO_2/kWh	0.243 kg CO_2/kWh	0.243 kg CO_2/kWh	Bilan Carbone (2016)
Electrical Coefficient of Conversion	0.256 kg CO_2/kWh	0.441 kg CO_2/kWh	0.058 kg CO_2/kWh	European Environment Agency (2016)

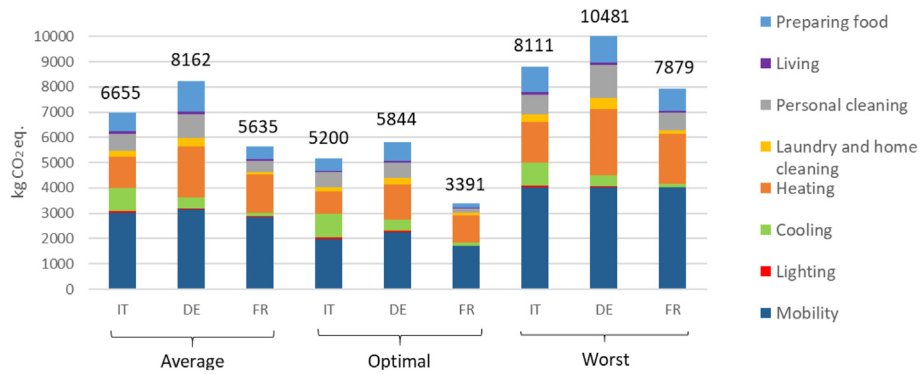

Fig. 3. Environmental impacts (kg CO_2 eq. normalized for 1 year) distribution between generic functions, for the three configurations in the three countries (Italy-IT, Germany-DE and France-FR).

count respectively for 36%, 2% and 69% in the composition of the impacts of the average configuration in the tree countries.

These data are useful both to achieve a value of the carbon footprint for a single home and to compose these data for gathering an approximate evaluation at the neighborhood or city level. However, although the provided results represent an estimate of impacts based on multiple aspects (i.e. raw material extraction, manufacturing, use and end-of-life), they do not consider the contribution of transports, whose consideration could also significantly increase these values. Weber and Matthews (2008), by collecting the carbon footprint of the main domestic appliances in United States market, estimated the transportation phase responsible for the 15% of them. Even if this datum cannot be considered as such also for our study, due to the different geographical and temporal considered scenario, it provides a rough estimate about the impacts arising from transportation.

Excluding mobility, the obtained results can be compared to those achieved by the previous study of Moran et al. (2014), which concerns the environmental impacts of different types of houses located in Bath (United Kingdom), having structural characteristics very similar to those analyze and including standard appliances and installations. By normalizing the specific impacts identified by the authors to the functional unit considered in this study, that house should have a carbon footprint of about 5000 kg CO_2 eq., which is similar to the average result for Germany (excluding the impacts of mobility). This comparison corroborates the results obtained, also since the parameters that describe the climatic and infrastructural situation of Bath are comparable to the average German scenario.

The second observation regards the considerable variabilities of the impacts between the optimal and the worst configurations of the domestic components for enhancing sustainability. It suggests that the alternative domestic components to perform each function are characterized by very different impacts and that combined appropriately or not can significantly affect the overall impacts of the home.

In order to comment this second observation and to analyze the distribution of the impacts between the domestic functions, we must move on in the analysis of the results by deepening the contribution of each function. They are detailed examined in the following, by sorting them according to order of the magnitude of their impacts.

Mobility is the most impactful function with the 45% (IT), 38% (DE) and 51% (FR) of the impacts of the average configuration. It consists for more than 90% of the contribution of the car in all the countries and it is characterized by a large variability between the worst and the optimal configuration (−50% in IT, −44% in DE, and −57% in FR), where the optimal configuration consists in the adoption of electric vehicles (i.e. EC and ES) everywhere.

These data show the significant impact of this function on total domestic impacts, as well as the clear advantage of electric vehicles in reducing the carbon footprint in the current situation. Other contributions from literature confirm this result also for other car models, which were not considered in our study. According to Dechezleprêtre and Sato (2017) alarger electric family car has an impact of 36% less than an ICC, during the entire life cycle in Italy, while Helmers et al. (2017) estimated that the electric conversion of a conventional city car can lead to a 16% reduction in impacts, considering the German scenario. In addition, electric mobility is also supported by encouraging future projections: Gallego-Schmid et al. (2016) estimated a further 4% reduction in the annual impacts of electric cars by 2030 in Italy, analyzing cars of the same size as that considered and relying on the expected improvements in the national electricity mix, in accordance with the planned interventions.

In line with these considerations, for some years, EU, US and Canadian governments are promoting the adoption of electric mobility by introducing permanent restrictions on the use of ICCs in several areas, mainly urban centers, and in certain periods when the concentration of particulate matter in the air is higher. There are also proven evidences that government incentives to favor the purchase of ECs (Jenn et al., 2018) and the adoption of electric public transport (Mersky et al., 2016) were effective to reduce environmental impacts on local scale. Also following these political choices and the growing investments of manufacturers, nowadays in the considered countries, overall costs during the lifecycle of EC and ICC do not differ significantly, with some advantages of the fist option at a regional scale, depending by the national electricity power plant portfolio and the charging strategy (Jochem et al., 2016). However, despite the economic competitiveness, the adoption of ECs is still very low and mostly limited to customers with a strong environmental awareness, mainly due to the reduced presence of charging stations on the territory, especially in Italy (Sierzchula et al., 2014).

The main shortcoming of the provided result about mobility deals with the consideration limited to only to the carbon footprint, which as unique indicator is not enough to summarize all environmental considerations regarding the adoption of ECs that are worse than ICCs for other environmental indicators, such as acidification, human toxicity, particulate matter and depletion of resources (Dechezleprêtre and Sato, 2017).

Heating is the second source of impact in our study with 18% in IT, 25% in DE and 27% in FR of the overall impacts of the average configuration. Also, in this case there is a substantial difference between the optimal and the worst configuration: in the first one was adopted the condensing boiler, while in the second one the wood stove that is almost 90% more impactful in all the countries. The impacts of conventional gas boiler and oil boiler are respectively higher than +4% and +20% than the condensing boiler, while fireplace is more impactful than +500% (of the condensing boiler), even if it was not considered within the worst configuration due to the many Italian regional legislative decrees limiting its use in different regions.

The great variability between the various country is due to the different climatic factors, with a linear correspondence of heating impacts with the local HDD. This correlation is in line with Moran et al. (2014) from which it emerged that the carbon footprint resulting from the use of the gas boiler in a similar home to that considered and located in the UK, where HDD are slightly higher than Germany, is about 8% higher than this latter in our study.

The main limitation of these results deals with the absence of considerations about the different internal regions, which can be significant given the extent of the considered territories: in the case of Ivanova et al. (2016) esteemed a difference in the carbon footprint during used of the same gas boiler of about 25% between northern and southern regions.

However, the obtained outcomes are not supported by economic considerations that they do not encourage to abandon wood as a means of heating: in Italy, the operating cost of the wood stoves is about 0.038 €/kWh while those of the gas and the oil boilers are respectively equal to 0.11 €/kWh and 0.15 €/kWh (Casasso et al., 2019). In addition, there is not even economic convenience of replacing an old model with a new and more sustainable one. In our study, the greenhouse Pay Back Time (PBT) dealing with the replacement of the considered conventional boiler with the considered condensing one, was estimated between 3 and 4 years, respectively in FR and IT, while the economic PBT, collected by Bălănescu and Homutescu (2018) for the same models of boilers is comprised between 8 and 19 years in EU. Where the greenhouse PBT indicates the number of years needed to balance the reduced annual impacts of use phase, in kg CO_2 eq., ensured by the adoption of the new product and the impacts deriving from its production (material extraction and manufacturing) and end-of-life. Finally, also geographical factors can limit the use of gas boilers by favoring wood stove and oil boilers: in some mountainous areas of northern Italy, where the methane grid is not widespread, the percentage of use of gas boilers is about 10%, while that of oil boilers is higher than 80% (Casasso et al., 2019).

The **preparing food** function, including storing, cooking and heating food, making coffee and tea and washing dishes, is the third source of impacts, with contributions of 11% in IT, 15% in DE and 9% in FR in the average configuration. The distribution of the impacts on its constituting sub-functions is shown in Fig. 4, in relation to the average, the optimal and the worst configurations in the three countries.

Among the sub-functions of preparing food, "washing dishes" is the most impactful one with 68% (IT), 72% (DE), 69% (FR) of the overall impacts in the average configuration. It presents a wide variability in the three country and in the configurations due to the different evaluated options. Among them, the dishwasher was considered in the optimal configuration everywhere since it allows a reduction of the impacts of −51% (IT), −54% (DE) and −81% (FR) compared to the worst configuration, corresponding to the hand washing with the electric boiler in IT and DE and with the gas boiler in FR. The reason of the reduced impact of the dishwasher is due to its ability to work with smaller amounts of water and with less temperature, by consequently requiring a lower energy consumption (Richter, 2011). The choices of the water heaters for the hand drying in the worst configuration depend by the national electricity mixes which make electricity more or less impactful than natural gas. The choice of the dishwasher against the hand washing is justified also from the economical point of view because the savings due to the lower energy demand justify its purchase and maintenance costs (Blum and Okwelum, 2018). In addition, the adoption of the "eco" mode can guarantee a further 23% reduction of the impacts during use, if exploited in those specific conditions suggested by the manufacturers (Presutto et al., 2007). Finally, a further environmental advantage will occur in the coming years if the current evolution trend of dishwashers is confirmed, with the development of their active role in suggesting the most sustainable programs depending on the cases (Blum and Okwelum, 2018).

The "cooking food" function represents the second average source of impact in the kitchen, which percentages are comprised between 13% in DE and 15% in FR of the overalls in this room. In this case, the impacts of induction hob are lower than those of the gas hob of 11% in IT and 78% in FR, while they higher of 34% in DE. However, the environmental comparison is not always economically justified, especially in some areas of central and southern Italy where electricity is much more expensive than gas (Fan et al., 2019). Both "storing food" in the refrigerator and "heating food" impact between 5% and 6% of the overall impacts of the kitchen in the average configuration. In the second case, the microwave oven was selected in the optimal configuration everywhere since it is 66% less impactful than the gas oven in IT and FR, and 72% compared to the electric oven in DE. In "making coffee", with 4–5% of the average impacts of the kitchen, and making tea (1%), the automatic machine is more sustainable than instant coffee in MW oven of 64% in IT, 41% in DE and 89% in FR, while the two tea kettles are almost equal.

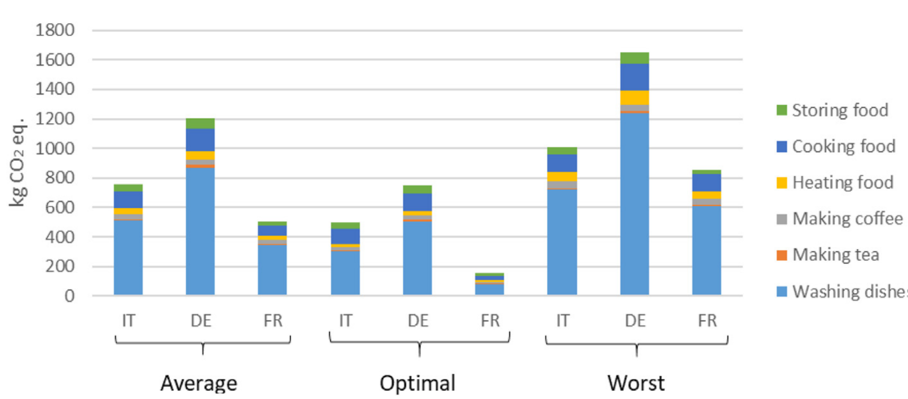

Fig. 4. Environmental impacts (kg CO_2 eq. normalized for 1 year) distribution between the specific sub-functions of "preparing food", for the three configurations in the three countries (Italy-IT, Germany-DE and France-FR).

The impacts of the **personal cleaning** count for the 10% in IT, 12% in DE and 8% in FR of the overall impacts of the average configuration and they exclusively depend by the amount of used water and the means used for heating it. For this reason, the shower is less impactful than the bathtub (−15% in all the counties), requiring less water according to the functional unit. While the gas alimented WH is more sustainable than the electric one in IT (−10%) and in DE (−47%) and less in FR (+69%) because of its more favorable electricity mix. These considerations are confirmed by the findings of Yuan et al. (2016), which also demonstrated the cost effectiveness of WH gas with up to 50% lower usage costs per kWh in countries where electricity production is less sustainable, like in DE.

The impacts of **cooling** are characterized by a large variability between the countries (14% in IT, 5% in DE and 2% in FR of the overall impacts in the average configuration) since they mainly depend by climatic factors (i.e. CDD) and the electricity mix, where the second one plays a preponderant role. In fact, despite the air conditioner usage request in FR is 2.4 times higher than that in DE, in relation to the respective CDDs, the impacts in the first country are less than 12% compared to those in DE, due to the more favorable electricity mix. The degree of technological advancement is also fundamental for sustainability, in relation to the increase in energy efficiency. For this reason, the greenhouse PBT resulting from the substitution of an old conditioner of 2007, with the one considered in the analysis is comprised between 2 and 4 years, respectively in IT and DE (Dechezleprêtre and Sato, 2017). However, even the more structured government economic incentive programs, aimed at reducing cooling related impacts through the early replacement of the plants (e.g. Japanese Home Appliance Eco-Point Program), proved to be ineffective in reducing greenhouse gas emissions, because of the too high initial investment costs, which cannot be filled with savings during use and incentives (Nishijima et al., 2019).

In **laundry and home cleaning**, the impacts of the average configuration are divided between washing clothes (36% in IT, 32% in DE and 49% in FR of the impacts of the functions laundry and home cleaning), drying clothes (28% in IT, 27% in DE and 32% in FR), ironing clothes (28% in IT, 32% in DE and 12% in FR) and using vacuum cleaner (8% in IT, 9% in DE and 6% in FR). Regarding the choice of the domestic components, it was found that the Pulsator WM reduces the impacts compared to the to the conventional WM (−52% in IT, −62% in DE and −24% in FR) and the Heat pump TD in comparison with conventional TD (−32% in IT, −39% in DE and −3% in FR). In addition, the impacts of all the models could be further reduced by adopting more environmentally conscious behaviours, favoring water savings and using lower temperatures (Stamminger, 2011) and by favoring the diffusion of the more technological and efficient WM and TD with community-based education, salesman supervision, information transparency of water and electricity bills in order to remove the barrier of their higher purchase prices (Fan et al., 2019).

Living impacts are just over 1% of the overall everywhere and they are divided between watching televisions (39% in IT, 50% in DE, 18% in FR of living function) and reading (61% in IT, 50% in DE and 82% in FR). In the first case, the technological evolution of the televisions plays a fundamental role in reducing the impacts. In fact, the greenhouse PBT related to the replacement of an old Plasma TV, described by Hischier and Baudin (2010) with the considered LED TV is extremely reduced and equal to 1 year in IT and DE and 2 years in FR, contrary to the average life of 8 years. In the second case emerged instead that the impacts of e-readers during their life cycle are less than 80% of those arising from the equivalent number of produced paper books for one year, assuming that each purchased book was read by only one family member.

Finally, **lighting** has an extremely limited impact compared to the other considered domestic components of about 1% of the overall in the three countries, which can be further reduced by introducing sensors for limiting the consumption, such as additional sweeping extinction signal, automatic detection and daylight control (Kaminska and Ożadowicz, 2018).

5.2. Sensitivity analysis

The sensitivity analysis of the environmental impacts was conducted by considering the variation of the home size (±10%), the number of people (±1), the climate features (±5% of HDD and CDD) and electricity mix (±10% of the specific impacts of the produced electrical energy - kg CO_2 eq./kWh). The study considered both the overall impacts and the those of the specific functions interested by the considered variations that present the widest variations, by reporting the results for the different configurations in the three countries. In all the cases considered, the compositions of the domestic components in the configurations were not changed. The sensitivity analysis parameters were selected because among all those of functional analysis, they are the only ones that describe the domestic system at a general level, while their considered variations were defined on a statistical basis in order to include the great majority of cases in the three countries. In particular, the variations of the climatic factors and the electricity mixes can also be exploited to comprehend the differences between the internal regions of the countries.

The main findings of the sensitivity analysis are summarized in Fig. 5.

Analyzing the results, emerged that the variation of the people number has the biggest influence on the overall impacts, especially about the function washing dishes and personal cleaning. The variation of the size of the house strongly influences the results, since it takes more resources for heating. The phenomenon is practically evident in France. Variations of HDD and CDD follow the other two and they respectively affect only heating and cooling. In this last case it can be seen how its influence is marked in IT due to the climatic factors and less in FR, where the more sustainable electricity mix is able to contain the impacts arising from the increased request. The variation of the electricity mix exclusively concerns the electric domestic components, with a great influence on the overall impacts in the German worst configuration, while it is extremely limited in FR, and in particular on personal cleaning with electric WH, electric mobility and cooling (especially in IT).

5.3. Improvements

The obtained results confirm that the environmental impacts resulting from domestic activities are considerable; fortunately, there are many measures to improve this situation.

In this section, a selection of improvements for the considered scenario and based on ISO 50001 (ISO, 2011) are proposed. This normative suggests possible improvements to energy management in order to reduce the environmental footprint of a system and it specifies the criteria for guiding the users during their introduction, monitoring and evaluation. Following an iterative approach aiming at continuous improvement, it focuses on the reduction of the energy demand from external sources to the system, on the energy self-production, on the selection of the energy sources and it prescribes to raise the awareness of all personnel involved about energy consumptions. The evaluation of the interventions is prescribed to be conducted by considering also potential risks and the repercussion on all the requirements in addition to the environmental considerations.

The first hypothesized intervention consists in increasing the

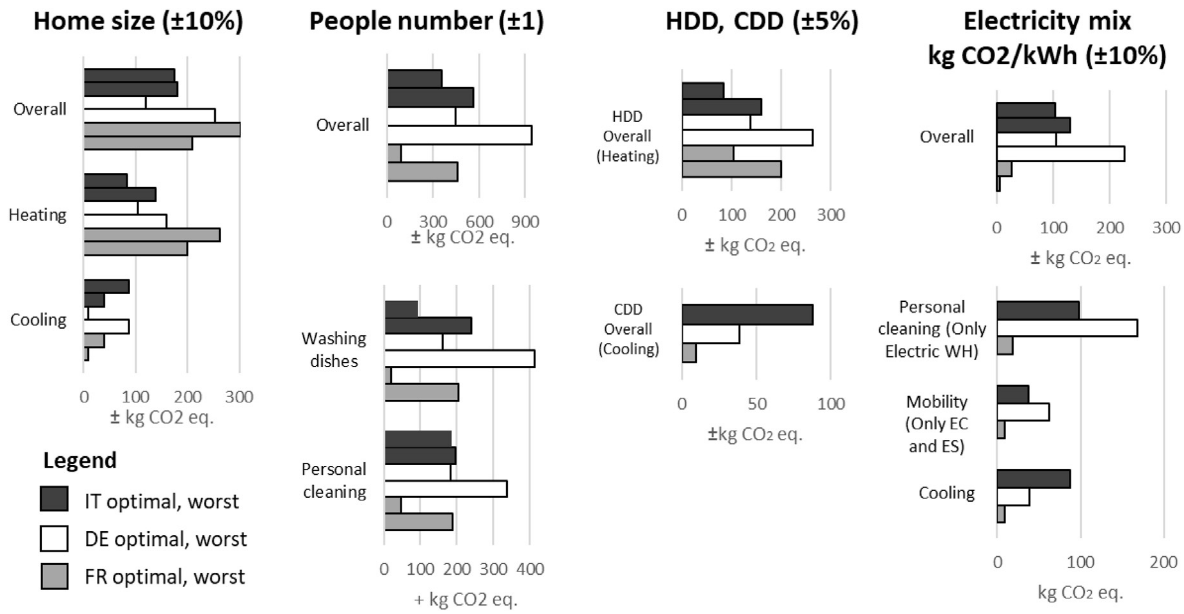

Fig. 5. Environmental impacts variation of the overall configurations and the domestic functions by changing home size, people number, climatic factors (HDD, CDD) and electricity mix in the three countries.

energy efficiency of those considered appliances powered by the same energy source, in order to provide an evaluation at a pure technological level (Russo and Spreafico, 2020). It is conducted by comparing the reduction of the environmental between an old air conditioner of 2007 (Dechezleprêtre and Sato, 2017) and the considered conventional gas boiler, WM and TD respectively with the considered air conditioner, condensing gas boiler, Pulsator WM and Heat pump TD.

The second intervention concerns the adoption of a more sustainable user's behaviour to reduce energy consumption, by collecting a series of best practices mainly derived from literature. They act in reducing the parameters of the specific functional unit for some of the considered domestic components. They are: the annual reduction of 100 uses of the dishwasher, of 50 uses per capita of the hob (Favi et al., 2018) and of 70 uses per capita of the oven (Landi et al., 2019), the substitution of the frozen meals with home-made ones for avoid defrosting, the elimination of the television stand-by time, the reduction of 4 min of the average time per shower (Laffell, 2000) and of 10 h per year in using the vacuum cleaner (European Commission, 2013), the use of semi-closed blinds for reducing the energy required for cooling, net of the increasing in the lighting (Stazi et al., 2014).

The third intervention concerns the reduction of the required externally energy, through the introduction of systems exploiting renewable sources. Among the possibilities, solar PV system and solar thermal system were selected since they are the most diffused in the considered scenarios. Both the systems are planned to be installed on to be on the south side of the roof. The solar PV system one consists of non-orientable monocrystalline silicon modules having a total area of 20 m^2 and a useful life of 25 years (Cao et al., 2016), while the solar thermal system are flat plate collectors with an area of 4 m^2, mounted with an optimum inclination of 30° (Greening and Azapagic, 2014) and they are used as back-up for gas and electric alimented WH. In both cases, the user's demand was not changed from the parameters specified in the functional unit, while the calculation of the saved impacts was obtained by considering the reduction in energy demand and by relating the performances of the two systems to the ASIs of the three countries (see Table 2).

The fourth intervention concerns the improvement of the structural insulation of the house, by introducing wall insulator and double-glazed windows, in order to reduce heat loss and consequently the energy required for heating and cooling functions. The selected wall insulator is meant to cover the entire external surface of the home with panels of Polyurethane having an insulator thickness of 5 mm (Su et al., 2016). This material was selected among the different options provided by the same authors because of its better performances. The double-glazed windows have an interior thickness of 5 mm and a frame made by Polyvinyl chloride (Switala-Elmhurst and Udo-Inyang, 2014). In both cases, the reductions of the impacts were calculated by quantifying the impacts of the avoided consumption of energy for heating and cooling, following their introduction, net of the impacts arising from their production and disposal.

In addition to those presented, we also compared other two possible options not based on ISO (2011) but which are linked to what has been proposed so far.

The first one regards the adoption of the optimal configuration of the domestic components. It collects the better domestic components for each function and in each country, in relation to the electricity mix and the climatic factors (see Section 5.1). Its benefits are estimated by comparing its carbon footprint with that of the worst configuration in each country.

The last option aims to quantify the benefits achievable by upgrading the Italian and German electricity generation and distribution networks (electricity mix) to the current French standard, where the specific impact of the produced electricity is equal to 0.058 kg CO_2 eq./kWh. Despite, this scenario is clearly hypothetical, since the variation of the electricity mix is not contemplable in short periods, it provides us the quantification about the related environmental advantages achievable at local level (Zurano-Cervelló et al., 2019). The benefits have been assessed considering the averages configurations of the domestic components in IT and DE.

In order to compare all proposed improvements, a bar chart shows in Fig. 6, the saved environmental impacts (in kg CO_2 eq.

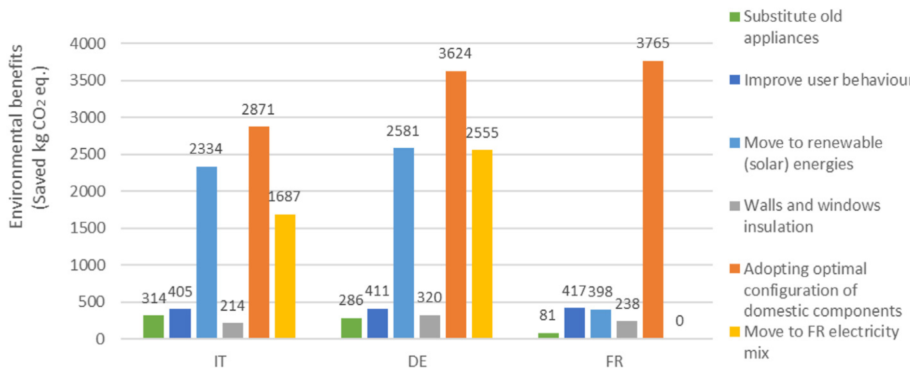

Fig. 6. Potential savings in environmental impacts (kg CO_2 eq. normalized for 1 year) by introducing the proposed improvements based on ISO 50001, adopting the optimal configuration of the domestic components according to electricity mix and climatic factors (see Section 5.1.) and adopting FR electricity mix.

normalized for 1 year) in each country, arising from the introduction of the proposed improvements in the considered scenarios.

Analyzing the results, it emerged that the selection of the domestic components having the less impacts for each function (optimal configuration) leads to the greater advantages for the environment, including in this case the large contributions guaranteed by the adoption of EC and condensing stove instead of ICC and wood stove, as shown in Section 5.1.

The solar energy exploitation systems represent the second most advantageous option in IT and DE, while in FR their benefits are greatly reduced due to the already little impacting electric energy from the national distribution network. Among them, solar PV systems guarantee the highest percentages in the reduction of the impacts, equal to 76% in IT, 83% in DE and 68% in FR. These values are respectively 49% in DE and 3% in IT greater than impacts arising from their overall electricity consumption in the optimal configuration because the solar PV systems can generate more electricity than required. As consequence, this option suggests a greater use of electric appliances or to return the surplus of electricity to the grid. Solar thermal systems can instead reduce the environmental impacts of the water heaters in the optimal configurations up to 93% in IT, 74% in DE and 70% in FR, even these results are limited to the number of three occupants in the home. Analogous systems to those considered were also estimated to be convenient from the energetical and the economical points of view, with extremely low energy PBTs comprised between 1 and 4 years (Good, 2016), and economic PBTs between 2 and 4 years (Michael and Selvarasan, 2017; Yasin, 2017).

The update of the electricity mix in IT and DE to the French standard also ensured very encouraging results on the average configurations. The resulting benefits are distributed between preparing food functions (−18% of the overall benefit of this improvement in IT, −53% in DE), water heater (−19% in IT, −40% in DE), air conditioner (−40% in IT, −20% in DE) and mobility (−8% in IT, −16% in DE). Song et al. (2018) highlight the benefits about the update of the electricity mix in reducing household impacts, by proposing applications working at local level such as district energy solutions.

The other considered hypotheses lead to much more limited advantages. Those arising from the introduction of more efficient appliances are the air conditioner (−50% of the carbon footprint in IT, comparing the new model and the old one) washing machine (−39% in DE) and heating (−50% in FR). In improving the user behavior, 67% of the overall benefits of this option in the three countries are guaranteed by the reduction of shower time. Finally, 97% of the benefits arising from the structural insulation depends by that of the walls.

6. Conclusions

This study presents a LCA limited to the carbon footprint of all the main domestic components commonly used in Italy, Germany and France, by exploiting only sources from scientific literature. The functional unit and other assumptions for the study were defined in relation to climatic, infrastructural and ethnographic habits of the operative scenarios.

All the main outputs of this work have been reported, discussed and summarized through some graphics. They compare the overall domestic impacts in the three countries, in relation to the considered functions (i.e. heating, personal cleaning, washing dishes, etc.) and considering the optimal and the worst configurations of the alternative domestic components, by suggesting the least impacting alternatives for all functions in each country in relation to the electricity mix and climatic factors. They also show the variations of the impacts deriving from a sensitivity analysis and they compare the environmental benefits, in terms of impacts reductions, of some improvements about energy management, ecological user behaviour and structural insulation.

In conclusions, the proposed study provided all the elements for a rough quantification of the domestic carbon footprint in the three countries. Germany is the most impactful, France the less one. The most impacting functions for all countries are in order: mobility, heating, personal cleaning, washing dishes. Cooling functions has a big impact only in Italy. The greatest advantages were obtained by electric car, condensing gas boiler and dishwasher.

The achieved outcomes made also possible to answer the initial hypotheses, considering the limitations of the study related to the numerous assumptions made within the selection of the functions and the component, the definition of the functional unit, the considered sources and methods, the evaluation of the results limited to the carbon footprint. (HP.1) The geographical location proved strongly affect the domestic impacts, mainly because of the influence of HDD and electricity mix. (HP.2) The selection of domestic components also proved to have a great influence on impacts, leading to considerable variations comparing their worst and the optimal configurations. (HP.3) Generic criteria can be identified for defining the optimal configuration of the components for minimizing the environmental impacts. (HP.4) From the study of the common improvements emerged that their environmental benefits in reducing the carbon footprint are very contained compared to the adoption of the optimal configuration of the domestic components.

The answer to the hypotheses leads some common implications for legislators, manufacturers and users in order to improve environmental awareness at home and its sustainability. The selection of the components is a fundamental question and for this reason it must be considered very carefully in relation to the application context. The different geographical location significantly changes the overall impacts but only leads to a few differences in the choices of the components. Favoring components with improved energy efficiency absolutely pays when they are powered by the same energy source. On the contrary, it is more appropriate to make compromise choices between efficiency and careful evaluation of the energy sources, especially where the electricity mix is less favorable from an environmental point of view. The water and energy savings required to heat it up should always be taken into consideration. In this case many of the most technologically advanced components are the most appropriate. The early replacement of the appliances reduces the carbon footprint especially for those having a greater increase in energy efficiency, even if the economic convenience is still too marginal or insufficient. Heating plants generate higher impacts, especially in the colder countries. Among them, the most sustainable ones are based on natural gas while the worst ones on wood, although from an economic point of view, the situation is opposite. Finally, all these considerations proved to be better than other improvements, such as the self-production of electricity through solar systems, the considerable improvement of the national electricity mix and the adoption of sustainable behaviors.

In the future, further evaluations could be made by enlarging the perimeter of the study to other countries, considered functions and domestic components, by enlarging the proposed evaluation of the results to other environmental indicators and by introducing deeper economic considerations, especially about the evaluation of the alternatives.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Christian Spreafico: Conceptualization, Methodology, Data curation, Writing - original draft, Writing - review & editing. **Davide Russo:** Conceptualization, Supervision, Writing - review & editing.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.121883.

Appendix

Table 3
Annual environmental impacts (kg CO_2 eq.) of the lifecycle and its phases for each considered components in the three countries (Italy, Germany and France), according to the parameters of the functional unit.

Functions	Components		Overall Lifecycle (except use) kg CO_2 eq./year	Overall Lifecycle (including use) kg CO_2 eq./year		
				Italy	Germany	France
Storing food	Refrigerator		20.8	48	68	27
Cooking with hob	Gas		3.1	120	120	120
	Induction		3.6	107	181	27
Cooking with oven	Gas		16.2	46	46	46
	Electric		15.7	62	95	26
	Microwave		14.0	21	26	16
Washing dishes	Dishwasher		18.6	301	504	82
	Hand wash	with GWH	0.0	613	613	613
		with EWH	0.0	719	1236	162
Making coffee	Automatic coffee machine	No capsule	0.5	16	27	5
		With Capsule	0.4	28	38	16
	Instant coffee in microwave oven		n.c.	45	45	45
Making tea	Polypropylene kettle		2.1	10	17	4
	Metallic kettle		1.3	10	16	3
Watching TV	LED TV *43 inches*		4.2	28	46	10
Reading	Paper books		75	75	75	75
	e-reader		15	15	15	15
Personal cleaning	Gas WH	Shower	40	593	589	589
		Bathtub	40	698	69	693
	Electric WH	Shower	42	659	1102	181
		Bathtub	42	776	1304	207
Washing clothes	Washing machine		21.9	115	157	62
	Washing machine pulsator		29.3	56	60	47
Drying clothes	Tumble dryer		24.9	80	115	36
	Heat pump tumble dryer		29.9	55	70	35
Ironing			n.a.	67	109	14
House cleaning	Vacuum cleaner		3.6	18	29	7
House climate	Heating	Conventional Boiler	8.8	890	1455	1102
		Condensing Boiler	10.5	854	1395	1056
		Wood stove	n.a.	1606	2633	1990
		Fireplace	n.a.	4272	6973	5282
	Cooling	Air conditioner	51.1	930	438	140
Lighting			n.c.	64	42	7
Mobility	Car	ICC	2949.7	3689	3689	3689
		EC	1481.9	1756	1953	1544
	Scooter	ICS	179.3	334	334	334
		ES	147.5	241	309	169
Total Optimal configuration				5200	5300	2450
Total Worst configuration				8111	10481	7879

References

Allacker, K., Mathieux, F., Pennington, D., Pant, R., 2017. The search for an appropriate end-of-life formula for the purpose of the European Commission Environmental Footprint initiative. Int. J. Life Cycle Assess. 22 (9), 1441–1458.

Arduin, R.H., Charbuillet, C., Perry, N., 2018. LCA of Recycling Chains: Influence of Transport Modelling.

Austin, A., Barnard, J., Hutcheon, N., Parry, D., 2015. Media consumption forecasts 2015. РеЖим доступу. https://communicateonline.me/wpcontent/uploads/2016/06/Media-Consumption-Forecasts-2016.pdf.

Bilan Carbone, 2016. Clim'Foot EU project. Available at: http://www.climfoot-project.eu/en/bilan-carbone%C2%AE-clim%E2%80%99foot-tool.

Blum, H., Okwelum, E., 2018. Estimating an economic-efficient frontier for dishwasher consumer choice. Energy Effic. 11 (6), 1325–1340.

Brommer, E., Stratmann, B., Quack, D., 2011. Environmental impacts of different methods of coffee preparation. Int. J. Consum. Stud. 35 (2), 212–220.

Bălănescu, D.T., Homutescu, V.M., 2018. Experimental investigation on performance of a condensing boiler and economic evaluation in real operating conditions. Appl. Therm. Eng. 143, 48–58.

Cao, X., Dai, X., Liu, J., 2016. Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade. Energy Build. 128, 198–213.

Casasso, A., Capodaglio, P., Simonetto, F., Sethi, R., 2019. Environmental and economic benefits from the phase-out of residential oil heating: a study from the Aosta Valley region (Italy). Sustainability 11 (13), 3633.

De Almeida, A., Fonseca, P., Schlomann, B., Feilberg, N., 2011. Characterization of the household electricity consumption in the EU, potential energy savings and specific policy recommendations. Energy Build. 43 (8), 1884–1894.

Dechezleprêtre, A., Sato, M., 2017. The impacts of environmental regulations on competitiveness. Rev. Environ. Econ. Pol. 11 (2), 183–206.

EC-JRC, 2012. Life Cycle Indicators Basket of Products: Development of Life Cycle Based Macro-Level Monitoring Indicators for Resources, Products and Waste for the EU-27. European Commission. Publications Office of the European Union, Luxembourg, ISBN 978-92-79-25937-1.

Elduque, D., Javierre, C., Pina, C., Martínez, E., Jiménez, E., 2014. Life cycle assessment of a domestic induction hob: electronic boards. J. Clean. Prod. 76, 74–84.

EU Eurostat, 2019. Energy statistics, cooling and heating degree days. Available at: https://ec.europa.eu/eurostat/cache/metadata/en/nrg_chdd_esms.htm#stat_pres1554283803348.

EU-SILC, 2016. Distribution of households by household size. Available at: https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=ilc_lvph03&lang=en.

European Commission, 2010. COMMISSION DELEGATED REGULATION (EU) No 1059/2010 of 28 September 2010 supplementing Directive 2010/30/EU of the European Parliament and of the Council with regard to energy labelling of household dishwashers. Available at. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32010R1059&from=EN. L314, 1-16 30.11.2010.

European Commission, 2013. Commission regulation (EU) No 666/2013 of 8 July 2013 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for vacuum cleaners. Off. J. Eur. Union L, 192, 24–34 13.7.2013. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2013:192:0024:0034:EN:PDF.

European Environment Agency, 2016. Overview of electricity production and use in Europe. Available at: https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-2/assessment-4.

Fan, L., Tong, Y., Niu, H., 2019. Promoting consumer adoption of water-efficient washing machines in China: barriers and countermeasures. J. Clean. Prod. 209, 1044–1051.

Favi, C., Germani, M., Landi, D., Mengarelli, M., Rossi, M., 2018. Comparative life cycle assessment of cooking appliances in Italian kitchens. J. Clean. Prod. 186, 430–449.

Gallego-Schmid, A., Mendoza, J.M.F., Jeswani, H.K., Azapagic, A., 2016. Life cycle environmental impacts of vacuum cleaners and the effects of European regulation. Sci. Total Environ. 559, 192–203.

Gallego-Schmid, A., Mendoza, J.M.F., Azapagic, A., 2018a. Environmental assessment of microwaves and the effect of European energy efficiency and waste management legislation. Sci. Total Environ. 618, 487–499.

Gallego-Schmid, A., Jeswani, H.K., Mendoza, J.M.F., Azapagic, A., 2018b. Life cycle environmental evaluation of kettles: recommendations for the development of eco-design regulations in the European Union. Sci. Total Environ. 625, 135–146.

Good, C., 2016. Environmental impact assessments of hybrid photovoltaic–thermal (PV/T) systems–A review. Renew. Sustain. Energy Rev. 55, 234–239.

Götz, T., Tholen, L., 2016. Stock model based bottom-up accounting for washing machines: worldwide energy, water and greenhouse gas saving potentials 2010–2030. Tenside Surfactants Deterg. 53 (5), 410–416.

Greening, B., Azapagic, A., 2014. Domestic solar thermal water heating: a sustainable option for the UK? Renew. Energy 63, 23–36.

Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I., 2018. Life Cycle Assessment. Springer.

Helmers, E., Dietz, J., Hartard, S., 2017. Electric car life cycle assessment based on real-world mileage and the electric conversion scenario. Int. J. Life Cycle Assess. 22 (1), 15–30.

Hischier, R., Baudin, I., 2010. LCA study of a plasma television device. Int. J. Life Cycle Assess. 15, 428–438.

Hollingsworth, J., Copeland, B., Johnson, J.X., 2019. Are e-scooters polluters? The environmental impacts of shared dockless electric scooters. Environ. Res. Lett. 14 (8), 084031.

Hoxha, E., Jusselme, T., 2017. On the necessity of improving the environmental impacts of furniture and appliances in net-zero energy buildings. Sci. Total Environ. 596, 405–416.

ISO, 2006a. 14040:2006 Environmental Management - LCA - Principles and Framework.

ISO, 2006b. 14044:2006 -Environmental Management - LCA - Requirements and Guidelines.

ISO, 2011. Energy Management Systems — Requirements with Guidance for Use. ISO 50001:2011. International Organization for Standardization, Genf.

ISO/TS 14067, 2014. Greenhouse Gases - Carbon Footprint of Products - Requirements and Guidelines for Quantification and Communication.

Ivanova, D., Stadler, K., Steen-Olsen, K., Wood, R., Vita, G., Tukker, A., Hertwich, E.G., 2016. Environmental impact assessment of household consumption. J. Ind. Ecol. 20 (3), 526–536.

Jenn, A., Springel, K., Gopal, A.R., 2018. Effectiveness of electric vehicle incentives in the United States. Energy Pol. 119, 349–356.

Jochem, P., Doll, C., Fichtner, W., 2016. External costs of electric vehicles. Transport. Res. Transport Environ. 42, 60–76.

Judit, O., Péter, L., Péter, B., Mónika, H.R., József, P., 2017. The role of biofuels in food commodity prices volatility and land use. J. Compet. 9 (4), 81.

Kaminska, A., Ożadowicz, A., 2018. Lighting control including daylight and energy efficiency improvements analysis. Energies 11 (8), 2166.

Krasny, E., Klarić, S., Korjenić, A., 2017. Analysis and comparison of environmental impacts and cost of bio-based house versus concrete house. J. Clean. Prod. 161, 968–976.

Laffell, D., 2000. Total Skin: the Definitive Guide to Whole Skin Care for Life. Hyperion.

Laicane, I., Blumberga, D., Blumberga, A., Rosa, M., 2015. Reducing household electricity consumption through demand side management: the role of home appliance scheduling and peak load reduction. Energy procedia 72, 222–229.

Landi, D., Consolini, A., Germani, M., Favi, C., 2019. Comparative life cycle assessment of electric and gas ovens in the Italian context: an environmental and technical evaluation. J. Clean. Prod. 221, 189–201.

Lesteven, G., Leurent, F., 2016. Electromobility for tourists: testing business models in the Paris region. Transport. Res. Procedia 19, 164–175.

Leuenberger, M., Frischknecht, R., 2010. Life Cycle Assessment of Two Wheel Vehicles. ESU-Services Ltd.: Uster, Switzerland.

LG, 2016. Environmental product declaration LG FULL HD LED TV. Available at: https://www.lg.com/global/greener-products-application.

Makonin, S., Ellert, B., Bajić, I.V., Popowich, F., 2016. Electricity, water, and natural gas consumption of a residential house in Canada from 2012 to 2014. Scientific data 3, 160037.

Mardoyan, A., Braun, P., 2015. Analysis of Czech subsidies for solid biofuels. Int. J. Green Energy 12 (4), 405–408.

Maroušek, J., Strunecký, O., Stehel, V., 2019a. Biochar farming: defining economically perspective applications. Clean Technol. Environ. Policy 1–7.

Maroušek, J., Stehel, V., Vochozka, M., Kolář, L., Maroušková, A., Strunecký, O., et al., 2019b. Ferrous sludge from water clarification: changes in waste management practices advisable. J. Clean. Prod. 218, 459–464.

Mersky, A.C., Sprei, F., Samaras, C., Qian, Z.S., 2016. Effectiveness of incentives on electric vehicle adoption in Norway. Transport. Res. Transport Environ. 46, 56–68.

Michael, J.J., Selvarasan, I., 2017. Economic analysis and environmental impact of flat plate roof mounted solar energy systems. Sol. Energy 142, 159–170.

Moberg, A., Johansson, M., Finnveden, G., Jonsson, A., 2010. Printed and tablet e-paper newspaper from an environmental perspective—a screening life cycle assessment. Environ. Impact Assess. Rev. 30, 177–191.

Monfared, B., Furberg, R., Palm, B., 2014. Magnetic vs. vapor-compression household refrigerators: a preliminary comparative life cycle assessment. Int. J. Refrig. 42, 69–76.

Moran, F., Blight, T., Natarajan, S., Shea, A., 2014. The use of Passive House Planning Package to reduce energy use and CO2 emissions in historic dwellings. Energy Build. 75, 216–227.

Nishijima, D., Kagawa, S., Nansai, K., Oguchi, M., 2019. Effects of product replacement programs on climate change. J. Clean. Prod. 221, 157–166.

Page, T., 2019. Habits and behaviours in the use of domestic lighting. Int. J. Sustain. Econ. Manag. 8 (2), 68–85.

Park, C., Xing, R., Hanaoka, T., Kanamori, Y., Masui, T., 2017. Impact of energy efficient technologies on residential CO2 emissions: a comparison of Korea and China. Energy Procedia 111, 689–698.

Piroozfar, P., Pomponi, F., Farr, E.R., 2016. Life cycle assessment of domestic hot water systems: a comparative analysis. Int. J. Const. Manag. 16 (2), 109–125.

Presutto, M., Stamminger, R., Scaldoni, R., Mebane, W., Esposito, R., 2007. Preparatory Study of Eco-Design Requirements of EuPs; Lot 14: Domestic Washing Machines and Dishwashers; Task 3–5. ISIS.

Quintero, P., et al., 2019. Life cycle assessment of wood pellets and wood split logs for residential heating. Sci. Total Environ. 689, 580–589. https://doi.org/10.1016/j.scitotenv.2019.06.420.

Richter, C.P., 2011. Usage of dishwashers: observation of consumer habits in the domestic environment. Int. J. Consum. Stud. 35 (2), 180–186. https://doi.org/10.1111/j.1470-6431.2010.00973.x.

Rodrigues, E.M.G., Godina, R., Pouresmaeil, E., Ferreira, J.R., Catalão, J.P.S., 2017. Domestic appliances energy optimization with model predictive control. Energy Convers. Manag. 142, 402–413.

Ross, S.A., Cheah, L., 2017. Uncertainty quantification in life cycle assessments: interindividual variability and sensitivity analysis in LCA of air-conditioning systems. J. Ind. Ecol. 21 (5), 1103–1114.

Roux, C., Schalbart, P., Peuportier, B., 2016. Accounting for temporal variation of electricity production and consumption in the LCA of an energy-efficient house. J. Clean. Prod. 113, 532–540.

Russo, Davide, Spreafico, Christian, 2020. TRIZ-based guidelines for eco-improvement. Sustainability 12 (8), 1–24, 3412. https://doi.org/10.3390/su12083412. https://www.mdpi.com/2071-1050/12/8/3412, 2020. (Accessed 22 April 2020).

Santori, G., Frazzica, A., Freni, A., Galieni, M., Bonaccorsi, L., Polonara, F., Restuccia, G., 2013. Optimization and testing on an adsorption dishwasher. Energy 50, 170–176.

Schmitz, A., Stamminger, R., 2014. Usage behaviour and related energy consumption of European consumers for washing and drying. Energy Effic. 7 (6), 937–954.

Scur, G., Barbosa, M.E., 2017. Green supply chain management practices: multiple case studies in the Brazilian home appliance industry. J. Clean. Prod. 141, 1293–1302.

Sierzchula, W., Bakker, S., Maat, K., Van Wee, B., 2014. The influence of financial incentives and other socio-economic factors on electric vehicle adoption. Energy Pol. 68, 183–194.

Song, Q., Wang, Z., Li, J., Duan, H., Yu, D., Liu, G., 2018. Comparative life cycle GHG emissions from local electricity generation using heavy oil, natural gas, and MSW incineration in Macau. Renew. Sustain. Energy Rev. 81, 2450–2459.

Stamminger, R., 2011. Modelling resource consumption for laundry and dish treatment in individual households for various consumer segments. Energy efficiency 4 (4), 559–569.

Stazi, F., Marinelli, S., Di Perna, C., Munafò, P., 2014. Comparison on solar shadings: monitoring of the thermo-physical behaviour, assessment of the energy saving, thermal comfort, natural lighting and environmental impact. Sol. Energy 105, 512–528.

Su, X., Luo, Z., Li, Y., Huang, C., 2016. Life cycle inventory comparison of different building insulation materials and uncertainty analysis. J. Clean. Prod. 112, 275–281.

Switala-Elmhurst, K., Udo-Inyang, P., 2014. Life cycle assessment of residential windows: saving energy with window restoration. In: ASC Proceedings of the 50th Annual Conference.

Ürge-Vorsatz, D., Cabeza, L.F., Serrano, S., Barreneche, C., 2015. Heating and cooling energy trends and drivers in buildings. Renew. Sustain. Energy Rev. 41, 85–98.

Urraca, R., Huld, T., Lindfors, A.V., Riihelä, A., Martinez-de-Pison, F.J., Sanz-Garcia, A., 2018. Quantifying the amplified bias of PV system simulations due to uncertainties in solar radiation estimates. Sol. Energy 176, 663–677.

Vignali, G., 2017. Environmental assessment of domestic boilers: A comparison of condensing and traditional technology using life cycle assessment methodology. J. Clean. Prod. 142, 2493–2508. https://doi.org/10.1016/j.jclepro.2016.11.025.

Weber, C.L., Matthews, H.S., 2008. Quantifying the global and distributional aspects of American household carbon footprint. Ecol. Econ. 66 (2–3), 379–391.

Xiao, R., Zhang, Y., Liu, X., Yuan, Z., 2015. A life-cycle assessment of household refrigerators in China. J. Clean. Prod. 95, 301–310.

Yasin, A., 2017, May. Environmental impact assessmemt of a collective solar water heater system in west bank. In: Proceeding of, p. 76.

Yuan, Z., Zhang, Y., Liu, X., 2016. Life cycle assessment of horizontal-axis washing machines in China. Int. J. Life Cycle Assess. 21 (1), 15–28.

Zhang, J., Yu, B., Cai, J., Wei, Y.M., 2017. Impacts of household income change on CO2 emissions: an empirical analysis of China. J. Clean. Prod. 157, 190–200.

Zurano-Cervelló, P., Pozo, C., Mateo-Sanz, J.M., Jiménez, L., Guillén-Gosálbez, G., 2019. Sustainability efficiency assessment of the electricity mix of the 28 EU member countries combining data envelopment analysis and optimized projections. Energy Pol. 134, 110921.