Sustainable Production and Consumption 26 (2021) 1011–1020

Contents lists available at ScienceDirect

Sustainable Production and Consumption

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

Research article

Domestic hot water systems: Environmental performance from a life cycle assessment perspective

R. Gemma Raluy, Ana Cláudia Dias*

Centre for Environmental and Marine Studies (CESAM), Department of Environment and Planning, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal

ARTICLE INFO

Article history:
Received 7 September 2020
Revised 21 December 2020
Accepted 6 January 2021
Available online 7 January 2021

Editor: Prof. Chao Zhang

Keywords:
Domestic hot water heater
Ecodesign
Environmental impact
Life cycle assessment
Sustainability

ABSTRACT

Four types of commercially-available domestic hot water (DHW) systems (natural gas instantaneous, electric instantaneous, electric storage and heat pump) were analysed and compared from a life cycle assessment (LCA) perspective and their environmental hotspots (stages and processes) were determined. In addition, the influence of the origin of the energy consumed during their usage was analysed and their environmental performance was compared with that of new DHW systems recently developed. A cradle-to-grave analysis was adopted by employing data provided by the manufacturer and supplemented with secondary data from Ecoinvent. The ReCiPe 2016 (hierarchist perspective) method was used to perform the impact assessment. Regardless of the type of water heater, the use stage (due to high energy consumption) was clearly the main responsible for the environmental damage by DHW systems, but the stage of production of raw materials was also important. A comparative analysis of the four current water heating systems showed that the heat pump caused the least impacts (by litre of heated water provided per year), followed by gas-fired, electric storage, and electric instantaneous in that order. The environmental burdens are highly influenced by the country in which the DHW systems are installed because the origin of the energy source used varies. New water heaters developed by manufacturer demonstrated a trend to an environmental improvement compared to the current ones, although improvements with respect to materials consumed are still required.

1. Introduction

Households were responsible for 26% of the total final energy consumption in the European Union (EU) in 2018 (Eurostat, 2020). After space heating, the greatest contribution to energy consumption in EU households (up to 15%) is heating water for personal hygiene, washing, cooking, etc. Several energy sources are used to heat water in the EU. On average, gas provides the highest share (40.6%), whereas electricity accounts for 20.6%, derived heat for 13.1%, renewables and wastes for 12.6%, products from oil and petroleum for 11.3%, and solid fossil fuels for 1.8% (Eurostat, 2020). Besides, there are different domestic hot water (DHW) systems on the market, such as gas storage water heaters, gas instantaneous water heaters, electric storage water heaters, electric instantaneous water heaters and heat pump water heaters.

Sustainable production and consumption is currently a global priority, as recognised in the goal 12 of the Sustainable Development Goals of the United Nations (UN, 2020). To comply with this goal, DHW manufacturers should achieve an efficient use of natural resources and make efforts to reduce their emissions to the environment during product manufacturing to minimize their adverse impacts. They should also ensure that the DHW systems are environmentally-friendly during use and end-of-life, and provide usage recommendations to consumers so that they can make responsible use of DHW systems. Life Cycle Assessment (LCA) is a tool that can be used to support sustainable production and consumption as it quantifies a variety of environmental impacts from different stages of a product's life cycle (starting in raw material acquisition up to its final disposal). Therefore, information extracted from LCAs can be used as a basis or benchmark to inform stakeholders (manufacturers, end-users, and policy-makers) about the environmental performance of DHW systems and to support the development of more sustainable DHW systems. For instance, manufacturers could embed environmental LCA into the product value chain for decision support, and thus achieve more-sustainable production of DHW systems and report to end-users and policy makers, who are asking for the environmental impacts in the entire product value chain.

In recent years, several LCA or carbon footprint (CF) researches comparing different DHW heaters have been published. Piroozfar et al. (2016) evaluated the CF of different

* Corresponding author.
E-mail addresses: gemma.raluy@ua.pt (R.G. Raluy), acdias@ua.pt (A.C. Dias).

https://doi.org/10.1016/j.spc.2021.01.005
2352-5509/

Table 1
Technical specifications for the current (C) and new (N) water heaters. NGI: natural gas instantaneous; EI: electric instantaneous; ES: electric storage; HP: heat pump.

Technical data	Unit	NGI (C)	NGI (N)	EI (C)	ES (C)	ES (N)	HP (C)	HP (N)
Rated heat output	kW	19.2	17.4	24	1.5	1.5	2.6[a]	2.5[a]
System life-time	year	15	15	10	15	15	15	15
Rated pressure	bar	–	–	10	8	8	10	10
Warm water flow rate	L/min	2–11	4.6–10	2.6–7.1	–	–	–	–
Minimum pressure for maximum flow	bar	0.55	0.55	–	–	–	–	–
Storage tank capacity	L	–	–	–	50	50	270	270
Sound power level	dB(A)	69	67	15	15	15	55	<55
Load profile		M	M	S	M	M	XL	XL
Annual fuel consumption	GJ/year	7	6	–	–	–	–	–
Annual energy consumption	kWh/year	–	–	479	1367	1286	1094	929.9
Hot water heating energy efficiency	%	71	73	38.5	37.0	39.9	136.0[b]	160.0
Coefficient of Performance (COP)[c]		–	–	–	–	–	3.77[d]	4.43[d]
Approximate weight (without packaging)	kg	9.5	11.7	3.1	14.9	15.2	120	115

[a] Maximum rated power absorbed from the air by the HP for performance conditions according to EN 16,147, cycle XL, air temperature of 14 °C, 87% of humidity, water heating from 10 °C to 46 °C.
[b] The HP has an energy efficiency (i.e., ratio between useful energy provided and the energy required to generate it) greater than 100% because it uses ambient air to generate heat by transporting air from a cold region to a warmer one using electricity. The HP converts energy from the air into thermal energy with the addition of a small amount of energy.
[c] Coefficient of performance (COP) is the capacity declared for heating divided by the energy input.
[d] Under warmer climatic conditions, which are most comparable to Portuguese conditions (EU, 2013a, 2013b).

DHW systems in the UK; Moore et al. (2017) and Kumar and Mathew (2018) calculated the CF of several DHW systems in Australia; Liu et al. (2019) applied LCA to various DHW systems in China; and Raluy and Dias (2020) used LCA to evaluate a fuel-fired water heater in Portugal. These studies agree that the environment performance of DHW systems is mostly affected by the use stage but differ greatly according to the efficiency and energy consumption rates of the heaters used.

The present work aimed to quantify and compare the environmental impacts of four DHW systems (natural gas instantaneous, electric instantaneous, electric storage, heat pump) available on the market using LCA to identify the critical stages over their life cycles. Five scenarios of usage of DHW systems from different countries were assessed. As new generations of DHW systems are being developed to comply with current and future regulations regarding higher levels of efficiency, energy savings, and environmental-friendliness, and also to fulfil end-user requirements (e.g. reduce energy bills, facilitate use, lower sound level), another objective was the comparison of the environmental performance of older and newer DHW systems to evaluate whether the technological improvements made mitigate environmental impact, and if so, to what extent.

This paper continues the research of Raluy and Dias (2020) by expanding the LCA to other commonly-used DHW systems. As far as we know, there are no other works on the environmental performance of DHW systems in Portugal. Moreover, this LCA study also included new features not considered in previous international studies, that is, a comparison of current DHW systems with newly-designed system developed by the manufacturer and an assessment of how different factors of annual water usage affect environmental performance. By considering a wide set of environmental impact categories, this study went beyond previous studies that relied only on the CF by providing a more complete and comprehensive ranking of the environmental burdens of these systems to better support decision making by stakeholders.

2. Methodology

2.1. Goal and scope definition

The goals of this study were: i) to estimate the environmental burdens and identify the hotspots of four different DHW systems (natural gas instantaneous, electric instantaneous, electric storage, heat pump) currently available on the market, ii) to compare the environmental performance of those DHW systems, iii) to evaluate the influence of the energy origin during the use stage of the DHW systems, and iv) to compare the environmental impacts of the current DHW systems with the new ones. This LCA is a cradle-to-grave assessment and the most relevant aspects of the scope are defined in the following subsections.

2.1.1. Functional units and DHW systems

The functional unit (FU) used in the LCA of each DHW system was, generically, the provision of a certain amount of hot water with a temperature of at least 45 °C for the expected service life of the DHW system; however, due to different capacities of heated water provision and expected service life of different water heaters, the FU must be normalized (and expressed as litres of heated water provided annually (L/year)) for comparison. Water volumes were calculated on the basis of declared load profiles regarding the energy required to produce hot water following Commission Regulations 812/2013 and 814/2013 (EU, 2013a, 2013b).

The basic technical data for the four DHW systems currently available on the market (hereafter referred to as current DHW systems) and the three new DHW systems are shown in Table 1. The DHW systems selected for this analysis were:

- Natural gas instantaneous (NGI) current and new water heaters with a maximum capacity of 10–11 L water/min and an M load profile (EU, 2013a, 2013b). The LCA of the current NGI was analysed by Raluy and Dias (2020), and the main technical specifications and results are summarised in this study to facilitate comparison with the other DHW systems. The newer NGI water heater showed better combustion performance and lower fuel consumption and NO_x emissions (up to 35 mg/kWh) than the current one. The FU was providing 42,822 L heated water /year with a minimum temperature of 45 °C during 15 years of service life for both current and new NGI water heaters.

- Electric instantaneous (EI) current water heater with a maximum capacity of 7.1 L water/min and an S load profile (EU, 2013a,2013b). The FU was providing 16,470 L heated water/year with a minimum temperature of 45 °C during 10 years of service life. No new EI water heater was assessed.

- Electric storage (ES) current and new water heaters with a 50 L-tank and an M load profile (EU, 2013a, 2013b). The new ES water heater contains a smart control that adapts water heating to individual conditions of use to reduce energy consumption. The FU was providing 42,822 L heated water /year with a minimum tem-

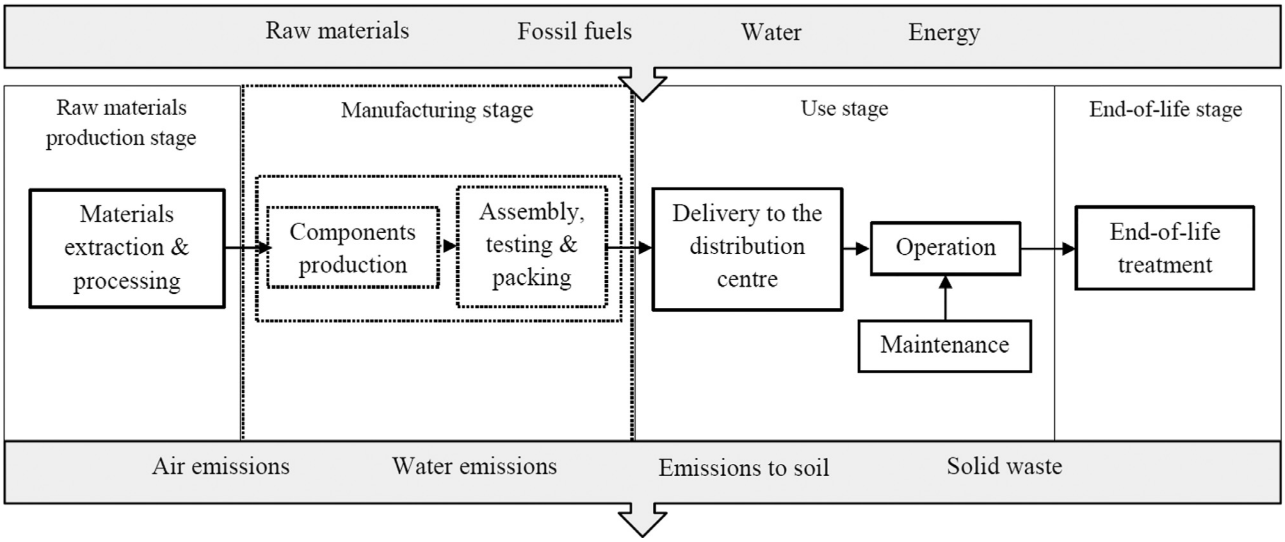

Fig. 1. System boundaries in the life cycle of DHW systems. Solid boxes represent stages and processes considered and dotted boxes represent stages and processes excluded from assessment.

perature of 45 °C during 15 years of service life for both current and new ES water heaters.

- Air source heat pump (HP) current and new water heaters with a 270 L-tank and a XL load profile (EU, 2013a, 2013b). The new HP water heater had higher energy efficiency, lower energy consumption, and uses a natural refrigerant (R1234ze). The FU was providing 144,936 L heated water /year with a minimum temperature of 45 °C during 15 years of service life for both current and new HP water heaters.

2.1.2. System boundaries

The system boundaries, shown in Fig. 1, cover the DHW systems from cradle-to-grave, including raw materials production, the use stage (delivery of water heaters to a distribution centre, energy consumption (natural gas or electricity), water consumption, and maintenance along the service life) and, finally, the end-of-life (landfilling and recycling). The stage of product manufacturing was not considered given the lack of information. However, the impacts associated with this stage were considered negligible based on the results obtained by Raluy and Dias (2020) for the gas-fired water heater assessed. Distribution up to final end-users was also excluded due to data unavailability, nevertheless, the contribution to overall burdens of this process was expected to be insignificant.

Given that DHW systems are composed of a variety of materials (some in very small amounts), the raw materials production stage excludes materials that cumulatively comprised less than 1% of the gross weight of the DHW systems, provided that materials with potentially-relevant impacts were not excluded.

2.2. Inventory analysis

2.2.1. Raw materials production stage

The production of raw materials comprises manufacture of materials contained in the water heaters, including packaging materials. Table 2 presents data on the quantities of materials by type of material for both current and new water systems, provided by the manufacturer, considering the aforementioned cut-off criteria. The bill of materials and quantities of each component of the water heaters are given in Tables S1-S7 of the Supporting Material (SM). Data on the extraction and processing of raw materials were supplied by Ecoinvent database v3.4 (Wernet et al., 2016).

2.2.2. Use stage

The use stage included delivery of water heaters to the distribution centre, water consumption, energy consumption (electricity for EI, ES and HP; natural gas for NGI) and maintenance (when applicable). Table 3 outlines the inventory data of this stage gathered from the producer of the water heaters, except emission of carbon dioxide (CO_2) from NG combustion in NGI system which was figured according to emission factors from the IPCC (2006).

Portugal was assumed to be a country in which all types of DHW systems are used. NGI, EI and current HP were manufactured in Portugal, whereas ES and new HP were produced in Bulgaria and delivered to Portugal. Thus, a euro 3 lorry of 16–32 t was assumed to deliver the household appliances from the producer until the distribution place in Portugal, considering 3900 km and 250 km of average distance for the water heaters produced in Bulgaria and Portugal, respectively.

Maintenance is required for NGI, ES and HP systems. For the NGI, a hydrochloric acid solution applied every two years to remove solidifications (Raluy and Dias (2020)); while for the ES and HP, maintenance involves changing the magnesium anode every three years for water consumption equal to the tank capacity (i.e., 50 L for the ES and 270 L for the HP). Thus, the total number of maintenance operations for both current and new water heaters over a 15-years service life was seven for the NGI system and five each the ES and HP systems. Data for the lorry and production of natural gas, electricity, tap water, magnesium, and hydrochloric acid were taken from Ecoinvent v3.4 (Wernet et al., 2016). However, the natural gas origin was modified, based on DGEG (2017), to better represent the natural gas used in Portugal.

2.2.3. End-of-life stage

The end-of-life encompassed landfilling and recycling, considering the recyclability rates given in Table S8 of SM for each material and the inventory data available in Ecoinvent 3.4 (Wernet et al., 2016).

2.3. Impact assessment method

The method selected to estimate the potential environmental impacts of the DHW systems was the ReCiPe 2016 Midpoint v1.01 at the hierarchist perspective (Huijbregts et al., 2017) available with SimaPro 8.5.0 software. Eight impact categories were selected: Global Warming (GW), Stratospheric Ozone Depletion

Table 2
Raw materials of the current (C) and new (N) water heaters per FU. NGI: natural gas instantaneous; EI: electric instantaneous; ES: electric storage; HP: heat pump.

Material	NGI (C)	NGI (N)	EI (C)	ES (C)	ES (N)	HP (C)	HP (N)
Corrugated board box (g)	300	1000	150	1650	1650	–	–
Graphic paper (g)	39	46	121.5	–	–	–	–
Pine wood (kg)	–	–	–	–	–	10.04	10.04
Copper (kg)	2.179	2.67	0.189	1.05	1.05	2.71	0.157
Brass (g)	161	168.5	64	–	–	1670	270
Steels (kg)	6.0	7.39	0.276	9.60	9.60	79.55	89.77
Iron-nickel-chromium alloy (g)	–	–	66	–	–	–	–
Aluminium (kg)	0.631	0.873	–	–	–	3.93	6.93
Zinc (kg)	–	–	–	–	–	4.50	–
Magnesium (g)	–	–	–	300	300	1000	1000
Polystyrene expandable (EPS) (g)	235	205	56	200	200	2560	2560
Polypropylene (PP) (g)	2	2	468.7	–	–	4470	4670
Acronitrile-butadiene-styrene (ABS) (g)	21	21	639.1	–	–	–	2370
Polyethylenes (PE) (g)	76.6	90.2	–	700	700	1400	700
Nylon 6–6, glass-filled (g)	137	137	165	–	–	–	–
Glass fibre reinforced plastic (g)	–	–	897	–	–	–	–
Polyphenylene sulphide (g)	–	–	9.4	–	–	–	–
Polyurethane (PU) foam (kg)	–	–	–	2.55	2.55	8	4,61
Polyester-complexes biopolymer (g)	–	–	–	–	–	302	302
Polycarbonate (PC) (g)	72	57	–	–	–	–	–
Silicon (g)	–	–	5.5	–	–	760	–
Synthetic rubber (g)	–	–	–	–	–	79,30	79,30
Styrene (g)	–	–	–	–	–	312	110
Refrigerant R134a (g)	–	–	–	–	–	400	–
Refrigerant R1234ze (g)	–	–	–	–	–	–	1000
Electronic components (g)	138	160	350	750	950	280	280
Cables (m)	–	–	1.916	1.5	1.5	3.5	3.5
Switches, toggle type (g)	40	49	–	–	–	–	–
Transistors (g)	11	24	–	–	–	–	–

Table 3
Inputs and outputs data for the use stage of current (C) and new (N) water heaters per FU. NGI: natural gas instantaneous (15 years service life); EI: electric instantaneous (10 years service life); ES: electric storage (15 years service life); HP: heat pump (15 years service life).

Parameter	NGI (C)	NGI (N)	EI (C)	ES (C)	ES (N)	HP (C)	HP (N)
Inputs							
Natural gas (Nm^3)	2924.79	2506.96	–	–	–	–	–
Electricity (kWh)	–	–	4790.0	20,505.0	19,290.0	16,410.0	13,948.5
Tap water, use (L)	642,330	642,330	164,000	642,330	642,330	2174,040	2174,040
Tap water, maintenance (L)	9	9	–	250	250	1080	1080
Hydrochloric acid, maintenance (kg)	3.91	3.91	–	–	–	–	–
Magnesium, maintenance (kg)	–	–	–	1.2	1.2	4.0	4.0
Outputs							
Hot water (L)	642,330	642,330	164,000	642,330	642,330	2174,040	2174,040
Wastewater from maintenance (L)	9	9	–	250	250	1080	1080
Refrigerant R134a (g)	–	–	–	–	–	45	–
Refrigerant R1234ze (g)	–	–	–	–	–	–	45
CO_2 fossil (kg) [a]	5980.5	5049.0	–	–	–	–	–
NO_x (g) [a]	5349.2	875.0	–	–	–	–	–
CO (g) [a]	6112.8	8686.6	–	–	–	–	–

[a] air emission from NG combustion.

(SOD), Ozone Formation-Human Heath (OFHH), Terrestrial Acidification (TA), Freshwater Eutrophication (FE), Marine Eutrophication (ME), Mineral Resource Scarcity (MRS) and Fossil Resource Scarcity (FRS). These eight impact categories encompass emissions typical of fuel combustion (i.e. CO_2, CO, NO_x,), and are frequently used in LCA researches of DHW systems (e.g. Liu et al., 2019), thus facilitating comparisons.

3. Results and discussion

3.1. Hotspot analysis of current DHW systems

Table 4 present the total environmental impacts over the service life of the four current water heaters used in Portugal expressed per FU. The share of each stage of the life cycle to the environmental impacts of each system is presented in Tables S9-S12 of SM and depicted in Fig. 2, which presents impacts expressed per litre of heated water provided per year.

The use stage had the greatest hotspot in almost all categories analysed regardless of the type of system, with contributions ranging from 80 to 99.6% in these cases. The exceptions are MRS for all heaters and the eutrophication-related categories (ME and FE) for the current NGI water heater. The raw materials production stage was the most significant stage in MRS (contribution of 86 to 96%), due to the use of resources. This stage made the largest contribution to FE (62%) and ME (52%) for the NGI water heater because of emissions associated with the production of several raw materials (predominantly copper, brass, steels and electronic components). The end-of-life stage generated environmental benefits (negative absolute values), which were more evident in MRS through recycling of materials, thus reduction of the need for virgin materials. The only exceptions were for SOD and ME in EI, but the impacts were negligible.

Table 4
Total environmental impacts of the current (C) and new (N) DHW systems over their service life per FU. The use stage occurred in Portugal.

Impact categories	Unit	NGI (C)	NGI (N)	EI (C)	ES (C)	ES (N)	HP (C)	HP (N)
GW	t CO_2 eq.	8.24	7.09	2.02	8.72	8.23	7.97	6.93
SOD	g CFC-11 eq.	2.01	1.75	0.72	2.96	2.80	3.06	2.41
OFHH	kg NO_x eq.	8.42	3.60	4.88	21.05	19.88	19.03	16.83
TA	kg SO_2 eq.	4.79	3.16	12.70	53.29	50.28	47.94	40.73
FE	kg P eq.	0.41	0.45	0.76	2.96	2.84	3.35	2.74
ME	g N eq.	26.37	28.66	49.56	194.84	185.60	222.07	184.15
MRS	kg Cu eq.	4.28	4.74	2.14	7.27	7.43	43.59	37.85
FRS	t oil eq.	3.28	2.82	0.43	1.87	1.77	1.78	1.58

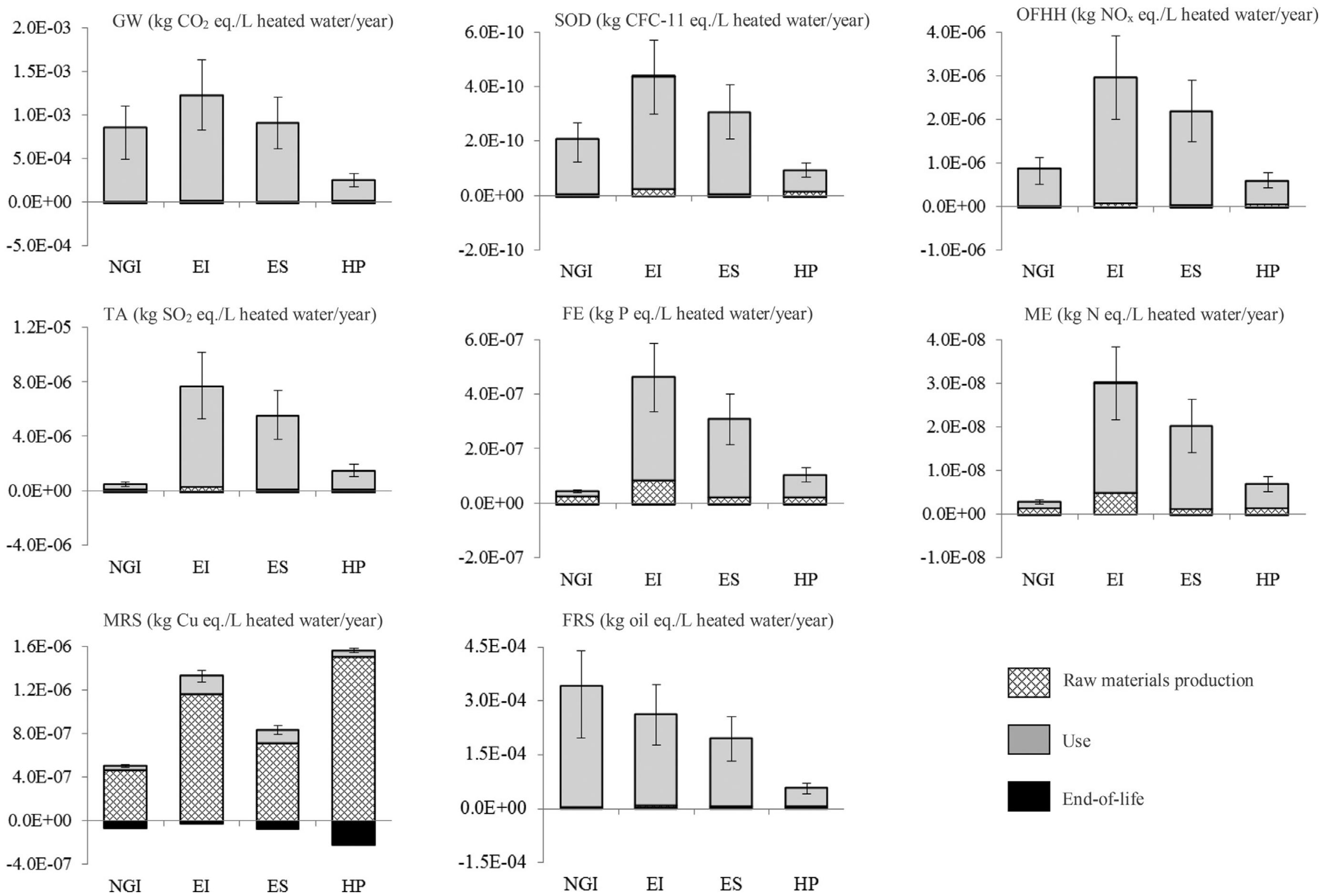

Fig. 2. Life cycle environmental impacts of the current DHW systems by stage, expressed per litre of heated water provided per year; error bars represent the variation range in sensitivity analysis by changing the factor of annual use (0.4 and 0.8). The use stage occurred in Portugal. NGI: natural gas instantaneous; EI: electric instantaneous; ES: electric storage; HP: heat pump.

Fig. 3 presents the use stage in Portugal subdivided into several processes: transport, consumption of water, production and burning of natural gas for NGI, consumption of electricity for electric water heaters, maintenance, and loss of R134a refrigerant in the HP system. Regarding the three electrical DHW systems (EI, ES, HP), the consumption of electricity was clearly the main source of environmental impact in seven out of the eight categories, and accounting for 74–99% of the impacts largely as a result of emission of fossil CO_2 in GW, N_2O in SOD, NO_x in OFHH, SO_x in TA, nitrate in ME and phosphate in FE, and consumption of coal and natural gas (in FRS) from electricity production. In the MRS category, electricity consumption was still the main contributor for the EI and ES water heaters (64–65%). In the case of the HP system, electricity consumption was not so relevant and the main contribution came from the processes related to tap water provision (67%, i.e. water abstraction, treatment and distribution), largely as a result of aluminium, uranium and iron depletion. These processes were also the main source of impact related to FE, ME and MRS for the NGI water heater (88 to 97%) due to phosphate and nitrate emissions, and depletion of aluminium and nickel. The impact of the NGI on the other categories was dominated by natural gas pre-combustion and combustion, which together represent 83–99% of the impact (Raluy and Dias, 2020).

Environmental damages due to transport, maintenance and refrigerant loss were almost insignificant compared to the damages of the other processes.

3.2. Comparison between current DHW systems

A comparative analysis of the total environmental impact of the four current water heaters expressed per litre of heated water per year (Fig. 2) showed that the HP was the best option in

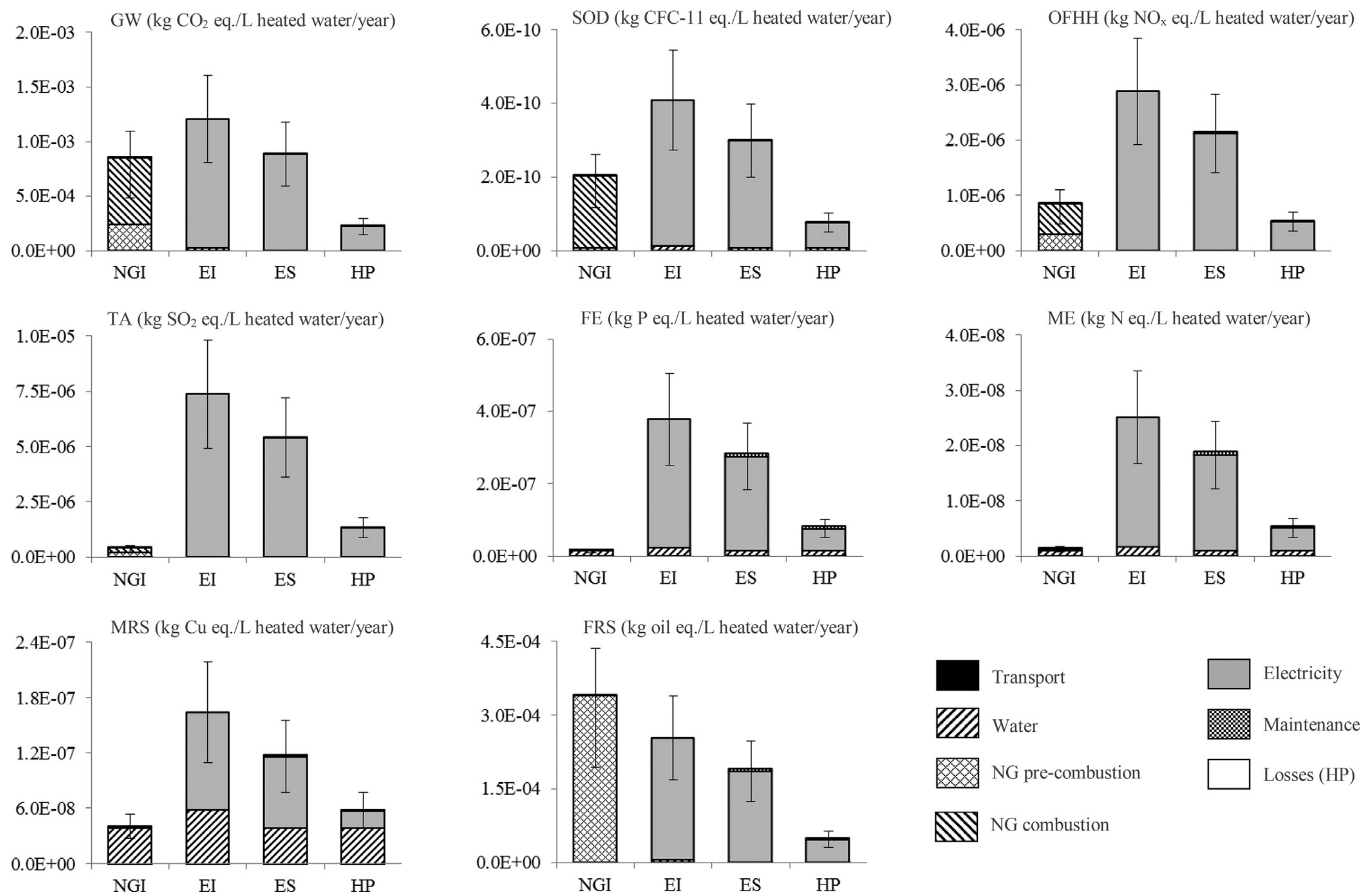

Fig. 3. Environmental impacts of the current DHW systems by process of the use stage (in Portugal), expressed per litre of heated water provided per year, the error bars represent the variation range in sensitivity analysis by changing the factor of annual use (0.4 and 0.8). NGI: natural gas instantaneous; EI: electric instantaneous; ES: electric storage; HP: heat pump.

GW, SOD, OFHH and FRS due to its lower electricity consumption rate (0.05 Wh/L heated water per year compared to 3.03, 2.91 and 2.13 Wh/L heated water per year for NGI, EI and ES systems, respectively). However, the HP was the worst option in MRS because of the large quantity of materials used (Tables 2 and S6), especially those comprising the water storage tank. The NGI system had the best environmental performance in TA, FE, ME and MRS due to low emissions and less need for mineral resources associated with NG pre-combustion and combustion as compared to systems that use electricity produced in the grid (Fig. 3). However, the NGI system had the worst performance in FRS due to the depletion of natural gas. The EI system was the worst DHW system in six of the eight impact categories (GW, SOD, OFHH, TA, FE an ME) due to the high rate of electricity consumption and high emissions related to production of electricity. The ES system had the less of an environmental impact than the EI system due to the lower rates of electricity consumption.

3.3. Comparison to previous studies

Other LCA and CF studies of DHW systems differ from this study in several normative choices (i.e., system boundaries, functional units, databases, impact categories and impact assessment methods) that prevent a fair comparison of the respective results. Despite this limitation, a comparison was made for the GW category, and regardless of the type of DHW system, Liu et al. (2019), Moore et al. (2017) and Piroozfar et al. (2016) also found that the usage was the largest contributor to GW (Table S16 of SM), with contributions ranging from 52% to near 100%.

Comparison of the impact of GW on the current NGI system with that reported in other studies is reported in Raluy and Dias (2020) and not addressed here. Besides, a comparison was not possible for the EI water heater because this system was not considered in other studies. Fig. S1 of SM shows that the total GW (expressed in g CO_2 eq./L heated water/year) of the current ES was about three times higher than the GW obtained for the ES system used in Piroozfar et al. (2016), but much lower than the GW obtained for the ES systems assessed by Liu et al. (2019) and Moore et al. (2017). An HP system assessed by Liu et al. (2019) had much higher GW impact per litre of heated water per year than the current HP system of this study. Disparity in the results is mainly attributed to differences in the consumption rates of electricity per litre of heated water per year and emission factors of greenhouse gas emissions produced in the electricity production (Table S16). Variations observed in these parameters reflect local legislation stablished by each jurisdiction in which electrical DHW systems are used (i.e. standards to measure and calculate energy consumption) and local/regional particularities (i.e. climatic conditions, temperature of inlet water, water demand, electricity production mix).

3.4. Sensitivity analysis

To calculate annual water and energy consumption of DHW systems, EU Regulations 812/2013 and 814/2013 (EU, 2013a, 2013b) established a default factor or percentage of annual use of water heaters of 0.6, assuming 220 days of use per year. However, annual DHW usage varied depending on the number of individu-

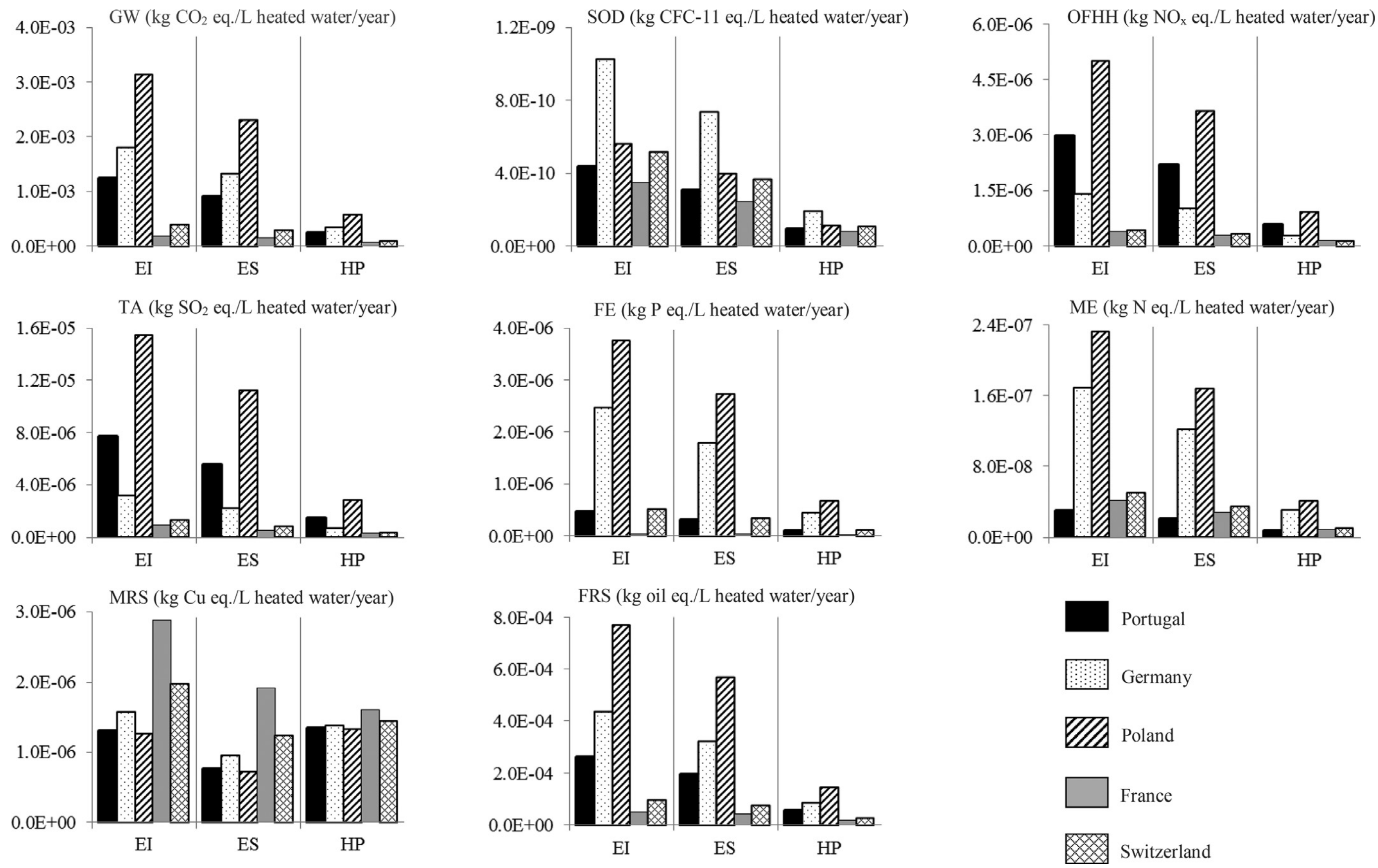

Fig. 4. Influence of the electricity production mix on the life cycle environmental impact of current DHW systems expressed per litre of heated water provided per year. EI: electric instantaneous; ES: electric storage; HP: heat pump.

als per household (occupancy rate) and their consumption patterns (e.g. water flow rate, duration of water usage events), climatic conditions (temperature of cold water input), and demanded comfort (temperature of hot water output). With these factors in mind, a sensitivity analysis was carried out by considering different factors of annual usage of DHW systems: 0.8 and 0.4 (corresponding to 292 and 146 days of use per year, respectively). Figs. 2 and 3 show the sensitivity analysis results, through error bars, for total environmental impacts and for the environmental impacts of the use, respectively, expressed per litre of heated water per year, when used in Portugal. Regardless of the type of DHW system, according to Fig. 2, the total impact (except for MRS) presented significant differences when compared to the reference scenario (up to 23–55%), due to the large share of the use to the total impacts. This stage was the only one that responded to the sensitivity analysis, and the impacts varied between 48 and 55% relative to the reference scenario (Fig. 3). In MRS, the variation in the total impact ranged from 3 to 10% because the use stage was not as relevant to the total impact.

3.5. *Influence of energy origin*

The results of this study highlight the relevance of the use stage, more specifically consumption of energy, to the total environmental impact of the current water heaters; therefore, it is essential to analyse how the origin of the energy consumed in this stage contributes to the environmental burdens of each system.

Regarding NGI, five different origins of NG, which corresponded to different countries (Table S17 of SM) indicated that some impact categories were more influenced by the origin of energy (Raluy and Dias, 2020). For example, TA was reduced by almost 50%, while MRS remained almost unchanged. For electrical systems, another five models of electricity production corresponding to different countries were considered (Portugal, Germany, Poland, France, and Switzerland). These countries were selected amongst the countries where these products are consumed to take into account different scenarios of electricity origin (Table S18 of SM). In Portugal, the energy source was balanced (base case), Germany and Poland were mainly based on fossil fuels, France was predominantly based on nuclear energy, and Switzerland had a high presence of renewable energies and nuclear energy.

Results for each impact category per litre of heated water provided per year reveal variations in every impact category depending on the electricity origin (Fig. 4). Variation in degree of impact ranged from 6–60% for the worst case in GW, 33–59% in SOD, 7–61% in OFHH, 5–52% in TA, 3–67% in FE, 12–74% in ME, 38–90% in MRS, and 6–59% in FRS. Poland had the greatest environmental impact in six of the eight categories considered: GW, OFHH, TA, FE, ME, FRS. In Poland, 79% of the electricity is largely produced from hard coal and lignite (IEA, 2014). The German scenario was worse in SOD mainly due to the large share of power energy derived from lignite. France, where nuclear energy contributed up to 79% of the electricity consumed, had the poorest environmental performance in MRS due to the uranium consumed at nuclear plants, but France presented the best performance in the remaining impacts except for ME for which Portugal had the best performance. Switzerland tended to have impacts slightly higher than France for most of the impacts. Regardless of the impact category, the ranking of the electric DHW system in environmental terms remains the same in all countries.

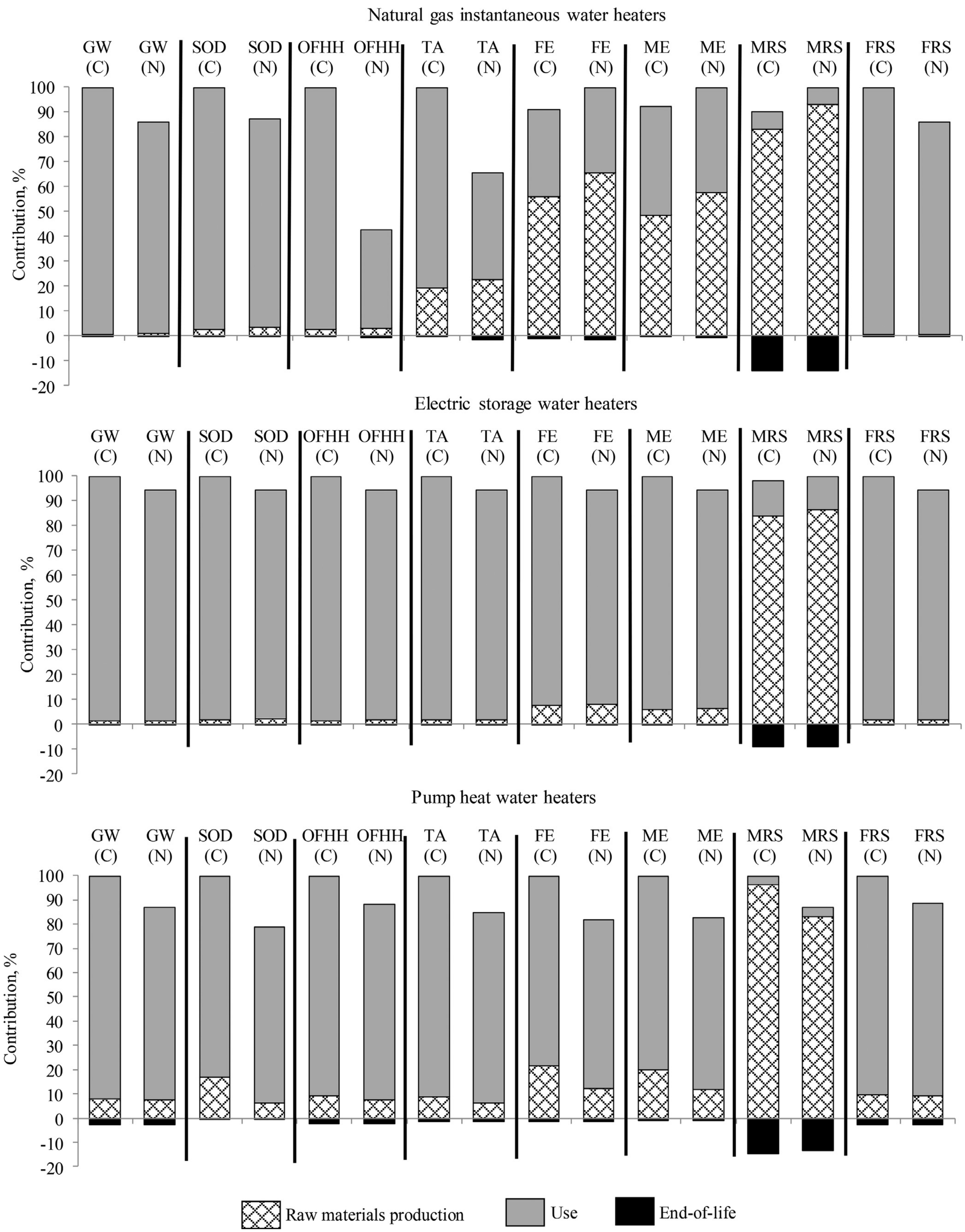

Fig. 5. Comparison between current and new DHW systems. The use stage occurred in Portugal. C: current DHW systems; N: new DHW systems.

3.6. New generation of DHW systems

The total environmental impacts over the service life of the new water heaters (used in Portugal), expressed per FU, is presented in Table 4, and the breakdown by stage is provided in Tables S12-S14 of SM. Comparison between the environmental impacts of current DHW systems and new ones when use occurs in Portugal is shown in Fig. 5 (assigning 100% to the water heaters with the highest burden in each impact category). The new NGI system had a better environmental performance than the current NGI system in categories where the use stage had a high contribution (i.e., GW, SOD, OFHH, TA and FRS) due to a reduction in fuel consumption and air emissions (mainly NO_x and CO_2). The reductions achieved with the new NGI system are 57% in OFHH, 34% in TA, and 14% in GW, SOD and FRS. In contrast, in FE, ME and MRS, in which the production of raw materials had a greater contribution, the new NGI system was worse than the NGI system of reference (up to 9–11%) due to increased quantities of materials used (mostly steel). Regarding the ES water heaters, less electricity was consumed during the use stage in the newer model leading to a slightly better environmental performance (5–6%) in all categories except in MRS; the impact in MRS increased by 2% because the electronic component was a smart control. Finally, the new HP water heaters showed better environmental performance (11–21%) in all categories, due to smaller quantities of materials used and lower electricity consumption during the use stage.

3.7. Limitations of study

This section discusses the main assumptions (potential limitations) of this study to be considered for future discussions and research. First, the manufacturing stage of DHW systems was omitted due to absence of the necessary data, but the results obtained for the current natural gas water heater indicated that the impacts of that stage was negligible compared to the total impact (Raluy and Dias, 2020). This conclusion is supported also by an environmental assessment of two domestic boilers in Italy (Vignali, 2017) and by an LCA of DHW systems in China (Liu et al., 2019). Regarding the use stage, there are uncertainties once the house appliance is installed, since the real behaviour of the final end-users is unknown and unpredictable, and we do not know if the maintenance routine of these systems (required by law and/or recommended by the manufacturer) is carried out. The system end-of-life was also undefined, and it is assumed that as electrical and electronic equipment, it was collected and then either recycled or landfilled. Maximum recyclability rates for each material were adopted which can introduce bias because the real rates were unknown and unpredictable.

4. Conclusions

Environmental impacts of four current DHW systems (NGI, EI, ES, HP) were evaluated using LCA methodology, showing that the use stage plays a major role for all impact categories other than MRS, where the production of raw materials had the largest impact. Energy consumption was the dominant factor during use, although water consumption and fuel combustion were also relevant, specifically in the NGI system.

The comparison of the environmental impacts of the four current water heaters per litre of heated water provided per year showed that the EI system is the worst in six of the eight impact categories, while HP and NGI systems were the best option in four categories but worst in one. These performance disparities were mainly caused by different energy consumption rates and raw materials quantity of the different DHW systems.

Despite these general trends, the sensitivity analysis highlighted that the total impacts of the DHW systems varied depending on the use factor that determines the consumption of water and energy during use, because this stage was the main hotspot as mentioned before. Moreover, the results clearly differed in all impact categories according to the country in which each DHW system is used due to the different electricity mixes (for electrical water heaters) or fuel origin (for NGI system).

The new generation of DHW systems evaluated presented a better environmental performance than the current ones but with some exceptions. The new ES system had slightly higher impacts in MRS impact, whereas the new NGI system presented worse scores in the three impact categories where the hotspot was the raw materials production stage (FE, ME and MRS), indicating that more efforts should be done to decrease the impacts of the materials used by reducing the amounts and/or selecting materials with lower impacts.

The results of this research are valuable for diverse stakeholders to accomplish more sustainable DHW systems, especially in production and use. Manufacturers should focus not only on aspects covered by existing directives and standards such as energy consumption and air emissions in the use stage, but should also consider environmental aspects with a large improvement potential, e.g. related with raw materials (type, quantities and origins). Moreover, information is provided to support end-users choice on water heaters with lower impacts, thus guiding on the usage and encouraging sustainable and responsible use. Finally, based on the hotspot analysis performed, policy makers are more informed on the consequences of reducing energy consumption and air emissions, and on the importance of resource efficienc y improvement. All with the ultimate goal of achieving sustainable production and use of DHW systems.

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.

Acknowledgements

This study was performed within the project “Smart Green Homes”, a co-promotion between the University of Aveiro and Bosch Termotecnologia S.A. (POCI-01–0247 FEDER-007678), funded by the European Regional Development Fund, and by Portugal 2020, within the framework of the Competitiveness and Internationalization Operational Program. Authors are also grateful for funding from FCT/MCTES to CESAM (UIDB/50017/2020 + UIDP/50017/2020) through national funds and to the contract of Ana Cláudia Dias (CEECIND/02174/2017).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.spc.2021.01.005.

References

DGEG, 2017. Energia em Portugal 2015. Direção-Geral de Energia e Geologia Lisbon, Portugal.

Eurostat, 2020. Energy Consumption in Households. Statistics Explained. Luxembourg, Luxembourg https://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_consumption_in_households . [Accessed December 2020].

EU, 2013a. Commission Delegated Regulation (EU) No 812/2013 of 18 February 2013 supplementing Directive 2010/30/EU of the European Parliament and of the Council with regard to the energy labelling of water heaters, hot water storage tanks and packages of water heater and solar devices. Off. J. EU. L 239 (56) 6 September 2013. Luxembourg, Luxembourg.

EU, 2013b. Commission Delegated Regulation (EU) No 814/2013 of 2 August 2013 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to eco-design requirements for water heaters and hot water storage tanks. Off. J. EU. L 239 (56) 6 September 2013. Luxembourg, Luxembourg.

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Hollander, A., Zijp, M., Zelm, R., 2017. ReCiPe 2016 v1.01. A harmonized life cycle impact assessment method at midpoint and endpoint level. Report I: characterization. RIVM Report 2016-0104a Bilthoven, Netherlands.

IEA, 2014. World Energy Statistics and Balances 2014. OECD iLibrary ISSN 1683-4240. Paris, France.

IPCC, 2006. Energy. Chapter 2. Stationary Combustion, Intergovernmental Panel on Climate Change. IPCC 2006. Guidelines for National Greenhouse Gas Inventories 2.

Kumar, M.N., Mathew, M., 2018. Comparative life-cycle cost and GHG emissions analysis of five different water heating systems for residential buildings in Australia. Beni-Suef Univ. J. Basic Appl. Sci. 7, 748–751. doi:10.1016/j.bjbas.2018.11.001.

Liu, W., Chen, C., Wu, H., Guo, C., Chen, Y., Liu, W., Cui, Z., 2019. Environmental life cycle assessment and techno-economic analysis of domestic hot water systems in China. Energy Convers. Manage. 199, 111943. doi:10.1016/j.enconman.2019.111943.

Moore, A.D., Urmee, T., Bahri, P.A., Rezvani, S., Baverstock, G.F., 2017. Life cycle assessment of domestic hot water systems in Australia. Renew. Energy 103, 187–196. doi:10.1016/j.renene.2016.09.062.

Piroozfar, P., Pomponi, F., Farr, E.R.P., 2016. Life Cycle assessment of domestic hot water systems; a comparative analysis. Int. J. Constr. Manage. 16 (2), 109–125. doi:10.1080/15623599.2016.1146111.

Raluy, R.G., Dias, A.C., 2020. Life cycle assessment of a domestic gas-fired water heater: influence of fuel used and its origin. J. Environ. Manage. 254, 109786. doi:10.1016/j.jenvman.2019.109786.

UN, 2020. United Nations Development Programme. Goal 12: Responsible consumption and Production https://www.undp.org/content/undp/en/home/sustainable-development-goals/goal-12-responsible-consumption-and-production.html.

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. htpps://dx.doi.org/10.1016/j.jclepro.2016.11.025.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21 (9), 1218–1230. doi:10.1007/s11367-016-1087-8.