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Fostering investment on energy efficient appliances in India—A multi-perspective economic input-output lifecycle assessment

Vivek Kumar Singh [a, e, *], Carla Oliveira Henriques [b, d, e], António Gomes Martins [c, d, e]

[a] MIT-Portugal Program, University of Coimbra, Coimbra, Portugal
[b] Polytechnic Institute of Coimbra, Coimbra Business School ISCAC, Portugal
[c] Dept. of Electrical Engineering and Computers University of Coimbra, Coimbra, Portugal
[d] INESC Coimbra, Pólo II, R. Silvio Lima, Coimbra, Portugal
[e] Energy for Sustainability Initiative, University of Coimbra, Portugal

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ABSTRACT

Energy planning in many developing Asian countries has neglected the structure of energy demand and how it is likely to evolve as development takes its path. The limited availability of energy consumption data makes it very difficult to assess the energy savings potential at end-use level. Energy planning requires the formulation of a proper modelling framework that supports the definition of energy policies. From the different approaches available, Input - Output (I-O) models are particularly useful, since they allow considering different impacts that can be consistent with different energy policy options. This paper proposes a novel I-O modelling framework by introducing a bottom-up approach into an I-O model which is combined with technical data for the holistic assessment of energy efficient technologies in the residential sector, which can assist energy decision-makers of India on the appraisal of the future impacts of the current national energy saving targets. A large size platform of real data has also been gathered considering different data sources, namely the household building stock characterization, the number of operating days according to the climatic regions of India, the lifetime and the investment cost of equipment. Finally, the main results are discussed and future research opportunities are identified.

1. Introduction

In 2012 the residential sector was responsible for consuming nearly one fourth of total world electricity consumption [1]. The growing penetration rate of electric appliances in developing countries, such as India, is one of the leading causes of the current energy demand and CO_2 emissions increase. In fact, according to India's Central Electricity Authority, electricity consumption in all households was 203 TWh in 2013 [2]. In the past decade, population and energy consumption grew at a similar rate to GDP (i.e. about 7%) and it is anticipated that energy consumption will likely surpass GDP's growth rate in about 10–30 years [3]. The level of comfort in the residential sector has been reported to steadily increase along with an increasing dependence on electricity. The residential sector is at the second rank after industry with about 24% of total electricity demand in 2013–2014 [4] and appliances account for 35–40% of that demand [5]. Energy consumption has traditionally been tied to economic development. However, its environmental implications have been a driving factor for the definition of contemporary environmental policy around the world, highlighting the role of energy efficiency (EE) in the reduction of GHG emissions [6,7]. Therefore, the consequent rise in energy consumption and GHG emissions can be significantly reduced if consumers are motivated to buy energy efficient appliances [8].

The International Energy Agency anticipates that by 2030 one of the lowest cost GHG emissions abatement option in Organisation for Economic Co-operation and Development countries will come from energy efficient end-use technologies (EET) [9]. The support of EE policies can thus be seen as a cost-effective driver of energy consumption and GHG emissions reduction, while providing economical energy services in different activity sectors [10]. The need for energy autonomy and EE plays a decisive role in the economic development and the societal prosperity for worldwide [11]. EE is an important element that needs to be included in any program associated with the promotion of economic development in

* Corresponding author. Energy for Sustainability Initiative, MIT-Portugal Program, University of Coimbra, Coimbra, Portugal.
E-mail address: Vivekkumarsingh22@gmail.com (V.K. Singh).

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Nomenclature

BAT	Best Available Technology
BAU	Business-As-Usual
BEE	Bureau of Energy Efficiency
CEA	Central Electricity Authority
CF	Ceiling fan
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
COM	Computer
E3S	Economy, Energy, Environment and Social
EET	Energy efficient technology
EG	Electric water heater/geyser
EIO	Economic Input-Output
FR	Freezer
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GVA	Gross Value Added
GWP	Global Warming Potential
IND	India
I-O	Input-Output
kW	kilowatt
kWh	kilowatt-hour
LBNL	Lawrence Berkeley National Laboratory
LCA	Lifecycle Assessment
MOLP	Multi Objective Linear Programming
N_2O	Nitrous oxide
NH_3	Ammonia
NMVOCs	Non-Methane Volatile Organic Compounds
NOx	Nitrogen oxide
O&M	Operation and maintenance
RAC	Room air conditioners
SDA	Structural decomposition analysis
SO_x	Sulphur oxide
tCO_2eq	Tonnes of CO_2 equivalent
TESP	Technical energy savings potential
TFL	Tubular Fluorescent Lamp
tNMVOCeq	Tonnes of NMOC equivalent
TOFP	Tropospheric ozone formation potential
TPS	Technical potential saving
tSO_2eq	Tonnes of SO_2 equivalent
TV	Television
TWh	Terawatt-hour
UEC	Unit energy consumption
WEP	Water electric pumps
WM	Washing machine

all the countries without increasing the level in the use of energy sources for electricity generation.

Several studies have estimated the impacts of the adoption of EET in the residential sector in India. Most of these studies are focused on household electricity consumption [12]. For instance, the Lawrence Berkeley National Laboratory (LBNL) estimated the energy savings obtained for two particular appliances used in the residential sector: refrigerators and air conditioning [13]. A study conducted by the Energy Resources Institute assessed the energy savings in the residential sector as a whole and not per appliance/end-use [14]. Reddy and Balachandra [15] computed the implicit energy savings potential from the usage of more efficient appliances. A bottom–up analysis approach was also developed by the LBNL (see Refs. [16,13]) for the residential sector in India by considering different use categories (e.g. lighting, water heaters, television, fan, washing machine, air coolers, air conditioners, refrigerators, etc.). A similar study was also published by the World Bank [17] that uses both an end-use and a bottom-up modelling approach. Most of the studies herein reviewed present big discrepancies between the projected and the real energy potential savings per appliance/end-use and are also lacking an integrated E3S assessment.

Energy models have been extensively used to address and assess the impact of different energy policy options [18]. These models became the focus of attention of researchers in the early seventies of the twentieth century with the first oil crises. In the framework of energy systems, I-O analysis has been applied in a multitude of contexts: to estimate China's energy disparities in energy consumption [19]; to provide primary energy forecasts in the Spanish economic system [20]; to analyse the employment impacts of EE retrofit investments [21] and renewable energy targets in Portugal [22]; to account for the economic impacts of EE and renewable energy in Germany [23]; to compute direct and indirect energy use and carbon emissions in the production phase of buildings in Sweden [24]. Over the last decades, several I-O models were also coupled with other mathematically based formulations in order to enhance the understanding and prediction of future impacts of energy use. For example [25], identified strategies for mitigating the global warming impact of the European Union-25 economy by using a multi-objective I-O approach [26], optimized sectoral production with energy and GHG emission constraints in Greece and [27] assessed the E3S trade-offs in the Brazilian economic system. A review of Input-output (I-O) analysis with Multi Objective Linear Programming models for the study of E3S interactions can be found in Ref. [28]. Suitable E3S models allow assessing the impacts of market transformation in the framework of EE. I-O analysis provides a modelling approach that can be particularly useful to compute the primary energy and GHG embodied in final demand [29].

In this context, this paper presents an I-O framework instantiated with real data which provides an integrated assessment of the E3S impacts of nine energy efficient appliances currently used in India's residential sector, i.e. lighting sources (TFL), refrigerators (FR), room air-conditioners (RAC), water, electric heaters (EG), televisions (TV), computers (COM), ceiling fans (CF), water pumps (WEP) and washing machines (WM). The time horizon considered for the study herein conducted comprises 2011 to 2030 and it is assumed that the adoption of energy efficient appliances/end-uses will have started in 2011 (the reference year of the study for which the most recent data was available) and that all new appliances purchased will be energy efficient (i.e. will correspond to the BAT). Although this also means that it is not possible to benchmark the outputs of the model with real data even for past years between 2011 and the present date, the I-O modelling framework herein suggested is designed to assist planners and energy decision-makers of India on the appraisal of the future impacts of the current national energy saving targets, providing a contribution that can help to shape future energy plans in the country.

In the next Section a description of the I-O modelling framework developed is given. Section 3 provides the main assumptions considered in order to instantiate the model. Section 4 presents a discussion of the main illustrative results obtained. Finally, some conclusions are drawn and future work developments are suggested.

2. Methodology

The E3S impact assessment of energy use of an economy in a resource-constrained world requires an understanding of the relationships between its economic, social, and energy-use elements [22].

I-O is an approach that allows capturing all the economy-wide interdependencies. Generalized I-O analysis allows obtaining total factor multipliers, which describe embodiments of production factors (e.g. labour, energy, resources) and pollutants per unit of final consumption of commodities [18].

The traditional economic I-O model is based on an I-O matrix with the economic flows between industries that can be extended with information regarding the E3S impacts, creating additional columns and rows that represent the E3S impacts per each activity sector/industry [30]. This additional information is obtained just by combining national accounts with satellite national statistics for pollutant emissions, employment and energy.

According to the traditional I-O framework, the productive system at a national level can then be represented in its matrix form following the basic I-O system of equations:

$$\mathrm{x} = \mathrm{A}\mathbf{x} + \mathbf{y}, \tag{1}$$

where A is a matrix of technological coefficients, **y** is a vector of final demand (household consumption, government consumption, investment and net exports) and **x** is a vector of the corresponding outputs.

In order to finally obtain the output multipliers, the Leontief inverse matrix needs to be obtained. Equation (1) can then be readjusted to:

$$\mathbf{x} = (\mathrm{I}{-}\mathrm{A})^{-1}\mathbf{y}, \tag{2}$$

where I is the identity matrix with convenient dimensions and $(\mathrm{I} - \mathrm{A})^{-1}$ is also known as the Leontief inverse. Each generic element of $(\mathrm{I} - \mathrm{A})^{-1}$ represents the total amount of good or service i directly and indirectly needed to deliver a unit of final demand of good or service j [31]. Indeed, the Leontief inverse indicates the direct, indirect and induced requirements of production that are needed to satisfy a particular final demand vector. Thus, this matrix is also known as the multiplier matrix.

An approach for obtaining the E3S impacts associated with inter-industry activity consists of assuming a matrix of direct impact coefficients, R. Hence, the level of E3S impacts associated with a given vector of total outputs can be expressed as:

$$\mathbf{r} = \mathrm{R}\mathbf{x}, \tag{3}$$

where **r** is the vector of E3S impact levels. Thus, we can compute vector **r** as a function of final demand, i. e:

$$\mathbf{r} = \mathrm{R}\,(\mathrm{I}{-}\mathrm{A})^{-1}\mathbf{y}, \tag{4}$$

Finally, from (4) we can interpret $\mathrm{R}\,(\mathrm{I} - \mathrm{A})^{-1}$ as a matrix of total E3S impact coefficients; i.e., an element of this matrix is the total E3S impacts per monetary unit of final demand presented to the economy.

Since official published I-O data do not provide the clear identification of the E3S impacts that are likely to be created by an increase in the demand for the use of a typical BAT/BAU appliance, in the next Section of the paper we provide a thorough explanation of the approach herein suggested, by combining data on expenditures for domestic appliances with I-O modelling techniques to arrive at the related direct, indirect and induced economic, energy, environmental and social impact effects.

2.1. A new framework for assessing energy efficient appliances

In order to assess these E3S estimates, the economic impulses that originate these impacts must be identified (as in Table 1). Therefore, the lifecycle of a BAT/BAU appliance is divided into different lifecycle phases (i.e. installation and operation and maintenance - O&M) and then these phases need to be further decomposed into their corresponding activities/components. Through collecting information on the total expenditure connected to each lifecycle phase, along with data on the cost share of each relevant activity/component as a percentage of the corresponding lifecycle phase, it is then possible to calculate the total output (in monetary units) of each of these relevant activities/components.

The lifecycle phases can then be economic activities that provide impulses in the form of expenditures that can generate different E3S effects. Impulses (e.g. expenditures for O&M, manufacturing and installation of BAT/BAU appliances) are regarded as exogenously determined parameters that trigger an economic mechanism that leads to several effects. Effects (e.g. a direct positive effect could be an increase in BAT/BAU appliance production; a negative induced effect could be a decrease in the consumption of goods) relate to how impulses influence the economy – positively, negatively, directly, indirectly or induced. The most important impulses herein analysed are: investment and O&M expenditures, including impacts on upstream industries (direct and indirect effects – obtained through type I multipliers, i.e. (direct effect + indirect effect)/direct effect); the impulse from household income due to changes in the investment on BAT/BAU appliances (obtained through type II multipliers – i.e. (direct effects + indirect effects + induced effects)/direct effect). Fig. 1 depicts the relationship between impulses, effects and impacts.

The methodological approach followed has various implementation steps which are provided below, being also depicted in Fig. 2.

Step 1 – Defining the system boundaries of BAU/BAT appliance industries:

- The BAU/BAT appliance industries include all economic activities that are related to and are characteristic for or specific to BAU/BAT appliance use.
- The term “BAU/BAT appliance use” comprises the complete lifecycle of the BAU/BAT appliance use, which can be roughly split into: manufacturing and operation.
- The life cycle consists of various activities such as manufacturing the various components needed for the BAU/BAT appliance use, O&M and replacement of parts after their defined lifetime is over (see Fig. 3).

Step 2 - Determine expenditures for the BAU/BAT appliance use:

- Compute the number of households for the time horizon of the analysis and obtain the appliance ownership and sales up to 2030. Estimate the number of BAT appliances needed to calculate the investment on new energy efficient appliances.
- Determine energy consumption during operation based on the computation of total annual energy demand with expressions (5) and (6).
- Obtain the technical energy savings potential with expression (7).

Table 1
Methodology application of the EIO-LCA framework.

Divide into lifecycle phase	• Manufacturing and Installation.
Decompose lifecycle phases into their activities/components	• Example of components involved in the manufacturing phase of washing machines: glass, metal, rubber, plastics, insulation material and electronic component
Calculate total output of each relevant activity/component	• Obtain appliance costs and material shares (as a %). • Connect total expenditure to each component and compute domestic output.
Match the domestic output of each relevant activity/component of BAT/BAU appliance to the industry in the IO table	• Assign the domestic output of each activity/component previously calculated to the corresponding industries.
Calculate the multiplier effects of each activity/component	• Compute IO multipliers (for each emission type considered or for obtaining embodied energy), to arrive at indirect and induced effects.

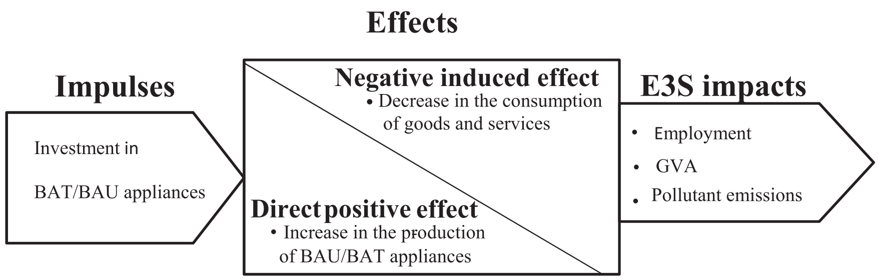

Fig. 1. Impulses, effects and impacts relationship.

1) Energy Demand

$$EBAU_k = \sum_i [NOH_k \times (RPA_i \times OTA_i) \times TNS_i] \quad (5)$$

$$EBAT_k = \sum_i [NOH_k \times (RPA(BEE\eta)_i \times OTA_i) \times TNS_i] \quad (6)$$

2) Energy Savings per year k

$$\Delta E(y)_k = EBAT_k - EBAU_k. \quad (7)$$

where $EBAU_k$ is the BAU energy demand at year k, $EBAT_k$ is the BAT energy demand at year k, NOH_k is the projected number of dwellings for year k, RPA_i is the rated power of appliance/end-use i, $RPA(BEE\eta)_i$ is the rated power of appliance/end-use i for the star labelling efficient appliances according to the BEE, OTA_i is the operational time per year of appliance/end-use i and TNS_i the average number of appliance/end-use of type i per household.

Step 3 - Calculate domestic output by BAU/BAT appliance technology:

- Distribute the expenditures to cost components which can be related to certain economic activities (see Fig. 3).
- Determine, at the cost component level, the import shares and subtract imports from expenditures to obtain domestic output.
- Allocate the domestic output for each economic activity to the appropriate industry as represented in the I-O model.
- Compile a vector of domestic output by industry for each life-cycle phase of each technology. Put all the vectors into a matrix of direct domestic output by industry.

Step 4 - Calculate direct, indirect and induced E3S net impacts:

1) Economic impacts

- The GVA is the value of output less the value of intermediate consumption and it can be seen as a measure of the contribution to GDP made by the industry sectors engaged with the BAU/BAT appliances.
- The computation of the net GVA has been done in two stages:
- Computation of the direct, indirect and induced GVA generated during the production and installation of BAT and BAU appliances.
- Computation of the direct, indirect and induced GVA throughout the lifetime of the equipment due to energy consumption.
- The computation of the net GVA is then obtained by considering:
- GVA from BAT (BAU) appliances = GVA during production and installation of BAT (BAU) appliances + GVA generated throughout the lifetime of the BAT (BAU) appliances due to energy consumption.
- Net GVA = GVA from BAT appliances − GVA from BAU appliances.

2) Environmental impacts

- The computation of the net pollutant emissions has been done in two steps:
- Computation of the direct, indirect and induced emissions generated during the production and installation of BAT and BAU appliances.
- Computation of the direct, indirect and induced emissions throughout the lifetime of the equipment.
- The computation of the avoided emissions is then obtained by considering:
- Avoided emissions = BAU emissions - BAT emissions
- Emissions from BAT (BAU) appliances = Emissions during production and installation of BAT (BAU) appliances + Emissions throughout the lifetime of the of BAT (BAU) appliances.
- The emissions associated with the decommissioning and dismantling of the appliances have not been considered due to the lack of data sources and the absence of electronic waste management facilities in India.

3) Social impacts

- The computation of net employment has been done in two steps:

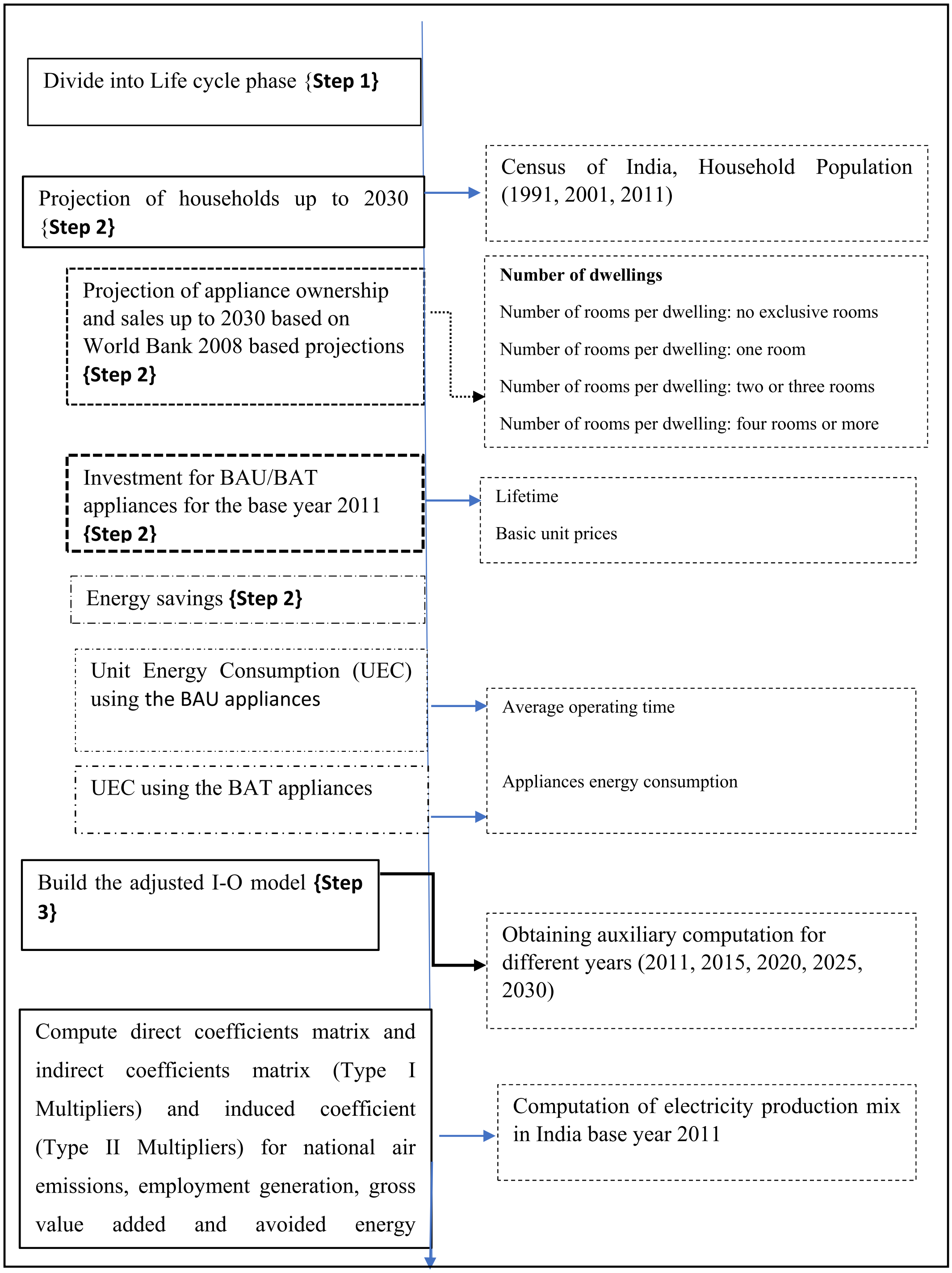

Fig. 2. Schematic illustration of the implementation steps required for the application of the I-O modelling approach.

- Computation of the direct, indirect and induced employment generated during the production and installation of BAT and BAU appliances.
- Computation of the direct, indirect and induced employment throughout the lifetime of the equipment.

• In this case, we consider that the employment generated during the manufacturing stage of BAU appliances will be kept with the replacement of old appliances with BAT appliances, assuming in this situation that an upgrade of the job skills is sufficient. Therefore, the computation of the net employment is then obtained by considering:

- Net employment = Employment from BAU appliances + Net employment change − Employment loss.
- Net employment change = Employment from BAT appliances − Employment from BAU appliances.
- Employment from BAT (BAU) appliances = Employment during production and installation of BAT (BAU) appliances.

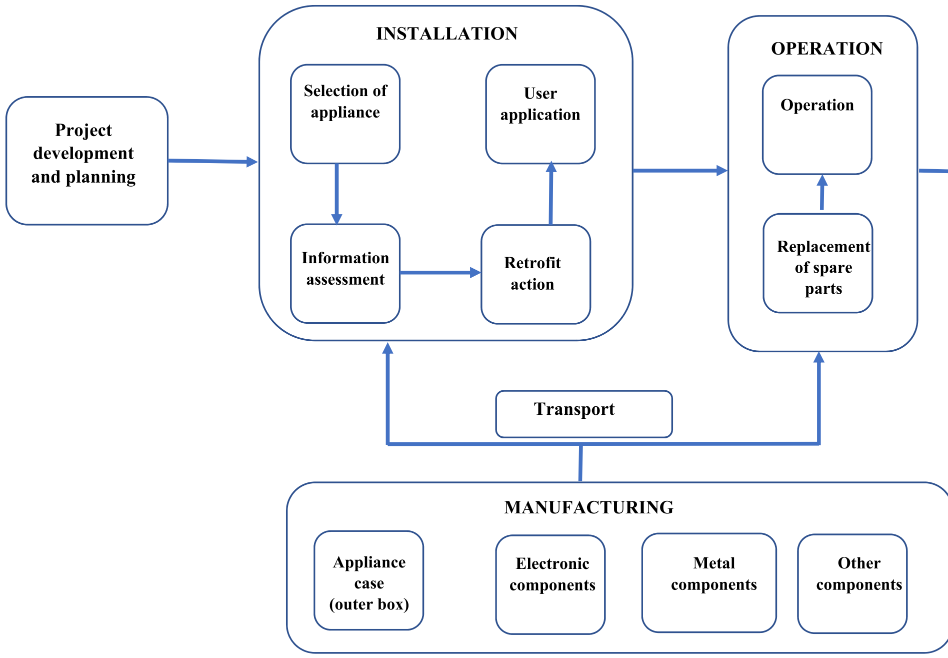

Fig. 3. Lifecycle and supply chains of appliances.

Table 2
Specific features of BAT appliances.

Appliance/end-use	Lifetime (years)	Energy saving (kWh/year)
TFL	14	35
EG	15	119
TV	10	153
CF	15	58
FR	15	270
RAC	10	950
WM	15	219
COM	5	146
WEP	15	400

- Employment loss = Employment due to electricity consumption with BAU appliances - Employment due to electricity consumption by BAT appliances.

3. Assumptions and estimates

In order to apply the I-O adjusted modelling framework to our problem, a large size data platform of real data for the residential sector in India has been gathered considering different data sources in particular: national I-O tables [32] and satellite accounts (socio economic accounts and environmental accounts) published by the world I-O database (http://www.wiod.org/) for India, the household building stock characterization, the number of operating days according to the climatic regions of India, the lifetime and the investment cost of each energy efficient equipment/measure (see Table 2, Table 3, and Table 4).

The average share of materials and corresponding costs were obtained from Refs. [33–36] – see Table 3. The investment costs used for each BAT appliances were attained from web based market research on several shopping websites and star labelling efficient appliances. Table 5 provides the projected overall investment on BAT appliances according to basic constant prices for several land mark periods. Data regarding energy consumption has been obtained from the energy balance of India and then combined with the World I-O Database.

The base year of our study is 2011 because this is the year for which validated census data is available. The time frame considered in our analysis goes from 2011 to 2030. The reason for this choice lies on the fact that it is expected that major technological changes will only take place within the next 16–20 years (see for example the replacement of cathode ray tube television by plasma display or

Table 3
Share of materials and costs.

		TFL	EG	TV	CF	FR	RAC	WM	COM	WEP
Share of material	Glass	90.0%	00.0%	10.0%	80.0%	0.0%	0.0%	0.0%	55.0%	0.0%
	Metal	4.0%	70.0%	10.0%	15.0%	60.0%	60.0%	60.0%	10.0%	75.0%
	Rubber	0.0%	0.0%	0.0%	0.0%	5.0%	5.0%	5.0%	10.0%	0.0%
	Plastics	4.0%	0.0%	60.0%	0.0%	10.0%	20.0%	5.0%	5.0%	10.0%
	Insulation material	0.0%	25.0%	0.0%	0.0%	10.0%	10.0%	20.0%	0.0%	0.0%
	Electronic	2.0%	5.0%	20.0%	5.0%	15.0%	5.0%	10.0%	20.0%	15.0%
Share of cost	Glass	40.0%	00.0%	15.0%	35.0%	0.0%	0.0%	0.0%	20.0%	0.0%
	Metal	5.0%	40.0%	20.0%	15.0%	25.0%	35.0%	20.0%	20.0%	40.0%
	Rubber	0.0%	0.0%	0.0%	0.0%	5.0%	5.0%	5.0%	20.0%	0.0%
	Plastics	25.0%	0.0%	15.0%	0.0%	5.0%	10.0%	5.0%	5.0%	10.0%
	Insulation material	0.0%	30.0%	0.0%	0.0%	5.0%	10.0%	10.0%	0.0%	0.0%
	Electronic	30.0%	30.0%	50.0%	50.0%	60.0%	40.0%	40.0%	35.0%	50.0%

Table 4
Prices of BAU/BAT appliances.

Appliance/end-use	BAU					BAT				
	Wholesaler Price $ (cost) without tax	VAT %	Price $ (cost) tax	Consumer price $	Basic Price $	Wholesaler Price $ (cost) without tax	VAT %	Price $ (cost) tax	Consumer price $	Basic Price $
TFL	4	4.5	0.18	4.18	1.2	12.27	4.5	1.5	13.77	3.07
EG	114	12.5	14.2	128.2	39.9	136.4	12.5	17	153.4	34.09
TV	150	12.5	18.7	168.7	52.5	300	12.5	37.5	337.5	105
CF	28	12.5	3.5	31.5	4.2	100	12.5	12.5	112.5	15
FR	216	12.5	27	243	64	381.8	12.5	47.7	429.5	114.55
RAC	450	12.5	56.2	506.2	135	554.6	12.5	69.3	623.9	166.3
WM	250	12.5	11.2	261.2	62.5	309.1	12.5	102	411.1	92.7
COM	620	12.5	77.5	697.5	186	818.2	12.5	38.6	856.8	204.5
WEP	40	12.5	5	45	10	76.36	12.5	9.5	85.86	85.91

Table 5
Overall anticipated investment on BAT appliances in million ($).

Appliance/end-use	2011	2015	2020	2025	2030
TFL	405	464	543	622	700
EG	37	54	70	91	109
TV	26,949	29,756	36,165	42,462	48,823
CF	2618	3381	4335	7586	10,838
FR	3890	6207	9104	13,241	17,379
RAC	437	1228	2216	551	6947
WM	163	205	257	308	360
COM	3734	5992	8859	11,700	14,556
WEP	21	32	45	58	72

liquid crystal display television) [6]. In our study, we have assumed that the adoption of energy efficient appliances/end-uses will have started in 2011 and that all new appliances purchased will be energy efficient (i.e. BAT appliances), meaning that it is not possible to benchmark the outputs of the model with real data even for past years between 2011 and the present date.

3.1. Household projections

The household size is usually considered in this sort of studies and projection [8,17]. Nevertheless, our methodology is slightly different and based on the classification of households, according to the Census of India [37,38], (see Table 6).

According to the Census of India, the total number of households will reach 344,978,775 by 2030. Following Step 2 of the methodology explained in the previous Section, the annual percentage of growth rate is projected to be 2.2% by 2030 (see Table 7).

3.2. Appliance ownership and sales

In order to estimate future sales, we have used a linear regression model based on data of the sales within the period of 2007–2011. The results obtained were validated and contrasted with the data published in Refs. [6,17,39,40,41]. Data regarding the rate of appliance ownership were based on several data sources. The total share of sales to the residential sector are given in Table 8. Data regarding the rate of appliance ownership were based on several data sources (see Table 9).

3.3. Selection of appliances

We have identified twenty typical appliances/end-uses in the residential sector. However, only nine appliances are accounted for in the energy efficient star labelling appliance/end-use categories of the BEE by Government of India (see Refs. [48,49]). Therefore, our study will only focus on those nine electrical appliances/end-uses (see Table 10).

The average yearly energy consumption values considered in our analysis for BAT/BAU appliances are provided in Table 11.

3.4. Operating hours per year

Table 12 shows the operating hours per year considered for each BAT/BAU appliance, which were based on [12–14,17,41], and [71].

4. Discussion of results

The I-O framework herein developed allows estimating the net E3S impacts obtainable with the investment in BAT appliances within a consistent framework. Our approach combines data on expenditures for domestic appliances with I-O modelling to assess the related direct, indirect and induced E3S effects. The illustrative results regarding the E3S impact assessment of the nine electrical appliances under evaluation are presented below.

4.1. Energy consumption

Some of the impacts of avoided electricity consumption during the operation stage of the nine energy efficient appliances (BAT), as compared to the corresponding conventional ones (BAU) herein considered were computed according to the methodology followed in Section 2 and to data and assumptions provided in Sections 3 and 4. The results obtained for the time horizon considered in this study are presented in Fig. 4, where TESP stands for technical energy savings potential.

Out of the nine appliances under assessment three (TV, CF, FR) are responsible for more than 80% of the energy consumption in

Table 6
Household dwelling classification.

Years	Number of dwelling rooms: No exclusive - Households, Total	Number of dwelling rooms: one - Households, Total	Number of dwelling rooms: Two or three - Households, Total	Number of dwelling rooms: Four and above - Households, Total	Total Household
1991	45,300	61,139,900	67,089,300	22,725,500	151,000,000
2001	5,972,416	73,856,117	85,113,213	27,022,189	191,963,935
2011	9,638,369	91,491,894	113,928,405	31,633,999	246,692,667

Table 7
Household projections up to 2030.

Sources	Years	Number of dwelling rooms: No exclusive - Households, Total	Number of dwelling rooms: one - Households, Total	Number of dwelling rooms: Two or three - Households, Total	Number of dwelling rooms: Four and above - Households, Total	TOTAL
Census data India	**1991**	**45,300**	**61,139,900**	**67,089,300**	**22,725,500**	**151,000,000**
	2001	**5,972,416**	**73,856,117**	**8,51,13,213**	**27,022,189**	**191,963,935**
	2011	**9,638,369**	**91,491,894**	**113,928,405**	**31,633,999**	**246,692,667**
Projections	***2012***	*10,494,883*	*92,189,567*	*114,471,814*	*3,2026,904*	*2491,83,168*
	2013	*10,667,276*	*94,375,666*	*118,280,152*	*32,515,149*	*255,838,243*
	2014	*11,295,750*	*95,569,480*	*119,911,870*	*32,939,834*	*259,716,935*
	2015	***11,620,170***	***97,424,818***	***122,994,668***	***33,406,893***	***265,446,548***
	2016	*12,147,293*	*98,839,140*	*125,110,080*	*33,845,702*	*269,942,214*
	2017	*12,539,280*	*100,547,472*	*127,870,415*	*34,303,345*	*275,260,512*
	2018	*13,021,358*	*102,059,798*	*130,200,802*	*34,748,432*	*280,030,389*
	2019	*13,443,375*	*103,702,795*	*132,817,821*	*35,201,889*	*285,165,880*
	2020	***13,905,433***	***105,258,677***	***135,243,752***	***35,649,766***	***290057628***
	2021	*14,340,797*	*106,872,636*	*137,797,075*	*36,101,363*	*295,111,871*
	2022	*14,793,957*	*108,447,877*	*140,265,470*	*36,550,481*	*300,057,785*
	2023	*15,235,253*	*110,048,930*	*142,790,483*	*37,001,251*	*305,075,918*
	2024	*15,684,458*	*111,632,775*	*145,277,751*	*37,450,919*	*310,045,904*
	2025	***16,128,391***	***113,228,092***	***147,790,183***	***37,901,322***	***315,047,989***
	2026	*16,575,838*	*114,815,762*	*150,285,839*	*38,351,236*	*320,028,674*
	2027	*17,020,943*	*116,408,529*	*152,792,678*	*38,801,476*	*325,023,626*
	2028	*17,467,609*	*1179,97,898*	*155,292,062*	*39,251,498*	*330,009,067*
	2029	*17,913,234*	*119,589,533*	*157,796,417*	*39,701,665*	*335,000,848*
	2030	***18,359,553***	***121,179,657***	***160,297,457***	***40,151,735***	***339,988,403***

Bold values signifies the base/projected year of time -horizon.

Table 8
Share of sales per each appliance in the residential sector.

Appliance/end-use	TFL	EG	TV	CF	FR	RAC	WM	COM	WEP
% of sales	66	85	85	85	85	60	85	50	50

Table 9
Appliance ownership projections.

Type of Appliance/end-use	Stock in million					Data Sources
	2011	2015	2020	2025	2030	
TFL	194	222	260	298	335	[6,17,39,40,41]
FR	47	75	110	160	210	[6,17,41]
TV	336	345	392	477	560	[6,17,41,42]
RAC	7	21	37	77	116	[6,17,41,43]
CF	242	312	400	700	1000	[6,17,41,44,45]
EG	2	2	3	4	4	[6,17,41]
WM	2	3	4	5	5	[6,17,41,46]
COM	91	146	217	286	356	[6,17,41]
WEP	2	2	3	4	5	[47]

Table 10
Energy Labelling scheme up to 2016.

With energy label scheme		Without energy label scheme
TFL	M	Tape recorder, CD player
FR	M	Radio
TV	M	Air cooler
RAC	M	Room heater
CF	V	Set-Top Box
EG	M	DVD Players
WM	V	Electric Oven,
COM	V	Incandescent bulb
WEP	V	Compact Fluorescent Lamp
Legend: M-Mandatory Label		V-Voluntary Label

2011 (see Fig. 4).

If the replacement of BAU with BAT appliances took place in the time of horizon of this study, the avoided electricity consumption would correspond to 97 TWh in 2011, 129 TWh in 2015, 194 TWh in 2020 and 326 TWh in 2030 (see Table 13).

Table 11
Average yearly energy consumption for BAT/BAU appliances.

Appliance/end-use	BAT kWh/year	BAU kWh/year	References
TFL	53	88	[50–52]
EG	319	438	[53,54]
TV	175	329	[55,56]
CF	161	219	[56,57]
FR	330	600	[58–60]
RAC	2204	3154	[61,62]
WM	146	365	[63–65]
COM	219	365	[66–68]
WEP	400	799	[69,70]

According to our projections and to the penetration rate of the electrical appliances evaluated in 2030 a reduction is anticipated of 98.6 TWh, 74.7 TWh and 56.7 TWh of electricity consumption with the replacement BAU with BAT for TV, COM and FR, respectively (see Table 12).

A study conducted to estimate the electricity savings obtained from the replacement of RAC, FR, TV and CF BAU with BAT suggests a reduction of electricity consumption in Indian households of 165 TWh in 2030 [8]. LBNL estimated a reduction of electricity consumption for Indian households of 78 TWh in 2030 just with the replacement of RAC and FR [72]. According to our assessment the overall amount of energy savings attainable in 2030 with the replacement of BAU RAC, FR, TV and CF with BAT would be 227 TWh.

These results illustrate the tremendous impact on the energy savings if measures to promote the investment in energy efficient appliances are adopted and become effective, namely avoiding the need of installing new thermal power plants in India.

4.2. Avoided energy costs

We have computed the cumulative electricity savings and corresponding energy avoided costs by taking into account the energy savings obtainable with the energy efficient technologies (BAT)

Table 12
Appliance operating hours per year.

Type of Appliance/end-use		2011	2015	2020	2025	2030	References
TFL	Hrs/Year	1460	1460	1460	1460	1460	[12–14,17,39,69].
EG	Hrs/Year	100	100	100	100	100	
TV	Hrs/Year	2190	2190	2190	2190	2190	
CF	Hrs/Year	1600	1600	1600	1600	1600	
FR	Hrs/Year	8760	8760	8760	8760	8760	
RAC	Hrs/Year	1080	1080	1080	1080	1080	
WM	Hrs/Year	365	365	365	365	365	
COM	load/Year	1400	1400	1400	1400	1400	
WEP	Hrs/Year	548	548	548	548	548	[6]

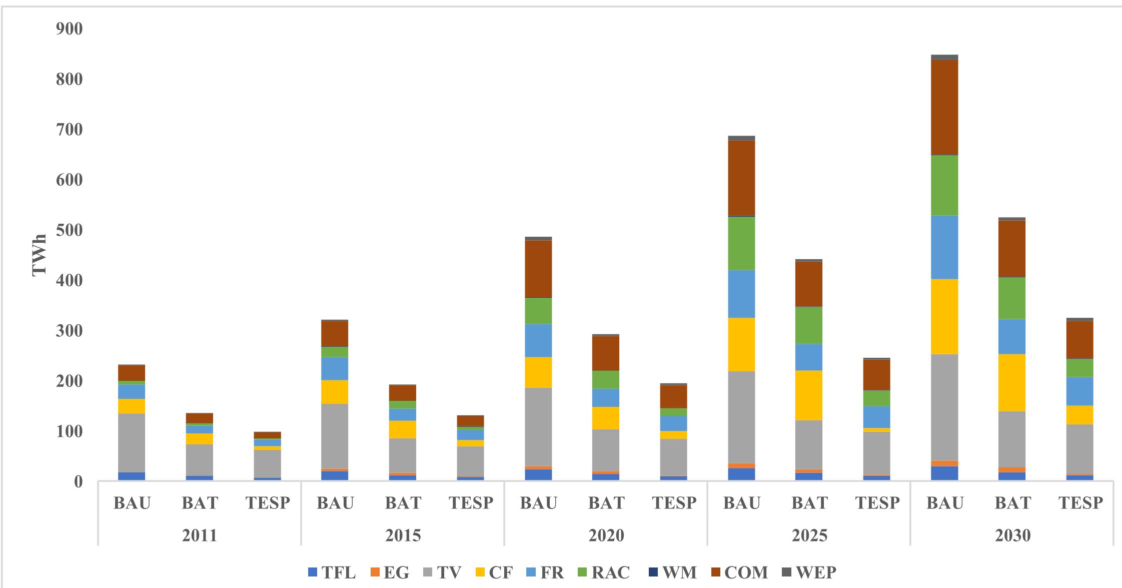

Fig. 4. Energy consumption of BAT/BAU appliances and the corresponding technical energy savings potential.

against conventional technologies (BAU). Fig. 5 illustrates the avoided energy costs in different time frames indicating that the investment in more efficient TV, COM and RAC offers the highest potential for reducing energy costs. Out of the nine BAT appliances considered, TV, COM and RAC (Fig. 5) are accountable for more than 80% of the expected avoided energy costs. Namely, the replacement of BAU appliances with BAT appliances corresponds to an overall avoided energy cost in million $ of about 6109 in 2011, 70,519 in 2015, 281,837 in 2020, 566,242 in 2025 and 937,349 in 2030.

4.3. Economic impacts

The anticipated direct, indirect and induced impact on GVA resulting from the investment in energy efficient appliances for the different time horizons of this study is provided below (see Fig. 6).

Out of the nine BAT appliances considered only COM, TV, CF and FR are responsible for more than 80% of the expected net GVA in 2011 (see Fig. 6). The replacement of BAU appliances with BAT appliances corresponds to a net positive direct, indirect and induced GVA of 5, 460 million $, 4406 million $, and 144 million $, in 2011, respectively (see Table 14). The positive impacts on GVA always occur in the manufacturing lifecycle stages while the negatives impacts are obtained in the operation stage. This explains the anticipated overall negative economic impact on direct, indirect and induced GVA in 2015, 2020, 2025 and 2030.

4.4. Environmental impacts

The emissions accounted for in our study include both CO_2 emission and non-CO_2 emissions and involve energy-related and non-energy related combustion, covering their corresponding global warming potential (GWP) in tonnes of CO_2 equivalent (tCO_2eq) [73,74]. SO_2, NO_x and NH_3 are the primary gases used to account for the acidification potential [75]. The tropospheric ozone potential involves emissions of the following gases: NO_x, NMVOC, CO and CH_4 [76].

The avoided GHG emissions were computed by considering that each GHG has a different GWP and persists for a different period of time in the atmosphere. The three main GHG and their 100-year GWP compared to carbon dioxide are [76]: $1 \times CO_2$; $25 \times CH_4$ (i.e. releasing 1 kg of CH_4 into the atmosphere is almost equivalent to releasing 25 kg of CO_2); $298 \times N_2O$ (i.e. releasing 1 kg of N_2O into the atmosphere is almost equivalent to releasing 298 kg of CO_2).

The calculation of the acidification potential is analogous to the GWP and is stated in SO_2 equivalents (tSO_2eq). The chosen acidifying substances (i.e. SO_2, NO_x and NH_3) are aggregated into a single indicator, after assigning to each specific pollutant the corresponding acidification potential: $1 \times SO_2$; $0.7 \times$ of N_2O and NO_X (i.e. releasing 1 kg of N_2O and NO_X into the atmosphere is almost equivalent to releasing 0.70 kg of SO_2); $1.88 \times NH_3$ (i.e. releasing 1 kg NH_3 into the atmosphere is almost equivalent to releasing 1.88 kg of SO_2) [76].

The calculation of the tropospheric ozone formation potential

Table 13
Technical energy savings potential.

Energy consumption	Appliance/end-use	2011	2015	2020	2025	2030
		GWh/yr	GWh/yr	GWh/yr	GWh/yr	GWh/yr
BAT	TFL	10,197	11,695	13,681	15,664	17,642
	EG	300	4, 400	5700	7356	8863
	TV	62,238	68,721	83,522	98,064	112,754
	CF	21,261	34,320	44,000	77,000	110,000
	FR	15,510	24,750	36,300	52,800	69,300
	RAC	5, 289	14, 852	35740	73895	84,038
	WM	36	448	559	672	784
	COM	19,168	30,760	68,217	90,089	112,078
	WEP	608	925	3496	4514	5534
BAU	TFL	16,994	19,491	22,802	26,106	29,403
	EG	360	5280	6840	8827	10,635
	TV	116,695	128,851	156,603	183,869	211,413
	CF	28,992	46,800	60,000	105,000	150,000
	FR	28,200	45,000	66,000	96,000	126,000
	RAC	7569	21,254	51,149	105,754	120,269
	WM	89	671	1398	1679	1960
	COM	31,947	51,267	113,695	150,149	186,797
	WEP	1215	1849	6991	9028	11,069
TPS	TFL	6798	7796	9121	10,442	11,761
	EG	60	880	1140	1471	1773
	TV	54,458	60,131	73,081	85,806	98,659
	CF	7731	12,480	16,000	28,000	40,000
	FR	12,690	20,250	29,700	43,200	56,700
	RAC	2280	6403	15,409	31,858	36,231
	WM	53	224	839	1007	1176
	COM	12,779	20,507	45,478	60,059	74,719
	WEP	608	925	3496	4514	55,34
Overall	**GWh/yr.**	**97,456**	**129,595**	**194,263**	**266,358**	**326,553**
	TWh/yr.	**97**	**129**	**194**	**266**	**326**

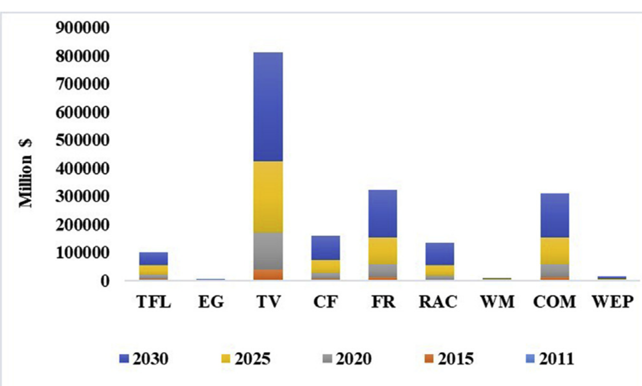

Fig. 5. Avoided electricity costs.

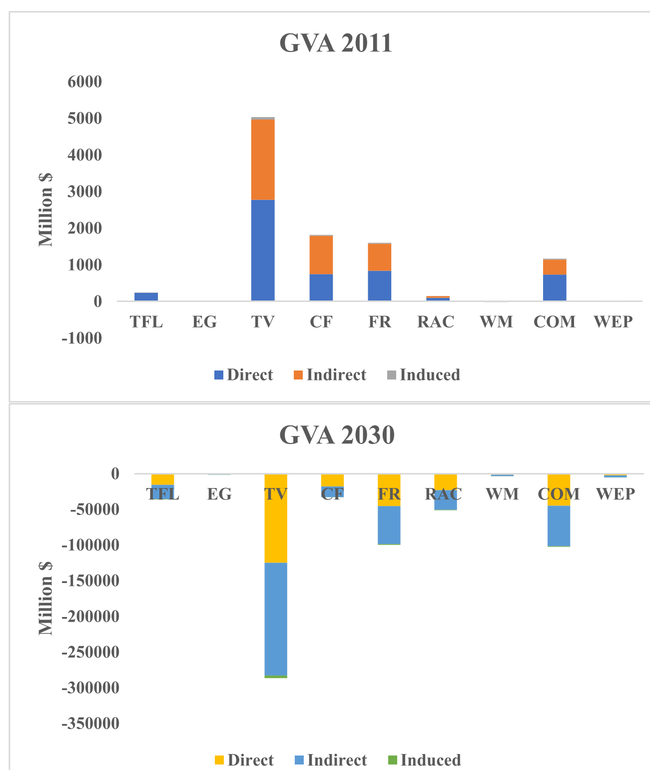

Fig. 6. GVA direct, indirect and induced impacts in 2011 and 2030.

(TOFP) follows the same reasoning of GWP and acidification potential and it is provided in tonnes of Non-Methane Volatile Organic Compounds (NMVOC) equivalent (tNMVOCeq). The chosen set of ozone precursors (i.e. NO_X, NMVOC, CO and CH_4) is aggregated into a single indicator, after allocating to each specific pollutant the corresponding TOFP: 1 × NMVOC; 1.22 × NOx; 0.11 × CO (i.e. releasing 1 kg of NMVOC, NO_X into the atmosphere is almost equivalent to releasing 1.22 kg of NMVOC and CO is equivalent to releasing 0.11 kg of NMVOC); 0.0144 × CH_4 (i.e. releasing 1 kg CH_4 into the atmosphere is almost equivalent to releasing 0.0144 kg of NMVOC) [76].

The appliances with the highest GHG reduction potential in 2011 and 2030 are COM, FR, TV, RAC, CF and TFL (see Fig. 7). If the replacement of BAU with BAT appliances took place in 2011, there would be no avoided GHG emissions in the starting year of the assessment with TV, CF, FR, corresponding to an overall increase of 2,874,234 tCO2eq in 2011. However, an overall reduction of GHG

Table 14
Net GVA in 2011 and 2030.

	Appliance/end-use	Manufacturing in Million $			Operation in Million $			Total in Million $		
		Direct	Indirect	Induced	Direct	Indirect	Induced	Direct	Indirect	Induced
2011	TFL	96	192	5	144	−190	−4	239	2	1
	EG	0	0	0	4	−5	0	4	−5	0
	TV	1623	3717	100	1151	−1524	−35	2775	2192	65
	CF	584	1260	33	163	−216	−5	747	1044	28
	FR	568	1096	33	268	−355	−8	837	741	25
	RAC	50	112	3	48	−64	−1	99	48	1
	WM	0	−1	0	11	−15	0	11	−16	0
	COM	462	767	33	270	−358	−8	732	409	25
	WEP	3	7	0	13	−17	0	16	−10	0
	Sum	**3387**	**7151**	**207**	**2073**	**−2745**	**−63**	**5460**	**4406**	**144**
2030	TFL	789	1589	44	−16,416	−21,738	−499	−15,627	−20,150	−455
	EG	−19	−38	−1	−621	−822	−19	−640	−860	−20
	TV	7016	16,445	438	−131,844	−174,587	−4007	−124,827	−158,141	−3569
	CF	10,634	22,955	592	−28,595	−37,866	−869	−17,961	−14,911	−277
	FR	11,487	22,152	665	−56,936	−75,394	−1730	−45,449	−53,242	−1065
	RAC	3460	7693	197	−26,602	−35,227	−808	−23,143	−27,533	−611
	WM	0	−10	2	−1515	−2006	−46	−1515	−2016	−44
	COM	8299	13,775	593	−53,211	−70,461	−1617	−44,911	−56,686	−1024
	WEP	42	94	2	−2322	−3075	−71	−2280	−2981	−68
	Sum	**41,708**	**84,655**	**2534**	**−318,061**	**−421,175**	**−9666**	**−276,353**	**−336,520**	**−7132**

emissions of 337,225,763 tCO2eq in 2030 is anticipated.

The appliances with the highest acidification reduction potential in both years are (once more) FR, TV, RAC, CF and TFL (see Fig. 8). If the replacement of BAU with BAT appliances was carried out in 2011, the avoided overall acidifying gas emissions would correspond to 11,908,928 tSO_2eq. Considering the same previous assumptions, our projections also indicate that in 2030 an overall reduction of acidifying gas emissions of 2,028,770,397 tSO_2eq is foreseen.

The appliances with the highest anticipated reduction projections for TOFP in 2011 and 2030 are TV, RAC, TFL and CF (see Fig. 9). With the replacement of BAU with BAT appliances in 2011, the avoided emissions of ozone precursors would correspond to 396,294 tNMVOCeq. Our projections also indicate that in 2030 an overall reduction of ozone precursors is predicted of 50,172,411 tNMVOCeq.

4.5. Social impacts

The foreseen overall net employment generation with BAT appliances is illustrated in Fig. 10 indicating that promoting EE will

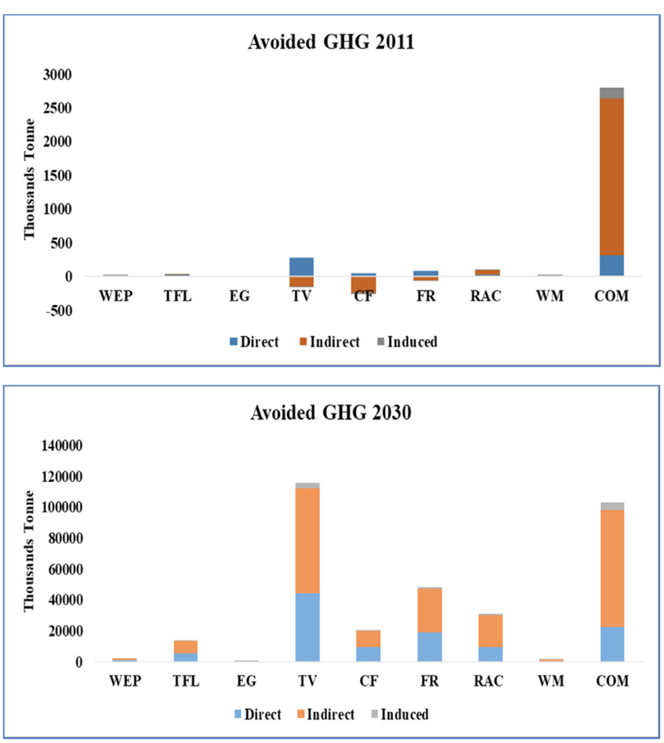

Fig. 7. Avoided GHG emissions with BAT appliances.

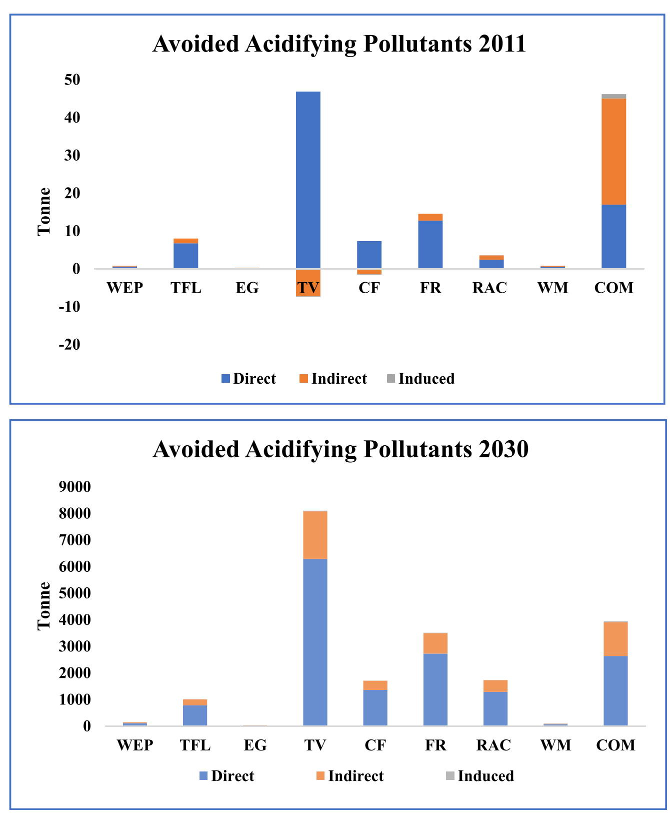

Fig. 8. Avoided acidification potential emissions with BAT appliances.

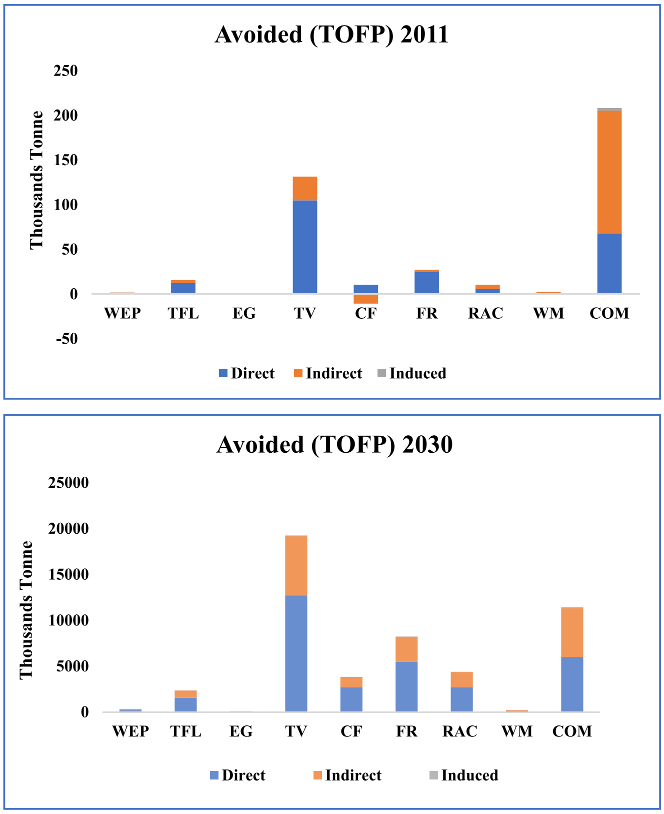

Fig. 9. Avoided tropospheric ozone formation potential with BAT appliances.

promote net job generation until 2030. In 2011 the replacement of BAU with BAT appliances would have been responsible for 337 thousand direct jobs, 857 thousand indirect jobs and 37 thousand induced jobs. In 2030 a generation of 2306 thousand direct jobs, 1217 thousand indirect jobs and 12 thousand induced jobs is foreseen. However, a loss of 2959 thousand indirect jobs and 176 thousand induced jobs is to be expected between 2025 and 2030. These outcomes are aligned with the conclusions of ACEEE, suggesting that there will be a job loss due to energy efficient technology [77,78].

5. Conclusions and future work developments

An I-O lifecycle assessment modelling approach has been suggested which allows obtaining several projections regarding the assessment of the E3S impacts associated with the replacement of less efficient appliances (BAU) with BAT appliances from the year 2011–2030. Several environmental impacts have been covered, including GHG emissions, acidifying substance emissions and TOFP emissions. According to the scenarios considered in our analyses, we have concluded that there will be no avoided GHG emissions in the starting year of our assessment for TV, CF, FR. This outcome is obtained because the impact of the manufacturing lifecycle stage will be more significant than the operational phase in the initial stages of our analysis. However, the longer the lifetime of the equipment, the higher the expected overall reduction of the GHG emissions throughout the equipment's lifetime. According to our projections in 2030, an overall reduction of GHG emissions is anticipated of above 337,225 10^3 tCO_2eq. The avoided acidifying gas emissions would reach more than 11,908 10^3 tSO_2eq in 2011, whereas in 2030 an overall reduction of more than 2,028,770 10^3 tSO_2eq is estimated. Regarding the TOFP avoided emissions these would correspond to above 396 10^3 tNMVOCeq in 2011, while in 2030 an overall reduction of more than 50,172 10^3 tNMVOCeq is expected. Our study also indicates that TV, CF, FR and RAC BAU appliances will have been responsible for more than 85% of the potential GHG emissions, in 2011. From the nine appliances herein considered, three (TV, CF, FR) alone are responsible for more than 80% of the energy consumption. In particular, the replacement of current less efficient models with BAT can reduce the overall energy consumption to 326 TWh in 2030. The cumulative electricity savings obtained with the replacement of BAU with BAT appliances, may correspond to an overall avoided energy cost in million $ of about 6109 in 2011, 70,519 in 2015, 281,837 in 2020, 566,242 in 2025 and 937,349 million $ in 2030.

Regarding the economic impacts, an expected net positive direct, indirect and induced GAV impact of about 5, 460 million $,4, 406 million $ and 144 million $ would be attained in 2011, respectively, while in 2030 net negative direct, indirect and induced GAV impacts are foreseen of 276, 353 million $ 336, 520

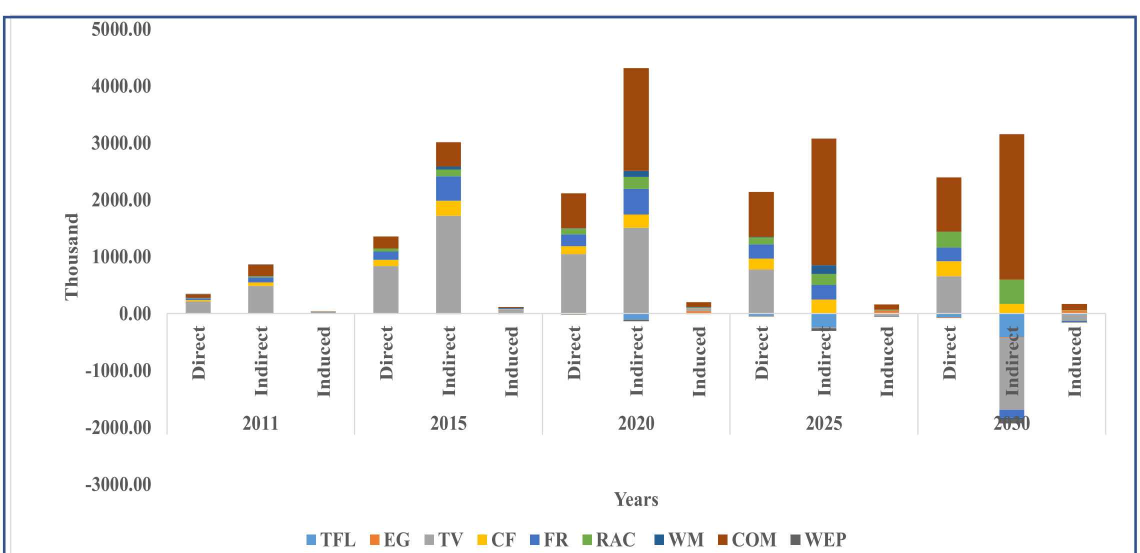

Fig. 10. Overall net employment generated from 2011 to 2030.

million $ and 7, 132 million $, respectively. The overall economic effect becomes negative because of the anticipated reduction of energy consumption. Nevertheless, this conclusion is not straightforward since an expected increase of private consumption might be anticipated with the money saved in electricity consumption.

The overall net employment generation caused by the adoption of BAT appliances suggests that promoting energy-efficient appliances will lead to positive direct net job generation of 337, 1352, 2089, 2082 and 2306 thousand jobs in 2011, 2015, 2020, 2025 and 2030 respectively. Although the overall employment effect is largely positive, a negative impact on indirect and induced employment in 2030 can be anticipated.

We can conclude that the adoption of more energy efficient technology will not necessarily lead to high economic impacts. However, it is expected that the avoided energy consumption costs can be used to further promote the investment in more efficient technologies (e.g. super-efficient appliances). Future work is currently under way to encompass these aspects into our analysis as well as to couple the I-O modelling framework developed with other mathematical modelling tools to better explore the main potentialities offered by different approaches, in particular, MOLP models.

Acknowledgements

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