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Felix Amankwah Diawuo, Joana Pedro and Carlos A. Silva

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***Felix Amankwah Diawuo*[a], *Joana Pedro*[b], *Carlos A. Silva*[c]**

[a] *IN+, Instituto Superior Tecnico, Lisbon, Portugal, email: felix.diawuo@tecnico.ulisboa.pt*

[b] *IN+, Instituto Superior Tecnico, Lisbon, Portugal, email: joana.pedro@tecnico.ulisboa.pt*

[c] *IN+, Instituto Superior Tecnico, Lisbon, Portugal, email: carlos.santos.silva@tecnico.ulisboa.pt*

Abstract

Residential electricity consumption continues to rise and accounts for 16-50% of the total energy use across different countries in the world. In many developing countries, people are deploying more and more household appliances for comfort and utility for which refrigerators are indispensable. Globally, refrigerator use constitutes a significant proportion of household demand ranging from 3-19%, because it operates steadily over time irrespective of seasons or place and thereby has a considerable impact on energy use and the environment. Ghana has commenced the implementation of the established mandatory minimum energy performance standards (MEPS) for refrigerators but no study has been done to understand its impact in time (2020-2050) and its regional variation based on the different socio-economic dynamics of each location. This study, therefore, aims to analyse temporally and spatially the impact of different scenarios of MEPS and labelling transitions in relation to energy savings and emissions for refrigerator use in households at the regional and district level, using the Greater Accra Region in Ghana as a case study. For the temporal analysis, a bottom-up approach is used to estimate energy consumption and savings based on top-down data such as population, income levels and appliance ownership. Then, for the spatial analysis, Geographic Information Systems (GIS) are used to map the spatial distribution of the results by disaggregating the overall energy consumption according to the population density of each district. Results showed that the considered efficiency standards and labels will potentially save at regional level, a cumulative total of 4.9-8.1TWh electricity, and reduce emission of 1.04-1.71 million tons of CO_2, for the period of 30 years (2020-2050), depending on the efficiency transition period scenario. In a more environmentally conscious case, a certified emission market value of 10-17 million USD could be fetched. These findings will apprise policy decisions in energy development planning.

Keywords:

Electricity consumption, Geographical information system, ArcGIS, Bottom-up and top-down approach, Appliance ownership.

1 Introduction

Residential electricity consumption continues to rise and accounts for 16-50% of the total energy use across different countries in the world [1]. The increasing trend in household electricity consumption is accounted for by rising population and economic growth, appliance ownership, electrification rate, lifestyle and behaviour change [2]. In many developing countries, people are deploying more and more household appliances for comfort and utility for which refrigerators are indispensable. The stock of domestic refrigerators and freezers is estimated at about 1.4 billion worldwide and 49 million in sub-Saharan Africa [3]. Refrigerator use alone constitutes a significant portion of household demand globally ranging from 3-19% [3]. This is primarily due to its steady operation over time irrespective of season or location, thereby having a considerable impact on energy use and the environment. Van Buskirk et al. (2007) [4] indicated that refrigerator electricity use and its potential energy savings may be considerably greater in Africa than other developing countries. This was attributed to factors such as: (1) higher ambient temperatures and humidity, (2) the prevalence of old, used and poorly reconditioned refrigerators, (3) more intensive use of refrigerators for productive and commercial activities, and (4) voltage and power supply fluctuations and inefficient use patterns that respond to such fluctuations.

Notwithstanding the many electricity challenges facing the sub-region where more than 600 million people lack access to electricity with an access rate of about 20% [5], policy initiation to reduce consumption is insufficient. Energy efficiency as part of demand-side management strategies is recognised as one of the mechanisms to address energy challenges- energy security and climate change at the least possible cost. Minimum energy efficiency performance standards (MEPS) do not exist in most parts of the sub-Saharan region, despite the possibility that refrigerator efficiency market transformation may be one of the most cost-effective and environmentally beneficial pathways for expanding electricity-based energy services supply on the continent [4]. Energy performance standards and labelling programs are typically the first order policy intervention to transform the market of a specific end-use where inefficient appliances are removed and replaced with new efficient ones to reduce energy consumption [6–8]. Fortunately, Ghana is of one the countries in the sub-region which has actively promulgated energy efficiency regulations for some electrical appliances. The case for the enactment of refrigerator regulation came to being after the Energy Commission of Ghana in 2006 carried out a survey to measure and evaluate energy consumption and efficiencies of refrigerators and freezers in 1000 households. The results revealed that the annual energy consumption of refrigerators and freezers ranged from about 150 to over 2000 kWh per appliance depending on the size of the appliance, and averaged at 1140 kWh per appliance [9]. This averaged refrigerator consumption is about three times the maximum allowed in countries with robust standards and labelling programs. Such inefficient appliances can result in US$50 to US$100 per year of potentially unnecessary electricity expenses for a typical consumer [9]. The MEPS regulation and labelling for refrigerator, refrigerator-freezer and freezer under the legislative instrument (L.I 1958) was finally passed into law by Parliament of Ghana in 2009 [10]. Thereafter, a legislative instrument (L.I 1932) has been passed to prohibit the manufacture, sales or importation of used refrigerators and freezers. Furthermore, fiscal and subsidy programs in a form a rebate scheme was introduced in 2012 and 10,000 old inefficient refrigerators have been replaced with new efficient ones [2].

For a successfully implemented policy, proper evaluation of its impact is key to ascertain the achievement of set objective(s). Buskirk et al. (2007) [4] discussed how meeting the challenges of the Ghanaian market will require modification of the usual energy efficiency labelling and standards paradigm and then proceeded to examine the possibility of implementing a refrigerator efficiency market transformation program in Ghana at the national scale. So far, no apparent study has been done to understand the MEPS impact in time at the spatial level based on the different socio-economic dynamics at the regional and district scale.

This study, therefore, seeks to fill this knowledge gap by analysing temporally and spatially the impact of different scenarios of MEPS and labelling transitions in relation to energy savings and emissions for refrigerator use in households at the regional level, using the Greater Accra Region and its 16 districts in Ghana as a case study. The Greater Accra Region is used in this study because of its heterogeneous characteristics at the district level. The 16 districts making up the Greater Accra Region is as indicated in Table 1. For the temporal analysis, a bottom-up approach based on a stock accounting model is used to estimate energy consumption and savings based on top-down data such as population, income and appliance ownership while for the spatial analysis, the ArcGIS software is used for the Geographic Information Systems (GIS) modelling to distribute energy consumption estimation according to the expected population density. The bottom-up model approach is used because of the high degree of technological detail which can accurately be used to assess future electricity consumption as compared to top-down [11].

Table 1. Names of districts within the Greater Accra Region

Code	Names of Districts	Population 2010
P1	Ledzokuku-Krowor Municipal District	227,932
P2	Ada East District	71,671
P3	Shai Osudoku District	51,913
P4	Ada West District	59,124
P5	Ningo Prampram District	70,923
P6	La Dade Kotopon Municipal District	183,528
P7	La Nkwantanang Madina Municipal District	111,926
P8	Ga East Municipal District	147,742
P9	Accra Metropolitan District	1,665,086
P10	Ga South Municipal District	485,643
P11	Ga West Municipal District	219,788
P12	Ga Central District	42,954
P13	Tema Metropolitan District	292,773
P14	Ashaiman Municipal District	190,972
P15	Kpone Katamanso District	109,864
P16	Adenta Municipal District	78,215

Note 1: In this study, the 2 metropolitans, 7 municipals and 7 ordinary districts are all considered as districts. A district unit corresponds to the smallest statistical unit with statistical information available, according to Ghana census 2010.

2 Methods and data

This section presents the modelling methodologies for estimating energy savings of an appliance while created scenarios and data assumptions are clearly defined.

2.1 Stock model

This subsection explains the methodology of modelling stock, survival and sales of household appliance. Stock accounting models are designed to follow the principle of mass conservation where material flow in a system can be quantified. Many studies have applied material flow analysis as the basis for their model in evaluating and projecting future flows of materials, products and emissions [12]. In applications where sufficient statistical data exist, the stock is modelled using historical sales data and survival rates over a period of at least twice the appliance's average lifetime [12]. In situations where no such data is present, but number of households and appliance ownership rates are known, the stock can be calculated, and appliance sales estimated [13]. The method used in this study is principally adopted from Diawuo et al. [14].

2.1.1 Appliance model

The sales of an appliance in a specific year, as presented in Eq. (1), is defined as the stock of refrigerators in the predicting year minus the stock in the previous year plus the stock of retired refrigerators in the current year.

$$S_i^a = stock_i^a - stock_{i-1}^a + AR_i^a \quad (1)$$

The appliance stock, as expressed in Eq. (2), is a function of the appliance ownership and the number of households.

$$Stock_i^a = HH_i \times \gamma_i^a \quad (2)$$

The total number of refrigerator retired in each year, as presented in Eq. (3), is the sum of the retired refrigerators that entered the system in previous years.

$$AR_i^a = S_i^a \times (1 - \varphi_a(0)) + \sum_{j=i-k}^{i-1} S_j^a \times (\varphi_a(\mathrm{i-j+1}) - \varphi_a(\mathrm{i-j})) \quad (3)$$

The refrigerator ownership evolution is modelled as a sigmoid function of time using a logistic function that captures consumer choice (see Eq. (4&5))[14]. The appliance ownership is a function of appliance household penetration and saturation. Appliance penetration is defined as the proportion of households in which one or more appliance type is present while saturation refers to the average number of appliances per household for those households with one or more of the appliance [14]. The logistic function by formulation has a maximum value of one, at which point penetration is reached. In this model, the maximum value could be more than one because of the propensity of households to own more than one appliance (e.g. fridges) [14]. The function is scaled by the saturation level parameter.

$$\gamma_t^a = \frac{\delta^a}{1 + e^{\log_e(\delta^a / \beta^a - 1) - bt}} \quad ; \quad \begin{array}{l} \delta = \alpha \times \rho; where\{^{\alpha \ge 1}_{\rho \le 1} \\ \beta = \alpha \times \rho; where\{^{\alpha = 1}_{\rho \le 1} \end{array} \quad (4)$$

And $$b = \frac{\log_e(\delta^a / \beta^a - 1)}{\vartheta(t)} \quad (5)$$

The appliance survival rate, as presented in Eq.(6), is modelled as a non-linear function using the modified Weibull probability distribution function as expressed in [15], where the survival rate is a function of the appliance average lifetime age.

$$\varphi^a(k) = \exp - \left[\left(\frac{k + c^a}{T^a} \right)^{c^a} \right] \; ; \; \varphi^a(0) \cong 1 \quad (6)$$

2.1.2 Appliance electricity consumption and savings

The unit energy savings (UES) of an appliance is calculated as the difference between the unit baseline energy consumption and the unit standard energy consumption. The unit energy consumption, fundamentally is a composite function of the power ratings, operating hours and the energy efficiency improvement factor. The annual energy savings of an appliance is expressed as a function of the appliance sales, survival rate and the unit energy saving (UES) as presented in Eq. (7).

$$AES_i^a = \sum_{j=i-k}^{i} S_j^a \times \varphi_a(\mathrm{i-j}) \times UES_j^a \quad (7)$$

2.2 Scenario modelling and data assumptions

2.2.1 Scenario definition

The scenarios created were based on time intervals of technological change, where different standards and labelling regimes are introduced. The transition in the labelling regime and its classification is designed subject to the technological advancement of manufactured appliance on the market. The implementation time intervals considered were assumed based on global experiences [16]. Three scenarios are created, and its specific definitions are explained in Table 2 and Table 3.

Table 2. Energy efficiency scenario definitions

Scenario	**Description**
BS	The baseline scenario assumes a slow gradual labelling transition relative to existing mandatory minimum energy performance standards (MEPS) and follows closely the present trajectory [17] (see Table 3).
EE-S-10-5	Assumed that refrigerator labelling classification under a mandatory MEPS regime is revised every 10 years from 2020 until 2040 and subsequently revised 5 years up to 2050 (see Table 3).
EE-S-5-5	Assumed that refrigerator labelling classification under a mandatory MEPS regime is revised every 5 years from 2020 to 2050 (see Table 3).

Table 3. Energy efficiency standard and labelling transition period

Scenario	**2020**	**2030**	**2040**	**2050**	**-**	**-**	**-**
BS	D	C	C	B	-	-	-
	2020	**2030**	**2040**	**2045**	**2050**	**-**	**-**
EE-S-10-5	C	B	A	A+	A++	-	-
	2020	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
EE-S-5-5	C	B	A	A+	A++	A+++	A+++

Note 2: Specific definition of the class labels is indicated in Table 7 while (-) indicates an empty cell.

2.2.2 Assumptions

This subsection provides the assumptions and data used in this study. Data in relation to population, gross domestic product (GDP), household size, appliance ownership, appliance survival rate and unit energy consumption (UEC) are presented.

2.2.2.1 Population, GDP and household size

Data estimates for population, income (GDP per capita) and household size were extrapolated based on datasets sourced from the Ghana Statistical Service (GSS) through its living standards survey and population census reports [18–22], Delali et al. [23] and WEF [24]. Dataset between 2020 and 2050 was estimated using the known single compound amount method. The set baselines for population, household size and GDP per capita are depicted in Table 4. The population of Greater Accra Region for the period 2020 to 2050 is estimated to grow at an average annual rate of 1.83% while that of GDP per capita and household size is estimated at 3.77% and -0.34% respectively.

Table 4. Baseline assumptions for household indicators

Indicator	**2020**	**2050**
Population (inhabitants)	5,055,805	8,700,125
Household size (number of people)	3.32	3.00
GDP/cap (current US$)	1,648	5,000

2.2.2.2 Appliance ownership

The historical data used for the initial appliance ownership parameter (β^a) was sourced from the Ghana Statistical Service (GSS) [18]. Based on the possible future socio-economic dynamics, the future appliance ownership parameter (δ^a) was assumed to be 0.89 based on the projected income level (GDP/cap is used as a proxy) [23]. The rising income levels will lead to high sales of refrigerators as reflected in the evolution of appliance ownership until 2050 (see Fig. 1). The parametric statistical data used based on Eq.(4&5) is given in Table 5 which includes the model accuracy indicator, Root Mean Square Error (RMSE). The statistical metric RMSE and R-Square values compare the real and modelled data of appliance ownership over time. The real data used is secured from GSS [18–21] for the period within 1990 and 2013. RMSE is the standard deviation of the predicted errors and it reflects the absolute fit of the developed model to the real data as well as how close the points are. Lower values of RMSE indicate better fit.

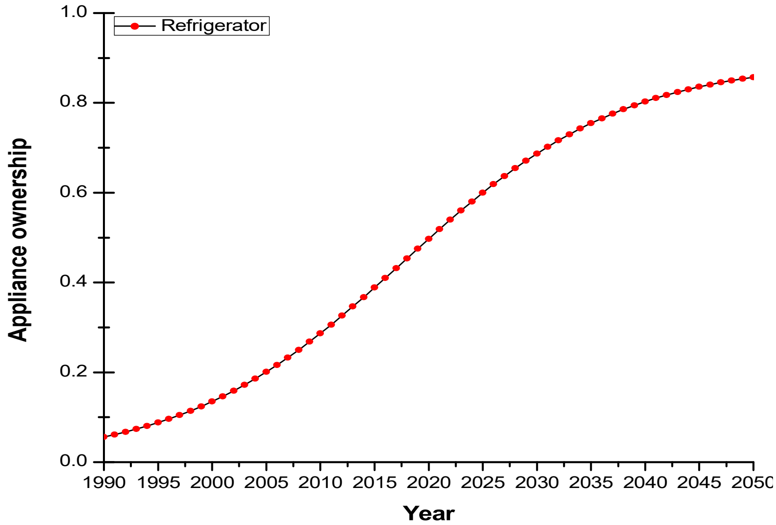

Fig. 1. Modelled appliance ownership evolution for refrigerator

Table 5. Statistical estimate of refrigerator ownership parameters

Appliance	δ [a]	***b***	**ϑ(t)**	**R^2**	**RMSE**
Refrigerator	0.8938	0.0976	27.6857	0.9937	2.3218

2.2.2.3 Appliance survival

The survival curves for the appliances were estimated based on assumed average age data sourced from literature [25]. The average appliance age is assumed to be the same for the different energy efficiency labelling classification [14]. The failure steepness and the characteristics service life as defined in Eq.(6) is assumed as approximately 50^{th} and 90^{th} percentile of the average lifetime of the appliance as expressed in [15], respectively. Fig. 2 displays the survival curve for the refrigerator, while Table 6 indicates the parametric data used for its formulation.

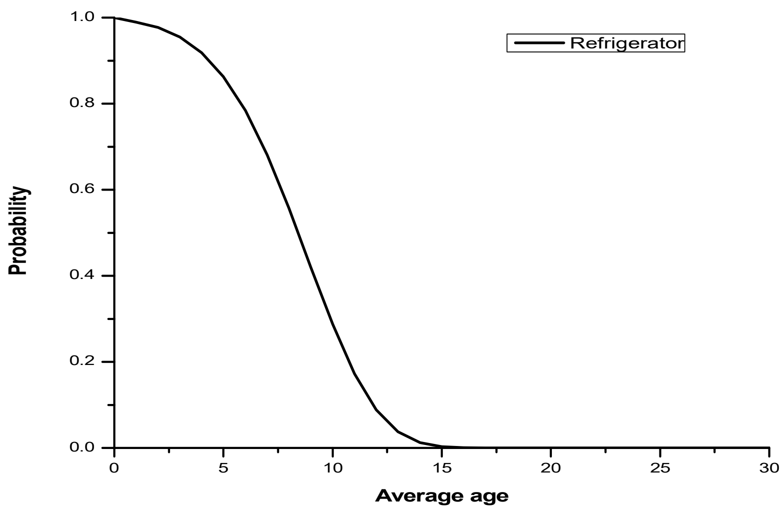

Fig. 2. Survival curve of appliance

Table 6. *Survival curve parameters estimate*

Appliance	Average age (*k*)	T[a]	c[a]
Refrigerator	15	14.85	5.46

2.2.2.4 Appliance unit energy consumption

The unit energy consumption for the appliances under a specific label classification is estimated using the methodology defined in the European Union (EU) energy efficiency regulations (EU Directive 2010/30/EU) [26]. Parametric data used in the formulation for the refrigerator was sourced from local survey reports and literature [27]. The estimated unit energy consumption for each appliance under a specific label is shown in Table 7.

Table 7. Label classification and respective annual unit energy consumption (kWh/year)

Appliances	A+++	A++	A+	A	B	C	D
Refrigerator	80.81	107.74	146.22	188.55	250.12	327.08	396.34

3 Results and discussion

3.1 Evolution of refrigerator electricity consumption

Using the methods and data presented in section 2, the yearly electricity consumption for the refrigerator at the regional level is shown in Fig. 3. In the BS scenario, the electricity consumption was estimated as 433 GWh and 733 GWh in 2020 and 2050 respectively, representing an average annual growth rate (AAGR) of 1.77%. This reflects a percentage share of 11% and 19% of the national residential electricity consumption in 2016 [28]. Regarding the EE-S-10-5 the estimated electricity consumption was 413 GWh and 386 GWh in 2020 and 2050 respectively, representing a 47% reduction in relation to the BS scenario in 2050. Regarding the EE-S-5-5 the estimated electricity consumption was 413 GWh and 237 GWh in 2020 and 2050 respectively, representing a 68% reduction in relation to the BS scenario in 2050. These results show that in the BS scenario, there is an increase in the electricity consumption and this is mainly due to the increase in the stock of household appliances over time. In the EE-S scenarios, there is relatively downward growth or a decline in electricity consumption over time ostensibly due to the gradual transition and replacement of relatively lower efficient appliance with higher ones.

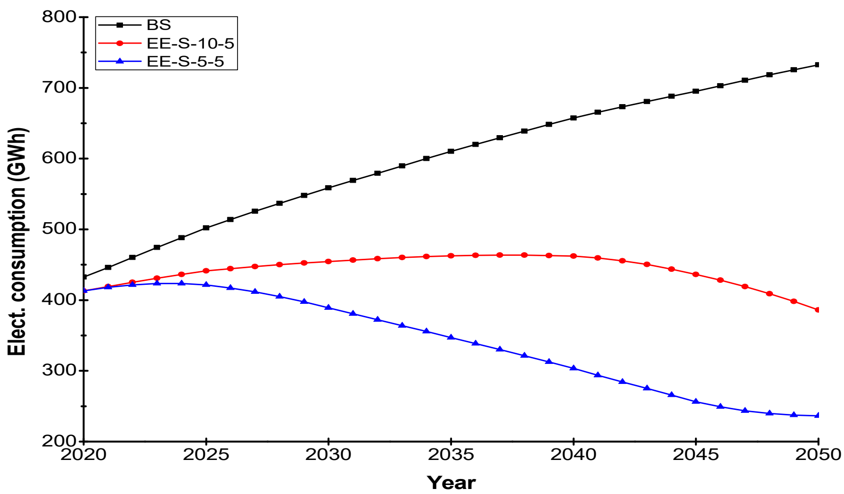

Fig. 3. Evolution of refrigerator electricity consumption from 2020-2050

At the spatial distribution level as depicted in Fig. 4, the results indicate that Accra Metropolis (P9) is the district with the highest energy consumption, having an expected electricity consumption of 178 GWh (2020) and 295 GWh (2050) for the BS scenario while for the efficient scenarios it ranged between 170 GWh (10-5-2020) and 95 GWh (5-5-2050). In comparison, Shai Osu Doku

(P3) is expected to have the lowest consumption, with an expected electricity consumption of 6 GWh (2020) and 10 GWh (2050) for the BS scenario while for the efficient scenarios it ranged between 5 GWh (10-5-2020) and 3 GWh (5-5-2050). The differences in the electricity consumption at the different districts are mainly due to the aggregate income and population levels which influence the sales of refrigerators thereby increasing its penetration and stock.

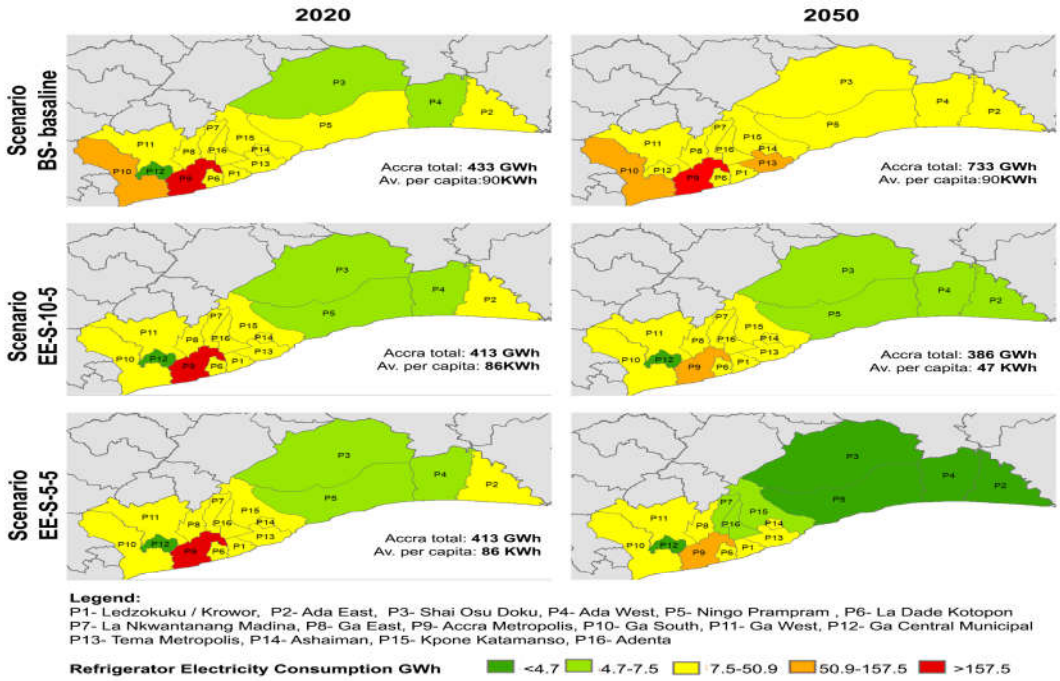

Fig. 4. Spatial distribution of the electricity consumption in 2020 and 2050

3.2 Energy savings

The unit energy saving of an appliance is calculated relative to the baseline scenario and therefore the energy savings are expected to grow as the stock of high efficient appliance increases. Fig. 5 shows the evolutions of the energy savings (ES) based on the difference between the EE-S scenarios and the baseline scenario. In 2020, the expected ES (ES-10-5 and ES-5-5) is estimated as 20 GWh while it increased to 347 GWh and 496 GWh by 2050 with the highest savings achieved with the EE-S-5-5 efficiency scenario. The cumulative savings for the period of 30 years between 2020 and 2050 indicates a total gained savings of 4.9 TWh and 8.1 TWh for EE-S-10-5 and EE-S-5-5 respectively. This indicates that the faster the replacement of old refrigerators with new efficient ones, the higher the savings.

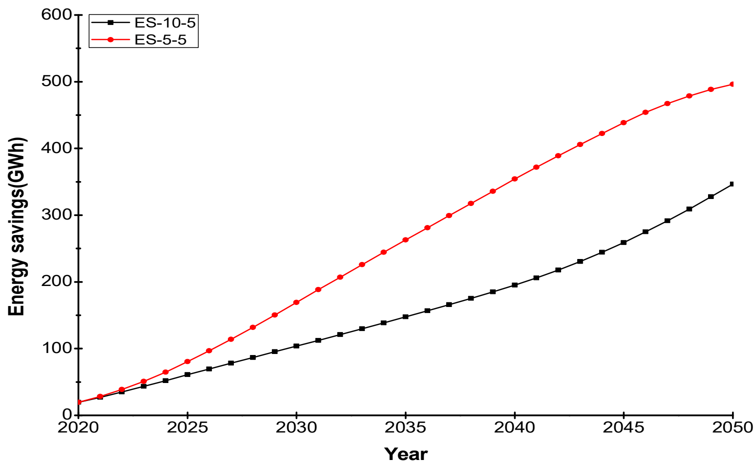

Fig. 5. Evolution of energy savings from implementing labelling regimes (2020-2050)

Regarding the spatial distribution of the results as depicted in Fig. 6, Accra Metropolis (P9) is the district with the highest energy savings potential, corresponding to 8 GWh (10-5-2020) and 200 GWh (5-5-2050). Comparatively, Shai Osu Doku (P3) is expected to have the lowest savings, ranging from 0.3 GWh (10-5-2020) to 7 GWh (5-5-2050). Districts with very high savings have a high stock of refrigerators which are being exchanged for new efficient ones.

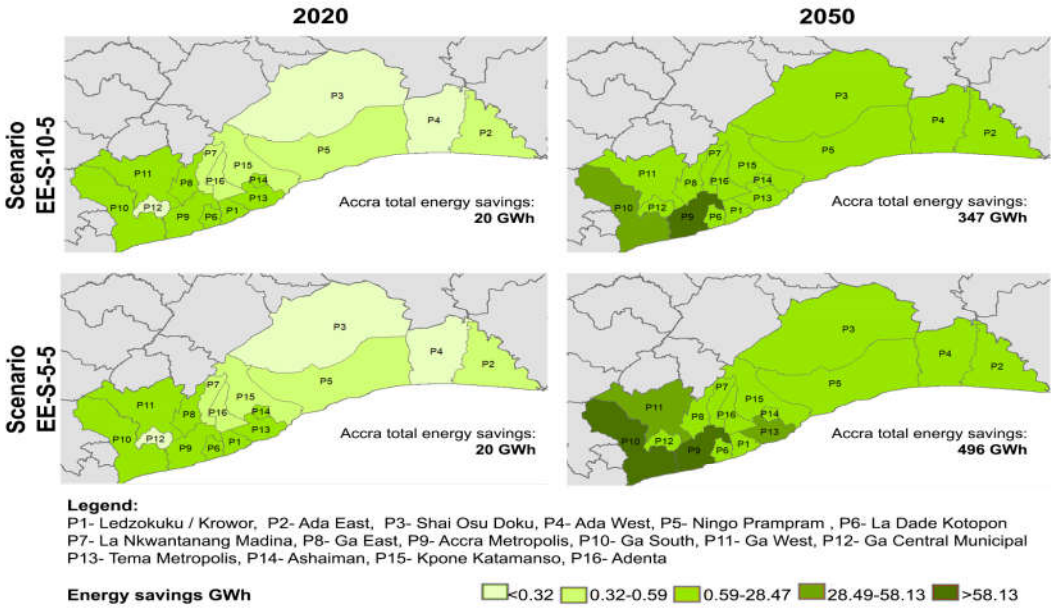

Fig. 6. Spatial distribution of the energy savings from implementing labelling regimes (2020 and 2050)

3.3 Avoided CO_2 emissions

Fig. 7 shows the estimated carbon dioxide emission savings from the refrigerator when market transformation programs are implemented with different standard and labelling transition strategies based on an emission factor of 0.212 kg CO_2 per kWh [4] which depends on the mix of primary energy sources for power generation. The avoided carbon emission based on the ES scenarios in 2020 was 4.17 kilotons (kt) while it increased to 73.48 kt and 105.19 kt for EE-10-5 and EE-5-5 respectively. The avoided cumulative CO_2 emissions for the 30-year period between 2020 and 2050 were 1.04 and 1.71 million tons of CO_2 for EE-10-5 and EE-5-5 respectively. This avoided emissions when converted to certified emissions reductions fetching a market value of around 10 USD per ton of CO_2 [29], will amount to a total of 10 to 17 million USD.

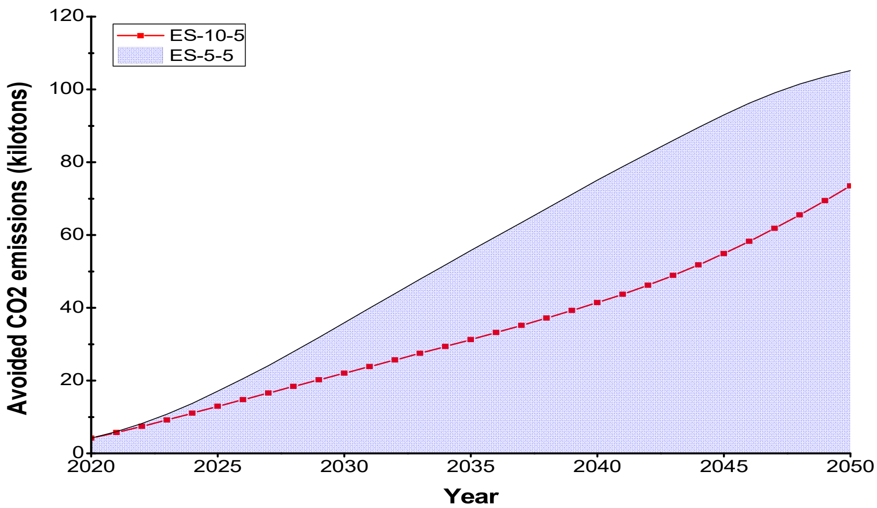

Fig. 7. Yearly CO_2 emissions avoided in the EE-S scenarios from 2020 to 2050

Regarding the spatial distribution of the results as shown in Fig. 8, Accra Metropolis (P9) is the district with the highest avoided carbon emission, corresponding to 1.7 kt (10-5-2020) and 43.3 kt (5-5-2050). In comparison, Shai Osu Doku (P3) is expected to have a lowest avoided carbon emission, ranging from 0.1 kt (10-5-2020) to 1.5 kt (5-5-2050). Districts with high CO_2 savings have high energy savings due to the increasing penetration of efficient refrigerators.

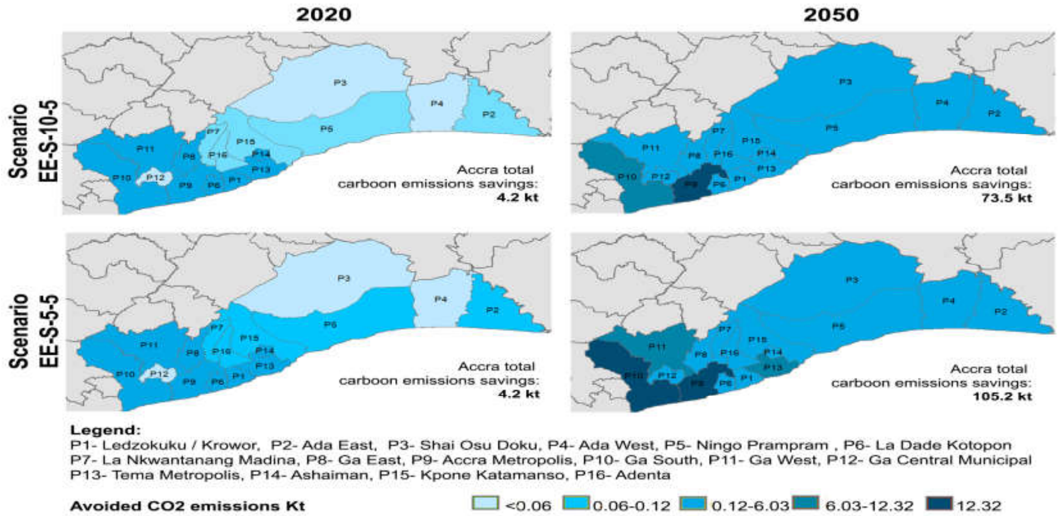

Fig. 8. Spatial distribution of CO_2 emissions avoided in the EE-S scenarios (2020 and 2050)

4 Conclusions

Energy consumption, energy savings and CO_2 emissions reduction of refrigerators in Greater Accra region and its 16 districts have been estimated for a period of 30 years (2020-2050) by introducing scenarios of different standards and labelling regimes. It is realized that the effective introduction and enforcement of MEPS and timeous revision (every 5 years) of standards and labelling of household appliances can ensure more savings and reduce energy consumption. The summary results indicate that electricity consumption at the regional level for the base scenario is expected to be 733 GWh by 2050 while the energy efficiency scenarios fall within 237-386 GWh relative to the transition periods. At the spatial distribution level, Accra Metropolis (P9) indicates the district with the highest energy and emissions savings while Shai Osu Doku (P3) district is the least in terms of overall electricity consumption and savings. The influence of aggregate income, population and propensity for households to possess more refrigerators are the main drivers that influence and differentiates the magnitude of energy and emission savings at the district levels. This study has indicated that there are tremendous benefits of implementing energy efficient standards especially in reducing growth in residential electricity demand. Based on the spatial analysis, specific policy interventions such are subsidies, incentives and public education can be used and targeted at specific districts to achieve significant benefits for consumers and other stakeholders. The proposed interventions are critical and timely, because increased consumption in some of the load centres (e.g. Accra Metropolis (P9)) in the Greater Accra Region can further deteriorate the increasing local distribution network congestion thereby reducing the reliability and security of electricity supply.

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Nomenclature

Symbols

AES	annual energy savings, kWh/year
AR	retired appliances
b	scale parameter
c	failure steepness (c > 1, i.e., survival rate decreases with age)
HH	number of households
k	appliance age, years (k = 0 to 30 since the maximum lifetime rarely exceeds 30 years)
S	number of sales of appliance
Stock	number of units of appliance
t	time, years (e.g. 0 for 1990)
T	characteristic service life
UES	unit energy savings, kWh/year

Greek symbols

α	saturation level
β	initial ownership of appliance at t=0
δ	theoretical maximum (future) ownership of appliance at at t=60
γ	appliance ownership, unit/HH
ρ	appliance penetration
ϑ	abscissa inflection point
φ	probability of survival of appliance

Subscripts and superscripts

a	appliance (refrigerator)
i	predicting/current year
j	starting or sales year

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