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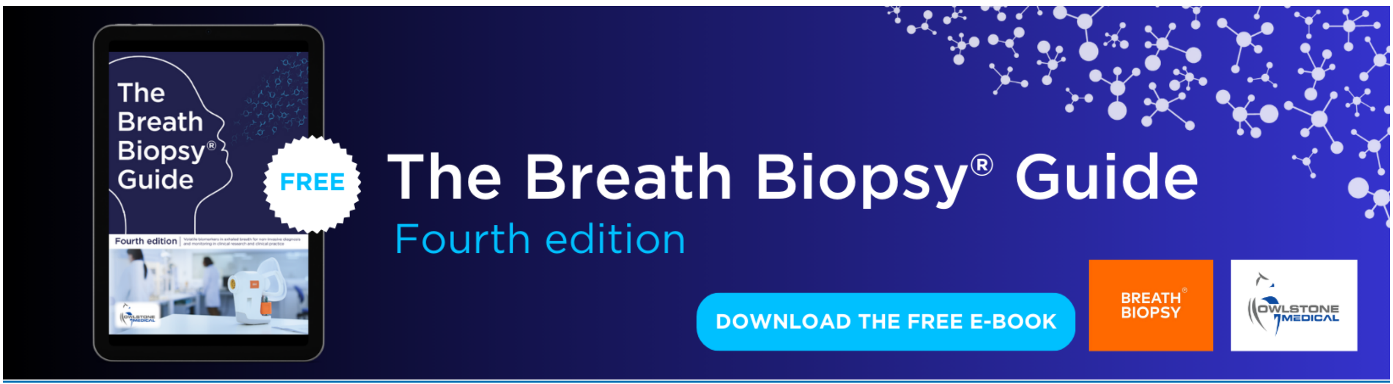

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LETTER

The potential of digital convergence and sharing of consumer goods to improve living conditions and reduce emissions

Nuno Bento
Instituto Universitário de Lisboa (ISCTE-IUL), Centro de Estudos sobre a Mudança Socioeconómica e o Território, Avenida das Forças Armadas, Edifício ISCTE-IUL, Sala 2W4-d, Lisboa 1649-026, Portugal
E-mail: nuno.bento@iscte.pt

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Abstract

Access to modern energy services (entertainment, food preparation, etc) provided by consumer goods remains unequal, while growing adoption due to rising incomes in Global South increases energy demand and greenhouse gas emissions. The current model through which these energy services is provided is unsustainable and needs to evolve—a goal that emerging social and technological innovations can help to achieve. Digital convergence and the sharing economy could make access to appliances more affordable and efficient. This article estimates the effect of innovations around digital convergence and sharing in a highly granular, bottom-up representation of appliances. We simulate changes in demand for materials and energy, assuming decent living standards for all and global warming limited to 1.5 °C. By 2050, these innovations could attenuate the increase in the number of appliances to 135% and reduce overall energy demand by 28%. The results contribute to understand under which conditions digital convergence and sharing can improve living standards and climate mitigation.

1. Introduction

The way in which the production and use of consumer goods[1] is organized is problematic, for several reasons. Emissions from appliance use are rising rapidly, threatening efforts towards climate mitigation. Appliances are among the fastest-growing categories of energy demand, given rising ownership of devices that is driven by increasing income [1]. Appliances already account for 15% of global final electricity demand, or one-third of the energy consumed in buildings (including lighting and cooking) [2]. If demand growth continues to outstrip efficiency gains, one in six units of final energy demand in 2050 will go to appliances, even in a low energy demand (LED) scenario [3]. On the one hand, income growth can have nonlinear effects on energy demand in developing countries [4]. On the other hand, global warming should further increase demand for services such as cooling [5]. Crises such as the pandemic could either attenuate or reinforce the increase in energy demand, depending on whether recovery leads to a more intensive utilization of appliances or the duplication of residential and non-residential space [6].

Access remains extremely unequal to basic appliances that provide modern energy services such as televisual entertainment, food and medicine refrigeration, or automatic laundry washing [7, 8]. For example, in Africa, average ownership rates per 100 households of TVs, fridges, and washing machines are just 17, 10, and 2, respectively—compared to 98, 95, and 92 in the Global North [9]. Attaining universal access to modern energy services by 2030 (UN SGD 7) will be challenging [10, 11]. Over 700 million people still lack access to reliable electricity, particularly in Central and Southern Asia as well as Sub-Saharan Africa (SSA) [12].

[1] Consumer goods are products that consumers buy to perform services (lighting, cooking, entertainment, etc) for their own use, as opposed to capital goods mainly used in business. We refer to consumer durable goods using energy in buildings (including appliances and electronics but not furniture or vehicles), excluding fixed thermal comfort systems that are often covered in a separated category. They include all sort of plug-loads in buildings that are not fixed (i.e. portable, not permanently installed in a location). Large and small household appliances, such as refrigerators and radio alarm clocks respectively, are a major group of consumer goods. In the rest of this paper, we refer to these goods interchangeably as 'consumer goods', 'appliances,' 'equipment,' or 'devices.'

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Current service provision is too costly, inefficient, and pollutive. Income is an important determinant for the acquisition of energy-using assets [4], and prices of appliances remain high for much of the population in low-income countries. Even though the prices of household appliances have declined over time—by 20% on average over the last 25 years in the European Union [13]—they remain out of reach for many in the Global South. In addition, there are variations within this region; for instance, an Indian household faces higher prices for TVs, fridges, and washing machines in terms of purchasing power parity than one in Brazil or South Africa [14]. Higher per capita income in the Global South by 2050—they are expected to double in the 'middle of the road' IPCC SSP2 scenario—would still not be enough to provide universal access [9].

Efficiency gains in consumer goods have slowed down in the past decade, and have stabilized for major appliances since 2014 [15]. On the other hand, smaller devices have increased in number twice as quickly as major appliances since 2010 [1]. Even though small consumer electronics (e.g. tablets or smartphones) have low energy consumption, they exhibit relatively higher manufacturing requirements (i.e. higher embodied energy) [16, 17].

In this context, an increasing number of voices calls for the importance of demand-side solutions in climate mitigation [18, 19], in a way that reduces disparities and improves the lives of the poor households [20].

We need to find a better way to modernize the provision of energy services with more accessible, efficient, and cleaner appliances. Previous research has focused on quantifying energy requirements from normatively defined services [e.g. 14, 21] and changes in access to services driven by rising incomes [9]. However, these analyses assume no technological change by 2050. There is no investigation of the contribution of new social and technological innovations that perform multiple services (e.g. TVs and radios replaced by smartphones) or serve multiple people (e.g. thermal equipment shared at the building level) that can improve access to modern services and lower energy demands.

New business models are emerging based on technological and social innovations, most often digitally enabled, that can change the way goods and services are provided [22]. In terms of transforming the production and use of consumer goods that provide important energy services, two particularly promising trends are digital convergence and the sharing economy.

Digital convergence refers to the tendency of standalone devices to converge into multifunctional equivalents that provide multiple services [23]. The typical example is the smartphone, which converged previously unrelated technologies such as the telephone, television, and computer [24]. Smartphones (and apps) can substitute at least 17 devices, from alarm clocks to GPSs and radios, with 30 times less power in use and 100 times less power in standby [3]. Even the basic mobile phone (feature phone) achieved an unprecedent speed of diffusion, becoming the most democratic technology in less than two decades [25]. These highly efficient devices have provided access not only to communication, but also to a wide range of services such as financial transactions in a developing context [26].

The *sharing economy* denotes multiple people using an otherwise underutilized good, such as cars, homes, or devices, as opposed to individual ownership. Digitalization has helped to up-scale the local sharing initiatives. In large scale, the sharing practice could significantly reduce the number of physical goods without loss of consumer welfare [27]. In the U.S., for example, 36% of the population reported the use of ridesharing services regularly in 2021, compared to 15% in 2015 [28]. In 2016, ridesharing apps displaced the sales of roughly two million cars worldwide, particularly in China (960 000) and India (540 000) [28]. Collective living or working makes people more likely to share more amenities, such as lighting, space heating/cooling, and appliances. Previous research shows evidence that collective living reduces emissions by an average of 0.3 tCO_2eq/cap per year [29]. Finally, several types of devices are increasingly being shared at building or community level. For example, shared laundry rooms are common in multifamily buildings in North America, and increasingly in other parts of the world too, with an estimated reduction in greenhouse gas (GHG) emissions of 26% [30]. Shared devices can run more efficiently at the lowest energy consumption and operational cost [29]. By reducing the number of devices through collective use, sharing also has the potential to reduce the embodied energy associated with avoidable goods [27]. Therefore, moving from owning to sharing presents several benefits such as more intensive use, minimizing waste (circular economy), and reducing material needs (dematerialization).

Both digital convergence and the sharing economy can help to significantly reduce the number of consumer goods required to meet the same needs. They open promising avenues to lower both the energy demand and the material consumption from appliances—provided that the impacts on direct energy/materials use and rebounds remain limited compared to the potential on enhancing efficiency and structural change [16, 31]. More importantly, digital convergence and sharing could make services cheaper, enabling widespread access to the modern services provided by consumer goods (entertainment, communication, etc), particularly for the more deprived population in developing countries.

This paper advances in the need to understand the effects of digitalization on climate mitigation [32, 33].

It does so by examining the effects of digitally enabled innovations such as digital convergence and sharing. The paper illustrates the potential of these innovations to improve standards of living and limit the raise in emissions in consumer goods—a category often overlooked in the analysis of energy and climate change. In particular, the impacts of digital convergence have only been estimated in Grubler *et al* [3], but at more aggregated level and not clearly autonomized.

The rest of the paper evolves as follows. Section 2 presents the empirical approach of this study. Section 3 shows the results and the societal benefits. Section 4 concludes with the main implications of the results, limitations and remaining questions for future research.

2. Methods

To estimate the impact of digital convergence and the sharing economy on providing decent living standards (DLSs) in the Global South and reducing energy and materials needs, we employ a mixed-methods approach. Here we describe more in detail the procedures, techniques and validations followed in this research.

2.1. Data sources and collection

We consider a wide range of consumer goods across different categories and domains of application. To estimate the stock of appliances and energy demand in 2020, we depart from existing projections in the Global Energy Assessment (GEA) [34] and the LED study [3], an influential and highly detailed scenario for decarbonization, including an explicit representation of consumer goods. We have enlarged the sample of goods and validated the estimates based on micro-level data from national representative statistics and household surveys [e.g. 35, 36], meta-analysis [e.g. 9], available datasets from international organizations [e.g. 37, 38] and peer-reviewed studies [e.g. 39].

To achieve a finer-grained categorization of consumer goods, we distinguish demand from residential and non-residential (commercial and services) sectors. In addition, we consider a broader range of consumer goods, comprised in several categories: hygiene (e.g. hot water, washing machine); food preparation (e.g. refrigerator, electric stove); communication & entertainment (e.g. mobile phone, television, personal computer); lighting (all types of lamps), thermal demand (e.g. fan, portable air conditioner), and miscellaneous (mainly small electric load devices, e.g. set-top boxes, routers, smart speakers). See table S1 in supplementary information (SI) for a detailed description of the categories and sources used.

To achieve a better representation of the regional diversity in the use of consumer goods, we expand the spatial resolution from two regions (Global North and Global South), used in the previous studies such as GEA and LED, to 11 regions. We follow the regional disaggregation of the world into 11 broad regions as defined in the MESSAGE model[2], resembling the classification commonly used by international organizations, including: Sub-Saharan Africa (SSA), Centrally Planned Asia and China (CPA), Central and Eastern Europe, Former Soviet Union, Latin America and the Caribbean (LAM), Middle East and North Africa (MEA), North America, Pacific OECD, Other Pacific Asia (PAS), South Asia (SAS) and Western Europe.

2.2. Modeling the demand, energy use and materials consumption of appliances

We estimate the energy demand from consumer goods through a Kaya equation, adapted to the analysis of appliances, following well-established practices in the field [40]. More specifically, for each year under consideration, we use the following disaggregation method by major group of appliances (i) and region (j):

$$\text{Energy demand (TWh)}_{ij} = \sum_{ij} h_j . \frac{n_j}{h_j} . \frac{u_i . W_i}{n_i} \qquad (1)$$

whereas, energy demand is explained in terms of the changes in the evolution of activity and intensity. Activity is represented by the change in the number of consumer goods (n) or in the number of devices per household ($\frac{n}{h}$) times the number of households (h). Thus, alterations in activity can have two main sources: 'Demographic' for changes in the number of households (h), which in turn can evolve through alterations in the population (p) or in the average number of people per household (h' where $h = p/h'$); and a behavioral component 'ownership' for changes in the average number of devices per household (n/h). On the other hand, intensity is represented by the change in the energy consumption per appliance. Intensity can further be decomposed into two main terms: 'usage' (or load factor) for changes in the annual number of hours of use per device (u); and 'efficiency' for changes in the average power (or wattage) of the appliances (W).

In practice, we estimate the future demand of devices (activity) by category of consumer goods based on the per capita income in 2050. Income is a well-known driver of demand for appliances [4]. On the other hand, we empirically observe a high correlation between the current ownership of applications (i.e. number of devices per 100 persons) and the GDP per capita of the different regions in the world (R^2 = 92% of the simple bivariate model fit as reported in SI, section 3.1). Therefore, we compute the demand of appliances for each of the 11 regions, separately. This procedure takes into account

[2] https://iiasa.ac.at/web/home/research/researchPrograms/Energy/MESSAGE-model-regions.en.html (last access 17 February 2023).

the regional differences in the per capita income, which is more consistent with the conceptual and empirical evidence. We use the projections for GDP and population in 2020 and 2050 that are available in the IPCC's shared socioeconomic pathways (SSPs) database [41–45]. (See a detailed explanation of the estimation in the SI, section 3.1 and appendix 2.) We model eventual saturation effects separately, as described in the presentation of the demand generator.

The base projections consider the trends observed in energy intensity over time. We revise the estimates for the energy efficiency of appliances in 2020 that were made in LED [3] and in GEA [34] based on the most recent evidence. Data is available for several types of appliances particularly in Europe and Japan [e.g. 15, 46]. In addition, we assume the same improvements in the energy efficiency of appliances between 2020 and 2050 as in LED that have been widely scrutinized and accepted.

We model the technological changes in appliances induced by digital convergence and the sharing economy through (narrative-driven) alterations in activity and intensity that translate the structural changes. Structural effects deal with the changes in energy demand from service provision that come from the substitution of consumer goods like analogue by digital appliances with functional convergence (e.g. shift from radio set to sound system to smartphone), as opposed to efficiency improvement (e.g. better radios, better sound systems). More specifically, we model structural effects through the changes in the preferences of consumers in relation to 'ownership' (number of devices per household or n/h) and 'usage' (load factor or u) of consumer goods. We elaborate more on the estimation of the effects of the structural change in the section 2.3 'Demand generator'.

Finally, we analyze the effects of the demand of appliances on material requirements in terms of both the total stock of materials and the annual material flows. Material stocks refer to the inputs that are necessary to produce the entire number of appliances in use at each moment. To estimate the material impact of appliances especially in 2050 that is very uncertain, we use the robust relationships found between the weight and the wattage ($R^2 = 52\%$), as well as between the weight and the volume of appliances ($R^2 = 85\%$), for a sample of representative devices of each type of appliances (see figure S6 in SI). Based on these strong correlations and on the evolution of efficiency and wattage, we derive the impact on material needs. For example, for the material weight, we use the correlation to estimate the average weights per type of device, by region; Then we multiply these coefficients of 'material intensity' by the stock of devices (per appliance and per region) to obtain the total weight of the material requirements.

Annual material requirements refer to the quantity of inputs needed to produce the new devices that both satisfy the new demand and substitute the old ones arriving to the end of the lifetime. We estimate the annual flows based on the total material requirements (as calculated in the previous step) and well-established estimates of the economic lifespan of the appliances that are obtained from the literature (see SI, table S2, for more details on the assumptions concerning the lifetime of devices).

We further compute the effect of the demand of devices on the main materials. The shares of the main materials (steel, aluminum and plastics) come from the analysis of the bill of materials of typical products that are provided by the manufacturers, following common practices in the literature [e.g. 16, 17, 47, 48]. In addition, we calculate the embodied energy of the appliances. This includes the energy required for raw materials extraction and for manufacturing, while excluding transportation. For that, we base our calculations on the estimates per type of technology that are available in the literature (see the inputs used in the material analysis in the SI, appendix 4).

2.3. Demand generator

We develop a demand generator with parameterizable key inputs to simulate the demand of consumer devices. The analysis allows the estimation of the effects of the change in different variables to reduce energy demand and materials consumptions from consumer goods, between 2020 and 2050, thanks to a new interactive Excel-based spreadsheet (see more details in the SI, appendix 5).

The spreadsheet includes an interface in which users can parameterize the main variables affecting the future demand of consumer goods. The interface allows to setting up assumptions for the Global North and the Global South separately, given the different dynamics of demand undergoing in these regions. Users can change the assumptions concerning the main aggregated variables affecting demand (activity) such as population, mean household size and income (GDP per capita). Concerning the latter, they have further the option to set a rate of decoupling between the growth of GDP per capita and demand for appliances to account for eventual effects of saturation.

More specific parameters concerning normative, behavioral and technological change are also customizable. The interface enables the parameterization of DLS in terms of the number of devices per capita (or by household depending on the nature of the appliance). Users can also define the maximum potential for digital convergence and sharing to reduce the number of devices and lower their energy intensity, in both the residential and commercial sector. As for sharing, in particular, users can additionally define different assumptions for key demographic variables such as the weight of urban population in 2050 or the share of population below 30 and above 65 living in shared spaces (co-living) in the year 2050.

Energy intensity and material intensity are both realistic and adjustable. We assume improvements in energy efficiency of 2.6% a year in the Global North and 3% in the Global South. These rates are close to the efficiency improvements of 2% a year observed in appliances over the past two decades [15], and less stringent than the 4% a year assumed in the Net Zero Scenario of IEA for the period between 2020 and 2030 [49, 50]. Users can therefore set higher (lower) efficiency improvements to compensate for a lower (higher) assumptions concerning the number of devices saved through digital convergence or sharing.

Finally, users can adjust several assumptions concerning the variables affecting material intensity. These include general parameters, such as the rate of decoupling of materials consumptions growth and respectively population growth and GDP growth. It also includes the possibility of adjusting specific variables concerning the annual rhythm of dematerialization (more specifically, the reduction of material weight per devices' wattage) or the lifetime of appliances. The spreadsheet can be provided upon request and reasonable justification.

3. Results

3.1. Demand of devices

We simulate the effects of digital convergence and sharing in promoting widespread access to consumer goods and reducing energy demand (see section 2 and SI for all calculations, assumptions, and data sources). Our analysis departs from the LED scenario [3]. Departing from such a scenario turns the reduction of the energy demand from consumer goods more challenging, even if LED estimates their final energy demand will increase 15% in 2050. We updated the estimates for the stock of appliances in 2020 with real data, taking more device categories into account (see SI, section 3.1). We also adjusted the projections for the number of appliances in 2050 by calibrating with the differences in per capita income among 11 regions (idem). This allowed a better estimation of the number of appliances in 2050 at 191 billion (+177% from 2020). These appliances would use roughly 13 000 TWh, assuming trends in efficiency improvement similar to those in the LED scenario.

We estimate the number of devices needed to provide DLS for all. This would require 8 billion devices in addition to the base estimate for 2050, distributed among the Global South regions as shown in figure 1. The most needed appliances are for food preparation (stoves, ovens) and thermal comfort (portable air conditioners). The regions with the greatest needs are SSA, SAS, and LAM, where half of the world population is expected to live in 2050 (figure 2). The needs of appliances vary with the region, from those for which scarcity is distributed across all categories (e.g. SSA) to those regions for which the need is more concentrated on thermal and food preparation (e.g. Other PAS) (figure 1).

3.2. Effects on energy and materials demand

Figure 3 show the effects of digital convergence and sharing on appliance numbers and energy demand. Digital convergence reduces the global number of devices in a way that more than compensates for the impact of providing enough energy services (lighting, communication, etc) to ensure DLS for all in 2050 (figure 3, top panel). Digital convergence also partially mitigates the estimated growth in the number of devices from 2020 to 2050, and sharing further reduces the number of devices in use in 2050. Overall, digital convergence and sharing limit the growth in the number of devices to 135% (instead of 177% in the base estimate for 2050).

Sharing devices has double the effect of digital convergence on lowering energy demand (figure 3, left-hand panel). Sharing devices such as washing machines and electric ovens instead of owning them increases the efficiency of providing services such as laundry washing or food preparation several times over. In fact, despite their higher energy intensity (which is assumed to double, at least), shared appliances replace several individually owned devices. As a result, sharing has a greater effect than digital convergence on reducing the energy demand per service provided. Overall, sharing and digital convergence together mean that a higher number of devices in operation in 2050 use 28% less energy than in 2020.

Sharing and digital convergence reduce the material needs of consumer goods. Compared with the levels in 2020, they lower the total material use by 21% in 2050 (figure 3, right-hand panel). This reduces the annual replacement flux by 34%, to 33 million tons in 2050, and embodied energy by 38%, to 2784 TJ (see the SI, sections 6 and 7, for analysis of the material impacts). Additional solutions can reduce the material requirements of consumer goods even further. Extending goods' average lifetime by 25% (i.e. one extra year every fourth year of lifetime) would reduce annual replacement flux by 47% (13 percentage points more), *ceteris paribus*. Similarly, reducing the weight of devices by another third lowers annual replacement flux in 2050 by 53% (roughly 20 percentage points more). These solutions could amplify the benefits of digital convergence and sharing in lowering the cost and carbon emissions of devices. Higher reductions in the number of devices are related to more savings in materials and energy, especially for larger regions (figure 3, down panels).

3.3. Socioeconomic gains with environmental co-benefits

How do digital-enabled innovations provide benefits to society, including widespread access to appliances and climate mitigation? Digital convergence and

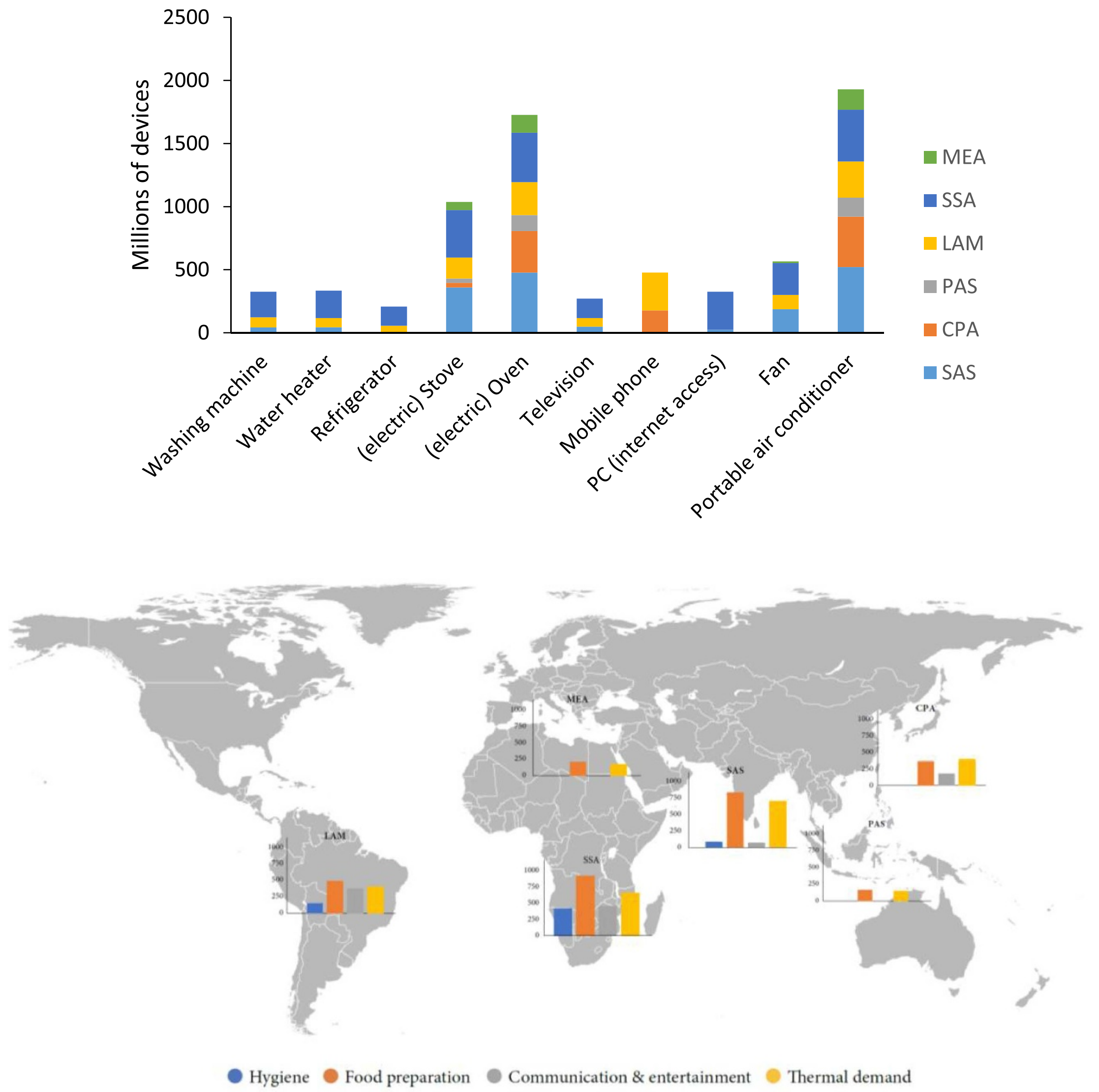

Figure 1. Number of devices needed to ensure decent living standards (DLS) in 2050 by regions of the Global South, in millions. Regions shown comprise Sub-Saharan Africa (SSA), Centrally Planned Asia and China (CPA), Latin America and the Caribbean (LAM), Middle East and North Africa (MEA), Other Pacific Asia (PAS), and South Asia (SAS). The different categories of devices are: hygiene (washing machine, water heater); food preparation (refrigerator, electric stove; electric oven); communication, entertainment & productivity (television, mobile phone, PC); thermal demand (fan, portable air conditioner). The graph below shows the breakdown of devices by regions, in million units.

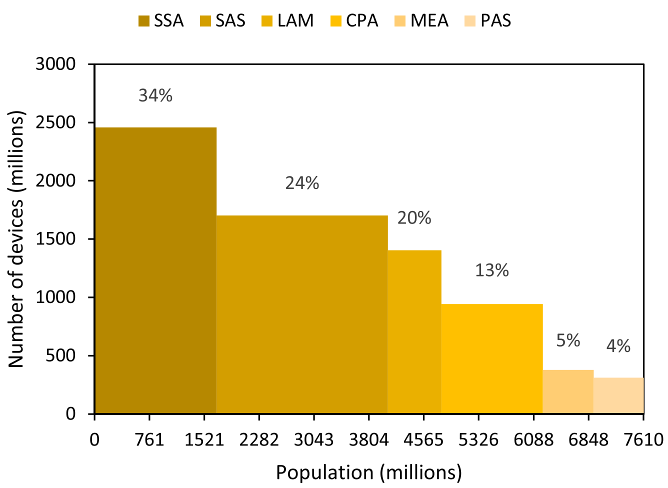

Figure 2. Number of devices needed to ensure decent living standards (DLS) in 2050 by regions of the Global South, in millions.

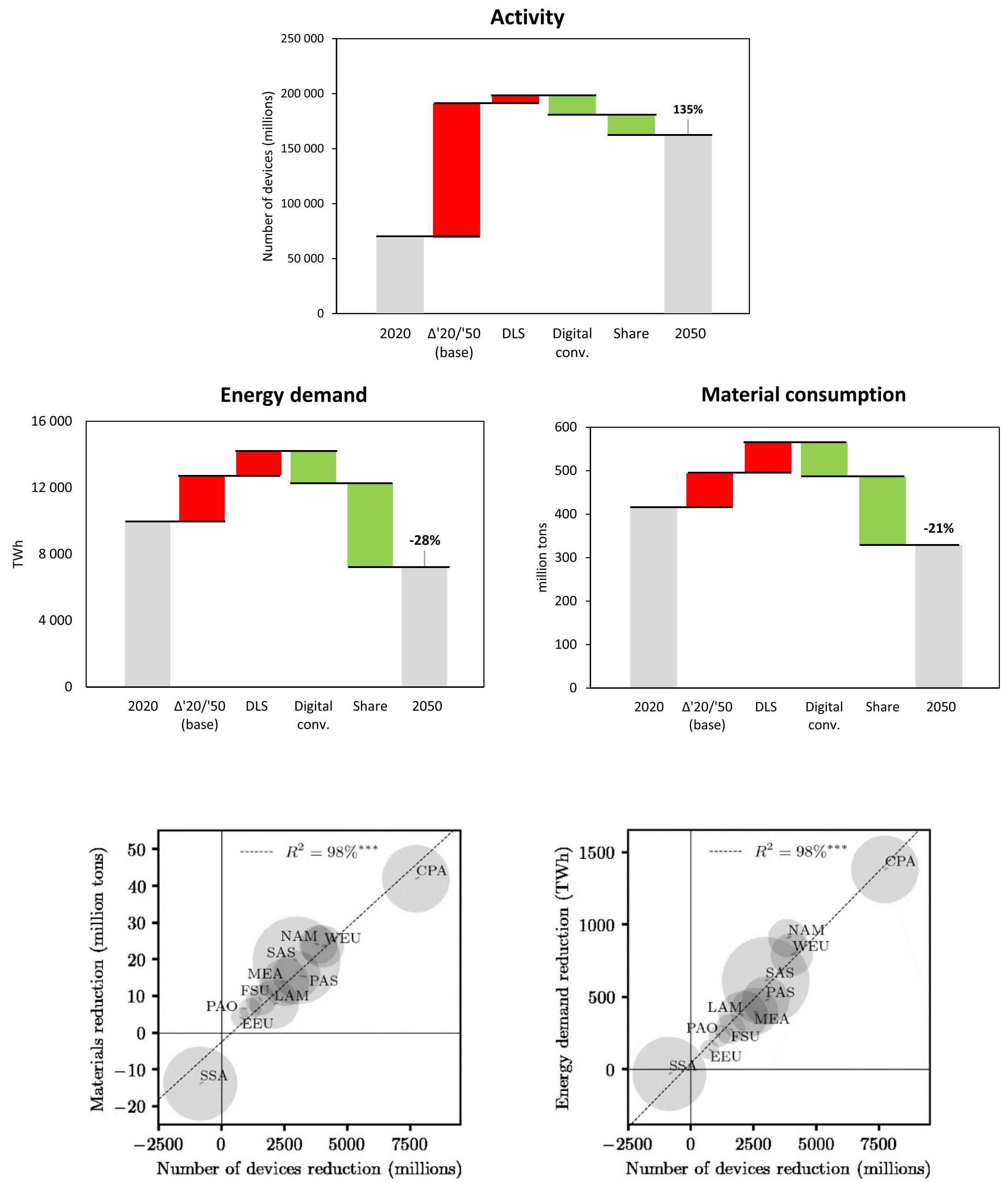

Figure 3. Effects of DLS, digital convergence, and sharing on the number of appliances, energy demand and material consumption from appliances in 2050 (top), and bivariate relation between activity and dematerialization (down-left) and activity and energy demand (down-right), by region. The size of the points is proportional to the population in each region.

sharing improve access to essential services provided by appliances (e.g. food preparation, communication, entertainment). On the one hand, digitally convergent innovations such as smartphones make several standalone devices redundant (e.g. alarm clocks, GPSs, pocket torches). On the other hand, sharing instead of owning lowers the barriers to low-income families accessing larger and more expensive devices such as washing machines, water heaters, or refrigerators. Under the scenario outlined here, there are 8 billion more devices (+6%) in the Global South than in the base case. By 2050, the number of devices per capita in the Global South increases by +200% to 16, narrowing the gap with the Global North.

Digital convergence and sharing make the widespread of DLS more feasible and accessible. We estimate that digital convergence and sharing together would save 29 billion devices (−15%) by 2050, corresponding to a saving of 9 trillion US dollars (−39%) at current prices.

New production practices and the use of more efficient appliances have positive effects on the environment. Compared to the base estimate, direct energy demand is reduced by 5547 TWh (−44%) by

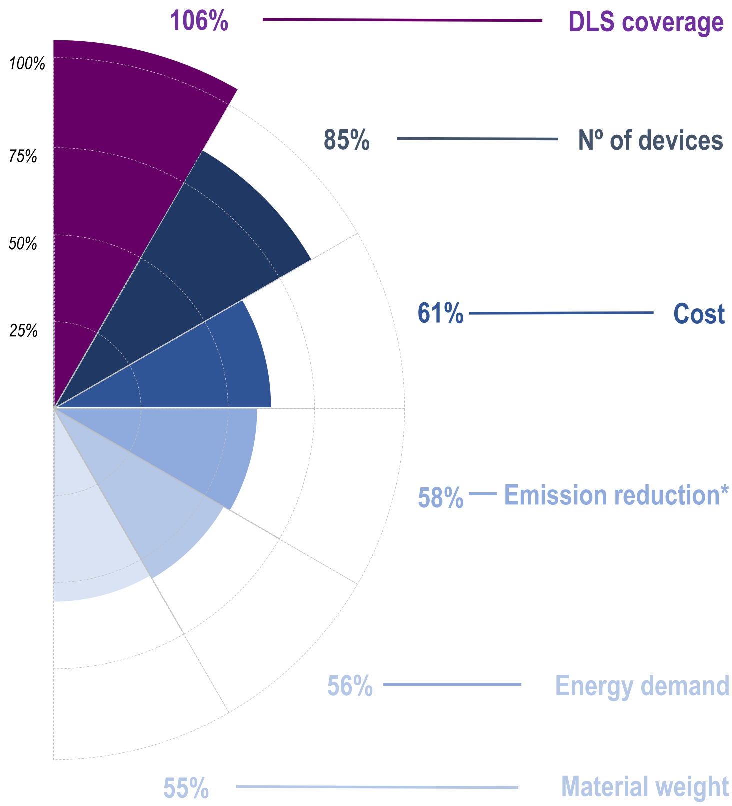

Figure 4. Social gains of digital convergence and sharing in appliances with decent living standards, in comparison with the base estimate for 2050. Index (100 = base estimate). Lower is better, except for DLS coverage, for which a higher value represents more social benefits. (* in relation to the emissions in 2020 and calculated by using the regional carbon intensities of electricity for that year).

2050 (cutting 42% of GHG from consumer goods in relation to the levels in 2020). In addition, annual material consumption falls by 45% to 33 million tons/annum. Figure 4 summarizes the social gains of digital convergence and sharing in appliances.

4. Conclusions

Consumer goods are increasing energy demand and contributing to further augment the share of household consumption in global GHG that is already responsible for more than 60% of emissions [51, 52]. This increase has been accelerated by the effect of the rising incomes in developing countries, more recently. Digitally-enabled innovations that enhance functional convergence and the sharing economy have the potential to raise the standards of living in low income countries without increasing the pressures in the environment. The analysis shows mechanisms, such as social and technological innovations, that can promote development and reduce GHG emissions. The effects of these mechanisms had not yet been studied in the literature [9], which has focused more on other factors such as the role of income in reducing emissions in the Kuznets Environmental Curve [53, 54].

These results have significant implications for policymakers. They demonstrate that there is a better way to organize the delivery of modern energy services—one that provides access to consumer goods more rapidly and efficiently, and at a lower cost. This shows once more the benefits of more granular approaches to climate mitigation [55, 56]. Public policy could tap into the opportunities opened by digital convergence and sharing by ratcheting up efficiency standards—especially in the Global South. Policymakers could also address more specific obstacles to the growth of sharing economies (e.g. promote the use of shared equipment in buildings) or of innovations in digital convergence (e.g. reinforcing electricity reliability; promoting affordable high-speed digital connectivity; enabling the dissemination of multi-functional equipment such as smartphones or tablets to replace small and large devices like TVs).

This analysis opens new perspectives for future research. Our approach builds on trends observed in consumer goods and estimates the effects of their dissemination. Future research could shed more light on the technological changes expected in appliances. Particularly, it could identify the full range of digitally convergent and sharing innovations that will be available in the short term. In addition, this study shows that improving the life of the most deprived does not lead necessarily to higher carbon emissions, relativizing previous results [e.g. 57]. It also illustrates the potential of granular demand-side innovations to improve quality of life and mitigate climate change, applied to consumer goods, in line with recent results [e.g. 58–60]. Future work could extend this analysis to other sectors (e.g. mobility, industry), as well as investigate the effect of the impact of disparities on the access to DLS.

A current debate questions the effect of digitalization on the growth of consumption, as well as of information and communication technologies (ICT) emissions and its part of global GHG emissions [e.g. 31]. The ICT's share of emissions is estimated between 1.8% and 3.9% [16]. Some studies emphasize the role of efficiency improvements in stabilizing the emissions from user devices, networks and data centers, and link ICT emissions to the number of users which will naturally saturate [25, 61, 62]. Others project that ICT emissions will increase as a result of slowing down efficiency improvements (as Moore's law reach physical limits) in network and data centers, as well as estimate a growing embodied energy associated with the dissemination of devices (including IoT) [63, 64]. However, these emissions should be compared with the ICT impacts on the rest of the economy. ICT will enable carbon savings in other sectors [65, 66], but some authors argue that it can increase global emissions as efficiency gains will lead to consumption rebounds and growth in other sectors (Jevons' paradox) ([67], see [68] for a critique of this argument). Overall, large uncertainty remains on the net effect of ICT on climate change. Similarly, new forms of deregulation or of promoting conspicuous consumption (e.g. some houses or rides schemes are more commercial exploitation than sharing) may limit the potential of sharing economies to improve sustainability [27, 69]. Other factors can limit the dissemination of sharing (e.g. a lower propensity of sharing in more affluent users [70]) or restrain the effect of sharing on reducing energy and materials demand through rebounds in consumption (income effect) or production (higher turnover of the shared products [71]). More research is needed to understand the extent of these effects in appliances. The role of social and technological innovations such as digitally-enabled functional convergence and sharing economy is relevant in these debates as they can increase the direct use of energy and materials, but also open promising avenues to significantly decrease global GHG emissions and to democratize the access to essential goods and services.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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ORCID iD

Nuno Bento https://orcid.org/0000-0002-5923-0666

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