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POLICY ANALYSIS

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Greenhouse Gas Emissions from the Consumption of Electric and Electronic Equipment by Norwegian Households

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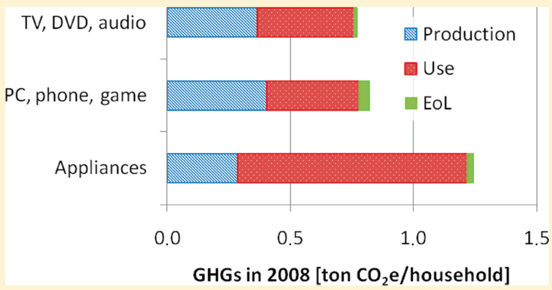
S Supporting Information

ABSTRACT: The number of electric and electronic equipment (EEE) owned by households has multiplied in the recent decade. We investigate the climate implications of the purchase, use and disposal of EEE by Norwegian households in 2008. While traditionally, large electric appliances such as washing machines, dryers, refrigerators and freezers have been responsible for most of the electricity use in households apart from heating and hot water, our results indicate that computers, TV sets and other electronic equipment are of comparable importance in terms of life-cycle greenhouse gas (GHG) emissions. For this electronic equipment, the GHG emissions caused by manufacturing are equal to or larger than those caused by their electricity use in operation. The production of EEE purchased in 2008 caused on average 1.2 t CO_2e ($\stackrel{\times}{\div}$ 2) per household. The electricity consumption for the use of EEE in 2008 caused between 0.15 and 1.7 t per household, assuming a Norwegian and an EU electricity mix, respectively. Telecoms networks and TV content caused between 0.13 and 0.3 t per household. The purchase rate of electronic products indicates that these products are replaced or down-cycled much more frequently than necessary based on their technical life span. To reduce the carbon footprint of EEE in Norwegian households, the rate of acquisition of new TVs and PCs needs to be reduced and the energy consumption in the production of these products needs to be addressed.



INTRODUCTION

The energy use and environmental impacts of household electric and electronic equipment (EEE) have been a continuous concern of energy analysts and environmental policy makers. Energy use of EEE constitutes an important portion of the total household energy use and has been the focus of numerous efficiency improvement strategies. Waste electric and electronic equipment (WEEE) contains precious but also toxic materials.[1] Waste handling and recycling is hence subject to regulation and informal recycling in developing countries is a concern. As a result of rapid technical development and product innovation, new environmental and resource issues are likely to arise as the consumption of electronic equipment rises rapidly around the world. The greenhouse gas (GHG) emissions of EEE are difficult to determine empirically, because the production of EEE draw on inputs from many suppliers across global value chains and equipment producers publish little verifiable data on the emissions, and because consumption is not specifically metered and usage patterns may differ significantly from technical lifetimes often assumed in life-cycle assessment (LCA). In this paper, we investigate the GHG emissions associated with the acquisition, use and disposal of EEE by Norwegian households in 2008. The paper presents novel insights about the relative importance of different product categories and the importance of production compared to the use and disposal of these products.

Conventional wisdom holds that large appliances, in particular washers, dryers, refrigerators and freezers, dominate residential energy consumption apart from heat, hot water and light.[2] It also holds that the use-phase is far more important than other life-cycle stages, to the degree that these other stages can easily be neglected.[3] This conventional wisdom is based on studies conducted in the 1980s and 1990s. Given the rapid proliferation of small appliances and new electronic products, it is time to investigate whether this conventional wisdom still holds. We do so using Norway as a case study, because relatively good data on energy use, appliance purchases and ownership are available.

In 1989, Tyler and Schipper[4] found that space heating was the dominant end-use of electricity in Scandinavia and electronics and small appliances were relatively unimportant, echoing similar findings all over the world. Since then, two divergent trends have influenced electricity use. On the one hand, efficiency improvements have probably stabilized electricity used for space and water heating in spite of rising floor space.[2] Labels and standards have helped to reduce use and stand-by consumption per unit of service. On the other hand, electronic equipment ownership has multiplied and service delivered, in terms of heated square meters and refrigerated liters, has increased.[5] Aside from the traditional refrigerator, washing machine and TV set, households now own a microwave, espresso machine, DVD, blue ray, MP3, game

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console, and even LCD photo frames or a fake fire place. Sanchez et al.[6] are widely credited for identifying the rise of the previously neglected "miscellaneous" category, and an important response has been the reduction of the stand-by consumption of electricity. Moreover, as technology changes continuously, replacement of equipment tends to accelerate[7] and consumers tend to waste instead of fix.[8,9] Williams[10] showed that desktop computers had a high energy consumption in the production phase, a finding confirmed by other studies.[11] Recent legislation such as the EU's WEEE and Ecodesign directive, as well as the REMODECE measurement campaign[12] show the rising concern in Europe about the life-cycle impact of what the EU calls energy-using products (EuPs).

EEE is investigated in several studies dealing with household's consumption and household's carbon footprint. Based on bottom-up market oriented LCA calculations, Labouze et al.[13] the GHG emissions due to EEE in Europe to be 0.8 tCO_2/capita/year, based on 1999 economic data and 2001 technology data, corresponding to 9% of the total household carbon footprint. Top-down studies find a share close to 10%.[14,15]

MATERIALS AND METHODS

This study addresses the average Norwegian household's consumption of white goods, brown goods, information and communication equipment, small appliances, and electronic games - categories 1,2,3,4 and 8 in the Norwegian electric and electronic products registry.[16] It excludes lighting, all professional equipment, space heating, hot water, garden or car equipment, fire alarms, and air conditioning. The study addresses the purchase of such products in 2008 and the energy use by such products owned in 2008, and the end-of-life impact of products disposed in 2008. It hence provides a snapshot of the life-cycle energy use – not the life-cycle energy use of products purchased in 2008, which would be harder to estimate as we do not know how long these products will be used. The calculation scheme is displayed in the Supporting Information (Figure S1).

Sales, Ownership, and Disposal Data. This data was obtained from EE-registeret[16] and the EEE[17] and ICT trade associations.[18] For PCs and periphery, some of the equipment is used by companies, but no data on the split between office and home was available for 2008. We assumed a 50% ownership of peripheral equipment by households reflecting numbers for France.[19] IKT Norge[18] provides breakdown for earlier year (2001, 2002, 2003) on professional and home computer. On average 34% of desktop computers were sold to households, which is the chosen ratio. Laptops were assigned to households. Estimates of purchases of computer peripherals are based on ownership rate ratio between peripherals and computer, assuming the same lifetime. The ownership and purchase rates used are indicated in the Supporting Information (Table S1).

Emissions Associated with the Purchase of EEE. Data on the GHG emissions associated with the production and distribution of products from LCA studies, environmental product declarations, and input-output calculations were collected for each product. Calculations on a per product and per kg of product basis were utilized. Reviewed studies include those from producers,[20−23] from EuP reports[24] for cold appliances,[25] dishwashers and washing machines,[26] laundry dryers,[27] computer,[28] imaging equipment,[24] TV set,[29] vacuum cleaner, from the EcoInvent database,[30] or from independent studies.[31−38] The number of studies utilized is listed in Supporting Information Table S2. For some products, we performed our own calculations using the available Ecoreport tool and the bills of materials[39] and waste composition per category.[40] Input-output LCAs were mostly used for comparison and to help select among product LCA data available. For these studies, product price data from bizrate.com, homeeverything.com, and ajmadison.com was discounted to 2002 using the US consumer price index and combined with the U.S. input-output table[41,42] and a modified Norwegian input-output table.[43] The results were then multiplied with sale of products, taken from ref 16 (in tons, no product specific distribution) and sales association data (in pieces, no size information).[17,18] This enables us to take into account the wide range of different technologies and products and to address size effects when LCA studies consider smaller products than what is usually sold.

Emissions Associated with the Use of EEE. The use phase is evaluated taking into account both direct electricity use and indirect impacts, related to services as telecommunication infrastructure and broadcasting. Electricity use per appliance is derived from the ownership rate of appliances and the energy use for different appliance types. Ownership (Supporting Information Table S1) is obtained directly from the REMODECE campaign report (Norway-specific when available[44] and EU as default[12]) or from Statistics Norway.[45] This ownership is then multiplied by average electricity consumption per appliance taken from REMODECE studies or results from an econometric model.[46] Country specific values were always favored as important differences were found between average Europe and Norway (higher replacement rate and bigger appliances but more eco-efficient) as highlighted in the REMODECE campaign measurement reports.[12,44] Our result in terms of total kWh per household per year was compared to REMODECE results, as well as measures of energy use in kWh/m^2 ratio for EEE used in building energy calculations. Final global warming impact is then estimated by using GHG emissions of three different electricity mixes that can legitimately be used for Norway: the Norwegian consumption mix (0.05 kg CO_2e/kWh), Nordic Production mix (0.21) and European mix (0.56) at low voltage including transmission losses.[47] Impacts from telephone and data (telecoms) network services and consumption of radio and TV content were derived from consumer expenditure 2006−2008[48] discounted back to 2002, converted into USD and inputted in US2002 Input-Output model corrected for electricity mix.

End-of-life impacts were calculated per kg waste in each category, using the amount (in tons) of discarded products in 2008. Basic handling impacts were calculated thanks to EcoInvent waste treatment processes.[49] When available, other sources have also been used, as producer data (Apple) or EuP studies. Collection, dismantling, shredding, incineration, and landfill process were taken into account, as well as some specific processes concerning batteries, cables, or LCDs.

RESULTS

In 2008, the purchase, use and disposal of EEE by the average Norwegian household caused between 1.5 and 3.1 t CO_2e (100y GWP), depending on the electricity mix assumed for the use phase (Figure 1), or 8 ± 3% of the total carbon footprint of these households. The CO_2 emissions associated with the electricity use dominate only when assuming European average electricity (see ToC art), otherwise the production of the equipment has the largest contribution to the total life-cycle CO_2 emissions.

Of the different equipment categories, refrigerators and freezers are the most important category when assuming an EU electricity mix, followed by TVs and broadcasting services, with more than 600 kg CO_2e each (Figure 2). Computers are the third most important category, with almost 500 kg. For electrical appliances (washing machines, refrigerators, cooking equipment), electricity use is the most important cause of GHG emissions, but

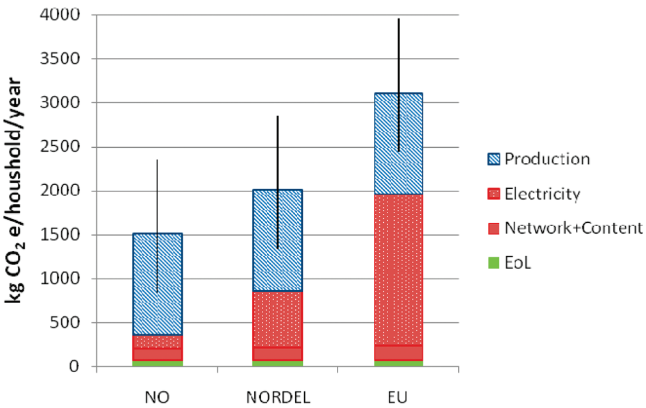

Figure 1. GHG emission associated with the consumption of electronic equipment by the average Norwegian household in 2008, depending on the electricity mix (Norwegian, Nordic grid, EU-average). The error bar indicates the uncertainty in production and end-of-life stages (from Tables 2–3).

for electronic products, emissions caused by the production is of equal or dominant importance. The end-of-life carbon footprint was found to be small (less than 5%), even if its share is expected to grow with a future increase in WEEE volume as a result of the increased input of products today.[1] It is not the GHG emissions that are of concern with WEEE, but the recovery of rare metals and toxic impacts in informal recycling operations.[1,50]

Given the importance of in-use electricity consumption especially for household appliances, the relative ranking of the different goods is strongly influenced by the GHG intensity of the electricity mix (Table 2). Given the fact that EEE is usually manufactured outside Norway with a region-specific electrcity mix assumed in the various studies, only the sensitivity of in-use electricity consumption to the regional electricity mix is investigated. With the Norwegian mix, freezers, refrigerators, washing machines, dish washers, tumble driers, and cooking appliances together account for only a quarter of the total GHG emissions from household EEE consumption, as much as the purchase, use and disposal of computers. A comparison of the present data with the study on environmental impacts of products (EIPRO) in the EU [51,52] shows marked differences.

When assuming an EU electricity mix, impacts from audiovisual equipment and PCs are significantly higher in Norway 2008 than in the EU average data presented in EIPRO (Table 2). Washing/drying equipment and telecommunications, on the other hand, is higher in EIPRO. Several factors may be at play here. One, the EIPRO study has combined several data sources and the date for which the results are representative is not provided in the study, but probably around the year 2000. PC and TV purchases have increased substantially since then. Two, there

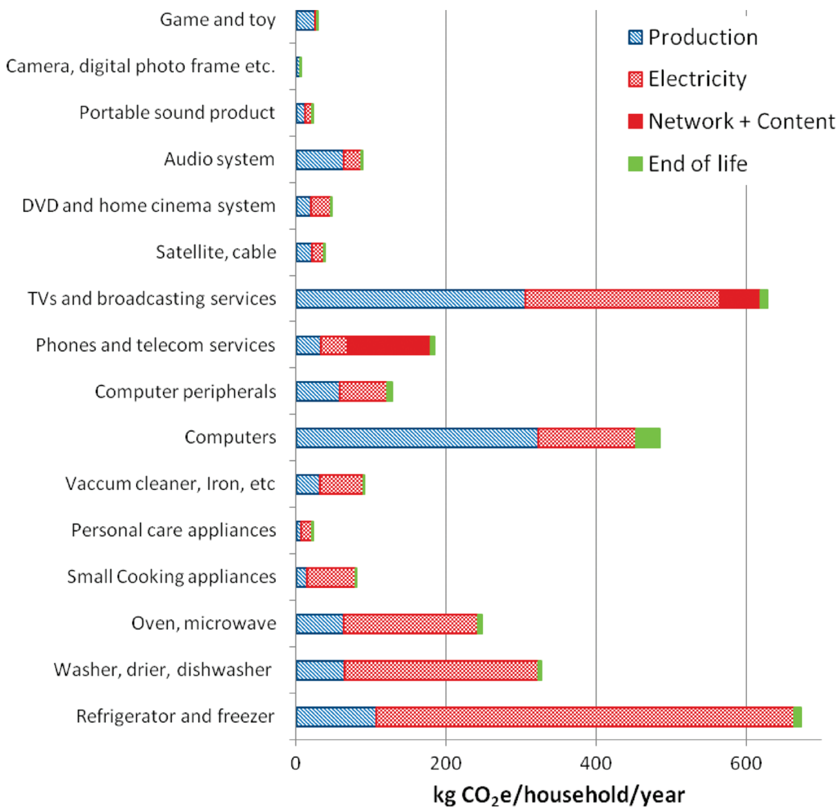

Figure 2. Greenhouse gas emissions caused by the consumption of different electric and electronic products by the average Norwegian household in 2008, assuming an EU-average electricity mix. Telecoms services include the Internet, while TV and broadcasting includes TV content.

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Table 1. Comparison of the total GHG Emissions Associated with the Consumption of Electric and Electronic Products and the Shares of Different Consumption Categories between This Study for Norway and the Results for the EU from EIPRO [51]

	this study		EIPRO
	Norwegian mix	EU mix	
audio-video-TV	35%	24%	14%
cold appliances	11%	22%	18%
computers	24%	16%	2%
wet appliances	6%	11%	24%
big cooking appliances	6%	8%	10%
telecommunications	6%	6%	15%
peripherals	6%	5%	2%
other small EEE	4%	5%	12%
vacuum cleaner, iron, etc.	2%	3%	2%
tCO_2e per person	0.7	1.4	1.0

are known difficulties in assigning electricity use to specific purposes, and different methods arrive at different results. The REMODECE results used in our work are from a measurement campaign conducted to resolve such differences. EIPRO used a UK study[53] as representative for the EU27. The differences in Table 1 can be explained by the higher turnover of equipment in Norwegian households, which results in more efficient appliances but a significantly higher impact from the production of the electronic products purchased.

In the following, we present more detailed results for the three main categories of EEE.

Large Appliances. The production of large appliances purchased causes 148 to 300 kg CO_2e on average per household and year, reflecting uncertainty in the LCA data for the production. The lowest values for cold appliances, washing machines and dryers are found in the EuP studies,[25−27] for the dishwasher in EcoInvent, and for cooking equipment in Jungbluth.[32] The highest values for cold appliances and washing machines are obtained using EcoInvent emissions intensities for electrical equipment times the weight of equipment sold. For cooking appliances it is based on own calculations with the EuP tool.[54] For reference, input-output calculations for these goods tend to show even higher carbon footprints. EuP studies indicate 4−6 kg CO_2/kg appliance. Rüdenauer[34] and EcoInvent report 8−10 kg CO_2/kg appliance for washing machines and cold appliances. For cooking equipment, Jungbluth reports 2.6 kg, while we obtain 4 and 6 kg from the EuP and input-output tools, respectively. Electricity use of Norwegian households is reported to be about 1000 kWh/y for cold appliances, 460 kWh/y for wet appliances, and 320 kWh/y for cooking, resulting in a total of 90−1000 kg CO_2e depending on the electricity mix assumed.

Information and Communication Technology. For the production of computers, telephones and other ICT equipment, we have found a significant range in the LCA results reported for each type of equipment. Using average numbers, we get ca. 380 kg CO_2e per household in 2008, which corresponds well to the numbers from assessing just the materials/components used in this equipment. The uncertainty range given the highest and lowest values obtained from different studies is, however, 130−860 kg CO_2e per household and year. Emissions from use-phase electricity are 18, 74, and 200 kg CO_2e for the Norwegian, Nordic

Table 2. Range of GHG Emissions Caused by the Consumption of Different ICT Items, Specifying Production, Use and Waste Treatment at the Level of Detail Calculated in This Study, in kg CO_2e per Household and Year

	low	average	high
cell phone production	12	29	35
cell phone use	1	5	15
telephone production	3	3	3
telephone use	2	8	21
monitor production	19	119	354
desktop production	1	19	104
desktop & monitor use	10	41	108
laptop production	57	158	290
laptop use	2	8	23
peripherals production	43	52	73
peripherals use	3	12	32
telecom network	127	139	164
eol	43	43	43
subtotal production	*135*	*380*	*859*
subtotal use	*145*	*213*	*363*
total	322	635	1264

and EU electricity mix. Emissions for end-of-life treatment of the equipment disposed in 2008 are estimated as 43 kg. The provision of telephone and data (telecoms) network services contributes in the range of 127−164 kg CO_2e.

The results per equipment type are specified in Table 2. Here, the low and high values for use come from the three electricity mixes, while for production they come from the range in results for underlying LCA studies found in the literature. The results show clearly that computers dominate the emissions both in production and use. The impacts from production are most likely larger than those from the use phase, even though the production and use of the telecoms networks clearly contributes significantly to the use-phase impacts in this category. Please note that results from the EuP study[28] and the underlying tool were not included in this presentation as they were found to be so low that we judged them to be not realistic, a judgment shared by.[11]

It is interesting to notice that impacts from telecom network services and TV licenses are higher than those of direct electricity use for both Norwegian and Nordic mix calculations. Similar findings have been made for mobile phone networks[37] and telecommunication infrastructure more generally.[35,55]

TV and Other Audiovisual Equipments. For audiovisual equipment, we see similar patterns as for ICT (Table 3). There is a wide range of results obtained from different sources. Production is even more dominant compared to electricity use, while radio and TV programs play a minor role. Overall, TV has the highest impact, but other devices cannot be neglected either. Please note that the calculations have been carried out on a more detailed level, distinguishing LCD and plasma screens, different receiver systems, video cameras, digital photo cameras, and frames.

■ DISCUSSION

This assessment of GHG emissions of EEE consumption is based on a wide range of disparate data source. Large uncertainty ranges reflect a limited quality of the underlying LCAs and a

Table 3. Detailed Carbon Footprint Results for Different Audiovisual Equipment, in kg CO_2e per Household and Year

	low	average	high
TV production	93	253	606
TV electricity use	23	97	260
video production	2	14	28
video electricity use	1	6	17
audio production	41	72	111
audio electricity use	3	12	33
other production	14	29	62
other electricity use	2	10	27
network/content use	43	46	54
end of life	6	14	26
subtotal production	*149*	*367*	*807*
subtotal use	*73*	*173*	*391*
total	227	553	1225

wide scope for improvements which need to be made in an open process by manufacturers, as discussed in the Supporting Information. Stopgap measures based on simplified methods such as the EU's EuP tool and studies may be valid for electric appliances but not for electronic products.

Andrae and Andersen[11] note that the lifetime of products is a significant source of uncertainty. In LCA, the lifetime is used to normalize the impacts from production and consumption to a functional unit of one year of TV or computer use. We did not use explicit lifetimes, as we assessed the production of the products purchased, the use of the products in possession, and the EoL of the products disposed in 2008. Present LCA studies have difficulty finding robust data on lifetime. First there is a definition issue as described by Babbitt[7] for PCs. Even when clearly defined, lifetime results conflict.[1,8,11,24−29,56,57] Some may be explained by country-specific behaviors and technology access, other by data aging due to rapid technology evolution.

We implicitly use a lifetime corresponding to purchase frequency. Our data shows that the average 2.2 person household buys a mobile phone every year, a laptop or PC every 1.9 years, a TV set every 3.5 years, a cold appliance every 6 years, a washing machine every 9 years, and a built-in oven every 12 years.

Contradicting conventional wisdom,[2,3,54] we find that EEE production causes a substantial part of the carbon footprint of energy using products. The rising importance of electronics manufacturing is connected to the rapid proliferation and accelerated turnover of a wide range of electronic products. The purchase rate of mobile phones and digital cameras doubled from 2001 to 2008, while Blue ray players, LCD picture frames, and digital TV tuners entered the market.[17] More important, however, is the doubling in the purchase rate of TVs, most likely caused by successive introduction and improvement of LCD and plasma screens. Trade statistics confirm a rising level of imports of electronic devices. A time series of Norway's trade evaluated with a multiregional input-output model[58] indicates that the GHG emissions embodied in the import of electronic products to Norway have increased from 0.96 $MtCO_2e$ in 1999 to 1.53 $MtCO_2e$ in 2008,[59] equivalent to the largest point source of emissions in Norway. The largest rise is in imports from China (see Supporting Information Figure S2). These high GHG emissions indicate the hidden environmental costs of rapid product innovation, high levels of affluence, and a dirty energy mix in producing countries.

Integrated product policy, that is, making producers responsible for the life-cycle impacts of the products they sell, has been the innovative policy response to this challenge. For EEE, the EU's Ecodesign directive has successfully focused the producers' attention on the energy use and stand-by use, leading to substantial increases in energy efficiency. Only recently has EU policy started to address production as part of a life cycle perspective. Developing reliable assessments is a necessary first step which has yet to be achieved, as our work shows. It may be advisible to challenge producers to provide data instead of developing estimates for them. In fact, drawing producers' attention to emissions in their value chain may already trigger actions to reduce those emissions through energy efficiency and a shift to clean energy sources. Finally, substantial impact reductions can be expected from slowing down the purchase frequency, for example, through product life extension, such as repairing products and avoiding replacement due to changing needs and fashions.[36] For the UK, Cooper has found that 33% of discarded household appliances were still functioning (and other 21% in needs of repair), with a special mention for ICT products, where 59% were still functioning.[9] News reports in Norwegian media suggest similar issues.

■ ASSOCIATED CONTENT

Supporting Information. Explanation of the calculation scheme, tables on equipment ownership and acquisition, as well as number of studies utilized per equipment, a time series of emission embodied in imports, and a discussion of uncertainty. This material is available free of charge via the Internet at http://pubs.acs.org.

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