Electricity consumption of network-connected devices in the residential sector in Germany

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Keywords
network-connected devices, upstream energy, common electricity, energy efficiency policy

Abstract
Digitalization in the residential sector is growing rapidly with the introduction of more smart devices and the development of the Internet of Things. To investigate the electricity consumption of household appliances from increasing network-connected devices, a bottom-up modelling approach is used. The FORECAST-Residential model by Fraunhofer ISI was developed to calculate the residential energy consumption based on of the Bass model in product growth and consumer purchases. The model is extended in this study to calculate upstream energy use, defined as the energy required by data centres and access network efficiency in transferring data. The electricity consumption of network-connected devices themselves is also extended in the model by distinguishing devices connected to the internet and determining the duration of their connected usage. The consumption of different operation states is investigated by further separating operation and standby usage into conventional and network-connected usage.

To determine the influence of different variables on the future development of energy consumption due to network-connected devices, several exploratory scenarios are simulated, covering policymaking, smart device purchases, user behaviour, and data centre efficiencies. The results show that the electricity consumption of devices can be strongly influenced by policies such as the European eco-design directive for household appliances. The conventional operation and network-connected standby consumption are the states with highest electricity consumption, consuming 73 % and 17 % of electricity in the year 2035 respectively. The other two investigated states: conventional standby and network-connected active consumed 6 % and 4 % respectively. Network-connected standby consumption is revealed to be the second most energy consumption mode due to standby mode of increasing smart devices labelled as being connected to the internet while on standby. Overall, the results indicate that the additional energy demand of network-connected devices and their upstream energy demand is relatively low. This reveals a large potential for smart devices to assist in achieving Germany's climate-neutrality target in the energy transition.

Introduction
According to the International Energy Agency (2021), in 2018 the electricity consumption of the residential sector in Germany amounted to 25 % of the overall sectoral final energy consumption. Although the energy efficiency of home devices has been significantly increased over the years, there has been significant growth of global plug-load devices, set-top boxes, tablets, and other connected devices being used (IEA, International Energy Agency, 2020). These devices are becoming responsible for an even bigger proportion of residential electricity consumption. According to the Bundesverband der Energie – Wasserwirtschaft. e.V. (2020), electronic and communication devices account for 17 % of electricity consumption in private households.

The rapid transformation of digitalization is partly due to the growing adoption of network-connected devices, particularly those that exist as part of the rising development of the

Internet of Things, more commonly known as "IoT". IoT or smart devices reflect the ability of devices to communicate between one another through transfer of data (Horwitz, 2019). IoT can be divided into two main categories: consumer IoT and Industrial IoT, where consumer IoT devices generally aim to improve consumers' daily lives, for example making them safer, healthier or simply more comfortable (Globally Cool B.V., 2021). The growth of digitalization and smart consumer devices may increase the number of centralized data centres (Altamira et al., 2019). The upstream energy demand of the devices and the applications which run on them, highly depends on further improvements in the efficiency of data centre infrastructure (Hintermann, R. & Hinterholzer, S., 2020, 2016; Garris, 2018).

Access network connect each subscriber to their immediate service provided (Breide et al., 2017). A study by Baliga et al. (2011), analysed the energy consumption of several wired and wireless access networks. They conclude that improvements in complementary metal oxide semiconductors (CMOS) and optical technology should lead to energy efficiency improvements in future network equipement generations. In addition, the study concludes that wireless technologies will continue to consume at least 10 times more power than wired technologies at comparable access rates and traffic volumes.

Moyer & Hughes (2012), investigated the impact of information and communication technologies (ICT) on global CO_2 emissions through a modelling platform which incorporated rebound effects, penetration rates via ICT diffusion forecasts, and scenario analysis. The study found that high ICT adoption has a generally positive potential to reduce carbon emissions via two paths: reduction in energy intensity and increased production of renewable energies.

Though market trends have inherent unpredictability, technological improvements in appliances and data centres with advanced energy efficiency play a large role in reducing total energy consumption of devices. Scenario analyses through energy modelling allows for better insight into uncertainties and provides a view of the impact of different developmental trends on the likely evolution of the energy system to inform decision-making (IRGC, 2015).

In this study, a bottom-up energy modelling approach is selected as it provides a high degree of technological detail to assess future energy demand (Herbst et al., 2012). Three research objectives are addressed by extending the existing bottom-up FORECAST-Residential model by Fraunhofer ISI (Elsland et al., 2013). First, upstream energy consumption of network-connected devices in the residential sector was investigated. The upstream energy refers to the combined energy of data centres and wide area network (WAN) that are involved in the transfer of data between connected devices. Secondly, the additional energy demand for appliances to remain network-connected is investigated. The two aforementioned demands are differentiated based on its boundary condition. The upstream energy is located in the data centres and networks, whereas the additional energy demand for appliances to remain network-connected is located within households. Scenario analyses are simulated to form the third research question, which queries on the effects of electricity consumption through the change in polices, user behaviour, and developments on the improvement of data centre power-usage-effectiveness (PUE).

Methodology

The FORECAST-Residential model developed by Fraunhofer ISI provides a platform for the development of long-term scenarios for future energy demand and is used to support strategic policy decisions. The model uses a bottom-up modelling approach that considers the dynamics of technologies and socio-economic drivers. It focuses on technology specific-level for delivering energy services (e.g. televisions or lighting) and gathers existing empirical data, taking into consideration market saturation effects as well as policy regulation. The empirical data consists on one hand of socio-economic data such as Germanys' gross domestic product (GDP), population and number of households and on the other hand of technical data of the modelled devices, for example the different energy efficiency classes in the stock and in the market, their rated power, average hourly usage, average investment as well as running costs, and others which are summarized in Elsland et al. (2013).

To calculate the additional power required by network-connected devices, technical parameter data are added to the model in a technology database. The calculation of network-connected energy use and upstream energy is introduced in the default model to investigate these types of energy demand in the residential sector and the tertiary sector, respectively. To analyse the impact of different scenarios on residential electricity demand, input parameters for policy changes and technical parameters were adjusted accordingly to reflect the desired scenario possibilities.

TECHNOLOGY OWNERSHIP MODELLING

The calculation of electricity use in the FORECAST-Residential model is highly dependent on its ownership modelling. Adoption and diffusion of end-use technologies is a complex and dynamic process involving interactions between technology, behaviour, market conditions, and public policy (Fraunhofer ISI et al., 2013). A diffusion model, developed by Bass (1969), represents a trend that has been shown to repeat over many new products and services over a variety of circumstances. Therefore, the projection of the appliance stock follows a sigmoid growth curve based on a Bass diffusion function in the form of percentage increments.

The Bass model calculates the stock increase for each type of end-use and time period[1]. The calculation follows the multiplication of an imitation coefficient, with the ratio of current stock and market potential. This ratio is again multiplied by the difference between the market potential and the current stock. The final addition of innovation coefficient provides the stock increase of a given end-use.

According to Bass, both "innovators" and "imitators" make the initial purchases of the product, where the difference between the two terms is their purchasing influence. Innovators are not influenced in the timing of their initial purchase by the number of people who have already bought the product. They are influenced by external factors such as advertisements. Imitators on the other hand are influenced by the number of previous buyers- essentially, the imitators are influenced by word-of-mouth (Bass, 1969). The Bass model is used to project the evolution of appliance stock; which is the ownership rate increase from the

1. The written equation is given under the sub-section Endnotes.

previous year. The coefficients inform the purchasing trend, whether it is driven by innovators, imitators, or both. The values are calibrated based on empirical and market data available for Germany.

Decision making in private households is based on the observation that each decision maker selects the option that offers the highest individual benefits or utility from a large number of alternatives (Fraunhofer ISI et al., 2013). To calculate the market share of new appliances, a utility or cost function is formulated to model the investment decision process of consumers. The utility function (Equation 2 in the Endnotes) defines the total cost of ownership (TCO) using the dynamic net present value (NPV) calculation and allows a choice comparison based on monetary terms. These costs are then divided by the number of alternatives within a particular device type.

The logit model delivers a distribution of market shares that considers each substitution alternative. The diverse decision-making process is captured by the lambda parameter of the logit model which is modified to reflect the influence of choice in the residential sector. Using the utility function, the market share is determined. The logit model is additionally able to capture the impact of regulatory requirements and restricts low efficiency products being introduced into the market. The final energy demand of each appliance calculated by the model is based on the stock distribution and the specific energy demand of the appliance depending on its technology and efficiency class.

UPSTREAM ENERGY

The upstream energy is defined as the energy used by data centres and WAN to transmit or receive data from a device connected to the network. For the calculation of upstream energy, the values for device' data usage, electricity intensity, device stock, and data centre efficiency are required, and are taken from Ryan et al. (2019).

The simplified structure diagram from the study by Aslan et al. (2017), is adapted in Figure 1 to show the system boundary considered in the calculation of upstream energy. For simplicity, the model assumes that all user devices access the network via a Digital Subscriber Line (DSL) and run on wireless local network (WLAN) for networking between devices. The DSL access network was chosen due to its dominance in Germany (Vanberg, 2002; Dialog Consult/VATM, 2020).

The calculation of total upstream energy follows the study from Ryan et al. (2019), Aslan et al. (2017), IEA, International Energy Agency (2014), and IEA, International Energy Agency (2019) is the product of the average data transmitted (d), energy intensity of data transmission (EI), and the efficiency of the data centres given as power usage effectiveness (PUE) with the stock of appliance (s), as in Equation 5 in the Endnotes.

The data was collected through different types of publicatons: Data transmission values given in Gigabytes (GB) per appliance type are taken from IEA, International Energy Agency (2014), research publications (Cisco, 2016), and market surveys (Statista, 2020b, 2020d, 2020a, 2020c; Ericsson, 2020). The energy intensity of internet data transmission, which measures the efficiency of data transmission through the internet over time is taken from the study by Aslan et al. (2017). According to Aslan et al., the electricity intensity of internet data transmission is a measure of the efficiency of data transmission through the internet over time and is measured in kilowatt-hours per gigabyte (kWh/GB). Aslan et al. found that, approximately, the electricity intensity of data transmission has decreased by half every 2 years since 2000 in developed countries. They further produced an estimate for electricity intensity between the years of 2000 to 2015 using a regression with a $\log_{10}$ scale. Figure 2 illustrates the regression formed by the energy intensity values between the year 2000 to 2015, taken from the study and the extrapolated values of the remaining years reaching 2035.

The PUE of data centres represents the effectiveness of a data centre based on the ratio between power coming into a data centre and the power needed to operate the data centre information equipment. The PUE value is assumed to gradually decrease annually, to reflect technological advances in energy efficient data centres and the strengthening of energy efficient policies. This follows the recorded 13 % improvement in PUE between 2010 and 2017 (Hintermann, R. & Hinterholzer, S., 2016).

NETWORK-CONNECTED ENERGY USE

The extension of the model refers to the works of Ryan et al. (2019) for their definition of network-connected energy consumption which is the additional function of a device being able to connect to the internet. A function of a device can be divided into primary and secondary function. The secondary function being the additional function of being able to con-

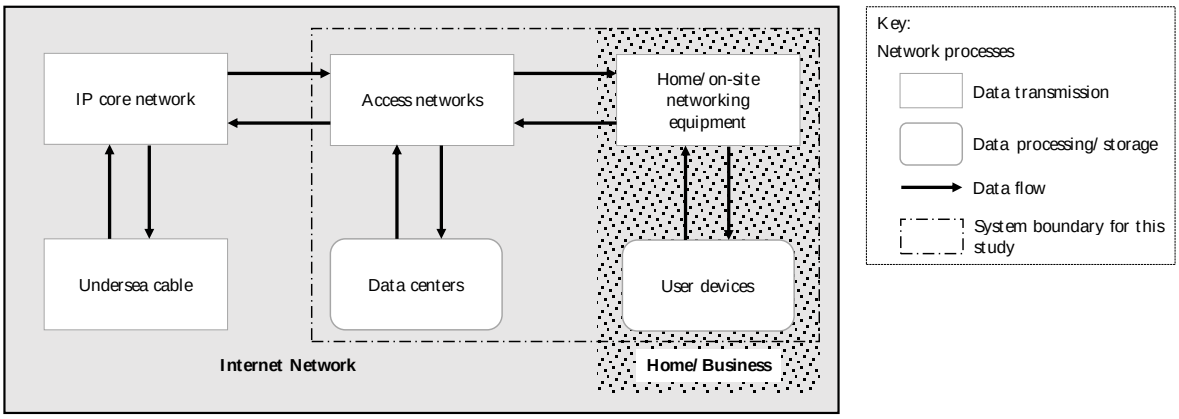

Figure 1. Simplified internet structure diagram of the system boundary for upstream energy.

nect to the internet. It can be further described by the end-use examples in Table 1.

The calculation of energy use from network-connected device resides in the distinction of the devices' mode and is characterizes by four operation modes adapted from IEA, International Energy Agency (2019). They are operation mode (ON mode) with network connection, standby mode without network connection, network active mode (ON smart), and network standby mode for smart appliances. The energy consumption as a result of being network-connected is firstly dependant on device type and secondly dependant on the mode of the device with the operation modes as described in Table 2.

The operation mode does not contribute to network-connected energy use but is an indication of the duration of use of a device when it is not considered 'smart'. The calculation of network-connected energy use and total energy demand in the residential sector follows Equation 4 in the Endnotes. The specific energy demand of active and standby usage of the device when it is network-connected is multiplied by the stock of device at the time period, t of each device. The devices' total energy demand, TED equates to the sum of the demand during operation without network connection, E (written: conventional energy demand) and demand during operation with network connection, EN.

To determine the period of smart connectivity for the active and standby network-connected modes, several considerations were made. Smart refrigerators are considered as only running in standby mode, as the main function of the appliance itself is consistently necessary, even without the device being connected to the internet. For both set-top boxes and modems, the active mode is defined for the entirety of the device being switched on.

The input values of network active and network standby power usages were taken from the extensive list by IEA, International Energy Agency (2019). Non-network operational and standby power remained as defined in the original FORECAST-Residential.

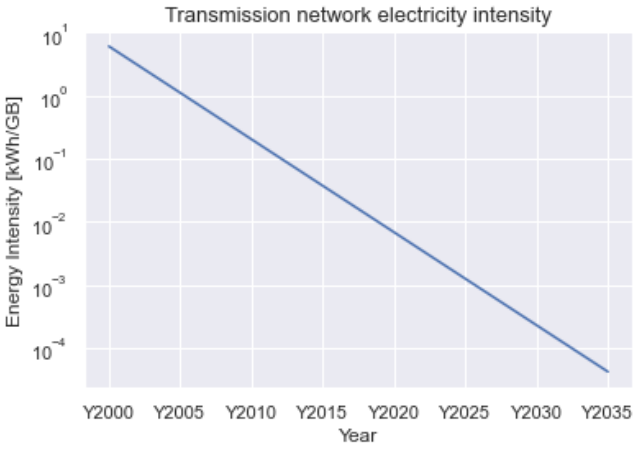

Figure 2. Global energy intensity of transmission network.

SCENARIO ANALYSES

The exploratory scenarios include quantitative scenarios that account for the effects of medium-term changes in current and new policy and unsuspected events such as increased user purchases and increased demand in data transmission. The reference scenario is defined as Business-as-usual (BAU) and the explored scenarios are divided into four main distinctions. They are Best-Available-Technology (BAT), User-Behaviour in smart device purchases (SD), User-Behaviour in increased data

Table 1. Examples for the differentiation of primary and secondary functions.

Refrigerator	Smart Refrigerator
Primary function: Keeping contents in refrigerator cool	
Secondary function: None. Not network-connected.	**Secondary function:** Sends information of condition of contents in the refrigerator to user via internet network.
Television (TV)	Smart TVs
Primary function: Provide video content by normal broadcast channels	
Secondary function: None. Not network-connected.	**Secondary function:** Provides access to online media content either related to or in addition to that accessed by normal broadcast channels.

Table 2. Description of different operation modes.

Mode	Description
Operation mode	Device operating its primary function.
Standby mode	Low power mode or sleep mode, whereby device is able to respond to signals but is inactive in operation. Does not operate its primary function.
Network active mode	Any state in which a device performs a function which requires interaction with a network.
Network standby mode	Device is not delivering its primary function but retains its capability to resume applications via a network connection.

Table 3. Summary of explored scenarios.

Scenario	Description
BAU	Minimum energy policy implemented and developed according to national law
BAT	Best available technology with only highly efficient appliances in the market
SD	Market share of at least 50 % smart devices in appliance sales by 2035
DT	Additional 30 % CAGR increment in data use compared to BAU
DC	Target PUE of 1.12 by 2035 compared to 1.4 by 2035 in the BAU

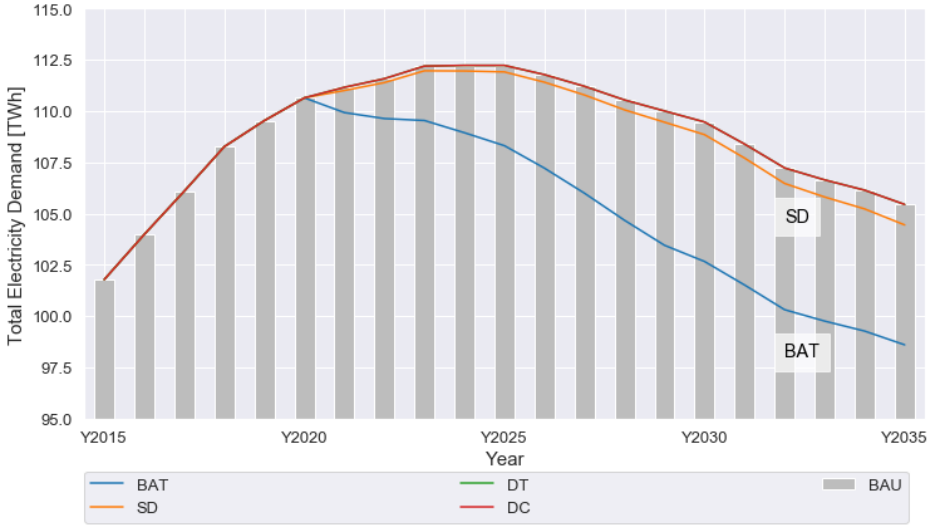

Figure 3. Total residential electricity demand in all five scenarios.

transmission (DT), and development of data centre PUE (DC) as summarized in Table 3[2,3].

The alteration of each aspect in the explored scenarios are each based on the BAU scenario. In all scenarios, the energy intensity of data transmission remains the same.

Results and Discussion

ELECTRICITY DEMAND

The total residential electricity demand in this study consists of the demand within the boundary of household appliances, which are the electricity demand from conventional and network-connected appliances. The BAT scenario leads to the largest difference in total residential electricity demand compared to the BAU as depicted in Figure 3.

Also, when analysing the combination of total residential electricity and upstream energy demand as in Figure 4, we observe that the BAT scenario leads to the largest savings. The BAT scenario restricts consumers into purchasing efficient devices, resulting in the highest percentage difference to the BAU scenario. In the BAU scenario, smart devices such as machine-to-machine (M2M) devices, laptops, smartphones, and computers have already dominated more than 50 % of the smart device share in its respective category. In the SD scenario, the increased share of smart white appliances, smart lighting, tablets, and smart televisions are captured. Due to the energy saving capabilities and more restrictive energy efficiency regulations that new smart devices need to fulfil, the result shows the reduction in absolute electricity demand is firstly the BAT scenario followed by increased in smart devices purchases as depicted in Figure 4.

The absolute electricity demand increases evidently in the scenario with increased data transmission, DT. The increased efficiency of data centre, DC scenario, remains relatively similar to the BAU due to the extremity in the model, in which the upstream energy is heavily reduced by the efficiency of data transmission. Comparing Figures 3 and 4, the differences prove to show that upstream energy plays almost no role within the boundary of residential and data centre demand to meet users' data demand. The results of the upstream energy are highly influenced by the exponential decrease of electricity intensity. The results raise an important discussion on the energy intensity of access networks with respect to the direct connection between data demand and energy consumption as well as the expected effects of reduced PUE which is not seen in the combined analysis.

UPSTREAM ENERGY

The trend in upstream energy is dependent on volume of data transmission, energy intensity of access network, and the development of data centre PUE. Figure 5 shows the resulting influence of these factors for the BAU scenario. Figure 5A shows upstream energy in TWh with values in the year 2015 amounting to 0.96 TWh and reduced to 0.05 TWh in 2035. The percentage

2. BAU minimum energy policy: Energy policies introduced in the model follows the eco-design directive.

3. CAGR: Compound annual growth rate (CAGR) is the mean annual growth rate over a specified period of time longer than one year.

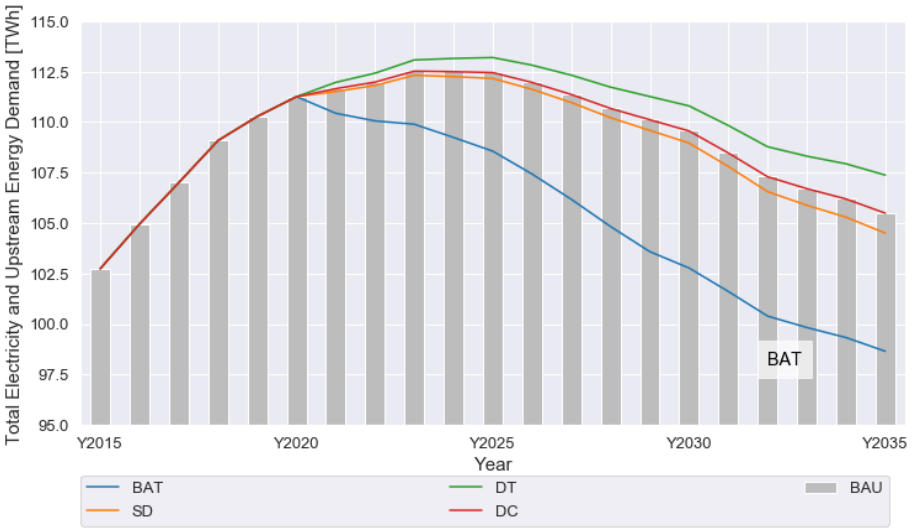

Figure 4. Comparison of the combined residential electricity and upstream energy demand against BAU scenario.

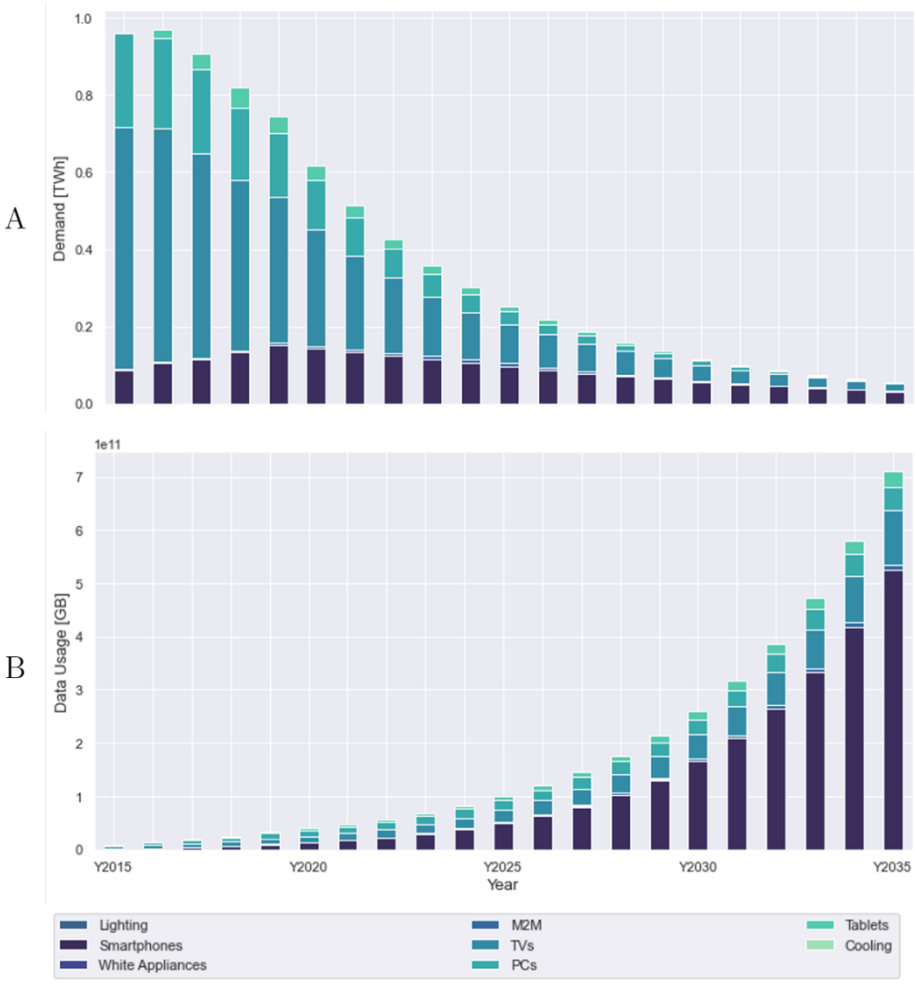

Figure 5. Upstream energy demand (A) and trend of data usage (B) for the BAU scenario.

contribution of upstream energy demand in 2035 referred in the resulting Figure 4 amounted to 0.05 % of combined total electricity and upstream energy demand.

In Figure 5B, the highest proportion of demand in data is demanded from smartphone devices. According to the statistics taken from various surveys (Statista, 2020a, 2020b, 2020c, 2020d) and a study from (Ericsson, 2020), this demand is expected due to a growing smartphone-savvy consumer base and video-rich applications in combination with large data plans. (Ericsson, 2020) continues to elaborate that the adoption of immersive consumer services using virtual reality (VR) and augmented reality (AR) will prompt an even higher growth rate.

Although Figure 5B shows increased internet usage in gigabytes of data traffic, the upstream energy consumption in Figure 5A decreases due to the assumption of the two-fold decrease in energy intensity, from material advancement in access network and software development, as well as advancement in data centre PUE. This decline in upstream energy consumption however, is highly due to the simplicity of the model and has several limitations which need to be discussed before a conclusion can be made.

NETWORK-CONNECTIVITY

Setting aside the operation mode (ON mode) of the devices, the largest percentage demand is followed by network standby mode, standby mode, and lastly network active mode as in Figure 6. The demand of standby network-connected mode, in red, dominates the three modes presented.

The distribution of network-connectivity electricity demand is reflective of the high amount of white appliances, for which network-connectivity is considered to be only on standby throughout their entire operation period.

The results for all the scenarios are expressed as percentage difference from the BAU scenario. Table 4 provides a list of highlighted results from the different scenarios based on the changes in electricity demand, upstream energy demand, and different operation modes. The highlights show either the highest percentage increase or decrease in the respective demand with the BAU scenario.

Limitation

The research model is limited by data uncertainties and scarcity like most quantitative models. The study however focuses on model development by which updated data can be replaced when available. The model assumes that the access network of all smart devices is connected via DSL connection. In December 2020, the Deutsche Telekom has set a goal of ensuring the availability of fibre optic networks to all households in Germany by 2030 (Kessing, 2020). The improvement of the access network in Germany is highly supported by the German Broadband Association – BREKO (2021) and is shaped by the impact of the different broadband technologies on the sustainability of the environment. Studies by Breide et al. (2017) and Obermann (2020) showed evidence that based on normalised energy consumption of maximum transmission volume per year, the fi-

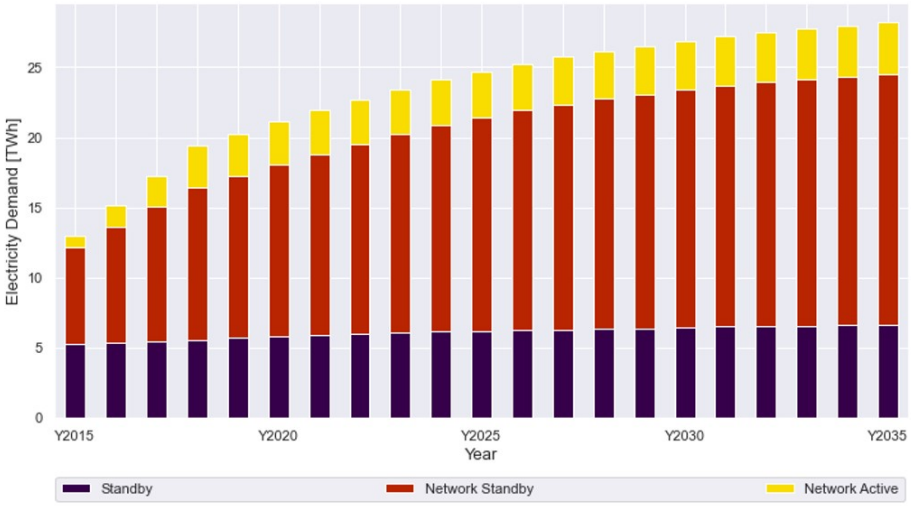

Figure 6. Electricity demand of standby, network standby and network active modes in BAU scenario.

Table 4. Points of interest.

Scenario	Description
BAT	Highest percentage decrease in total electricity demand
BAT	Highest percentage decrease in energy demand during operation mode
SD	Highest percentage increase in network-connected electricity demand
SD	Highest percentage increase in energy demand during standby and active network-connected mode
DT	Highest percentage increase in upstream energy demand
DC	Highest percentage decrease in upstream energy demand

bre network energetic performance captured in megabit per second is 10–12 times more in comparison to a copper-based vector DSL network. An improvement in the model would be to incorporate other access networks and distinguish between each set of appliances, based on its most commonly used access network.

The values of energy intensity extrapolated in this study for the calculation of upstream energy needs to be further discussed. There is no study as to how far the trend may extend in the future and whether continued improvement since 2015 has led to a two-fold decrease every two years as in the study by Aslan et al. The study by Malmodin (2020), investigating the power consumption of mobile and fixed network data services of video streaming and data downloading, found that energy usage is not directly correlated to increase in data traffic. Access networks, core network, data transmission based on data sources, user hourly usage, and data centres play a role in the power models. Data centres have unique behaviours for each application and therefore a global average, as used in this study, reduces the accuracy of the model. The model could be greatly improved by including the elements mentioned by Malmodin to project a more accurate figure of residential upstream energy consumption.

Conclusion and recommendations

The scenario with high adoption of smart devices shows that digitalization in the residential sector has a potential in supporting the energy transition due to the low contribution of not only upstream energy demand, but also the low efficiencies new smart devices have, resulting in lower electricity demand in the residential sector. The efficiencies of conventional appliances, on the other hand, rely on energy efficiency policies, which need to be intensified in order to significantly reduce overall electricity consumption.

Future development of the model can be improved by distinguishing between different access networks and including proximity data between data centres and end users for each appliance type. This would allow the presentation of a different development strategy for each access network type, depending on the outcome. The model could additionally be improved by incorporating specifications of user-based elements to project a value of upstream energy and residential electricity consumption more accurately. These elements include hourly usage of device, source of data transmission demanded by user, location of data centres to access networks based on demanded data, and type of user access network. The introduction of demand side management could better illustrate the electricity abatement; which smart devices may offer in the future.

Finally, to better exhibit the transformation stock of personal appliances such as smartphones, tablets, and game consoles, the selection criteria for the investment of these devices could be improved. The selection criteria include user preferences, such as market brands, device dimensions, and technology features.

The results of the study rely quite largely on the validity and source of its input data. Although this is a limitation of the model, the study provides a basis of discussion for future rapid development in digitalization and how low energy consumption of network-connected devices could play a role in the reduction of electricity consumption in the residential sector. The energy use of network-connected devices by IEA, International Energy Agency (2019) adopted in this study calculates the global energy consumption of network-connected devices dividing it into the following sectors: Entertainment, ICT, Security, Automation, and LAN. For future models, the incorporation of the aforementioned elements may improve the insight on the development of local and global digitalization according to end-use sectors in United Nations (2018).

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Endnotes

Equation 1. General form for stock transformation using the Bass model.

$$N_{t,s} = N_{t-1,s} + N_{t-1,s} * \left(p_s + q_s * \frac{N_{t-1,s}}{M_s} \right) * \left(M_s - N_{t-1,s} \right)$$

Equation 2: General form of the utility function.

$$U_{t,s} = \left(\beta_{t,s} \cdot x_{t,s} + \beta_{t,s} \cdot x_{t,s} + \beta_{t,s} \cdot x_{t,s} + \beta_{t,s} \cdot x_{t,s} + \beta_{t,s} \cdot x_{t,s} \right) \cdot \frac{1}{\varepsilon}$$

Equation 3: General form of the logit approach.

$$P_{t,s} = \frac{e^{U_{t,s}}}{\sum_{s=1}^{S} e^{U_{t,s}}}$$

Equation 4: Calculation for total energy demand of appliances.

$$E_{t,s} = \left(\alpha_{t} \cdot h_{t,s} + \alpha_{t} \cdot h_{t,s} \right) \cdot N_{t,s}$$

$$E_{t,s} = E_{t,s} + E_{t,s}$$

Equation 5: Calculation of upstream energy consumption.

$$E_{t,s} = E_{t,s} \cdot E_{t,s} \cdot E_{t,s} \cdot E_{t,s}$$

See the key on the next page … →

Key:			
Variables			**Unit**
x	=	Stock increase	–
X	=	Stock	[%]
p	=	Innovation coefficient	–
q	=	Imitation coefficient	–
m	=	Market potential	–
A	=	Annuity	[€]
S	=	Subsidy	[€]
MC	=	Maintenance costs	[€]
EC	=	Energy costs by fuel	[€]
r	=	Rival alternatives	–
ß	=	Coefficient	–
U	=	Utility of decision-maker	–
ms	=	Market share	
λ	=	Heterogeneity of the market	
z	=	Number of end-uses	
TED	=	Total energy demand	[TWh]
EN	=	Network-connected energy demand	[TWh]
E	=	Conventional energy demand	[TWh]
pan	=	Specific active power network-connected	[kW]
psn	=	Specific standby power network-connected	[kW]
ah	=	Active network-connected hours	[h]
shn	=	Standby network-connected hours	[h]
UE	=	Upstream energy	[TWh]
d	=	Data transmission	[GB/App.]
EI	=	Energy intensity	[kWh/GB]
PUE	=	Data centre Power-Usage-Effectiveness	–

Indices		
i	=	Type of end-use
t	=	Period
n	=	Number of rival alternatives