Investigating the real life energy consumption of refrigeration appliances in Germany: Are present policies sufficient?

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Nomenclature

EC	energy consumption
Rf	refrigerator
Fr	freezer
RFC	refrigerator-freezer combination
DUB	consumer's direct using behaviour in the interaction with household cooling appliances
IUB	consumer's indirect using behaviour in the interaction with household cooling appliances
PUR	polyurethane foam insulation
T_a	ambient temperature (in $^{\circ}\mathrm{C}$)
T_{in}	internal compartment temperature (in $^{\circ}\mathrm{C}$)
λ	thermal conductivity (in $\mathrm{W/m * K}$)
TA	test appliances: sample appliances exposed to dynamic temperature fluctuations
RA	reference appliances: sample appliances exposed to constant temperatures
τ_I	test value of a testing procedure determining insulation properties $(\mathrm{in\ min}^{-1})$

Dynamic energy model

P_{off}	stand-by power consumption (in W)
t_i	hours of a year (assumed to be constant, 8760h)
ε	impact of external heat sources on energy consumption (in %)
η^*	efficiency factor (in $\mathrm{W/K}$)
a	substitution factor
Q_{input_i}	consumer heat input in year i (in Wh)
d_λ	temperature-based degradation parameter
d_λ^{cc}	annual insulation degradation under a given thermal load (in %)
g_i	ageing-based degradation parameter
$T_{a\_maximum}^{c}$	maximum ambient temperature at the installation site of a consumer household (in K)
x	temperature difference between the ambient and the condenser surface (in K)
y	temperature difference between the compartment and the evaporator surface (in K)
α	weighting factor (in %)
DF	attenuation factor
$n_{door\_opening}$	total number of refrigeration appliance door openings (per day)
n_{food_frequ}	frequency of warm food storages (per year)
n_{food}	total number of food portions stored in a refrigeration appliance (per storage)
n_{bev}	total amount of beverages stored in a refrigeration appliance (in litres per week)
V_{net}	net volume of a refrigeration appliance (in m^3)

Subscripts

i	year of interest ($i \in 1, \ldots, \mathrm{n}$)
d	door, i.e. related to door openings
f	food, i.e. related to food storage
b	beverages, i.e. related to the storage of beverages
c	installation site at a respective consumer household
pc	regional weather condition based on the postcode of a consumer
cb	climatic boxes

Abstract

Domestic refrigeration appliances are standard household commodities. Although policies, such as the energy labelling, prompted technical improvements and decreased appliance energy consumption throughout recent decades, important parameters were disregarded. These refer to the efficiency loss over time and the consumer behaviour. The objective of this contribution was to develop a dynamic energy model to determine the consumption of refrigeration appliances considering degradation factors and behaviour. These were included by model parameters respecting direct consumer interactions, such as the storage behaviour, door openings and the temperature setting, as well as indirect actions, e.g. exposing an appliance to specific temperature conditions at an installation site. For this, an online-survey was conducted to evaluate the consumer behaviour. A total of 706 occupants participated in the national questionnaire, serving as input for the dynamic energy model. It was found that the efficiency loss increases the power consumption by at least 1% annually, i.e. an excess of 10% after 10 years of usage. Another important finding was that 32.5% of appliance’s power consumption results from consumer behaviour, whereas the promotion of behavioural changes leads to a significant decrease of the consumer-induced consumption. Consequently, this study provides a tool to evaluate the impact of policies targeting refrigeration appliances, stressing that the efficiency loss and behaviour should be integrated into future policy approaches.

Keywords

- Energy efficiency
- Refrigeration appliances
- Dynamic modelling
- Degradation
- Consumer behaviour
- Energy savings

1. Introduction

Energy efficiency has become increasingly important in recent decades. In 2018, the German residential sector accounted for roughly 25% of the total energy demand, making energy savings in private homes a key to minimise the future use of natural resources and to protect the environment **[Federal Environmental Agency of Germany,** 2018; German Federal Ministry of Economics and Energy, 2019]. In this light, the efficiency of domestic refrigeration appliances plays a crucial role. Refrigeration appliances are indispensable to preserve perishable food and usually operate continuously throughout their service life, rendering refrigerators (Rf), freezers (Fr) and fridge-freezer combinations (RFC) among the largest energy users in the residential sector. To address the increasing electricity demand of households, the EU introduced the energy consumption (EC) labelling for white goods and light bulbs via the directive 92/75/EEC in 1992, making a letter-grade labelling system visible to all EU consumers since 1995 [Baldini et al., 2018; EU, 1992; EU, 2017]. Clearly visible labels aimed at increasing the consumer awareness of EC [Baldini et al., 2018]. Referring to refrigeration appliances, such policies prompted technological progress and increased efficiency [Kim et al, 2006; Lu, 2006; Vine et al., 2001; Wada et al., 2012]. Heap found that the energy labelling led to significant energy savings in the UK, i.e. a reduction of 26% in consumption per refrigerator within ten years [Heap, 2001; James et al., 2017]. However, it can be doubted whether efficiency improvements translate into actual savings at the households, especially due to appliance's degradation over time and behaviour.

Policies paid no attention to the fact that the efficiency of refrigeration appliances diminishes with progressive use [Berardi and Madzarevic, 2020]. From a technical point of view, refrigeration appliances are subject to mechanical and thermal wear upon ageing, partially because they are exposed to daily and seasonal ambient temperature (T_a) fluctuations [Hasanuzzaman et al., 2009]. Although some system components, such as the door gasket, can be replaced, other components, e.g. the polyurethane foam insulation (PUR), must stay in place, i.e. the original efficiency cannot be restored [Kim et al., 2006; Weiss et al., 2010]. PUR rigid foam is commonly used as thermal insulation to minimise the heat flow through the appliance walls. Some studies indicate that the degradation of the thermal insulation has a significant impact on the increasing EC. Due to concentration differences between the inside of the PUR foam cells and the ambient, cell gas diffuses out of the insulation and is partially replaced by ambient air, resulting in degrading insulation properties [Albrecht, 2000; Albrecht, 2004; Khoukhi et al., 2016]. In addition to the efficiency loss, consumer behaviour further influences the EC of cooling appliances. Previous research pointed out that behaviour, i.e. the interaction of consumers with their refrigeration appliances by storing food, number of daily door openings etc., appears to have remained unchanged over recent decades **[James et al., 2008**; **Mc Donald and Schrattenholz, 2007**; **Young, 2008]**.

Consumer behaviour can be separated in two categories, direct using behaviour (DUB) and indirect using behaviour (IUB). DUB describes direct interactions with refrigeration appliances, e.g. by door openings, whereas IUB refers to the environmental impact exposed on appliances, depending on the installation site. For instance, Gemmell et al. (2017) conducted a survey study questioning a total of 766 householders across England about frequently performed interactions with their appliances in 2015 with its results further analysed by Biglia et al. (2018) in 2018 **[Gemmel et al., 2017**; **Biglia et al., 2018]**. In a broader context, the cold storage of groceries itself can also be regarded as a DUB. Although refrigeration appliances are indispensable to preserve perishable food, the cold storage of food is an important aspect from a sustainability point of view **[Masson et al., 2016**; **Marklinder et al., 2004]**. This is especially because shelves, drawers and compartments form different temperature zones (for appliances with a static cooling), providing varying cold storage options. The incorrect storage of groceries in a Rf or RFC might accelerate their perishability, consequently arising safety issues if the spoilage remains undetected or at least increases the food waste **[Terpstra et al., 2005**; **Marklinder et al., 2004]**. Regarding the DUB, researchers focused on the temperature setting, number of door openings and warm food placements, whereas special attention was paid to the T_a as an IUB. The mean internal compartment temperature (T_{in}) was 5.3 °C and survey results indicated that 50% of the respondents opened their appliances more than five times a day, while only 8% occasionally stored warm food in their appliances **[Biglia et al., 2018]**. On average, the T_a at the installation sites was 18.5 °C, and found to vary significantly for different seasons **[Biglia et al., 2018]**. Building on the findings of the 2015 project, the data was revisited by Foster (2019) to investigate key factors that impact appliance's EC, stating that besides the usage, age and the environment in which an appliance is kept influence the consumption **[Foster, 2019]**. Another questionnaire was conducted by Geppert et al. (2010), surveying a total of 1011 consumers in four European countries, namely Germany, France, Great Britain and Spain **[Geppert and Stamminger, 2010]**. The average T_{in} for all countries was 4.5 °C, but the temperature setting in Germany with 5.8 °C was found to be significantly higher than in Great Britain with 4 °C. Regarding the IUB, the mean T_a at the installation site was 16 – 23 °C **[Geppert and Stamminger, 2010]**.

A number of experimental studies was conducted to define the influence of DUB and IUB on the EC. With respect to the DUB, Saidur et al. (2002) investigated the effect of changes in thermostat setting on two RFC and found that the EC increases by 7.8% for each degree Celsius temperature reduction **[Saidur et al., 2002]**. Independent on the temperature setting, each door opening leads to an increase of T_{in} due to air exchange between the appliance's interior and the surrounding. Liu et al. (2004) conducted comparative measurements and found that the EC increases by 10% in the event of 65 door openings **[Liu et al., 2004]**. Additionally, T_{in} is influenced by the storage of food and beverages, i.e. the EC increases to dissipate the heat load introduced by stored food **[Geppert and Stamminger, 2010**; **Hasanuzzaman et al., 2009]**. Referring to the IUB, previous research stated that T_a is a dominant factor in the EC of refrigeration appliances **[Björk et al., 2006**; **Greenblatt et al., 2013**; **Harrington et al., 2018]**. Throughout a range of different experimental approaches, it was found that door openings, temperature setting and placement of warm food are the most dominant actions of the DUB. These interactions were found to influence appliance's EC more pronounced than other DUB factors (e.g. seasonal storage of large food quantities) **[Geppert 2011**; **Saidur et al. 2002]**. The same applies to the IUB, with experimental studies identifying the impact of the T_a on appliance's EC to be most pronounced **[Geppert 2011**; **Hasanuzzaman et al., 2009**; **Saidur et al. 2002]**. However, the T_a is a generic term that includes varying specifications, e.g. seasonal and daily fluctuations as well as long-term high or low temperature periods. Other interactions defined as IUB, such as the exposure of appliance's to sunlight or dirt contamination of distinct components, were either found to have no clear influence on the EC or to be considerably inferior to that of the T_a.

Furthermore, up to now no models exist that can be used to determine the EC of refrigeration appliances. Recent models follow static approaches, do not include the dynamic degradation and examine only limited aspects of consumer behaviour **[Dale et al., 2009**; **De Melo et al., 2010**; **Gottwalt et al., 2011**; **Hermes et al., 2009**; **Vendrusculo et al., 2009]**. However, a better understanding of the degradation and the impact of behaviour on the EC are critical topics for policy makers, manufacturers and consumers alike. The primary objective of this contribution is therefore to develop a dynamic model that determines the EC of refrigeration appliances under real life conditions. Thereby, the sufficiency of existing policies targeting the efficiency of refrigeration appliances can be evaluated.

2. Methodology

Figure 1 exemplifies the collection and processing of different data incorporated in the dynamic energy model and serves as a generic overview of processed data.

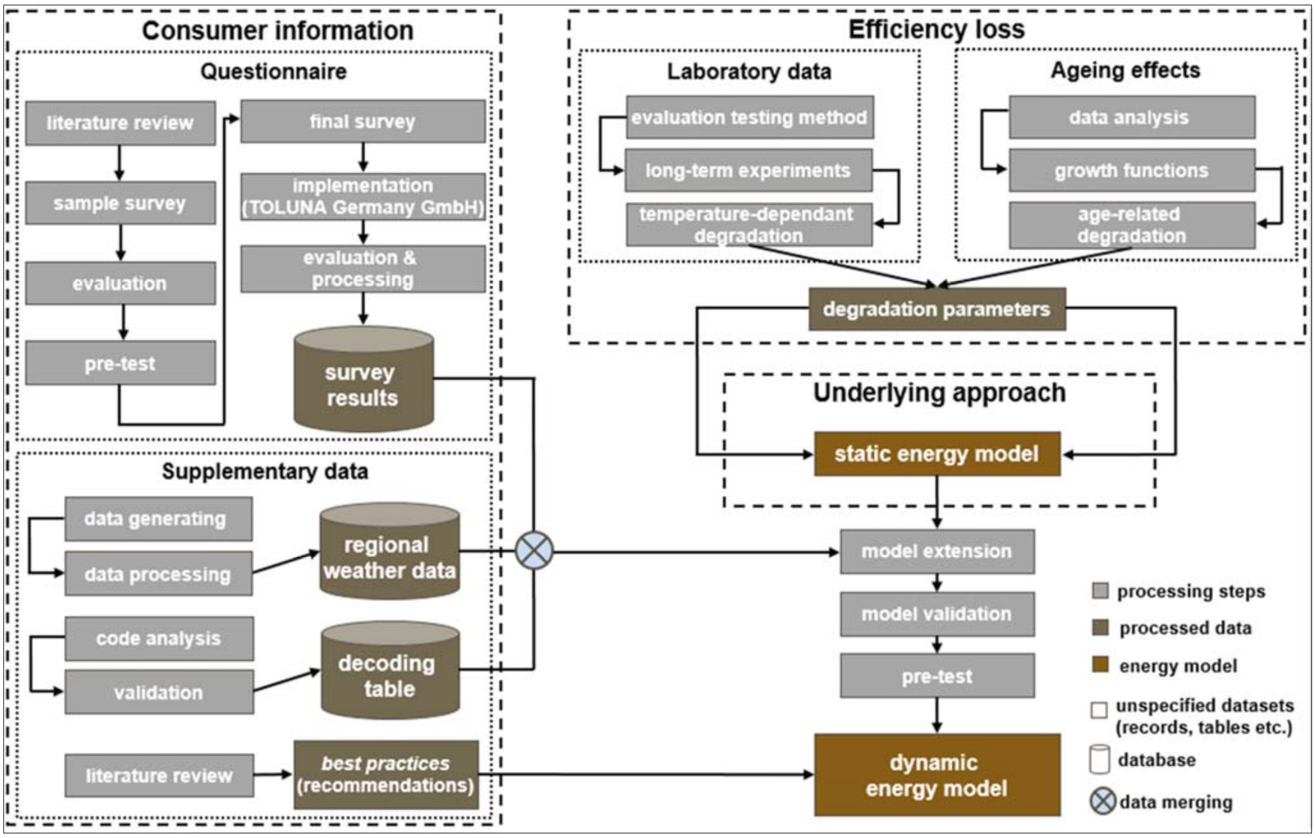

Figure 1: Generic overview of applied and processed data

2.1 Survey development and application

An extensive online-survey was conducted across Germany to monitor consumer’s day-to-day interactions with their mainly used refrigeration appliance and appliance installation conditions. This national survey was carried out in collaboration with TOLUNA Germany GmbH, a globally operating market research institute. Before the actual survey was conducted, a comprehensive pretesting phase was undertaken. Three main stages were included. First, several reviews to examine the comprehensibility of survey questions, subsequent revisions of critically reviewed questions and a pre-test (pilot study) with 20 randomly selected consumers. The final survey comprised 22 questions and was conducted over a 14-day field period in January and February 2020. Survey participants were selected from an online panel provided by TOLUNA Germany GmbH. The panel was designed to be representative for the German population and respected demographic characteristics. Participation conditions were pre-programmed to ensure the following. Age groups between 20-70 years participated, a balance between male and female interviewees prevailed, different household sizes were covered and answers were gathered from all 95 German postcode regions. All consumers participating in the final survey had to meet certain eligibility criteria (requirements), cf. Table 1.

Table 1: Eligibility criteria (set of requirements)

• Only appliances with digital temperature displays
• Only appliances from a specific group of manufacturers
• Only Rf and RFC
• Only appliances with clearly legible nameplates

Eligibility criteria set minimum requirements each interviewee needed to fulfil to participate and, thus, ensured that the information could subsequently be processed. The criteria did not diminish the representativeness of the collected data which was accounted for by the pre-programmed participation conditions. On the one hand, only consumers owning appliances with digital temperature displays could respond the actual T_{in}. Survey participants with a manual temperature setting (e.g. a dial) would have reported estimates of T_{in}, subject to a high degree of uncertainty, and were therefore excluded from the survey. On the other hand, it is impossible for consumers to report the actual age of their appliances and estimates are rather imprecise. A decoding table was developed to determine the production date of each appliance, given in the Appendix (Table A1).[1] Since the decoding constitutes sensitive manufacturer information, Table A1 presents only an extract that exemplifies the general approach how the production dates were evaluated. Depending on the appliance manufacturer, each survey participant had to copy specific number and letter codes from the nameplate to pre-programmed survey input fields. The decoding table encompassed 13 manufacturers of refrigeration appliances. Each survey respondent who indicated that his/her appliance was either from a manufacturer not listed in Table A1 or left blank (-) was automatically excluded from the survey.

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[1] On-site visits to household appliance and electronics stores in Germany, manufacturer interviews and an extensive online research were conducted to develop the decoding table, Table A1. The decoding of specific number- letter codes (given on the nameplates) was essential to identify an appliance model, age and to process the data for the dynamic energy model. Consequently, appliances from manufacturers with codes that could not be decoded were excluded because their information could not be further processed.

2.2 Supplementary data collection

Parallel to the design and implementation of the survey, an extensive literature review was conducted to compile a list of approaches that promote an energy-efficient interaction with refrigeration appliances. This list of *best practices* covers both DUB and IUB (**Table A2** in the **Appendix**). However, the listed strategies form behavioural approaches that can only be recommended as *best practices* from an energy-saving point of view. For instance, the recommended storage of perishable food under proper T_{in} is a sensitive part of the cold chain and ambiguously discussed in the literature. Many studies advise temperatures below 5 °C to prevent microbiological contamination **[Roccato et al., 2017; U.S. Food and Drug Administration, 2003; Ceuppens et al., 2016]**, whereas other studies state that storage temperatures of 7 °C for the refrigerator and -16 °C to -18 °C for the freezer compartment are sufficient **[Terpstra et al., 2005; Federal Environmental Agency of Germany, 2013]**. Referring to energy savings through behavioural changes, the upper limit is the food safety. In this light, the *best practice* regarding the T_{in}^{Rf} is 7 °C and -16 °C for the T_{in}^{RFC}. The above described example shows that each formulation of a *best practice* required a difficult balancing of different parameters **[Lu, 2006]**. The proposed *best practices* were implemented to the modelling approach to analyse end-use energy saving potentials through consumer behaviour.

Due to the distribution of interviewees all over Germany, regional variations in T_a could be taken into account. The German Metrological Institute provided a comprehensive data record of 99 weather stations distributed across the 95 German postcode areas. The data record reported the T_a of each station for two measuring points. Each measuring point recorded independently weather and temperature data at ten minute intervals throughout the year 2017, serving as a reference year in the following.[2] The temperature data of the year 2017 was used in the modelling approach to specify regional weather conditions at a consumer's domicile (T_a^{pc}). After data processing, each participant was ascribed to a weather station based on the given postcode.

2.3 Modelling approach

The following sections deal with the experimental evaluation of appliance's efficiency loss and how degradation parameters were deduced.

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[2] Temperature and weather data for the years 2017 and 2018 were sourced for this study. 2017 was chosen as a reference year because conditions were in line with previous years, whereas 2018 was exceptionally warm in Germany and would have biased the data basis and output of the dynamic energy model.

2.3.1 Investigating changes in insulation properties

A non-destructive testing method was applied in a series of experiments to sample appliances to determine the functional relationship between insulation degradation and increasing EC over time. The method investigates a temperature rise from T_{in} towards T_a after a cooling appliance was disconnected from the power supply. Since the drain hole and door gasket(s) were sealed, mass flow between the interior and the surrounding was minimised. Consequently, the heat flow that leads to the temperature rise was constituted by the temperature difference to the ambient. In this context, a testing value (τ_I) defined the quality of the insulation at the time of test application (in min^{-1}) **[Hueppe et al., 2020]**. An insulation degradation was reflected by changes in τ_I over time. The method was applied to ten initially new appliances, including Rf and RFC, for which τ_I was determined at regular intervals over the course of 1.5 years. All sample appliances incorporated a PUR rigid foam insulation which is, up to now, the most frequently used insulation material for refrigeration appliances. Consequently, cooling appliances with varying insulation technologies, e.g. Vacuum insulated panels (VIP) were disregarded. Two appliances of identical construction were obtained per model and clustered either as test appliances (TA) and reference appliances (RA). One appliance of each model was assigned as TA, whereas the other one was grouped as RA (**Table 2**).

Table 2: Specification of sample appliances

Type*	Production date**	Installation site
cooling-freezing (07)	May 2018	TA
cooling-freezing (07)	May 2018	RA
cooling-freezing (07)	February 2018	TA
cooling-freezing (07)	February 2018	RA
refrigerator (01)	May 2018	TA
refrigerator (01)	May 2018	RA
refrigerator (01)	January 2018	TA
refrigerator (01)	January 2018	RA
cooling-freezing (07)	January 2019	TA
cooling-freezing (07)	January 2019	RA

* Appliance type according to the coding system of the delegate regulation (EU) 1060/2010.
** The production date of each appliance was determined according to **Table A1** in the **Appendix**.

Apart from the time of test application, all sample appliances were continuously switched on and operated at the lowest T_{in}. TA operated in climatic boxes between test applications, whereas the RA counterparts were placed in a machine laboratory. The climatic boxes were specifically designed to perform dynamic changes in T_a between

20 °C and 40 °C in 12-hour intervals. The imposed temperature fluctuations simulated daily and annual T_a variations and, thus, accelerated the ageing process **[Bhattacharjee et al., 1994]**. Dynamic temperature changes were regulated by a fan heater connected to a timer that was located on the boxes' external cladding, whereas an axial fan ensured air circulation to prevent temperature stratification within the climatic boxes (cf. **Figure 2**). In contrast to the climatic boxes, the T_a in the machine laboratory was at 20 °C with daily and annual fluctuations below 2 K and 5 K, respectively. Consequently, RA experienced no accelerated ageing and it was expected that the degradation of a TA is above that of its RA counterpart.

Figure 2: Climatic boxes, interior view (left) and closed view (right)

Lascar electronics EasyLog EL-USB-1 were used for long-term recording of temperature data between two measurements. For each sample appliance, one logger was used to record T_a and one logger per appliance compartment to record T_{in}. Temperature sensors were placed at specific positions that marked the geometric centre of a compartment. Chosen sensors operated within a temperature range from −35 °C to 80 °C with a ±0.5 K accuracy and were set to record every minute. The testing method was applied simultaneously to a TA and RA of the same construction type. For this, both appliances were placed in a laboratory with a constant T_a of 20 °C ± 1 K. The test application followed the methodological approach described by Hueppe et al. (2020) **[Hueppe et al., 2020]**.

Changes of τ_I over time were determined for each sample appliance by the increase from the initial to the last measurement and related to one year ($\Delta\tau/a$), given in percent. The application of the non-destructive testing method over the course of 1.5 years resulted in two major findings. First, changes of insulation quality were detected for all appliances, regardless of the installation site. Throughout the investigation, $\Delta\tau/a$ was at least 3.5%, i.e. the heat flow through the insulation increased because of deteriorating insulation properties. Consequently, not only a temperature-dependent degradation took place, but also an ageing-based that was independent of the T_a. Second, TA suffered a more severe degradation than their RA counterparts. On average, τ_I increased for all TA by 8.5 % and for all RA by 4.0% per year.

2.3.2 Modelling of degradation parameters

Two degradation parameters were developed based on the experimental findings to consider both the impact of temperature fluctuations and ageing effects. Temperature-based degradation influences the variable d_λ, whereas the variable g_i presents the ageing-based degradation. d_λ is subject to the ambient conditions at the installation site. Depending on the location, the environmental impact, i.e. temperature changes and exposure to high temperatures, can be extreme. d_λ constitutes a unitless factor denoting the annual increase in the thermal conductivity of PUR due to the temperature-dependent degradation of the insulation, calculated according to **Equation (1)**.

$$d_\lambda = \frac{TL^c}{TL^{cb}} * d_\lambda^{cc} \tag{1}$$

TL^{cb} gives the total thermal load, defined as the sum of all temperature increases within the climatic boxes over one year (9767 K). Further, d_λ^{cc} constitutes the experimentally determined average annual insulation degradation under given installation conditions over all sample appliances (**Table 2**), resembling the changes in τ_I over time. TL^c reflects the annual thermal load of the actual installation conditions at the consumer households (in K), calculated with **Equation (2)**.

$$TL^c = DF * TL^{pc} \tag{2}$$

TL^{pc} denotes the total ambient thermal load at the domicile of a consumer (in K). Question 22 in the survey asked for the postcode of each participant, so that consumers could be assigned to the nearest weather station and the corresponding temperature data were evaluated. However, an attenuation factor (DF) was formulated to reduce the effect of the ambient thermal load on TL^{c}, since only appliances outside consumer homes, i.e. exposed unsheltered to the ambient, would suffer the total TL^{pc}. The DF of each appliance was established based on the information of a respective survey participant.

Unlike d_{λ}, g_i is independent of the temperature-based degradation and describes the age-related efficiency loss over time. g_i is a function from a set of four growth functions, namely linear (lin), exponential (exp), limited exponentially ($lim\ exp$) or sigmoid (sig). Since the actual efficiency loss of refrigeration appliances throughout their service life is yet unknown, the growth functions represent possible courses of how the degradation might impact the EC with progressive use. The set of growth functions is presented in **Table 3**.

Table 3: Growth functions

$g_i\ lin$	$\beta_{lin} * i$
$g_i\ exp$	$p_{exp} * e^{\beta_{exp} i} - p_{exp}$
$g_i\ lim\ exp$	$p_{\lim exp} * (1 - e^{-\tau_{\lim exp} i})$
$g_i\ sig$	$\left(\frac{1}{p_{sig} * \left(1 + e^{-\tau_{sig}(i - q_{sig})}\right)}\right) - \left(\frac{1}{p_{sig} * \left(1 + e^{q_{sig} i}\right)}\right)$

β is a dimensionless factor resembling the ageing-based gradient over time and differs for each growth function. In contrast, p constitutes a limitation factor that depends on the chosen functional form, whereas q determines the shift of the turning point in the sigmoid growth function. To achieve comparability between the different functions, g_i depends on a condition formulated according to **Equation (3)**.

$$EC_{15} = EC_0 * (1 + g_{15}) = EC_0 * 1.2 \qquad (3)$$

An ageing-based increase in EC by 20% 15 years after appliance production was assumed, i.e. the EC of an appliance at the age of 15 (EC_{15}) is 20% above the consumption within the first year after production (EC_0). Although the functional course of the efficiency is yet unknown, the assumption bases on previous studies **[Stiftung Warentest, 2013]**. Since the functional condition is variable, it can be adjusted to future findings without much effort.

Subsequently, three scenarios, namely BASE, POSITIVE and NEGATIVE, were developed to investigate the impact of the efficiency loss on the EC over time. For this purpose, the above described functional condition remained, whereas the annual insulation degradation changed per scenario, i.e. based on the experimental results each scenario included a different d_{λ}^{cc}. The BASE scenario reflected the realistic case, assuming a d_{λ}^{cc} of 6%, whereas the POSITIVE and NEGATIVE scenarios assume 4% and 8.5%, respectively.

2.3.3 Dynamic energy model

Based on previous experimental research regarding the impact of varying consumer interactions on refrigeration appliance's EC, the temperature setting (T_{in}), daily door openings (n_{door_open}), placements of warm food (n_{food} and n_{food_frequ}) as well as the storage of beverages (n_{bev}) were included as DUB parameters. Since the ambient temperature at the installation site (T_a^c) is, by far, the most influential IUB parameter, it was implemented in the dynamic model. Different characteristics, e.g. daily and seasonal temperature fluctuations, were respected. The present modelling approach is an extension of a previous model derived by Geppert (2011) to calculate domestic refrigerator's EC under real life conditions in Europe. The model is based on a concept to calculate the work input required for a Carnot refrigerator, constitutes a static approach and is presented by **Figure A1** in the appendix **[Geppert, 2011]**. The model was extended to a dynamic approach quantifying the EC of Rf and RFC based on appliance construction, efficiency loss and consumer behaviour. To increase the comprehensibility, the dynamic model is introduced on the basis of its three sections for an exemplary Rf at first. Subsequently, the sections are assembled to form the dynamic approach.

The first section considers that the construction of cooling appliances determines the basic EC, presented by

$$P_{off}^{Rf} * t_i$$

P_{off}^{Rf} describes the power consumption of a Rf during the compressor off-cycle (in W), i.e. the stand-by power and power needed for the control unit. Assuming that each year within a given period has the same length, t_i represents the number of hours (8760) per year of interest ($i \in 1, \dots, \mathrm{n}$).

The second section incorporates the efficiency loss, the IUB and components of the DUB, expressed by

$$(1+\varepsilon) * \frac{a}{\eta^*}^{Rf} * (1+d_\lambda)^i * (1+g_i) * \frac{\left[T_a^c + x^{Rf}\right] - \left[T_{in}^{Rf} - y^{Rf}\right]}{\left[T_{in}^{Rf} - y^{Rf}\right]} * \left[T_a^c - T_{in}^{Rf}\right] * t_i$$

Question 17 in the survey asked the participants whether their appliance was installed in close proximity to external heat sources (ε), e.g. an oven. This proximity leads to an annual surplus in EC of at least 0.9% of the labelled EC, depending on to what extent the T_a adjacent to the appliance is increased **[Lepthien, 2001]**. ε was modelled as a binary variable ($\varepsilon \in [0; 0.009]$). a^{Rf}/η^*describes an efficiency factor that is assembled by two appliance-specific values, the variables a and η^*. It was assumed that the absorbed heat of an appliance is partially dependent on the heat flux per unit area. This process is given by a, substituting the constant term $A * \lambda / \Delta\delta$. A is the appliance's surface area (m^2), λ gives the insulation's thermal conductivity (0.025 $W/m * K$) and $\Delta\delta$ the wall thickness (m), averaged to 0.04 and 0.05 m regarding Rf and RFC, respectively. In the case of model extension to introduce appliances with VIP, these parameters would have to be modified. The reduced efficiency of the cooling process due to the heat input from the ambient is described by η^*. The efficiency loss was included based on the aforementioned degradation parameters, d_λ and g_i. Regarding the influence of the T_a on the EC, the installation conditions at consumer homes play an important role and were, therefore, covered by a series of survey questions. Question 6 asked the participants whether their appliances were installed in heated or unheated surroundings, whereas questions 14 and 15 were designed to survey the average T_a^c for different seasons and the maximum perceived T_a^c within a year ($T_{a\_maximum}^c$). x^{Rf} and y^{Rf} are constant parameters constituting the temperature difference between T_a^c and the condenser surface (in K) as well as between the T_{in}^{Rf} and the evaporator surface (in K), respectively. It was assumed that $x^{Rf} = x^{Fr}$ and $y^{Rf} = y^{Fr}$.

The third section of the dynamic model, constituting most of the DUB, is presented by

$$\frac{1}{\eta^*}^{Rf} * Q_{input\_i}^{Rf}$$

$Q_{input\_i}^{Rf}$ determines the annual consumer-induced heat input (Wh), derived from three mutually independent model parameters (**Equation (4)**).

$$Q_{input\_i}^{Rf} = Q_{input\_i}^{d\_Rf} + Q_{input\_i}^{f\_Rf} + Q_{input\_i}^{b\_Rf} \tag{4}$$

$Q_{input\_i}^{d\_Rf}$ gives the heat input through door openings in year i (Wh). Based on survey question 9, the participants were asked to estimate how often the appliance door(s) were opened per day (considering all residents), providing the daily $n_{door\_opening}$ per household. In conjunction with other consumer information, $Q_{input\_i}^{d\_Rf}$ was calculated according to **Equation (5)**.

$$Q_{input\_i}^{d\_Rf} = V_{net}^{Rf} * \zeta * c_{air} * n_{door\_opening} * (n_{days}^{S} * \Delta T^{S} + n_{days}^{W} * \Delta T^{W}) \tag{5}$$

V_{net}^{Rf} is the net volume of the respective Rf (m^3) and c_{air} the volumetric heat capacity of air $(kJ/m^2 * K)$. Since the heat gain with each door opening is partially related to the load of the appliance, a weighting factor (ζ) was introduced (monitored by survey question 10). Additionally, the heat input per door opening depends on T_a^c at the time of the opening and is, thus, related to seasonal temperature changes. The total days per season are given by n_{days}^{S} (n=183) and n_{days}^{W} (n=182) subdivided according to German heating periods. Similarly, ΔT denotes the temperature difference between the T_a^c and the T_{in}^{Rf} in the summer and winter seasons (K), respectively.

The impact of the consumer-induced heat input through the storage of warm food is given by **Equation (5.1)**.

$$Q_{input\_i}^{f\_Rf} = m^f * c^f * \Delta T^f \tag{5.1}$$

Since the storage of warm food differs per consumer and for each storage, c^f denotes the average specific heat capacity of different foods commonly stored (3.5 $kJ/m^2 * K$). It was assumed that if participants stated that they place warm food in the refrigerator, the stored food was placed at a temperature of 323 K (50°C). Consequently, ΔT^f gives the temperature difference between the inserted warm food and the T_{in}^{Rf}. The frequency of warm food storages per year (n_{food_freq}) and the associated number of food portions n_{food} (250 g per portion) were surveyed by questions 11 and 13. Consequently, the mass of stored warm food (m^f) could be calculated (**Equation (5.1.1)**)

$$m^f = 0.25\ \text{kg} * n_{food} * n_{food\_freq} \tag{5.1.1}$$

The consumer impact on the EC through the storage of beverages is given by **Equation (5.2)**.

$$Q_{input\_i}^{b\_Rf} = m^b * c^b * \Delta T^b \quad \textbf{(5.2)}$$

Beverages are stored at respective T_a^c conditions, which is why ΔT^b resembles the temperature difference between the inserted beverages and the T_{in}^{Rf}. Similar to the storage of warm food, the exact storage of each beverage cannot be surveyed, which is why c^b was gives the specific heat capacity of water (1.0 $kJ/m^2 * K$). Each consumer was asked to estimate the total amount of beverages stored in the mainly used refrigeration appliance in litres per week (n_{bev}) (question 11), used to estimate the stored mass of beverages (**Equation (5.2.1)**).

$$m^b = 1\ \mathrm{kg} * n_{bev} * 52 \quad \textbf{(5.2.1)}$$

Assembling the previous terms of the approach results in the dynamic energy model for a Rf, presented by **Equation (6)**.

$$Work_i^{Rf} = P_{off}^{Rf} * t_i + (1+\varepsilon) * \frac{a}{\eta^*}^{Rf} * (1+d_\lambda)^i * (1+g_i) * \frac{\left[T_a^c + x^{Rf}\right] - \left[T_{in}^{Rf} - x^{Rf}\right]}{\left[T_{in}^{Rf} - x^{Rf}\right]} * \left[T_a^c - T_{in}^{Rf}\right] * t_i + \frac{1}{\eta^*}^{Rf} * Q_{input\_i}^{Rf} \quad \textbf{(6)}$$

$Work_i^{Rf}$ gives the annual EC of a household refrigerator for one year of service life (Wh) depending on construction, dynamic efficiency loss and consumer behaviour. Consequently, the total EC throughout its service life was calculated according to **Equation (7)**.

$$Work_{t_{total}}^{Rf} = \sum_{i=1}^{n} Work_i^{Rf} \quad \textbf{(7)}$$

Similarly to Rf, the dynamic model for RFC is presented by **Equation (8)**.

$$Work_i^{RFC} = P_{off}^{RFC} * t_i + (1+\varepsilon) * \alpha * \frac{a}{\eta^*}^{RFC} * (1+d_\lambda)^i * (1+g_i) * \frac{\left[T_a^c + x^{Rf}\right] - \left[T_{in}^{Rf} - y^{Rf}\right]}{\left[T_{in}^{Rf} - y^{Rf}\right]} * \left[T_a^c - T_{in}^{Rf}\right] * t_i + \frac{1}{\eta^*}^{RFC} * \\ Q_{input\_i}^{RFC} + (1+\varepsilon) * (1-\alpha) * \frac{a}{\eta^*}^{RFC} * (1+d_\lambda)^i * (1+g_i) * \frac{\left[T_a^c + x^{Fr}\right] - \left[T_{in}^{Fr} - y^{Fr}\right]}{\left[T_{in}^{Fr} - y^{Fr}\right]} * \left[T_a^c - T_{in}^{Fr}\right] * t_i \quad \textbf{(8)}$$

α constitutes a weighting factor that expresses the ratio of the net volume of the freezer compartment (V_{net}^{Fr}) to V_{net}. Similar to refrigerators, the total EC of a RFC is determined by the sum of each year of usage. Since the energy model uses the processed information of each monitored appliance as an input, the calculated annual EC

in the event of standard conditions **[DIN EN 62552:2013]** gives the labelled EC of an appliance. A sensitivity analysis was carried out to validate the dynamic model against real life energy consumption measurements and to determine its accuracy. **Table A3** in the appendix summarises the most important tests of the model validation. All consistency checks were positive, i.e. no output errors were produced by the dynamic model. Consequently, it was deemed valid and the consumer information implemented.

3. Results

3.1 Characteristics of monitored appliances

A total of 936 consumers participated in the national survey. 230 were discarded within the first data evaluation following the data cleaning. For the remaining 706 survey participants, the production date of each appliance could be determined and the actual age of their cold appliances be calculated. It was found that most of the appliances were between 2-5 years (37.5%) and 6-10 years (28.9%) old. A relatively large fraction of the reported appliances was estimated to be aged 1 year or younger (16.4%) and almost one in ten appliances was between 11-15 years (9.9%) old. On average, the appliance age constituted to 6.3 years. The appliance age estimated by each consumer was rather imprecise, i.e. interviewees estimated their appliances, on average, two years younger than they actually were. The difference between the actual ages and consumer estimations could be partly due to the time gap between the production and the purchase.[3]

Table A4 shows the processed survey data and summarises relevant empirical findings. The survey results of **Table A4** relate to all 706 valid responses. 364 men (51.6%) and 342 women (48.4%) were among the 706 participants. The average age was 47 years and a majority of survey participants either lived in a household with two (41.9%) or three residents (21.8%). A majority of 540 out of 706 householders stated to have a RFC as the mainly used cooling appliance. Regarding the IUB, a majority of 78% declared not to have their mainly used appliance placed in direct proximity to a heat source. More than 60% indicated that the average T_a^c in the summer season was within the range of 21-26 °C, whereas more than 70% estimated the average T_a^c in the winter season between 18-23 °C. Besides the seasonal shift in T_a^c, about 10% of the participants indicated that their appliances

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[3] On-site visits to a range of household appliance and electronics stores in Germany revealed that some appliances stayed in the stores for half a year up to a year after production before being sold as a *new* appliance.

suffer from high temperature peaks in the summer ($T^{c}_{a\_maximum}$). Regarding the DUB, 523 consumers (74.1%) stated that the T^{Rf}_{in} was between 5-8 °C and more than 70% set the T^{RFC}_{in} below -17 °C. A majority of roughly 54% stated to open appliance door(s) on average 6-15 times per day, and more than 60% declared to store between 4-10 litres beverages per week. 383 consumers (54.2%) noted that they never placed warm food in their appliances, whereas 199 of the remaining 323 participants replied that if warm food was stored, 2-3 portions are placed at once.

3.2 Dynamic model: Impact of the efficiency loss

At first, the modelled static EC, i.e. without efficiency loss, was determined for all 706 appliances and compared to the model output regarding the dynamic EC with degradation afterwards. **Figure 3a** and **Figure 3b** show the distribution of the calculated static EC for one respective year of usage.

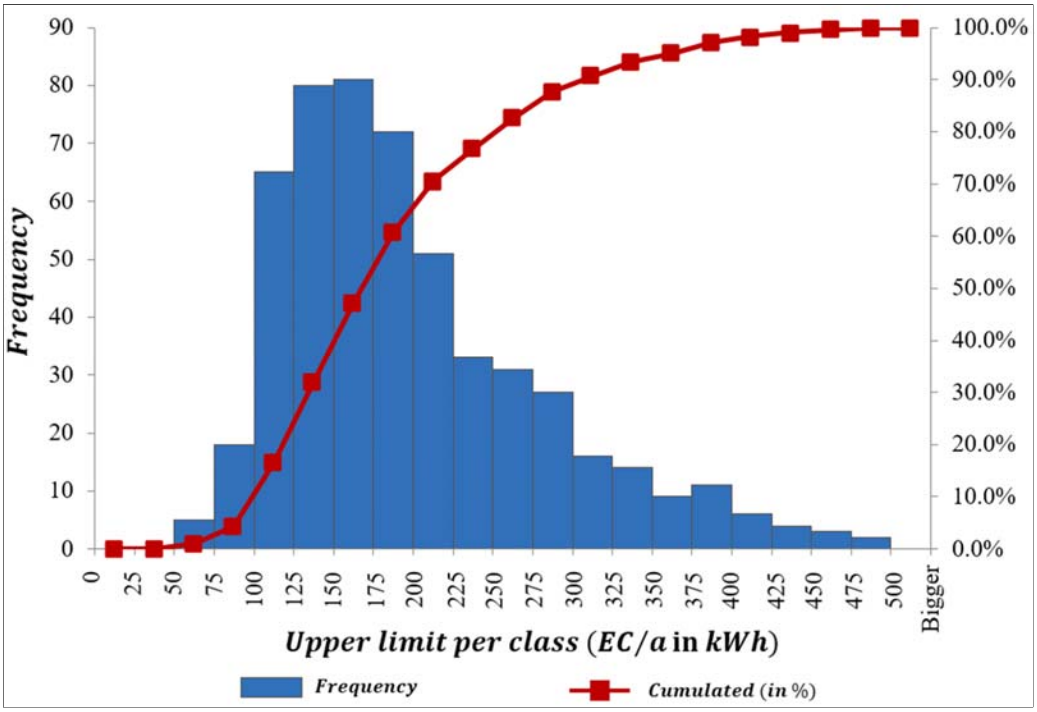

Figure 3a: Distribution of calculated annual EC regarding sample RFC

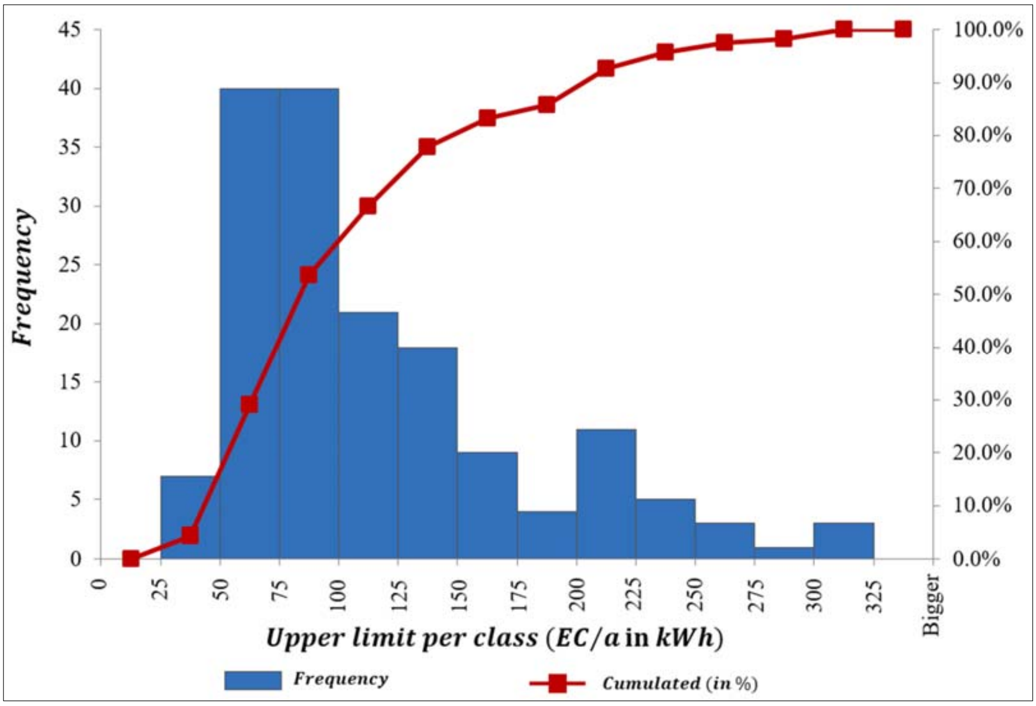

Figure 3b: Distribution of calculated annual EC of sample Rf

The average EC of the 540 monitored RFC (**Figure 3a**) constituted 199.7 kWh throughout one respective year of usage. However, a large variation around the mean consumption was found. The highest calculated EC was assigned to consumer 173 with a calculated annual EC of roughly 488.5 kWh, whereas the RFC of consumer 176 constituted the lower limit with 55.5 kWh. Referring to **Figure 3b**, the mean annual EC of all Rf was roughly 116.9 kWh with a large variation around the mean consumption.

In total, the annual static EC of all 706 monitored appliances sums up to 127.5 MWh. The static EC of some appliances was found to be considerably above the labelled consumption, whereas that of others was below the labelled values. Therefore, the total static EC approximated to that of the total labelled EC, constituting roughly 130 MWh. Subsequently, the efficiency loss was activated based on the degradation parameters d_λ and g_i. d_λ^{cc} took the BASE value of 6%, i.e. an annual increase in insulation degradation of 6%, and the functional condition outlined in **Equation (3)** was applied. **Figure 4** shows the impact of the efficiency loss on the EC, assuming the age of monitored appliances to be 15 years.

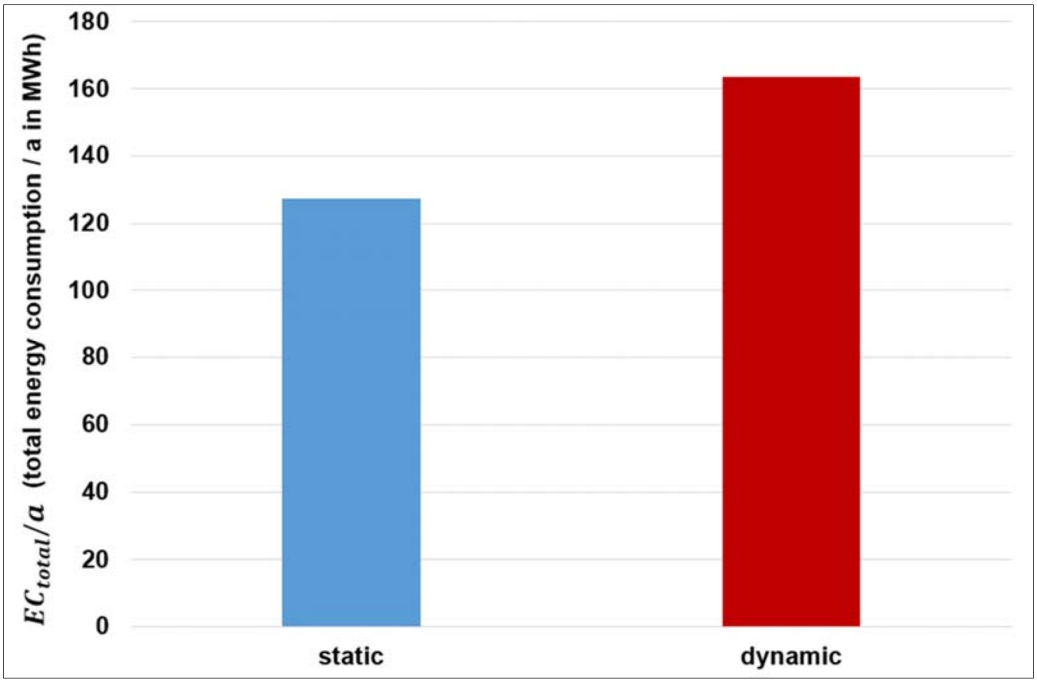

Figure 4: Impact of efficiency loss on the EC at g_{15} = 0.2

Figure 4 indicates that the total EC changes significantly if the degradation parameters are activated. Comparing the total annual EC of the aforementioned static approach (127.5 MWh/a) to the dynamic (163.5 MWh/a) results in an increase of 28%, corresponding to an increase of the labelled consumption from 130.0 MWh to 165.5 MWh.

To increase the comprehensibility, the results of the scenario analysis are subsequently explained on the example of a single monitored appliance before presented for all survey participants. The sample appliance is the 11th RFC that was monitored, referred to as RFC_{11} in the following. **Figure 5a** shows the output of the dynamic model for an anticipated use phase of 25 years regarding RFC_{11} in the POSITIVE scenario, whereas **Figure 5b** presents the model output of RFC_{11} for the NEGATIVE scenario.

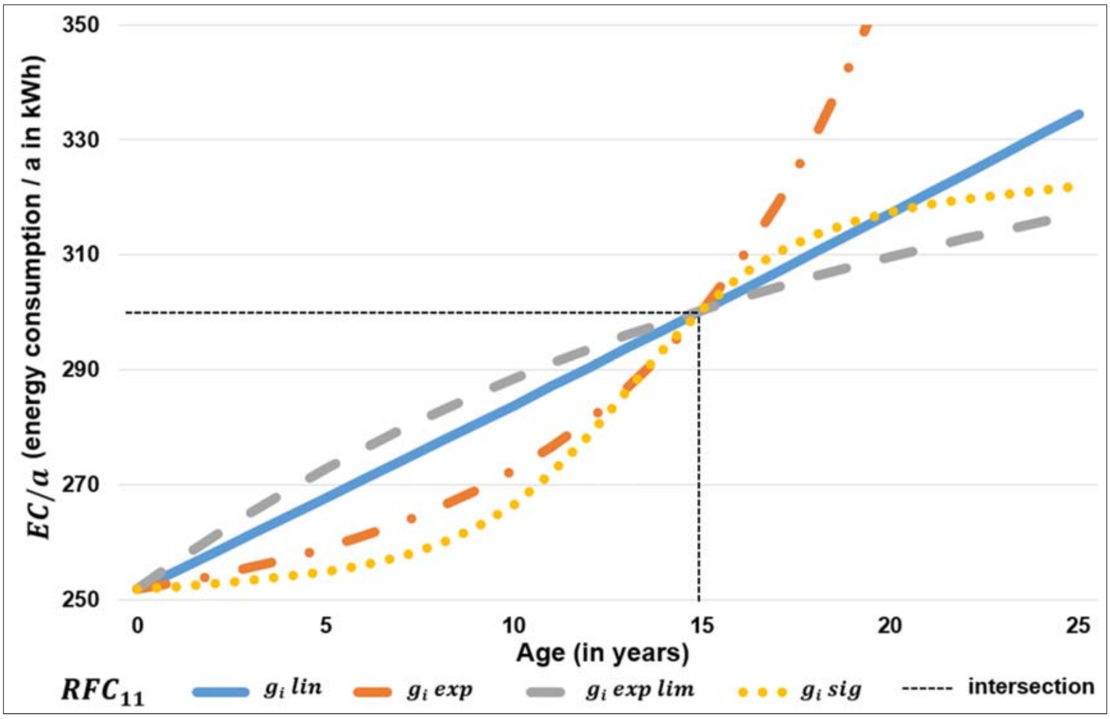

Figure 5a: POSITIVE scenario of RFC_{11}

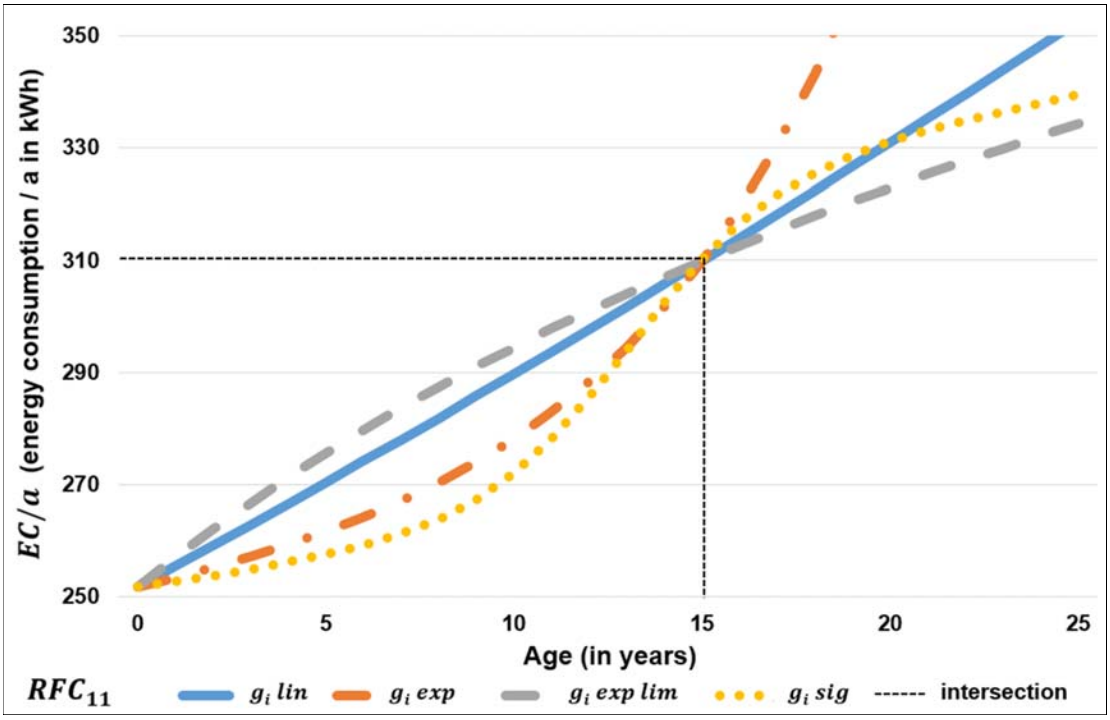

Figure 5b: NEGATIVE scenario of RFC_{11}

Dotted black lines mark the intersection of the EC in **Figure 5a** and **Figure 5b** at the age of 15, respectively. In the POSITIVE scenario, the EC of RFC_{11} is 295 kWh/a for all functional courses in the year 15, whereas the EC amounts to 311 kWh/a within the NEGATIVE scenario. In this light, the increase of d_{λ}^{cc} leads to an increase of 16 kWh, i.e. an annual excess consumption of more than 1 kWh/a. However, as soon as other years are considered, the courses of the EC show that varying growth functions lead to significant differences in consumption. For instance, $g_i\ exp\ lim$ indicates an EC of RFC_{11} that is more than 7% above that of $g_i\ sig$ at an appliance age of five years, whereas the EC with $g_i\ sig$ is roughly 3% above $g_i\ exp\ lim$ at an appliance age of 20 years. **Figure 6** summarises the output of the scenario analysis in percentage change of the EC for three respective years out of anticipated appliance ages of 25 years. All 706 monitored appliances were taken into account.

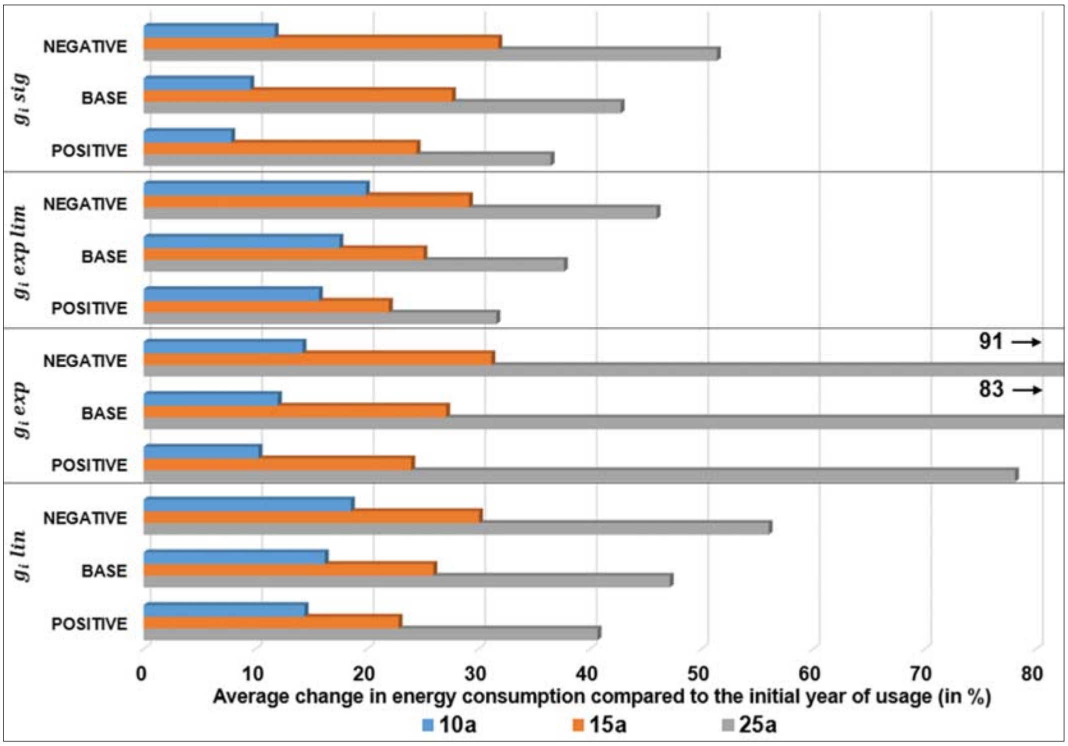

Figure 6: Scenario analysis – Average change in EC

For an use phase of ten years, the analysis shows that the increase of EC due to decreasing appliance efficiency would be smallest if the course resembles that of $g_i\ sig$. In contrast, the percentage change in EC is largest for all three scenarios in the case of $g_i\ exp\ lim$ up to an appliance age of 10 years. After appliances aged 15 years, an efficiency loss resembling the $g_i exp$ would lead to the largest increase of EC, i.e. at least 24% above the consumption in the initial year of usage ($g_i exp$ POSITIVE scenario). With progressive use, i.e. the older appliances get, the higher the annual excess of consumption. Even in the most positive case of the scenario analysis, appliances aged 25 years would consume almost 32% more than in the initial state ($g_i\ exp\ lim$).

3.3 Dynamic model: Impact of consumer behaviour

Figure 7 shows the proportions of the behavioural influence on the EC determined over all 706 monitored appliances for one year (anticipated appliance age = 15 years).

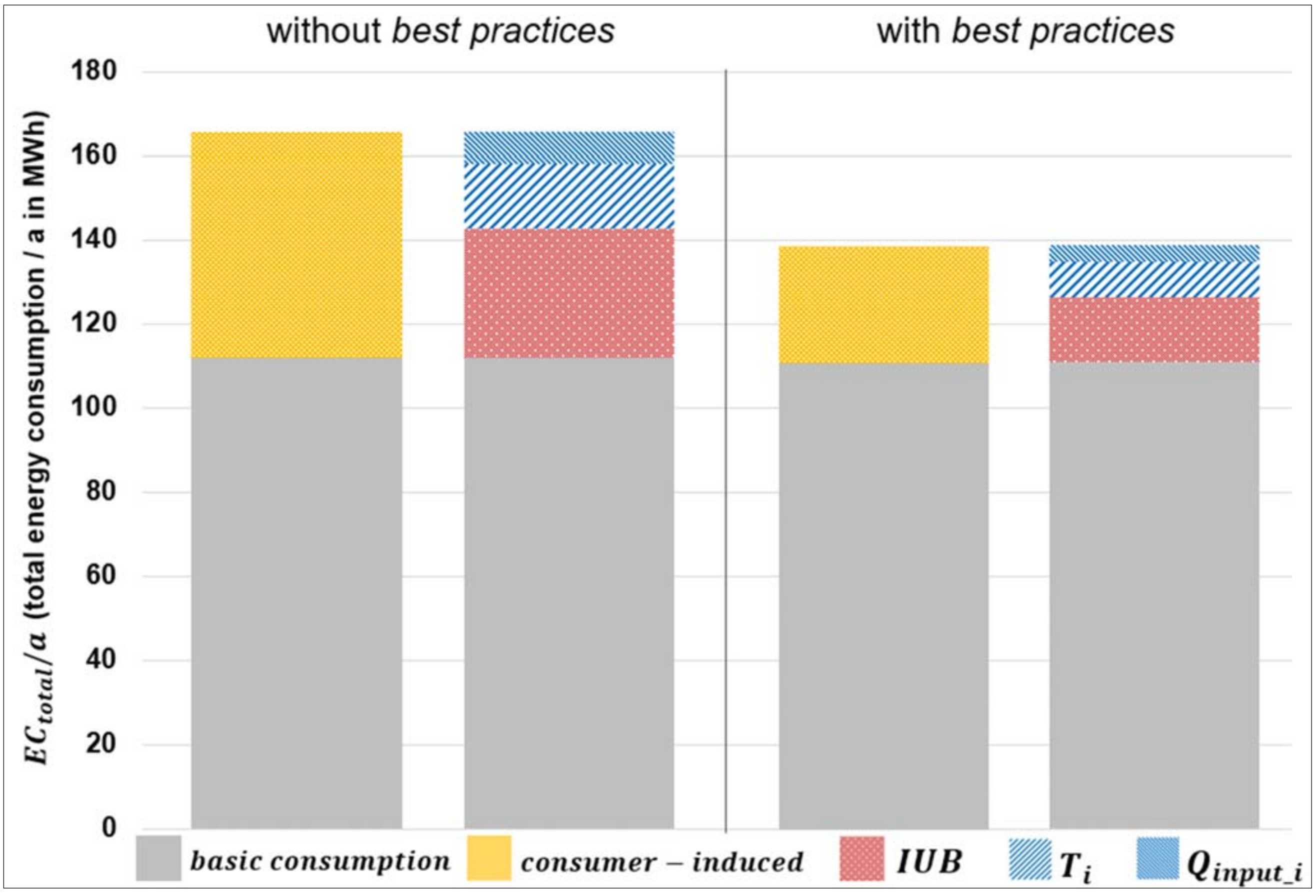

Figure 7: Consumer impact on the EC of cooling appliance

Relating to **Figure 4**, the left half of **Figure 7** indicates the total EC within the 15th year of appliances lifetime, constituting roughly 163.5 MWh. The basic consumption denotes the principal EC, depending on construction, stand-by consumption and, for an anticipated age of 15 years, the surplus due to efficiency losses. Unlike the consumer-induced proportion of the EC, the basic consumption is independent of behaviour. Approximately 53.1 out of 163.5 MWh are consumer-induced, i.e. 32.5% of the total EC results from consumer behaviour. A higher level of resolution (right-hand bar of the left half in **Figure 7**) shows that the consumer-induced EC results from 18.7% of IUB and 13.8% of DUB, whereas the DUB amounts to 9.3% from T_{in} and 4.5% from Q_{input_i}. No further subdivision was attempted for the IUB, since 18.6% is constituted by the T_a and only 0.2% by ε. The right half of **Figure 7** shows the calculated total EC over all 706 appliances in the event that the surveyed consumers followed the *best practices* (**Table A2**). The implementation of the *best practices* reduces the EC significantly, from initially 163.5 to 138.1 MWh due to a decrease of consumer-induced EC from 53.1 to 27.8 MWh.

4. Discussion

The survey to investigate the interaction of consumers with their refrigeration appliances constitutes one of the most comprehensive studies on the daily use of such devices in Germany. It was found that the average age of monitored appliances was 6.3 years. Up to date, no other study investigated the actual age and age distribution of operating refrigeration appliances in Germany, which is why comparative data from similar studies exist only for other countries. Biglia et al. (2018) found in their survey a mean appliance age of seven years **[Biglia et al., 2018]** and the local 'Domestic Fridge Survey' in New South Wales indicated that most appliances were either between five to ten years old or older than ten years **[NSW, 2009]**. However, other studies reported the appliance age based on estimations of the survey participants. Comparing the actual appliance ages to consumer estimations highlighted that householders often misjudge the age of their appliances. Referring to the IUB, the empirical results are in line with the study of Geppert et al. (2010), stating that T_a at the installation site ranges between 18-24 °C, whereas the T_a^c was with 22 °C for this study higher than found for English households by Biglia et al. (2018) with 18.5 °C **[Biglia et al., 2018; Geppert and Stamminger, 2010]**. With regard to the DUB, results of the T_{in} agree with those of Geppert et al. (2010) and Nauta et al. (2003) **[Geppert and Stamminger, 2010; Nauta et al., 2003]**. Similarly to the survey study of Biglia et al. (2018), only a minority of participants placed warm food (i.e. with an estimated temperature of 50°C) in the refrigerator, whereas the $n_{door\_opening}$ was found to be higher with 12 openings, compared to only five for English households [Biglia et al., 2018].

Based on the survey and experiments, a dynamic model was developed. A plurality of data from different sources was processed to derive the model (Figure 1) and some imprecisions form the basis for future research. On the one hand, only selected consumer actions were integrated into the model. Other parameters referring to the DUB and IUB, such as the seasonal storage of large food quantities or the exposure of appliances to direct sunlight additionally impact the EC of refrigeration appliances. Factors different from the chosen parameters were either found to have a negligible impact on appliance's EC or were, up to now, not investigated by previous experimental approaches. On the other hand, the extension of the formerly static model to a dynamic one considers the efficiency loss over time. Since d_{λ}^{cc} results from a series of long-term measurements regarding the insulation degradation, the impact of other system components' degradation that might have occurred simultaneously was ignored. Hueppe et al. (2020) indicated some limitations of the $Bonn\ method$ regarding the derivation of the test value (τ_I) or construction-specific restraints. τ_I reflects an estimate of the overall heat transfer coefficient, considering not only the heat conductivity through a planar refrigerator wall, but also other heat fluxes that depend on the construction and current appliance state [Hueppe et al., 2020]. Minor deviations regarding the degradation factor might have occurred, influenced the d_{λ}^{cc} and, thus, the modelled impact of the degradation on appliances EC. Nevertheless, Hueppe et al. (2020) reported that limitations were small and the validation of the test method indicated a negligible impact on measurement results [Hueppe et al., 2020]. With regard to g_i, the growth functions display possible courses of the excess consumption due to efficiency losses but cannot claim to reflect the real courses. Since the actual increase in consumption with progressive use is yet unknown, the growth functions show probabilistic courses.

The results of the dynamic energy model indicate that the T_a^c considerably impacts the EC of household cooling appliances. It was found that almost 18.5% of the total EC is determined by T_a conditions, constituting the largest consumer-induced impact factor. The results are in line with experimental studies of Saidur et al. (2002) [Saidur et al., 2002] and Hazanuzzaman et al. (2004) [Hazanuzzaman et al., 2009], stressing that the T_a is the dominant impact factor on the EC. In contrast to T_a, the influence of ε on the EC was almost negligible. Lepthien

[Lepthien, 2001] stated that the proximity of refrigeration appliances to heat sources (e.g. oven, stove) increases the EC by at least 0.9% per year compared to the labelled consumption. However, particularly built-in appliances are covered by an outer casing, such as a wooden frame, that increases the distance of appliances even though installed in direct proximity to a heat source and diminishes the thermal load from the surrounding. Similarly to the IUB, the results of the dynamic model found that DUB parameters significantly impact the EC, i.e. about 14% of the total EC result from direct behavioural interactions. Results indicate that the influence of T_{in} is the largest impact factor among the DUB. Previous research conducted by Geppert et al. (2013) concluded that a 1 °C change in T_{in} causes a 6-8% change in consumption **[Geppert and Stamminger, 2013]**. However, as outlined in chapter 2.2, *best practices* can only be recommended from an energy-saving point of view and especially the storage of perishable food under proper T_{in} is one of the most sensitive parts of the cold chain. The *best practice* T_{in} for Rf of 7 °C might accelerate the perishability of groceries compared to a T_{in} of 4 °C, thus, its implementation potentially leads to an increasing food waste despite energy savings. The effect of door openings on the EC was found to be rather small with a share of about 2% in total consumption. However, unlike Liu et al. (2004) who determined a 10% increase of EC in the event of 65 door openings, an average of 12 openings per day, as indicated by the interviewees, is more moderate **[Liu et al., 2004]**. The dynamic energy model only investigated the impact of single behavioural DUB and IUB parameters on refrigeration appliance's EC but did not attempt to further investigate intermediate effects. For instance, if a consumer reduces the n_{bev} according to the *best practices* the $n_{door\_openings}$ is likely to decrease as well. Interestingly, the excess consumption due to the efficiency loss for an anticipated appliance at the age of 20 is within the range of the reductions in energy use due to appliance replacement, estimated by Belshe and Kinney to be between 50-70% **[Kinney and Belshe, 2001; Arroyo-Cabañas et al., 2009]**. Concerning the results of the implementation of *best practices* listed in **Table A2**, it was highlighted that significant energy savings occur from an energy efficient behaviour. In this light, advice and recommendations have to be promoted much more and the behaviour integrated into future policies. Nevertheless, issues such as food safety and food waste additionally need to be addressed in the light of sustainability. This is especially because the consumer acts as a key player in the preservation and use of groceries, limiting the risk of food-borne illnesses, such as listeria or salmonella and unnecessary food waste by a forward-looking and proactive behaviour. For instance, food should be stored at the proper places (side- and storage compartments) and under correct conditions in a Rf or RFC to minimise its perishability along with its safety and food waste aspects.

The current dynamic energy model addresses refrigeration appliances with a PUR rigid foam insulation which is, up to now, the most frequently used refrigerator insulation material. However, in the future, the model can be extended to incorporate VIP to conduct comparative analysis.

5. Conclusions and policy implications

Policies prompted an efficiency increase of household refrigeration appliances but in-depth research and tools to evaluate the initiated policies were lacking. The present study provides an unprecedented approach by jointly considering technical aspects and consumer interactions in one dynamic energy model to test the sufficiency of policies targeting the efficiency of refrigeration appliances. One important finding of this study is that the efficiency loss increases appliance's EC over time. Based on the dynamic energy model, three different scenarios were derived for an anticipated appliance use phase of 10, 15 and 25 years, respectively. Even in the POSITIVE scenario, the impact of the efficiency loss was found to increase the annual average EC by no less than 1%, i.e. an excess of at least 10% of EC after 10 years of usage. However, present policies, such as the energy labelling, do not incorporate degradation aspects and may thus misinform consumers because an appliance's labelled efficiency potentially decreases several classes throughout its use phase. Another important finding of this study concerns the significant impact of consumer behaviour. It was found that the share of DUB in the total EC of a daily used refrigeration appliance amounts to more than 13.5% within one year of usage. The IUB was found to be larger than the DUB. Especially the impact of the T_a at consumer homes was identified to account for an average of roughly 18.5% of appliance's total EC. The implementation of *best practices* exemplified multiple initiatives to reduce the EC and are feasible for most consumers. Unlike the DUB, *best practices* regarding the external influences may not be feasible for all consumers. This is especially because some conditions, such as the T_a^c, are not only affected by behaviour but also by external factors, e.g. the housing insulation or the location of an apartment in a multi-story building. However, in the case that all formulated *best practices* can be implemented the results of this study highlight a reduction of almost half of the consumer-induced EC by behavioural changes.

The results of this study indicate that present policy approaches regarding refrigeration appliances are insufficient. Since neither appliance's efficiency loss over time, nor the impact of consumer behaviour were considered in past policies, the real life EC throughout an appliance's lifetime is not outlined to consumers. In fact, the results of this study show that, depending on the degree of efficiency loss, the labelled efficiency class of an appliance may decrease by several classes throughout its service life, whereas an energy-saving behaviour can counteract the degradation. A better understanding of the degrading efficiency and the promotion of energy saving behaviour are therefore critical topics that affect multiple stakeholders. For instance, information of impact factors on appliance's EC can be presented to consumers by an energy-saving label that is placed next to the energy label. Such a label was, among others, already designed by Lepthien (2001) but never implemented **[Lepthien, 2001]**. In the future, the dynamic energy model should be extended by further variables to increase the validity of its output and, thus, approximate a universal model. The exposure of appliances to direct sunlight and the dirt contamination of varying components over time, e.g. gradual loosening of the door gasket and dust accumulation on the condenser surface, could be included as additional IUB parameters. Further experimental approaches first have to be conducted to determine their impact on appliance's EC. Regarding the model application, it could be used to test the sufficiency of policies that aim to improve refrigeration appliance's efficiency. Furthermore, recommendations regarding an energy-saving behaviour have to be promoted much more, since consumers often seem to be unaware of the correct interaction with refrigeration appliances. These should especially refer to the T_{in}, T_a^c and advice on the $n_{door\_opening}$. The basis for such recommendations could be the list of *best practices* (**Table A2**) that could be graphically processed to a label and applied to refrigeration appliances next to the Energy Label, making it visible to all consumers.

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References:

Albrecht, W., 2000. Cell-gas composition – An important factor in the evaluation of long-term thermal conductivity in closed-cell foamed plastics. *Cell. Polym.* 19, 319-331.

Albrecht, W., 2004. Change over time in the thermal conductivity of ten-year-old PUR rigid foam boards with diffusion-open facings. *Cell. Polym*. 23, 161-172, 10.1177/026248930402300303.

Arroyo-Cabañas, F.G., Aguillón-Martínez, J.E., Ambríz-García, J.J., Canizal, G., 2009. Electric energy saving potential by substitution of domestic refrigerators in Mexico. *Energy Policy*. 37, 4737-4742. https://doi.org/10.1016/j.enpol.2009.06.032.

Baldini, M., Trivella, A., Wente, J.W., 2018. The impact of socioeconomic and behavioural factors for purchasing energy efficient household appliances: A case study for Denmark. *Energy Policy*. 120, 503-513. https://doi.org/10.1016/j.enpol.2018.05.048.

Bhattacharjee, D., Irwin, P.W., Booth, J.R., Grimes, J.T., 1994. The acceleration of foam aging by thin-slicing: some interpretations and limitations. *J. of Build. Phys.* 17, 219-237. https://doi.org/10.1177/109719639401700305.

Berardi, U., Madzarevic, J., 2020. Microstructural analysis and blowing agent concentration in aged polyurethane and polyisocyanurate foams. *Appl. Therml. Eng.* 164. 114440. https://doi.org/10.1016/j.applthermaleng.2019.114440.

Biglia, A., Gemmell, A.J., Foster, H.J., Evans, J.A., 2018. Temperature and energy performance of domestic cold appliances in households in England. *Int. J. of Refrig.* 87, 172-184. https://doi.org/doi:10.1016/j.ijrefrig.2017.10.022.

Björk, E., Palm, B., 2006. Performance of a domestic refrigerator under influence of varied expansion device capacity, refrigerant charge and ambient temperature. *Int. J. of Refrig*. 29, 789-798. https://doi.org/10.1016/j.ijrefrig.2005.11.008.

Böhmer, T., Wicke, L., 1998. Energiesparen im Haushalt: So schonen Sie Umwelt und Geldbeutel, DTV-Beck, Munich.

Ceuppens, S., Van Boxtael, S., Westyn, A., Devlighere, F., Uyttendaele, M., 2016. The heterogeneity in the type of shelf life label and storage instructions on refrigerated foods in supermarkets in Belgium and illustration of its impact on assessing the Listeria monocytogenes threshold level of 100 CFU/g. *Food Control.* 59, 377-385. https://doi.org/10.1016/j.foodcont.2015.06.009.

Cravitio, J., Yasunaga, R., Yamasue, E., 2017. “Comparative analysis of average time of use of home appliances.” *Procedia CIRP*. 61, 657-662. https://doi.org/10.1016/j.procir.2016.11.248.

Dale, L., Antinori, C., Mc Neil, M., Mc Mahon, J.E., Fujita, K.S., 2009. Retrospective evaluation of appliance price trends. *Energy Policy*. 37, 597-605. https://doi.org/10.1016/j.enpol.2008.09.087.

De Melo, C.A., de Martino Jannuzzi, G., 2010. Energy efficiency standards for refrigerators in Brazil: A methodology for impact evaluation. *Energy Policy*. 38, 6545-6550. https://doi.org/10.1016/j.enpol.2010.07.032.

DIN EN 62552:2013, Household refrigerating appliances–characteristics and test methods (IEC 62552:2007, modified+corrigendum Mar. 2008), Beuth Verlag, 2013, Berlin.

EU, 1992. Council Directive 92/75/EEC on the indication by labelling and standard product information of the consumption of energy and other resources by household appliances. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A31992L0075 (accessed: 05.08.2020).

EU, 2017. European Commission - Energy efficient products. https://ec.europa.eu/info/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/energy-label-and-ecodesign_en (accessed: 05.08.2020).

Federal Environmental Agency of Germany, 2013. Energy saving in households. https://www.umweltbundesamt.de/sites/default/files/medien/381/publikationen/energiesparen-im-haushalt.pdf (accessed: 12.05.2020).

Federal Environmental Agency of Germany, 2018. Energy consumption of private households. https://www.umweltbundesamt.de/daten/private-haushalte-konsum/wohnen/energieverbrauch-privater-haushalte#endenergieverbrauch-der-privaten-haushalte (accessed: 02.04.2020).

Federal Ministry for Economic Affairs and Energy, 2020. 10 coole Tipps , wie Sie mit Ihrem Kühlschrank Energie sparen. URL: https://www.deutschland-machts-effizient.de/KAENEF/Redaktion/DE/NTRI/Standardartikel/galerie-kuehltipps.html (accessed: 07.06.2020).

Federal Ministry for the Environment, Nature Conservation and Nuclear safety**.** Stromverbrauch beim Kühlschrank: Tipps zum Gebrauch & Kaufberatung. URL: https://www.co2online.de/energie-sparen/strom-sparen/strom-sparen-stromspartipps/kuehlschrank/ (accessed: 07.06.2020).

Foster, Helen. Factors affecting the energy efficiency of cold appliances, in: ECEEE summer study proceedings, pp. 1593-1601. https://www.eceee.org/library/conference_proceedings/eceee_Summer_Studies/2019/9-improving-energy-efficiency-in-ict-appliances-and-products/factors-affecting-the-energy-efficiency-of-cold-appliances/ (accessed: 18.06.2020).

Gemmell, Andrew; Foster, Helen; Siyanbola, Busola; Evans, Judith: Study of Over-Consuming Household Cold Appliances, Building Research Establishment Ltd. (BRE). URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/585520/Cold_appliances_field_trial_report_FINAL_230117__2_.pdf (accessed: 12.05.2020).

Geppert, J. 2011. Modelling of domestic refrigerators' energy consumption under real life conditions in Europe. Rheinische Friedrich-Wilhelms-Universität Bonn, Institut für Landtechnik, Dissertation, 2011.

Geppert, J., Stamminger, R., 2010. Do consumers act in a sustainable way using their refrigerator? The influence of consumer real life behaviour on the energy consumption of cooling appliances. *Int. J. of Consumer Stud.* 34, 219-227. https://doi.org/10.1111/j.1470-6431.2009.00837.x.

Geppert, J., Stamminger, R., 2011. Modelling of domestic refrigerators' energy consumption under real life conditions in Europe, Shaker Verlag, Bonn.

Geppert, J., Stamminger, R., 2013. Analysis of effecting factors on domestic refrigerator's energy consumption in use. *Energy Convers. and Manag.* 76, 794-800. 10.1016/J.ENCONMAN.2013.08.027.

German Federal Ministry of Economics and Energy, 2019. Energy efficiency in numbers. https://www.bmwi.de/Redaktion/DE/Publikationen/Energie/energieeffizienz-in-zahlen-2019.pdf?__blob=publicationFile&v=72 (accessed: 02.04.2020).

Gottwalt, S., Ketter, W., Block, C., Collins, J., Weinhardt, C., 2011. Demand side management - a simulation of household behavior under variable prices. *Energy Policy*. 39, 8163-8174. https://doi.org/10.1016/j.enpol.2011.10.016.

Greenblatt, J., Hopkins, A., Letschert, V.E., Blasnik, M., 2013. Energy use of US residential refrigerators and freezers: function derivation based on household and climate characteristics. *Energy Efficiency*. 6, 135-162. 10.1007/s12053-012-9158-6.

Harrington, L., Aye, L., Fuller, B., 2018. Impact of room temperature on energy consumption of household refrigerators: lessons from analysis of field and laboratory data. *Appl. Energy*. 211, 346-357. https://doi.org/10.1016/j.apenergy.2017.11.060.

Hasanuzzaman, M., Saidur, R., Masjuki, H.H., 2009. Effects of operating variables on heat transfer and energy consumption of a household refrigerator-freezer during closed door operation. *Energy*. 34, 196-198. https://doi.org/10.1016/j.energy.2008.11.003.

Heap, R.D.,2001. Refrigeration and air conditioning – the response to climate change. Bulletin of the IIR No 2001-5. Paris.

Hermes, C.J., Melo, C., Knabben, F.T., Goncalves, J.M., 2009. Prediction of the energy consumption of household refrigerators and freezers via steady-state simulation. *Appl. Energy*. 86, 1311-1319. https://doi.org/10.1016/j.apenergy.2008.10.008.

Hueppe, C., Geppert, J., Stamminger, R., Paul, A., Elsner, A., Wagner, H., Hoelscher, H., Vrabec, J., Becker, W., Gries, U., Freiberger, A., 2020. Age-related efficiency loss of household refrigeration appliances: Development of an approach to measure the degradation of insulation properties. *Appl. Therm. Eng.* 173. 115113. https://doi.org/10.1016/j.applthermaleng.2020.115113.

James, S.J., Evans, J., 1992.The temperature performance of domestic refrigerators. *Int. J. of Refrig.* 15, 313-319. https://doi.org/10.1016/0140-7007(92)90047-X.

James, S.J., Evans, J., James, C., 2008. A review of the performance of domestic refrigerators. *J. of Food Eng.* 87, 2-10. https://doi.org/10.1016/j.jfoodeng.2007.03.032.

James, C., Onarinde, B.A., James, S.J., 2017. The use and performance of household refrigerators: a review. *Comp. Rev in Food Sci. and Food Saf.* 16, 160-179. https://doi.org/10.1111/1541-4337.12242.

Khoukhi, M., Fezzioui, N., Draoui, B., Salah, L., 2016. The impact of changes in thermal conductivity of polystyrene insulation material under different operating temperatures on the heat transfer through the building envelope. *Appl. Therm. Eng.* 105, 669–674. 10.1016/j.applthermaleng.2016.03.065.

Kim, H.C., Keoleian, A., Horic, Y.A., 2006. Optimal household refrigerator replacement policy for life cycle energy, greenhouse gas emissions, and cost. *Energy Policy*. 34, 2310-2323. https://doi.org/10.1016/j.enpol.2005.04.004.

Kinney, L., Belshe, R., 2001. Refrigerator Replacement in the Weatherization Program: Putting a Chill on Energy Waste. *E Source*. https://www.larryweingarten.com/uploads/1/0/7/3/107350339/kinney_fridge_replacement.pdf. (accessed: 20.06.2020).

Kosa, K.M., Cates, S.C., Karns, S., Godwin, S.L., Chambers, D., 2007. Consumer Home Refrigeration Practices: Results of a Web-Based Survey. *J. of Food Prot*. 70, 1640-1649. 10.4315/0362-028X-70.7.1640.

Lepthien, K., 2001. Umweltschonende Nutzung des Kühlgerätes im Haushalt, Shaker Verlag, Bonn.

Lu,W., 2006. Potential energy savings and environmental impact by implementing energy efficiency standard for household refrigerators in China. *Energy Policy*. 34, 1583-1589. https://doi.org/10.1016/j.enpol.2004.12.012.

Liu, D-Y., Chang, W-R., Lin, J-Y., 2004. Performance comparison with effect of door opening on variable and fixed frequency refrigerators/freezers. *Appl. Therm. Eng*. 24, 2281-2292. https://doi.org/10.1016/j.applthermaleng.2004.01.009.

Masson, M., Delarue, J., Blumenthal, D., 2017. An observational study of refrigerator food storage by consumers in controlled conditions. *Food Quality and Preference*. 56, 294-300. https://doi.org/10.1016/j.foodqual.2016.06.010.

Marklinder, I. M., Lindblad, M., Eriksson, L. M., Finnson, A. M., Lindqvist, R., 2004. Home storage temperatures and consumer handling of refrigerated foods in Sweden. *J. of Food Prot.*. 67, 2570-2577. 10.4315/0362-028x-67.11.2570.

Mc Donald, A., Schrattenholz, L., 2007. Learning rates for energy technologies. *Energy Policy*. 29, 255-261. https://doi.org/10.1016/S0301-4215(00)00122-1.

Nauta, M.J., Litman, S., Barker, G.C., Carlin. F., 2003. A retail and consumer phase model for exposure assessment of Bacillus cereus. *Int. J. of Food Microbiol*. 83, 205-218. 10.1016/s0168-1605(02)00374-4.

NSW (New Sout Wales) Food Authority, 2009. Domestic Fridge Survey, NSW/FA/CP039/0912. https://www.foodauthority.nsw.gov.au/_Documents/scienceandtechnical/Domestic_%20Fridge_Survey.pdf (accessed: 02.06.2020).

Preparatory Studies for Eco-design Requirements of EUPs (Tender TREN/D1/49-2007), 2007. https://www.eup-network.de/fileadmin/user_upload/Lot_13_Final_Report_Taks_3-5.pdf (accessed: 20.06.2020).

Rahman, S., Sidik, N.M., Hassan, M.H., Rom, T.M., Jauhari, I., 2005. Temperature performance and usage conditions of domestic refrigerator-Freezers in Malaysia. *HKIE Trans.* 12, 30-35. https://doi.org/10.1080/1023697X.2005.10668000.

Roccato, A., Uyttendalaele, M., Membré, J-M. 2017. Analysis of domestic refrigerator temperatures and home storage time distributions for shelf-life studies and food safety risk assessment. *Food Res. Int*. 96, 171-181. 10.1016/j.foodres.2017.02.017.

Saidur, R., Masjuki, H.H., Choudhury, I.A., 2002. Role of ambient temperature, door opening, thermostat setting position and their combined effect on refrigerator-freezer energy consumption. *Energy Convers. and Manag*. 43, 845-854. https://doi.org/10.1016/S0196-8904(01)00069-3.

Stiftung Warentest, 2013. Stromhunger wächst, test. 2013 60.https://www.test.de/Kuehl-und-Gefriergeraete-Stromhunger-waechst-4579954-0/ (accessed: 20.12.2019).

Terpstra, M.J., Steenbekkers, L.P.A., de Maetelaere, N.C.M., Niijhuis, S., 2005. Food storage and disposal: Consumer practices and knowledge. *Brit. Food J.* 7, 526-533. https://doi.org/10.1108/00070700510606918.

U.S. Food and Drug Administration, 2003. Quantitative assessment of the relative risk to public health from foodborne Listeria monocytogenes among selected categories of RTE foods. http://www.foodsafety.gov/dms/lmr2-toc.html (accessed: 15.06.2020).

Vendrusculo, E.A., Queiroz, G.C., Jannuzzi, G.D.M., 2009. Life cycle cost analysis of energy efficiency design options for refrigerators in Brazil. *Energy Efficiency*. 2, 271-286. https://doi.org/10.1007/s12053-008-9034-6.

Vine, E., Du Pont, P., Waide, P., 2001. Evaluating the impact of appliance efficiency labelling programs and standards: Process, impact, and market transformation evaluations. *Energy*. 26, 1041-1059. https://doi.org/10.1016/S0360-5442(01)00053-6.

Wada, K., Akimoto, K., Sano, F., Oda, J., Homma, T., 2012. Energy efficiency opportunities in the residential sector and their feasibility. *Energy*. 48, 5-10. https://doi.org/10.1016/j.energy.2012.01.046.

Weiss, M., Patel, M.K., Junginger, M., Blok, K., 2010. Analyzing price and efficiency dynamics of large appliances with the experience curve approach. *Energy Policy*. 38, 770-783. https://doi.org/10.1016/j.enpol.2009.10.022.

Young, 2008. Who pays for the ‘beer fridge’? Evidence from Canada. *Energy Policy*. 36, 553-560. https://doi.org/10.1016/j.enpol.2007.09.034.

Appendix:

Table A1: Decoding table (extract)

Manufacturer / Brand	Identification model	Identification production date	Comments
AEG; Electrolux; Zanker; Juno; Zanussi; Progress	**Model** Declared as Modell / Model	**Serial number** Declared as Ser.Nr. / Ser.No. / Nr.	• The code comprises only the year, not the corresponding decade.
Bauknech; Whirlpool; Privileg	**Model** Indicated by SERVICE and / or a sequence of numbers	**Serial number** Declared as S/N / Serial number	• The sequence of numbers specifying the model has 12 digits, starting with 85 or 86. • The serial number is usually a 12-digit number sequence.
Bosch; Siemens (BSH); Constructa; Neff; Junker	**Model number** Declared as E-Nr.	**Production date** Declared as FD	• The production date is a 4-digit number sequence.
Beko	**Model** Declared as Model / Modell	**Serial number** Declared as SERIAL NUMBER / SERIAL NO	• The number sequence can be written with and without hyphens. • Same coding system as Grundig.
Blomberg*	-	-	-
Bomann*	-	-	-
EXQUISIT	**Model** Declared as Modell	**Production date** Declared as Batch	• Alphabetic coding, i.e. one letter for the production year. • Same coding system as OK.
Gorenje	**Model** Declared as MODEL / MODELL	**Serial number** Declared as SER. N° / Serial number	• Same coding system as AEG.
Grundig	**Model** Declared as MODELL / MODEL	**Serial number** Declared as SERIENNUMMER / Serie Number	• The number sequence can be written with and without hyphens. • Same coding system as Beko.
Haier	**Model** Declared as MODEL	**Serial number** Declared as Serial Number	• Alphabetic coding, i.e. one letter for the production year, number-letter coding for the production month(s) • Similar to SAMSUNG.
Hisense*	-	-	-
Hoover (Candy)*	-	-	-
LG (LG Electronics)	**Model** Declared as Model / Modell / Modello	**Serial Number** Declared as Serial No. or combination of numbers and letters under the barcode	• The number-letter code specifying the serial number is often a 12-digit sequence. • The code comprises only the year, not the corresponding decade.
LIEBHERR	**Model** Declared as Service-no. / No.-Service	**Production date** Declared by three-digit code or Serial-Nr.	• If the three-digit code (left-bottom corner on the nameplate) is not given, the customer service evaluates the production date using the 9-digit serial number. • Similar coding system as Miele.
OK.	**Model** Declared as Model	**Production date** Declared as Batch	• Alphabetic coding, i.e. one letter for the production year. • Same coding system as EXQUISIT.
Miele	**Model** Declared as combination of letters and numbers	**Production date** Declared by three-digit code, or letter-number combination (starting with Nr.)	• If the three-digit code (left-bottom corner on the nameplate) is not given, the customer service evaluates the production date using the letter-number combination. • Similar coding system as LIEBHERR.
SAMSUNG	**Model** Declared as MODEL	**Serial number** Declared as S/N / S/no.	• Usually 15-digit number-letter code. • Alphabetic coding, i.e. one letter for the production year, number-letter coding for the production month(s). • Similar to Haier.
Other *	-	-	-

*No freely available data exist to decode the production date of appliances of these manufacturers/brands. Consumers with such appliances were automatically discarded from the survey.

Table A2: Best practices

Direct using behaviour (DUB)	
I.) T_i[a]	• Refrigerator compartment: 7 °C • Freezer compartment: -16 °C References: **Böhmer and Wicke, 1998**; **Ceuppens et al., 2016**; **Cravitio et al., 2017**; **James et al., 2008**; **Federal Environmental Agency of Germany, 2013**; **Federal Ministry for Economic Affairs and Energy, 2020**; **Preparatory Studies for Eco-design Requirements of EUPs, 2007**; **Roccato et al., 2017**; **Terpstra et al., 2005**
II.) $n_{door\_opening}$	• R_f ≤ 10 openings/day • RFC ≤ 12 openings/day References: **Böhmer and Wicke, 1998**; **Federal Ministry for Economic Affairs and Energy, 2020**; **Federal Ministry for the Environment, Nature Conservation and Nuclear safety, 2019**; **Geppert and Stamminger, 2010**; **James and Evans, 1992**; **Saidur *et al.*, 2002**
III.) n_{food}	• No storage of warm food References: **Böhmer and Wicke, 1998**; **Federal Ministry for Economic Affairs and Energy, 2020**; **Federal Ministry for the Environment, Nature Conservation and Nuclear safety, 2019**; **Geppert and Stamminger,2010**;
IV.) n_{bev}[b]	• Storing ≤ 10 l of beverages per week Reference: **Böhmer and Wicke, 1998**
Indirect using behaviour (IUB)	
I.) T_a[c]	• T_a ≈ 19°C • T_a fluctuation: T_a^{max} ≤ 25 °C T_a^{min} ≥ 16 °C Temperature fluctuations should be as small as possible and appliances kept at approximately constant T_a References: **Böhmer and Wicke, 1998**; **Federal Ministry for Economic Affairs and Energy, 2020**; **Federal Ministry for the Environment, Nature Conservation and Nuclear safety, 2019**; **James et al., 2017**; **Hasanuzzaman et al., 2009**; **Preparatory Studies for Eco-design Requirements of EUPs, 2007**
II.) ε	• No proximity to heat sources: $\varepsilon = 0$ References: **Federal Ministry for Economic Affairs and Energy, 2020**; **Lepthien, 2001**

Some DUB and IUB parameters are unchangeable, such as the T_a at the installation site. Due to the household conditions, a consumer may have no influence on this parameter.

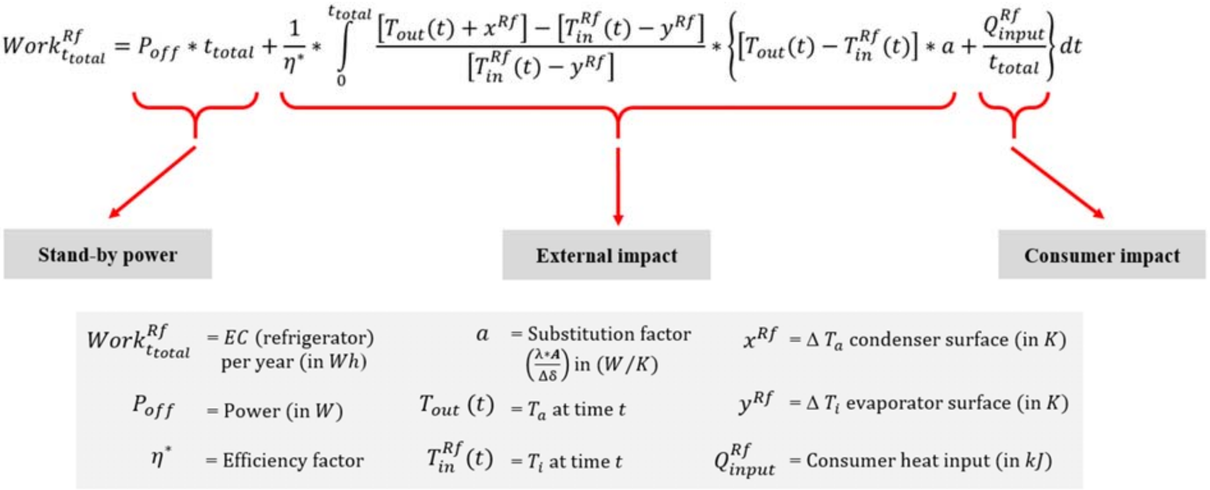
Most advice on the energy-saving handling of refrigeration appliances was gathered from governmental institutions, academic research or consumer information boards. Recommendations are inconsistent for different countries (see chapter 2.2), thus deviations among single advice exist for varying regions.

[a] Depending on the country or region, the energy–saving advice regarding the T_{in} varies for Rf between 5 °C to 7 °C and for RFC from -18 °C to -16 °C. Since 7 °C and -16°C constitute the upper limits, these were chosen as *best practices* regarding the T_{in} and implemented to the dynamic energy model.

[b] Non-perishable beverages do not have to be stored in the refrigerator (water, soft drinks etc.).
- Best practice requires a forward-looking and well-planned shopping of beverages.
- Best practice partially depends on appliance type and household size.

[c] An ambient temperature of 16 °C forms the lower limit of the climatic classes. Temperatures below 16 °C may activate the appliance's winter switch at RFC, causing additional energy consumption or lead to a stop of the compressor and subsequent warming-up of stored food.

Figure A1: Static model to determine the EC of refrigeration appliances


$$Work^{Rf}_{t_{total}} = P_{off} * t_{total} + \frac{1}{\eta^*} * \int_0^{t_{total}} \frac{[T_{out}(t) + x^{Rf}] - [T^{Rf}_{in}(t) - y^{Rf}]}{[T^{Rf}_{in}(t) - y^{Rf}]} * \left\{[T_{out}(t) - T^{Rf}_{in}(t)] * a + \frac{Q^{Rf}_{input}}{t_{total}}\right\} dt$$

$Work^{Rf}_{t_{total}}$ = EC (refrigerator) per year (in Wh)
P_{off} = Power (in W)
η^* = Efficiency factor
a = Substitution factor $\left(\frac{\lambda * A}{\Delta\delta}\right)$ in (W/K)
$T_{out}\ (t)$ = T_a at time t
$T^{Rf}_{in}\ (t)$ = T_i at time t
x^{Rf} = $\Delta\, T_a$ condenser surface (in K)
y^{Rf} = $\Delta\, T_i$ evaporator surface (in K)
Q^{Rf}_{input} = Consumer heat input (in kJ)

Figure A1: Static energy consumption model derived by Geppert (2011)

The static approach consists of three main sections. The first refers to the stand-by power, the second to the external impact exerted on appliances by the environment, e.g. the T_a, whereas the third section comprises the interactions of consumers with their household refrigeration appliances on a daily basis. Geppert's (2011) static approach was extended by the integration of degradation factors (d_λ and g_i), additional behavioural parameters (e.g. the proximity to heating sources (ε)) and modified to make it applicable for the introduction of real life consumer information (see chapter 2.1 and 2.2).

Table A3: Model validation

	Model validation and consistency
1.)	Model results ($Work_{i=1}^{Rf,RFC}$) have to be equal to the labelled EC under standard conditions for the first year after production (cf. DIN EN 62552:2013). Model input (test specification): a.) Age-related efficiency loss: g_i = 0 ; d_λ = 0 b.) Standard conditions: (Q abbreviates ‘question’, i.e. survey answers that would have led to the labelled consumption) Q6 = heated ; Q9 = 0 ; Q10 = empty ; Q11 = 1 litre (equals 0 in this case) ; Q12 = never ; Q13 = 1 portion (equals 0 in this case) ; Q14 = 24 – 26 °C (each) ; Q15 = 25 °C (each) ; Q17 = no ; Q18 = 4 °C T_{in}^{Rf} , –18°C $T_{in}^{RFC,Fr}$
2.)	Temperature changes (ambient temperature at the installation site T_a^c and changes to the temperature setting $T_{in}^{Rf,RFC}$) only impact the second and third section of the equation underlying the dynamic energy model. Model input (test specification): a.) All parameters are formulated as in **1.)**, but Q14 and Q18 either increase or decrease
3.)	Increases to $T_{in}^{Rf,RFC}$ decrease $Work_{1,\ldots,n}^{Rf,RFC}$, whereas decreases to $T_{in}^{Rf,RFC}$ increase $Work_{1,\ldots,n}^{Rf,RFC}$ Model input (test specification): a.) All parameters are formulated as in 1.), but $T_{in}^{Rf,RFC}$ increases b.) All parameters are formulated as in 1.), but $T_{in}^{Rf,RFC}$ decreases
4.)	Increases of T_a / T_a^c increase $Work_{1,\ldots,n}^{Rf,RFC}$, whereas decreases of T_a / T_a^c decrease $Work_{1,\ldots,n}^{Rf,RFC}$ Model input (test specification): a.) All parameters are formulated as in 1.), but T_a / T_a^c increases b.) All parameters are formulated as in 1.), but T_a / T_a^c decreases
	Model validation (ambient influence)
5.)	Changes to d_λ only impact the second section of the equation underlying the dynamic energy model. Model input (test specification): → All parameters are formulated as in **1.)**, but d_λ increases (to a positive value).
6.)	Changes to g_i only impact the second section of the equation underlying the dynamic energy model. Model input (test specification): → All parameters are formulated as in **1.)**, but g_i either increases or decreases.
7.)	Changes to ε (Q17) only impact the second section of the equation underlying the dynamic energy model. Model input (test specification): → All parameters are formulated as in **1.)**, but ε is either positive (0.009) or zero.
	Model validation (consumer influence)
8.)	Changes to n_{door} (Q9) only impact the third section of the equation underlying the dynamic energy model. Model input (test specification): → All parameters are formulated as in **1.)**, but n_{door} either increases or decreases.
9.)	Changes to n_{bev} (Q11) only impact the third section of the equation underlying the dynamic energy model. Model input (test specification): → All parameters are formulated as in **1.)**, but n_{bev} either increases or decreases.
10.)	Changes to n_{food_freq} (Q12) only impact the third section of the equation underlying the dynamic energy model. Model input (test specification): → All parameters are formulated as in **1.)**, but n_{bev} either increases or decreases.

Table A4: Summary of empirical results regarding survey participants and monitored appliances

Participants		**Household size**	**1 resident**	**2 residents**	**3 residents**	**4 residents**	**More than 4 residents**			∑
			105 (14.9%)	296 (41.9%)	154 (21.8%)	115 (16.3%)	36 (5.1%)			**706 (100%)**
		Age	**20–29 years**	**30–39 years**	**40–49 years**	**50–59 years**	**60–74 years**			∑
			70 (9.9%)	156 (22.1%)	162 (22.9%)	146 (20.7%)	172 (24.4%)			**706 (100%)**
		Gender	**male**	**female**						∑
			364 (51.6%)	342 (48.4%)						**706 (100%)**
Appliance characteristics		**Type**	**refrigerator**	**refrigerator-freezer combination**						∑
			166 (23.5%)	540 (76.5%)						**706 (100%)**
		Brand [a]	**BSH**	**SAMSUNG**	**LIEBHERR**	**AEG**	**LG**	**Bauknecht**	**OTHERS**	∑
			300 (42.5%)	106 (15.0%)	85 (12.0%)	61 (8.6%)	52 (7.4%)	26 (3.7%)	76 (10.8%)	**706 (100%)**
	IUB	**Installation site**	**heated**	**unheated**						∑
			495 (70.1%)	211 (29.9%)						**706 (100%)**
		ε	**proximity to external heat sources**	**no proximity to external heat sources**						∑
			156 (22.1%)	550 (77.9%)						**706 (100%)**
		T_a^c **summer**	**less than 15 °C**	**15–17 °C**	**18–20 °C**	**21–23 °C**	**24–26 °C**	**27–29 °C**	**more than 29 °C**	∑
			36 (5.1%)	28 (4.0%)	85 (12.0%)	253 (35.8%)	234 (33.2%)	53 (7.5%)	17 (2.4%)	**706 (100%)**
		$T^c_{a\_maximum}$	**less than 15 °C**	**15–20 °C**	**20–25 °C**	**26–30 °C**	**31–35 °C**	**36–40 °C**	**more than 40 °C**	∑
			1 (0.1%)	33 (4.7%)	316 (44.8%)	287 (40.7%)	49 (6.9%)	19 (2.7%)	1 (0.1%)	**706 (100%)**
		T_a^c **winter**	**less than 12 °C**	**12–14 °C**	**15–17 °C**	**18–20 °C**	**21–23 °C**	**24–26 °C**	**more than 26 °C**	∑
			26 (3.7%)	28 (4.0%)	90 (12.8%)	271 (38.4%)	265 (37.5%)	22 (3.1%)	4 (0.5%)	**706 (100%)**
	DUB	T_i **cooling** [b]	**below 3 °C**	**3–4 °C**	**5–6 °C**	**7–8 °C**	**above 8 °C**			∑
			20 (2.8%)	142 (20.1%)	269 (38.1%)	254 (36.0%)	21 (3.0%)			**706(100%)**
		T_i **freezing** [b]	**below -20 °C**	**-20 to -19 °C**	**-18 to -17 °C**	**-16 to -15 °C**	**above -15°C**			∑
			42 (6.9%)	88 (14.4%)	306 (50.1%)	102 (16.7%)	73 (11.9%)			**611(100%)**
		$n_{door\_opening}$ [c]	**less than 6 per day**	**6–15 per day**	**16–25 per day**	**26–35 per day**	**more than 35 per day**			∑
			98 (13.9%)	381 (53.9%)	160 (22.7%)	38 (5.4%)	29 (4.1%)			**706(100%)**
		n_{food_frequ}	**almost) daily**	**once a month**	**weekly**	**quarterly**	**never**			∑
			81 (11.5%)	32 (4.5%)	139 (19.7%)	71 (10.1%)	383 (54.2%)			**706 (100%)**
		n_{food} [d]	**1 portion**	**2 – 3 portions**	**more than 3 portions**					∑
			111 (34.4%)	199 (61.6%)	13 (4.0%)					**323 (100%)**
		n_{bev}	**1l / week**	**2–3l / week**	**4–6l / week**	**7–10l / week**	**11–15l / week**	**more than 15l / week**		∑
			19 (2.7%)	177 (25.1%)	271 (38.4%)	158 (22.4%)	65 (9.2%)	16 (2.2%)		**706 (100%)**

[a] BSH (BOSCH, SIEMENS) additionally includes appliances branded as Constructa, Neff, Junker.
AEG additionally includes appliances branded as Electrolux, Zanker, Juno, Zanussi, Progress.
Bauknecht additionally includes appliances branded as Whirlpool.
OTHERS group appliance brands or manufacturer of those brands for which no decoding of the actual production date could be done.

[b] The lines present temperature classes for cooling- and freezing compartments, i.e. all monitored appliances have at least one cooling compartment.
Low-temperature compartments with adjustable internal temperature are thus given within the freezing values.

[c] This table does not differentiate between refrigerators and refrigerator-freezer combinations.

[d] Only those participants who actually placed warm food into their refrigeration appliances are listed, i.e. 706 less 382 participants who stated to never place warm food into their appliances.