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Consumption-Based Energy Footprints in Iceland: High and Equally Distributed

Anna Kristín Einarsdóttir [1], Gereon tho Pesch [2], Kevin Joseph Dillman [3], Marta Rós Karlsdóttir [4] and Jukka Heinonen [1,*]

[1] Faculty of Civil and Environmental Engineering, School of Engineering and Natural Sciences, University of Iceland, 107 Reykjavík, Iceland; ake10@hi.is
[2] Department of Economics, Faculty of Law and Economics, University of Bonn, 53113 Bonn, Germany; gereon.thopesch@uni-bonn.de
[3] Environment and Natural Resources, School of Engineering and Natural Sciences, University of Iceland, 101 Reykjavík, Iceland; kjdillman@hi.is
[4] Baseload Power Iceland ehf., Katrínartún 2, 105 Reykjavík, Iceland; marta.karlsdottir@baseloadpower.is
* Correspondence: heinonen@hi.is

Abstract: With the urgent global need to limit warming to 2 °C as well as a localized need in our case study to address rising energy demand amid electrical and thermal network limitations, a critical examination of demand-side energy reductions and the concept of energy sufficiency is needed. This paper contributes to the sparse literature on bottom-up analysis by utilizing Iceland—a leader in renewable energy generation—as a case study to explore the socio-economic factors influencing energy footprints. Our findings reveal significant energy footprints across various consumption domains, particularly housing and mobility, influenced by income levels, urbanization, and lifestyle choices. The study highlights the paradox of a high renewable energy supply leading to potential misconceptions regarding abundant and low-cost energy, resulting in substantial energy consumption-related environmental impacts. Using detailed household consumption survey data, this research provides insights crucial for developing sustainable energy policies that not only target technological advancements but also address the need for a reduction in energy demand and a shift towards energy sufficiency. This work marks a contribution to the literature through the provision of a case study of low income inequality and high energy footprints in a highly renewable energy system context. Further, this work is useful for Icelandic and international policymakers to understand in such high-demand contexts which consumption domains would be most relevant for sufficiency policies. This comprehensive analysis opens pathways for future research to further explore the intersections of energy consumption, socio-economic factors, and well-being, offering a nuanced understanding necessary for crafting sufficiency and demand-side policies aimed at a sustainable energy future.

Keywords: household energy footprint; consumption-based assessment; energy consumption; energy sufficiency; lifestyle; embedded energy

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1. Introduction

To limit global warming to 2 °C requires a rapid decline in global emissions from fossil fuel-based energy systems [1]. Existing policies fall short, requiring additional ambitious actions to align with the Paris Agreement goals [1,2]. The focus has primarily been on the decarbonization of energy systems and increased efficiency to reduce emissions. However, another important aspect that has received less attention is demand-side reductions and considerations of energy sufficiency [3–5].

Energy systems play a crucial role in societies and are widely recognized as a fundamental component of human development [6], acknowledged in international initiatives such as the United Nations Sustainable Development Goal 7, which aspires to achieve universal access to modern energy by 2030 [7]. Despite this, millions of people in the Global South still lack access to electricity and billions rely on harmful fuels for cooking [8]. At the same time, in the Global North, people exhibit excessive an consumption of energy, surpassing levels deemed necessary for decent living [9]. It is important to recognize that wealthier nations not only consume substantial energy within their borders for housing and transportation but also indirectly through the production and consumption of goods and services sourced globally [10,11].

Overconsumption and the focus on energy transition in developed countries, rather than the actual reduction in energy demand, are significant concerns in global efforts to mitigate climate change [10]. To address the issue of overconsumption in the Global North, it is crucial to reconsider how we satisfy our needs and differentiate between needs and wants. As such, demand-side solutions and sufficiency measures are increasingly being recognized as important additions to technological solutions for keeping warming below 2 °C [12]. Reducing energy demand through demand-side solutions could ensure a more equitable distribution of energy resources, enabling decent living conditions for all [3,13–15].

In recent years, the scientific literature on consumption-based carbon footprints has developed rapidly, providing a consumption perspective on the drivers of anthropogenic climate change [16]. Many studies attempt to link well-being to emissions [17], but the relationship between energy consumption and well-being is also of interest as energy is closer to well-being than emissions, the latter only being an (avoidable) byproduct of energy use [18,19]. In the past, most studies have taken a production-based perspective on energy, thus not accounting for the energy embodied in imports and exports of products and services. Energy footprint (EF), a consumption-based metric comparable to carbon footprint, takes a consumption perspective and can be calculated top-down or bottom-up. The former means that aggregated, typically country-level data are used to compute EFs. More recently, EF studies taking a bottom-up perspective have emerged, using household-level data. This enables more granular analyses, including analyzing household-level variables and their effect on EF [20].

Iceland is often considered a global sustainability leader and a pioneer in low-carbon energy transitions [21,22]. Iceland currently has a share of more than 85% of renewables in its total primary energy supply [23]. The majority of electricity is generated from hydropower (70.55%) and geothermal (29.4%) [24], and the share of geothermal energy in space heating is now over 90%, with the remainder of heat being supplied using electricity. A total of 80% of electricity generation is used by heavy industry, with the majority utilized by aluminum smelters, accounting for 64%. Only 4.5% is used directly by Icelandic homes [25]. The Icelandic government aspires to achieve carbon neutrality by 2040, a target that they suggest may necessitate doubling domestic energy production [26] due to the growing need for electricity to produce sustainable fuels for long-distance transport such as aviation and ships, namely, fishing vessels.

Although it may appear that Iceland has largely completed the transformation to a sustainable energy system, that is not the case. The country uses considerable amounts of fossil fuels for domestic and international travel [23], and, as a wealthy island country with a small population, it also imports many goods and services [27]. In fact, despite its ambitious policies and focus on a low-carbon energy transition, Iceland has been shown to have a high-carbon footprint mainly due to its high dependence on imports, which require energy produced elsewhere. Therefore, while Iceland's stationary energy supply is almost entirely derived from renewable sources, its carbon footprint is among the highest globally [28]. Further, due to the provision of a seemingly limitless supply of renewable energy, high energy demand from households and limited capacity have led to national energy companies raising the alarm regarding electricity and heating network capacities [29,30].

Therefore, to design and implement effective demand-side solutions to address these problems associated with overconsumption, an understanding of in what domains this consumption occurs (e.g., mobility, housing, food), what the footprints of them are, and the socio-economic factors that influence them is pertinent. The research objective of this work, therefore, was to study the Icelandic energy footprints by domain through survey data with rich socio-economic information, to give the context to provide policy guidance on Icelandic consumption and associated energy footprints. This also marks a contribution to the sparse literature of bottom-up studies examining EFs, utilizing Iceland as a case study for a high-share renewable energy system, and exploring the impact of socio-economic factors on Icelandic EFs. By leveraging detailed household consumption survey data, we sought to explore disparities in energy use across income levels and urbanization, offering insights crucial for sustainable energy policy development in Iceland, as well as giving perspective from its unique context of a renewable energy supply, which other countries are working towards. Further, by decomposing the energy footprints by domain, it allows for clearer insights into which domains are contributing the most to energy footprints, the knowledge of which allows for more targeted policy guidance.

The article is structured as follows: The methodology section provides the Icelandic study context and reviews the data collection and footprint calculation processes. The results cover the significant findings on energy consumption patterns by income and urbanization and the predictors of higher footprints. The discussion contextualizes these findings in the literature and discusses the limitations, future research, and policy implications of the study. The final section concludes the paper.

2. Materials and Methods

With the research goal of studying Icelandic energy footprints, we organized the research methods such that first we describe the Icelandic study context, as well as the survey data used for the analysis. Second, the methods employed to calculate the EFs from the survey data are explained. Lastly, we describe the methods used to analyze the estimated EFs.

2.1. Study Context and Survey Data

Iceland, located in the North Atlantic, is among the largest oceanic islands in the world. With a population of just under 400,000 people, it has the lowest population density in Europe, at 3.63 people per km^2 [31,32]. A total of 63% of the population lives in the capital region, with the rest dispersed through larger towns in the southwest and north as well as rural areas [31]. The climate is cold, with average annual temperatures around 5–6 degrees Celsius in the capital region; this leads to a high demand for space heating [33]. As a relatively unique energy and consumption context, Iceland makes an interesting EF case. Iceland has some of the highest living standards globally, and Icelanders enjoy access to electricity and district heating from almost exclusively renewable energy sources (hydropower and geothermal) [34]. These high living standards, combined with an isolated geography, cold climate, and sprawled urban form, however, are reflected in Icelandic consumption, where Iceland has one of the highest environmental footprints in the world [28,35,36]. Furthermore, analyzing the energy footprint of a high-share renewable energy system, as developed in Iceland, can provide important insights into possible correlations between energy consumption behavior and the perception of using clean renewable energy resources.

The data used to estimate the EFs and to study the spatial and socio-economic drivers came from a larger Nordic survey designed to measure the consumption-based carbon and energy footprints of residents in the Nordic countries (further description of the survey and data can be found in Heinonen et al. [37]). This survey was administered via a dedicated website (carbonfootprint.hi.is), and the survey was tailored to each Nordic country in terms of language, income levels, and specific footprint assessments. Its primary aim was to capture the consumption patterns, lifestyle behaviors, climate attitudes, and engagement in pro-environmental actions of the respondents while also collecting extensive background information, including household composition and income levels. Respondents were asked about their household income, with responses provided in income deciles corresponding to their country of residence. The 10th income decile was then divided into two, with the 11th representing the most affluent. Participation was restricted to adults who were involved in their household's financial decision-making, thereby focusing on a demographic capable of providing accurate and relevant consumption data.

From this survey dataset of ~8000 respondents, we utilized a subset of ~1500 responses from Iceland. In Iceland, the online survey was primarily actively promoted through social media channels during the autumn of 2021 and spring of 2022, leading to ~3000 responses, of which the mentioned ~1500 were completed. The Icelandic portion of the survey saw a notably higher participation rate relative to the country's total population (~380,000), compared to other Nordic countries. This robust response rate enhances the relevance and applicability of the findings to the Icelandic context. After excluding outliers to prevent a skewed result, the final sample sized used for this paper was 1511. Information about the sample including the variables used in the regression analyses can be seen in Table 1.

Table 1. Sample information including the variables utilized in the regression analyses.

Sample Size (N)	**1511**
Political orientation	
Green	7.2%
Left	32.8%
Center	18.9%
Right	12.9%
Other/no preference	28.1%
Housing size and type	
Average living space size (m^2/cu)	61.4
Apartment	55.8%
Semi-detached/Row-house	20.7%
Detached house	23.5%
Gender	
Male	46.4%
Female	52.1%
Other	1.5%
Income	
Average personal income (€/cu)	3266
Average household income (€)	6583
Low income group (decile 1–4)	27.9%
Medium income group (decile 5–8)	31.1%
High income group (decile 9–11)	41%
Education	
Low education	22.2%
Vocational	13.9%
Medium education	28.1%
High education	35.9%
Degree of urbanization	
Urban	71.7%
Semi-urban	11.6%
Rural	16.6%
Age	
Average age	43
Early adulthood	39.7%
Early middle age	29.5%
Late middle age	18.1%
Late adulthood	12.7%

Table 1. *Cont.*

Sample Size (N)	1511
Household size and composition	
Average consumption unit	2.1
Single adult	17.8%
2+ adults	37.8%
Single parent	5.7%
Couple w/children	38.7%
Domain participation	
Vehicle ownership	90%
Leisure travel participation	52.2%
Public transport participation	24.7%
Second home ownership	22.9%

2.2. Energy Footprinting

In this study, energy footprints in Iceland were determined using a tailored consumption-based approach. This methodology employed a hybrid assessment model that integrated the household consumption survey responses regarding annual consumption patterns by domain (Housing, Transport, Food, Goods and Services, and Second Home) and energy intensity factors for these consumption categories. The energy intensity factors were developed using a hybrid approach using both process data for technologies (e.g., car types/fuel) as well as input–output (IO) approaches for financial flows (e.g., consumption of goods and services and food). For the sake of brevity, we provide below a short description of how the energy intensity factors were estimated for each domain. Expanded descriptions are provided in the Supplementary Materials with detailed information on the exact energy intensity factors used in each domain.

2.2.1. Functional Unit

The per capita unit is the most commonly used functional unit to capture the sharing that occurs within households [16], assuming that all household members have the same resource needs. However, this unit does not fully capture the economies of scale that exist within households. To address this limitation, this paper employs the consumption unit as its functional unit, avoiding the assumption of direct proportionality between the additional resources required by larger households and the number of people within the household. Each member is assigned a weight and the consumption unit is the sum of these weights [38,39]. The weight of each member is as follows:

- First adult aged 18 and over = 1.0;
- Additional adults aged 18 and over = 0.7;
- Each member aged under 18 = 0.5.

This approach results in higher footprints for multi-person households compared to the per capita unit by avoiding exaggeration of the sharing benefit (e.g., [40]). Our survey design also allowed us to separate the shared domains (Housing, Vehicles, and Second Home) from non-shared domains and allocate personal consumption to the respondent and shared consumption to the household, only dividing the latter with the consumption units in the household.

2.2.2. Housing

Survey respondents provided details about their housing type, decade of construction, heating mode, and home size. In this context, a household comprised either a single individual or individuals who live together as a family or in a family-like situation. They share living spaces and financial resources, excluding roommates. Personal energy consumption of housing is the sum of energy consumed through heating and electricity, divided by the size of the household. For homes that use secondary heating modes, an 80–20 split was assigned between the primary and secondary sources. The direct energy consumption per square meter (kWh/m^2) for district heating and electricity use (other than heating) was taken from data supplied by Icelandic energy providers [41]. The embedded energy of these energy services associated with transmission losses and energy infrastructures was estimated using Ecoinvent v3.6 [42] and Karlsdottir et al. [43], where the sum of the energy indicators in the Cumulative Energy Demand (CED) was used. For other heating modes, values on energy consumption per square meter from Vimpari [44] and the CED of different heating sources from Cherubini et al. were used [45]. Finally, the estimated housing EF was divided by the consumption unit of the household.

2.2.3. Transport

Transport was broken down into several subcategories to assess individual EFs relating to Vehicles, Public Transport, and Leisure Travel. In order to accurately calculate EFs of transport, it is important to collect data on vehicle kilometers traveled for individuals as well as types of vehicles used for transport. For calculating the EFs of transport, individuals were asked to provide detailed information about vehicle kilometers traveled for both privately possessed vehicles and public transport. In addition, the respondents were asked about the long-distance trips they had taken during the past 12 months. Below, the calculations are explained briefly, whereas full descriptions can be found in the Supplementary Materials.

Vehicles

Participants reported details on the number and type of vehicles (petrol, diesel, hybrid electric, plug-in hybrid electric, electric, etc.) in their household, along with the fuel efficiency, fuel type, and estimated distance driven in the past year by each vehicle. These values were used to estimate the total fuel use per vehicle in a household and the share of the production and maintenance energy to allocate to each vehicle. The energy intensity factors, including the direct and the indirect components, for the different fuels (diesel, petrol, biodiesel, biomethane, natural gas, electricity) were extracted from the literature [46,47]. Multiplying these values, total energy use for that vehicle was estimated. Vehicle production and maintenance data were sourced from Chester and Horvath [48] for all internal combustion vehicles. For electric vehicles, a Life Cycle Assessment (LCA) value from the Ecoinvent v3.6 database [42] was used. These values were in kWh/km and were multiplied by the estimated distance driven in the past year. If individuals owned more than one vehicle, the values for each were added together. The per consumption unit EF of Vehicles was then derived by dividing the total EF by the number of consumption units in the household.

Public Transport

An average emission intensity for public transport was derived using data from Icelandic transport sources and environmental studies. Participants estimated their average weekly public transport use in km, which was extrapolated to determine their annual Public Transport EF. Indirect energy use from vehicle production and maintenance was derived from Chester and Horvath [48]. For direct energy consumption, fuel efficiency information for various bus types was sourced from the sustainability report of Iceland's largest public transport provider [49]. Calculations considered diesel, methane, and electrical buses, weighted by fleet composition. An average intensity was determined using the same energy content values for fuel as for the vehicles. These values were then divided by the average occupancy rate of public buses in Iceland [50].

Leisure Travel

Long-distance leisure travel was included in the survey, where respondents provided the estimated number of trips and distance per trip per vehicle mode. Long-distance train, ferry, bus, and plane trips were considered. For trains, information on direct and indirect energy use was sourced from Chester [51]. Energy use related to vehicle and infrastructure production and maintenance, as well as fuel production and supply chain considerations for buses and planes, was derived from Chester and Horvath [48]. Direct energy use for buses was also obtained from Chester and Horvath [48]. For direct energy use of ferries and indirect from fuel production, values from Åkerman [52] were used. For flight, fuel efficiency values from Amaas et al. [53] were used. Those values were then converted into kWh using greenhouse gas conversion factors published by the UK Government [54] for direct energy use estimation.

2.2.4. Goods and Services

Survey participants reported their personal purchases in various categories based on the Classification of Individual Consumption According to Purpose (COICOP), which were aligned with the EXIOBASE3 IO model [55], following a concordance matrix from Ottelin et al. [56]. Norwegian energy intensities from the Environmentally Extended Input-Output (EEIO) tables were used as a proxy for Iceland as Iceland is not included in the database. Inflation adjustments were applied to update the emissions' intensities to the survey year. The EF for each category was then calculated by multiplying the estimated expenditure (EUR) by the corresponding energy intensity factor (kWh/EUR).

2.2.5. Food

The EF of Food was calculated the same as Goods and Services, by multiplying the energy intensity of Groceries with the stated individual expenditure in that category. To determine the weight of each food category, EXIOBASE3 was used [55], where Norwegian consumption was used as a proxy for Icelandic consumption, and energy intensities were taken from the EEIO tables. For different diet types such as vegan, vegetarian, pescatarian, and omnivore, the calculations excluded food groups not aligned with those specific diets.

2.2.6. Second Home

Participants were asked if they possessed a second home, with a yes/no question. Those who answered positively were allocated EF values based on Heinonen and Junnila [57], considering respondents' degree of urbanization and type of housing.

2.3. Analytical Methods

To dissect the socio-economic and spatial factors influencing Icelandic EFs, our study employed primarily two analytical approaches. First, we utilized regression analysis to identify determinants of energy consumption patterns. This included multiple linear regression to assess continuous variables across different consumption domains and logistic regression for binary outcomes, such as the presence or absence of specific energy-consuming behaviors. In the domains of Vehicles, Public Transport, Second Home, and Leisure Travel, some respondents reported zero EFs due to non-participation (Table 1). For these domains, a binomial regression was used first to analyze participation, followed by a multiple linear regression for those who participated, studying the factors influencing the footprints. These methods followed similar approaches as previous studies (e.g., [58,59]) and are therefore only briefly described here.

Multiple linear regression is a statistical technique used to predict future values of a dependent variable or to measure the degree of association between a continuous outcome variable and two or more discrete and/or continuous predictor variables. It aims to quantify the impact of each independent variable on the dependent variable while accounting for the influence of other independent variables. In a multiple linear regression model with k independent variables, the equation takes the form:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_k X_k + \varepsilon \quad (1)$$

where:

- Y is the dependent variable.
- $X_1, X_2, \ldots X_k$ are the independent variables.

- β_0, β_1, β_2,. . . β_k are the coefficients that represent the relationship between each independent variable and the dependent variable.
- ε is the error term, representing the difference between the observed and predicted values.

In regression analysis, the F-test evaluates the overall significance of the model by collectively examining all coefficients to determine if the model as a whole explains a significant portion of the variance in the dependent variable. The coefficient of determination R^2 quantifies the proportion of the variance in the dependent variable that can be accounted for by the independent variables included in the model. It serves as a measure of the model's goodness of fit, ranging from 0 to 1, where higher values indicate a better fit.

Logistic regression was utilized for binary dependent variables, estimating the probability of occurrence based on independent variables. The model calculates the log-odds of the outcome using the equation:

$$ln\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k \tag{2}$$

where:

- p is the probability of the dependent variable occurring.
- X_1, X_2,. . . X_k are the independent variables.
- β_0, β_1, β_2,. . . β_k are the coefficients representing the impact of each independent variable on the log-odds of the dependent variable.

Odds ratios (ORs) are obtained by exponentiating each regression coefficient, transforming them from the log of the odds to an OR. The OR compares the odds of an outcome occurring given a particular exposure to the odds of an outcome occurring without it. An OR greater than 1 signifies a positive association between the independent variable and the dependent variable, while an OR less than 1 indicates a negative association. An OR equal to 1 suggests no association. The Hosmer–Lemeshow goodness of fit test shows how well the data fit the model. It results in a chi-square value (X^2) and a significance value. A large significance value indicates a good fit and small significance value indicates a poor fit. The Nagelkerke R^2 determines the proportion of the variance in the outcome that can be predicted by the model.

The Interquartile Range method, employing a factor of 2.2 [60], was used to detect and exclude outliers, preventing skewed results. Additionally, a natural logarithm transformation was applied to enhance the normality of the data distribution. The independent variables were chosen as they have been found to be influential in other studies taking a consumption-based perspective on energy or carbon [10,59,61–64]. The independent variables were checked for multicollinearity using the Variance Inflation Factor, which was under 2 in all the regression models, indicating low multicollinearity among the predictors.

Secondly, our spatial analysis leveraged Geographic Information Systems (GIS) to map and analyze energy consumption across Iceland's geography. To accomplish this, auxiliary spatial data were used. While this study is the first to examine EFs using participants' exact locations, the methodology builds on the work by Jones and Kammen [63] on household carbon footprints. Vector data from [64] were used both as a base map as well as for assigning participants to 42 statistical output areas (SOAs) in QGIS. Smaller-scale statistical areas exist, but the population size of the survey data within these smaller subsets set did not allow for meaningful comparisons within them.

3. Results

The study found that the average EFs in Iceland reached 40,400 kWh/cu/year (Figure 1). Housing and Vehicles were the two dominating domains. As can be seen, the average footprints increased as the income decile increased, with average footprints at ~35,000 kWh/cu/year in the lowest income segment (deciles 1–3) and close to 55,000 kWh/cu/year in the 11th bracket. There was a clear leap from the 10th to the 11th income bracket, indicating that those in the 11th bracket had much higher affluence than those in the 10th, whereas from the 1st until the 10th, the bracket-to-bracket differences were relatively small (see the Methodology Section for details about the income brackets). The footprints also increased in every domain along with income, except for Public Transport and Food. The highest difference was observed in the Housing domain, where those in the 11th income bracket had 27,690 kWh/cu/year compared to 13,298 kWh/cu/year in income decile 1. Other domains where significant growth along the income brackets could be seen were Goods and Services, Leisure Travel, and Vehicles.

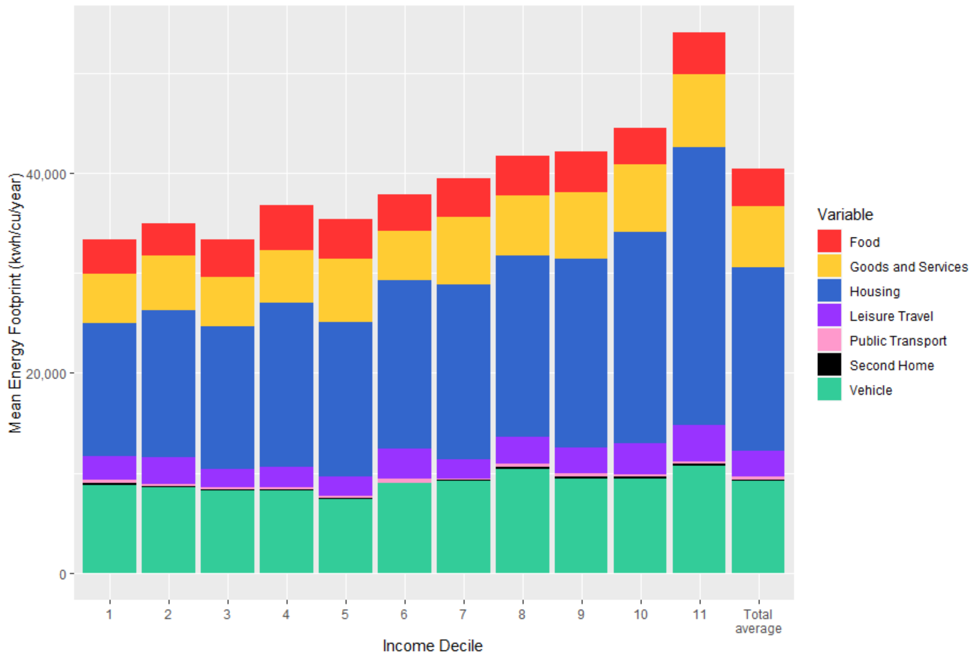

Figure 1. The average EFs in each consumption domain by income deciles and the sample average.

3.1. The Geography of Energy Footprints in Iceland

A spatial trend was also observed. As the degree of urbanization decreased, the average EF increased, where rural areas had the highest EF (43,172 kWh/cu/year) followed by semi-urban areas (41,514 kWh/cu/year) and urban areas (39,572 kWh/cu/year) (Figure 2). The differences relate mainly to the domains of Housing and Vehicles, the highest contributing domains. Interestingly, urban residents exhibited the highest EFs in the domains of Food, Goods and Services, Leisure Travel, Second Home, and Public Transport, with a difference of over 1000 kWh/cu/year in the Leisure Travel domain compared to rural areas. However, the differences were not as pronounced in these domains as those observed in Housing and Vehicles, leading to rural residents having the highest total average.

The geographic distribution was also uneven. Figure 3 shows Iceland divided into 42 statistical output areas (SOAs) and their average EFs per cu per year, with a map insert for the capital region. While the small sample sizes outside the capital region did not allow for comparison between individual SOAs, the capital region clearly showed a spatial pattern: EFs were lowest in the city center and increased towards the suburbs. This trend was primarily driven by lower-than-average EFs in the Vehicles and Housing domains in the city center. Appendix A shows the domain footprint variation across the SOAs.

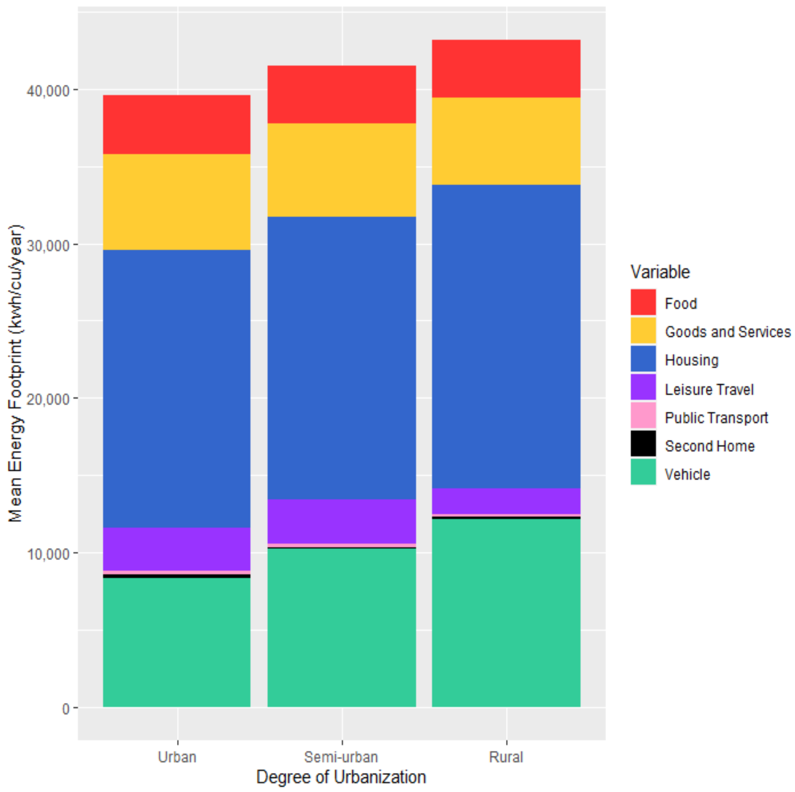

Figure 2. The average EFs in kWh/cu/year in each consumption domain by degree of urbanization.

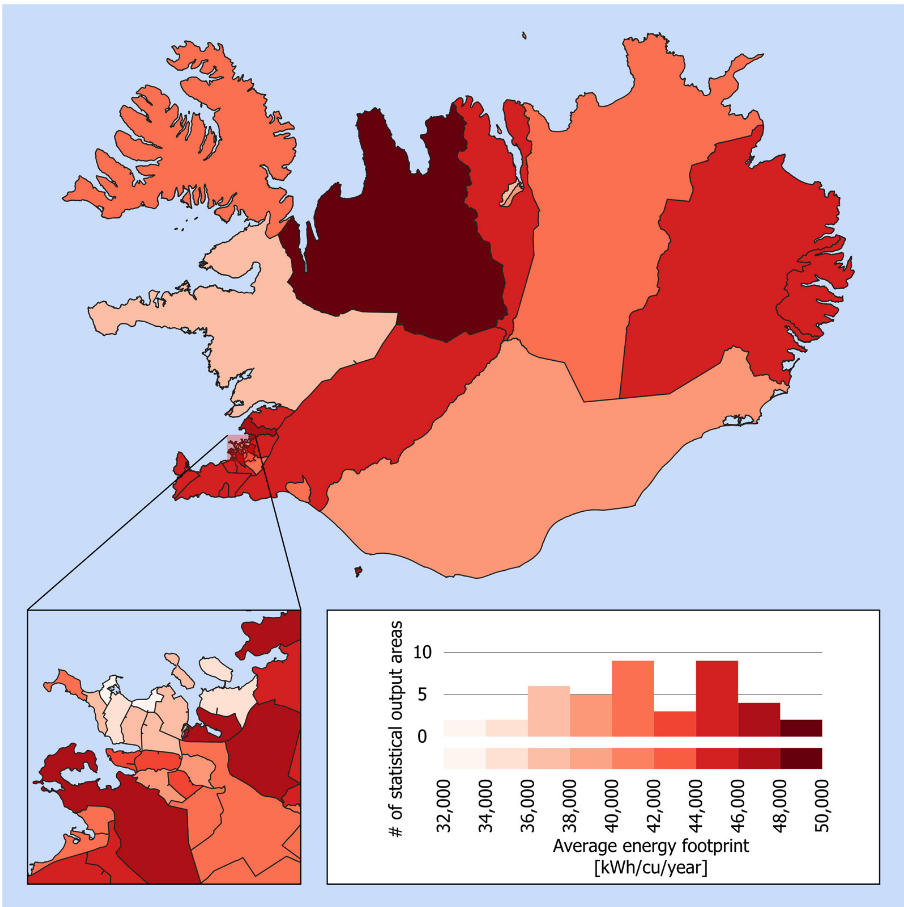

Figure 3. Average energy footprints by Statistical Output Area. Map insert for the capital region.

3.2. Predictors of High Energy Footprints

To study further the influences of socio-economic and spatial factors, a multiple linear regression was run for the Total EF and for the domains of Housing, Food, and Goods and Services (Table 2). For domains with an important share of the sample not participating at all (Vehicles, Public Transport, Leisure Travel, Second Home), first a binomial model was run, which continued with a linear regression to those participating in the domain (Table 3).

Income level was found as a strong predictor of the Total EF, with medium income level displaying a significant positive association with the Total EF (β = 0.122, $p < 0.001$) compared to those with low income and high income demonstrating an even more pronounced positive impact (β = 0.231, $p < 0.001$). Interestingly, though, detached from the income impact, political orientation showed a significant positive relationship with the Total EF among those identifying as center (β = 0.116, $p < 0.01$), right (β = 0.210, $p < 0.001$), and other/no preference (β = 0.122, $p < 0.01$) compared to green.

Table 2. Multiple linear regression models of the Total EF and the EFs for Housing, Food, and Goods and Services.

Multiple Linear Regressions N = 1511		**Total**	**Housing**	**Food**	**Goods and Services**
Model No.		**1** **β**	**2** **β**	**3** **β**	**4** **β**
	Intercept	10.342	9.522	7.601	7.863
Political orientation	Green	-	-	-	-
	Left	0.039	0.042	0.039	0.092
	Center	0.116	0.037	0.134	0.148
	Right	0.210	0.073	0.188	0.354
	Other/No preference	0.122	0.070	0.151	0.130
Housing type	Apartment	-	-	-	-
	Semi-detached/Row-house	0.128	0.173	0.012	−0.003
	Detached house-	0.272	0.401	0.013	−0.021
Gender	Male	-	-	-	-
	Female	0.025	0.012	−0.027	0.022
	Other	−0.152	−0.035	−0.305	−0.128
Income level	Low income	-	-	-	-
	Medium income	0.122	0.182	0.058	0.230
	High income	0.231	0.345	0.045	0.313
Education level	Low education	-	-	-	-
	Vocational	−0.011	−0.036	0.080	0.030
	Medium education	−0.036	0.024	−0.023	0.053
	High education	−0.046	0.013	0.072	0.109
Urban degree	Urban	-	-	-	-
	Semi-urban	−0.003	−0.036	−0.060	−0.053
	Rural	−0.058	−0.115	−0.062	−0.178
Age group	Early adulthood	-	-	-	-
	Early middle age	0.019	0.055	0.052	0.098
	Late middle age	0.151	0.266	0.148	0.101
	Late adulthood	0.177	0.274	0.163	0.066
Household composition	Single adult	-	-	-	-
	2+ adults	−0.174	−0.354	0.174	0.116
	Single parent	−0.078	−0.128	0.327	0.271
	Couple w/children	−0.222	−0.425	0.349	0.260
R^2		0.27	0.29	0.06	0.08
F		26.37	28.631	4.384	5.85

Note: $p < 0.05$ highlighted in green, $p < 0.01$ highlighted in yellow, and $p < 0.001$ highlighted in red.

Table 3. Binomial regression models of Vehicles, Public Transport, Leisure Travel, and Second Home and multiple linear regression models of Vehicles, Public Transport, and Leisure Travel.

		Vehicles		**Public Transport**		**Leisure Travel**		**Second Home**
Regression Type **Sample Size**		**B** [1] **N = 1511**	**L** [2] **N = 1360**	**B** [1] **N = 1511**	**L** [2] **N = 373**	**B** [1] **N = 1511**	**L** [2] **N = 788**	**B** [1] **N = 1511**
Model No.		**5** **OR**	**5a** **β**	**6** **OR**	**6a** **β**	**7** **OR**	**7a** **β**	**8** **OR**
	Intercept	0.86	8.952	0.77	6.526	0.91	8.259	0.15
Political orientation	Green	-	-	-	-	-	-	-
	Left	0.93	0.106	0.92	−0.214	0.81	−0.062	0.84
	Center	2.02	0.295	0.48	−0.043	0.73	−0.062	1.05
	Right	1.93	0.346	0.26	0.035	1.13	0.250	1.37
	Other/No preference	1.54	0.269	0.47	0.206	0.76	0.039	0.73
Housing type	Apartment	-	-	-	-	-	-	-
	Semi-detached/Row-house	1.92	0.110	1.07	0.050	0.91	0.173	1.12
	Detached house	3.60	0.152	0.69	0.248	0.87	0.163	1.28
Gender	Male	-	-	-	-	-	-	-
	Female	1.00	0.010	1.04	−0.004	1.40	0.0067	1.24
	Other	1.02	−0.177	2.44	0.452	0.49	−0.631	0.71
Income level	Low	-	-	-	-	-	-	-
	Medium	1.68	0.117	1.12	0.043	1.22	−0.068	1.20
	High	2.45	0.144	0.95	0.025	1.61	−0.062	1.39
Education level	Low	-	-	-	-	-	-	-
	Vocational	0.76	−0.028	0.97	−0.230	0.89	0.008	1.32
	Medium	0.69	−0.148	1.42	−0.228	1.24	−0.057	1.41
	High	0.48	−0.260	1.78	−0.401	1.21	0.040	1.48
Urban degree	Urban	-	-	-	-	-	-	-
	Semi-urban	1.78	0.100	0.55	0.226	1.35	−0.155	0.58
	Rural	2.24	0.169	0.23	0.367	0.91	−0.472	0.58
Age group	Early adulthood	-	-	-	-	-	-	-
	Early middle age	1.73	−0.180	0.77	−0.004	0.98	−0.018	0.90
	Late middle age	2.67	0.000	0.51	0.134	1.00	0.033	1.00
	Late adulthood	4.89	−0.050	0.49	0.042	0.76	0.054	1.73
Household composition	Single adult	-	-	-	-			
	2+ adults	3.15	−0.186	0.83	0.037	0.93	−0.041	1.38
	Single parent	4.26	−0.252	0.62	−0.111	0.86	−0.216	1.01
	Couple w/children	13.39	−0.399	0.75	−0.157	0.88	−0.359	1.23
Nagelkerke R^2		0.28		0.17		0.05		0.06
X^2 goodness of fit [3]		5.15		10.215		5.328		6.81
R^2			0.10		0.08		0.06	
F			6.994		1.475		2.322	

Notes: $p < 0.05$ highlighted in green, $p < 0.01$ highlighted in yellow, and $p < 0.001$ highlighted in red. [1] Binomial regression model. [2] Multiple linear regression model. [3] Hosmer–Lemeshow test of goodness of fit.

Housing type also had a strong impact as could be expected based on the bivariate results. Individuals residing in semi-detached/row-houses (β = 0.128, $p < 0.001$) and detached houses (β = 0.272, $p < 0.001$) showed a significant positive relationship with the Total EF compared to those in apartments. Household composition showed a significant negative relationship with the Total EF in the couple (β = −0.174, $p < 0.001$) and couple with children groups (β = −0.222, $p < 0.001$) compared to single adults, indicating the economies-of-scale effect beyond what is captured by the consumption unit as utilized as the functional unit in this study. Late middle age and late adulthood were associated with higher Total EFs ($\beta = 0.151$, $p < 0.001$ and $\beta = 0.177$, $p < 0.001$, respectively), compared to early adulthood.

Very similar trends were observed in the Housing domain (model 2) except that political orientation was not found as significant. Income exhibited a significant positive relationship with the EF of Housing, with the EF increasing with increased income. Unlike with the Total EF model, urban degree was found as a significant factor in the Housing domain with rural compared to urban ($\beta = -0.115$, $p < 0.01$).

In the Food domain (model 3), only 6% of the variability was explained by the model, which indicates that important predictors were missing. Unlike the Total and Housing domain, income lacked statistical significance. Significant results included a positive association of older age and larger households with higher EFs in the Food domain. Political orientation towards right and other/no preference were found to predict a higher Food EF compared to green. Additionally, gender other showed a significant negative effect compared to male ($\beta = -0.305$, $p < 0.5$).

Only 8% of the variability was explained by model 4 for the Goods and Services domain. Income level demonstrated a significant positive relationship, consistent with the Total EF and EF of Housing. Household composition also played a role, with larger households having positive associations compared to single adults. Rural residency ($\beta = -0.178$, $p = 0.003$) was associated with a significant decrease in the EF of Goods and Services, suggesting urbanization's influence on consumption. Of political orientations, only identifying as right had a statistically significant effect ($\beta = 0.354$, $p < 0.001$) compared to green.

The rest of the domains were first studied with a binomial model for the drivers of participation in the domains and then with a linear model for the predictors of the EF size when participating (Table 3). With the Vehicles domain (model 5), income, housing type other than apartment, older age, rural residency, and more than one household member were associated with increased odds of owning a vehicle. The highest odds ratio was observed in the couple with children category, with individuals in this group being 13.39 times more likely to possess a vehicle than single adults.

When possessing a vehicle, the EF size predictors were interestingly found to be very similar to the possession predictors (model 5a), except that higher education was found to predict a lower EF and, contrary to the likelihood to possess a vehicle, a larger household size was found to predict a significantly lower EF from the Vehicles domain compared to single adults, reflecting the economies-of-scale effect.

The multiple linear regression model for Public Transport was not significant suggesting that the utilized set of predictors did not have a statistically significant effect on the variation in Public Transport use. The sample size was also small for the group using Public Transport (N = 373). Overall, the role of Public Transport in the full EF was found as low (Figures 1 and 2), potentially though magnified somewhat through it being an alternative for Vehicles. Of the few significant factors in the binomial model (model 6), political orientation other than green, higher age, and residency outside the most highly urbanized areas were found to reduce the likelihood of taking public transport, whereas high education level increased the odds of using public transport.

With Leisure Travel, only female gender and high income were found to predict participation with statistical significance. When participating, rural residency and household type of couple with children were the only statistically significant variables, both indicating lower energy footprints in the domain. Overall, therefore, the Leisure Travel models had quite limited explanatory power, indicating that the travel decisions were driven by other factors.

For Second Home, only a binomial model was run due to the limitations posed by the calculation method and due to the low significance of the domain. High income, a higher education level, a more urban residential location, and being in late adulthood were found to be associated with increased odds of owning second homes.

4. Discussion

This work performed a bottom-up analysis of Icelandic energy footprints from a consumption perspective across domains and ran regressions on the socio-economic variables that may have influenced these footprints. This marks a contribution by adding an Icelandic case study to the sparse literature on bottom-up footprints. The analysis produced interesting results that will be discussed here along with their policy implications, a review of some of the limitations of the approach, and avenues for future research.

4.1. High and Equal Footprints in Iceland

First, reviewing the average Icelandic results, it could be seen that the average total EF (40,400 kWh/cu/year) was similar to bottom-up EFs found in the UK (44,000 kWh/cap/year) [10] and somewhat higher than the ~36,000 kWh/cap/year reported by Villamor et al. [65] for Spain and the 41,000 kWh/cap/year for the Basque country. Interestingly, however, the variation across income groups in Iceland, particularly within deciles 1–10, was much lower than that in the UK (~±100%). We considered three possible explanations for this. First, and likely most significant, was Iceland's lower income inequality (2022 Gini Index = 24.2) [66] as compared to the UK's (2022 Gini Index = 34) [67]. Second, our use of consumption units instead of the more typical per capita may also have reduced the variation as it better captures the within-household sharing effect (e.g., [40]). Third, in the UK study [10], they found that the growth in EFs between income deciles was mainly driven by private car and air transport. Although we observed an increasing trend in our footprints (Figure 1) between income deciles in Leisure Travel and Vehicles, it was not as pronounced as in the UK EFs. This could be attributed to the timing of the survey, which took place during the COVID-19 pandemic, affecting people's travel behavior, but also to Icelandic households, to a very high extent, possessing cars even in the lower end of the income range [68].

Placing these footprints in a sustainability context, however, the footprints' values remained significantly in excess of the sufficiency threshold suggested by works such as the Decent Living Standards or Low Energy Demand scenarios (~15,200 kWh/cap/year for Global North) [9,13,14] and certainly more than the 2000 Watt society idea (17,520 kWh/cap/year) [69]. Connecting back to the lower income inequality seen in Iceland as compared to the UK, this also implies that even the lowest earners see high EFs, illustrating the potential challenges associated with further reducing these footprints.

Income was found as an important predictor of the EF, similar to many other energy and carbon footprint studies [10,19,70]. Housing energy was both the largest individual domain and the source of the main variation across income groups. The regressions also revealed that, along with income, living in detached and semi-detached houses, smaller family size, and older age were all associated with higher footprints. In Iceland, energy is perceived as very cheap and the building stock has low energy efficiency, despite the necessity for heating homes all year round due to the country's cold climate. Virtually 100% of the stationary energy production is also renewable, which might have led to a situation in which not saving energy is considered acceptable. In reality, Iceland is already facing the challenge of meeting the increasing heating energy demand with the current production infrastructure, making energy sufficiency still an important discussion topic.

However, even without the Housing domain, the EFs in Iceland were well above the abovementioned sustainable level of 15,200 kWh/cap/year. The Vehicles domain alone reached this level in the rural areas, where virtually all households possess at least one car. The Vehicles' EF was high in the more urbanized areas as well, even in the capital region, stemming from the overall very strong car orientation in travel preferences in Iceland [68]. While Food was not a significant contributor to the EFs, it was interesting to see that there appeared to be some positive correlation between no political orientation/right orientation and increased Food EFs. This same effect could be seen in the Goods and Services category, where the influence of such leanings has been found in other studies to connect to climate concern and thus pro-environmental behaviors, such as changing diet [71].

4.2. The Geography of Energy Footprints in Iceland

While observed differences were small, the EFs increased towards less urbanized areas. The urban degree variable itself was not found to be significant in the regression for the total EF, but a lower degree of urbanization was found to predict a higher level of vehicle possession and more use when possessed. Moreover, an interesting, though potentially to-be-expected, contrast could be seen between urban and rural sub-groups, where urbanites compensate for the lower vehicle footprints with more leisure travel, reflecting the findings of previous studies in Iceland [72]. Urban dwellers also saw higher Public Transport EFs, though even in urban settings public transit use has historically remained significantly low [73,74], leading to high vehicle energy use for all groups; though, due to the extremely low population density in the countryside, this was particularly high for the rural sub-group.

Beyond the urban degree variable, Figure 3 shows how there was a concentration of low EFs in the central regions of Reykjavik and an increasing pattern towards the outer edges of the capital region. A concentration of very high footprints was also found from the northwestern part of the country. But, due to low sample sizes in the most rural types of areas of the country, it was not possible to further analyze this finding.

4.3. The Value of Taking a Bottom-Up and a Consumption-Based Perspective

A worthwhile note to make is the importance of taking a bottom-up and consumption-based perspective in a country such as Iceland, which has a small population and sees the presence of significant heavy industries, which can contort the energy use numbers. For example, many graphics such as in Our World in Data's primary energy consumption per capita (taken as a simple top-down example, but many such graphics exist) attribute more energy use per household (165,871 kWh per household per year) to Iceland than to almost any other country in the world, though our work here shows that this consumption-based bottom-up approach shows EFs much more in line with other nations.

Furthermore, we followed the so-called personal consumption-based footprint approach [16], which allocates to the consumers all direct and indirect energy use related to the goods and services they purchase and use regardless of the location where this happens. Most existing, typically top-down, consumption-based studies adopt the so-called areal footprint approach, which includes all consumption activities within the area in question, be the consumers locals or visitors, and excludes the consumption of locals outside the area. In touristic locations and particularly in sub-national scale assessments, this choice might significantly affect the outcome. The areal consumption-based studies also typically include capital production and governmental consumption, whereas in a personal consumption-based approach, they cannot be straightforwardly allocated to a consumer [16]. The personal consumption-based approach allows for direct comparisons across space and groups of people, which makes it a valuable information source for policymaking.

4.4. Policy Implications

The findings from our bottom-up analysis of Icelandic EFs underscore the urgent need for policy interventions that target both the housing and transportation sectors. National energy companies and institutions have raised concerns regarding both how the electricity and district heating networks are running at near full capacity [29,30], driven by increased population, lower housing densities (fewer people per m^2 of living facilities), and high energy use per person. Further, due to the renewable nature of this energy supply and a sprawled urban form in Reykjavik, transport has been found to be the leading domain of carbon emissions for Icelandic households, accounting for ~38% of Icelandic consumption-based carbon footprints [28].

Considering how to reduce this pressure on the energy system and related impacts associated with energy use, improved energy efficiency and sufficiency are the two primary levers available. In terms of energy efficiency, subsidies could be made for insulation retrofits and for more energy-efficient appliances. These are likely to be expensive solutions, however, and ones that might be difficult for households to justify when energy is viewed as inexpensive. In terms of mobility, the Icelandic government has already put in place subsidies to support the transition to more energy-efficient electric vehicles, which could be seen as successful in the sense that Iceland typically is in the top percent of new registrations of electric vehicles [75]. Due to Iceland's highly decarbonized grid, this provides additional benefits of GHG mitigation [76]; however, this high level of EV use also has the potential for a significant additional electricity demand on an already strained grid [77].

Considering these potential limitations to efficiency improvements, and due to rebound effects, sufficiency policies should be considered. An effort to improve urban density would have the dual benefits of reducing floor space per person, with more people living in apartments as compared to houses, as well as increasing the potential for public and active modes of transport [50,78]. Due to the perception of cheap and abundant clean energy, education would also be a crucial pillar to improving energy sufficiency in Iceland by helping the Icelandic population recognize the limitations of its energy system. Lastly, while due to COVID, the EFs associated with flying are likely nulled, efforts to increase the knowledge of flight impacts to reduce the number of flights taken would aid in keeping a lower EF, where, if the number of flights returns to normal, which has already been seen globally [79], Icelandic EFs are likely to rise significantly.

4.5. Limitations and Future Study

This study's findings are subject to some data-related and methodological limitations. First, regarding data, the timing of the survey during the COVID-19 pandemic could have influenced respondents' consumption and, particularly, travel habits. Due to travel constraints, this likely underestimated travel-related EFs, even though >70% of the respondents still participated in international travel. It is, anyway, likely that the COVID-19 restrictions affected the life of urban residents more than life in rural areas. Further, biases such as self-reporting, selection bias, and social desirability bias might have skewed the sample towards respondents inclined towards lower-energy lifestyles. Moreover, the representativeness of the survey data is limited, as the survey prioritized response quality over representativeness, as described in Heinonen et al. [37], resulting in a sample with higher urban, education, and income (~67,000 ISK/460€ higher) levels that may not fully reflect the general population's socio-economic and spatial distribution. Due to the higher equality and small proportion of Iceland's population affected by energy and transport poverty [74,80], we expect this to have a more reduced effect than in other locations.

In terms of methodological limitations, the reliance on multi-regional IO data for some of the domains, particularly the use of Norwegian data as a proxy for Iceland in the absence of specific Icelandic data within EXIOBASE, introduces uncertainty but is established practice in the literature (e.g., [81]). Further, the concordance mapping of survey data domains to EXIOBASE IO tables introduces subjective judgement that can vary across studies. The hybrid nature of our approach, taking direct energy use values for homes, process LCA for other domains, and IO data only for Food and Goods and Services, aids in reducing this uncertainty. Lastly, as commonly seen in personal consumption-based approaches [16,70], government consumption and capital formation, which may have significant EFs on which personal consumption may depend, were considered outside of the study boundary, but these exclusions should be taken into consideration when making cross-study comparisons [82].

Future studies could address some of these limitations by employing weighted datasets to improve representativeness or distributing a similar survey that could (a) reflect the "return to normal" post-COVID and (b) allow for temporal analysis. Further, studies could expand the scope of EF calculations to include government consumption and capital formation, thereby providing a more comprehensive assessment of environmental impacts. Particularly, the inclusion of these in the coefficients for final products would be an important advancement [83], allowing allocation of them to the consumers, following the personal footprint principle [16]. Additional important steps beyond the current study and the utilized EF methodology would be to differentiate between domestic and outsourced energy use and between renewable and non-renewable sources. Lastly, interesting avenues for future research similar to Baltruszewicz et al. [10] would be provided by connecting the EFs to various well-being indicators to understand how EFs connect to well-being in Iceland. This could potentially assist in evaluating what an energy-sufficient lifestyle in Iceland might look like and help in shaping policies that could support greater energy sufficiency. Building from this perspective, with sufficiency policies that entail behavioral and lifestyle changes, it could additionally be worthwhile to consider the political viability of various approaches to build social buy-in for such policies.

5. Conclusions

In conclusion, our study advances the understanding of Icelandic energy footprints through a comprehensive bottom-up analysis, delineating the impacts of socio-economic factors across different consumption domains. By navigating the intricacies of Iceland's unique energy context—characterized by high renewable energy production yet significant direct and indirect energy—we uncovered the complex interplay among lifestyle, income, urbanization, and energy use. Despite Iceland's facade as a country with a seemingly plentiful supply of renewable energy, energy sufficiency retains importance due to local infrastructural limitations as well as global impacts related to high levels of direct (flights, combustion vehicles) embedded energy use, associated carbon emissions, and other relevant environmental impacts (goods and services, food). This work not only contributes to the scarce literature on bottom-up energy footprint analysis but also provides actionable insights for policymakers to target high-impact domains such as housing and transportation as well as giving important insight into possible rebound effects resulting from high-share renewable energy systems where the perception of green energy can potentially increase energy consumption. Recognizing the limitations imposed by methodological approaches and data constraints, we call for future research to explore the interconnections between energy footprints and well-being, aiming to identify pathways towards energy sufficiency that do not compromise quality of life.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/en17102375/s1: The full method description for the Consumption-Based Energy Footprint Calculations. Table S1. Energy consumption of district heating and electricity use in kWh/m^2/year by housing type. Table S2. Embedded energy in kWh per kWh of district heating and electricity use in Iceland. Table S3. Energy consumption per m^2 (kWh/m^2/year) by housing type. Table S4. CER for heating sources other than district heating and for Icelandic district heating and electricity. Table S5. Energy content in kWh per unit of fuel. Table S6. Ratio of energy required to produce one unit of final energy. Table S7. Energy intensities in kWh/EUR from EXIOBASE3 for different consumption categories. Table S8. Energy intensities in kWh/EUR obtained from EXIOBASE3 for Food based on diet types. Table S9. Energy use in kWh per passenger km traveled for different transport modes. Table S10. Energy use of second home in kWh per household per year by degree of urbanization and housing type [84–87].

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Abbreviations

CED	Cumulative Energy Demand
COICOP	Classification of Individual Consumption According to Purpose
EEI	Environmentally Extended Input-Output
EF	Energy Footprint
IO	Input–Output
LCA	Life Cycle Assessment
SOA	Statistical Output Area

Appendix A

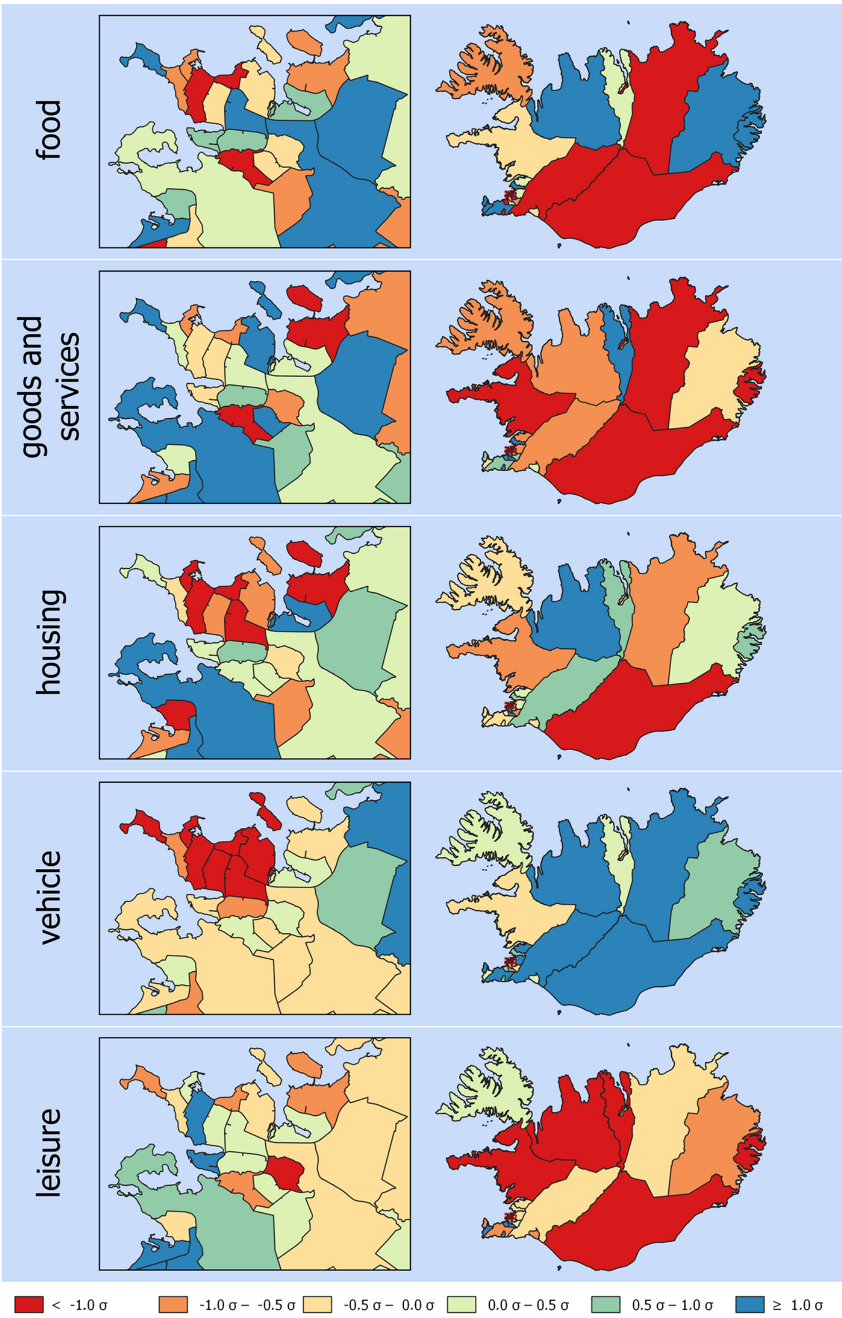

Figure A1. Standard deviations of energy footprint domains from the statistical output area averages.

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