ICT Sufficiency is Necessary: Results from Simulating Four Possible Futures

1st Gabriel Andy Szalkowski
Dept. of Inf. Sec. and Communication Tech.
Norwegian University of Science and Technology
Gjøvik, Norway
gabriel.szalkowski@ntnu.no

2nd Iwona Maria Windekilde
Dept. of Inf. Sec. and Communication Tech.
Norwegian University of Science and Technology
Trondheim, Norway
iwona.windekilde@ntnu.no

***Abstract*—To ensure that information and communication technologies (ICT) have a positive environmental impact, it is imperative to address their negative consequences. While efforts to enhance efficiency and ensure consistency in ICT production, use and disposal are essential, this study suggests that sufficiency measures are indispensable. This research provides evidence for this claim by developing a simulation model applied to studying the environmental impact of the interaction of a population, a government and a major technology producer, within four environmental policy scenarios. The results demonstrate that sufficiency measures are not only highly effective in mitigating emissions and e-waste but also represent a necessary condition for achieving our climate goals in the shortest time frame possible. The model provided in this research can serve as the basis of future policy studies and could have the potential to become a decision-support mechanism for policymakers.**

***Index Terms*—ICT4S, sustainable technology, simulation, technology policy, environmental policy, sufficiency**

I. INTRODUCTION

In the context of environmental sustainability, Information and communication technologies (ICT) can have both negative and positive contributions [1], while the nature of their net effect remains an open question [2]. To tilt the balance toward net positive, the negative environmental impacts of ICT, responsible for between 2.1% to 3.9% of global emissions [3], must be acknowledged and accounted for in policy making [4].

To address the unsustainability of the current system of production and consumption [5], especially in the context of ICT [6], three types of measures can be implemented, focusing on (i) *Consistency*, namely "closing material and nutrient cycles and bringing cycles of industrial production and consumption in line with natural cycles, including those of water, air, climate, or soil recovery", [2] (ii) *Efficiency*, "reducing resource and energy inputs per unit of service or product" [2], and (iii) *Sufficiency*, "decreasing the absolute level of resource and energy use by reducing the levels of production and consumption". (Similar to the concept of degrowth [6]). While the main focus of research and policy is often on consistency and efficiency [7], it is not a viable strategy if done in an unconstrained manner [4]. In fact, current research argues that digital sufficiency is a necessary goal for designing policies to effectively reduce the negative environmental consequences of ICT [2].

This paper provides a practical implementation of several measures intended for reducing the environmental impact of ICT, with an explicit focus on sufficiency, exploring the effects of interventions such as the ones described in [2]. This is done by providing a dynamic simulation tool for studying different policy scenarios, to demonstrate that sufficiency is both effective and necessary in achieving our climate goals. The simulation models the interaction between the population of a country, the government of the country, and a large technology-producing company, such as Apple or Samsung. In this study, four different scenarios are simulated, covering a range of approaches to environmental policy and sustainable development, based on measures from scientific literature (section III).

The first scenario presents a baseline situation where only efficiency improvements are implemented, with a heavy focus on inexpensive electricity and fast production cycles. Scenario 2 implements a set of consistency-focused measures, reducing considerably the environmental impact of the technology produced by the business. Scenario 3 presents a set of sufficiency measures in addition to the consistency improvements. Additionally, scenario 3 offers the perspective of a traditional sales business model (Scenario 3a) and a device-as-a-service[1] model (Scenario 3b), showing that the latter is superior both in terms of environmental outcomes and business indicators. Finally, Scenario 4 implements the extreme approach of an eco-centred totalitarian regime, that despite greatly reducing the negative environmental impacts of technology, considerably slows down technology adoption.

To analyse the results of the simulation (section V) three environmental indicators, namely energy consumption, CO_2 emissions, and e-waste are studied, as these are the most frequent indicators that appear in literature [9]–[13]. Further analysis is performed using a set of economic indicators that offer insight into technology adoption and business outcomes.

The results of this study should serve as a call for policymakers to implement more sufficiency-focused measures with regard to ICT. Moreover, the tool provided alongside this paper can be used and extended to explore different scenarios to

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[1] The device-as-a-service model is "a procurement model combining device leasing and managed services into a single periodic payment to one provider" [8]

the ones presented here, possibly assisting in decision-making processes in environmental and technological policy.

II. RELATED WORK

Recent research has shown that sufficiency is a key aspect of the sustainable development of ICT [14]. This claim is based on the fact that an exclusive focus on increasing efficiency leads to higher consumption due to higher-order effects, such as rebound effects [15], [16]. Furthermore, it is not sufficient to increase the consistency in the use and production of ICT [14], [16]. However, despite a progressive shift to studying sufficiency in the ICT and sustainability research community [6], [15], [17], the research on measures and policies to reduce the environmental impact of ICT still focuses to a high degree on solutions to first-order (direct) effects [13]. Because of this, the solutions to the negative higher-order impacts of ICT, addressed by sufficiency measures, remain largely under-researched [13], especially regarding regulations.

Several authors take a more comprehensive perspective to close this gap, addressing specifically higher-order effects and shifting the discussion towards sufficiency. For instance, the authors of [6] perform an in-depth qualitative analysis of the relationship between ICT and degrowth (closely related to sufficiency). Another example on the qualitative side is [17], where the authors analyse sufficiency measures for addressing rebound effects in remote work.

On the quantitative side, especially relevant to this research are simulation studies. One can find examples of studies that develop simulations of solutions to higher-order effects on a community [18] and country level [19]. However, these studies are not specifically focused on ICT. One attempt at bridging this gap was [20], where the authors simulated the implementation of one specific measure to mitigate rebound effects in the streaming service industry. This example, however, was very limited in scope. There have also been exhaustive large-scale simulation studies such as [21], that assess the impact of ICT on several sectors, although not explicitly focusing on sufficiency. In [21], however, the authors remark on the benefits of a product-to-service shift as a condition for dematerialization, a concept that relates to the results of this paper.

III. POLICY SCENARIOS

In this section, we define four national-level policy scenarios that will be used in the rest of the paper to study the environmental impact of the technology produced by a large company. Each scenario is characterized by a set of policies, designed to cover a range of approaches to sustainable development, from one extremely pro-fossil fuels society to eco-centered totalitarianism, and covering intermediate, more moderate, options.

A. Scenario 1. Profit-driven pro-fossil fuels society

This is a baseline scenario, fulfilling the role of a "worst-case" scenario, where climate change deniers have "won the battle" in most political arenas. Technological development and "profit at all costs" are the core values of this society. Fossil fuels are promoted as a cheap energy source to fuel development. The few people who may be worried about the effects of climate change are silenced, treated as outliers, or convinced that the effects of human actions on the environment are minimal in the present and will not have a meaningful impact until far in the future. This scenario could be interpreted as a pessimistic interpretation of some of the current trends, although it does not describe the present situation of environmental policy in most countries. In this scenario, the business model of the company is a traditional sales model.

This scenario is characterized by (i) Low eco-conscious population. (ii) High subsidies for fossil fuels, low investment in renewables, and decarbonization. This reduces the price of electricity and increases emissions, and could lead to producer-side, indirect rebound effects (Output effects) [22]. (iii) Standards for consistency in the production of technology are almost non-existent, so there is no control over the materials used, the recyclability of the products, the amount of energy used, etc. (iv) Companies are not responsible for the environmental impact of their products or their end-of-life treatment. There is no obligation for sustainability reporting. This results in an increase in emissions and e-waste, and enables actions such as greenwashing. (v) No required product warranty laws are in place. Planned obsolescence is legal and can be as short as desired by the manufacturer. No right–to-repair or backward compatibility laws are in place. This reduces the useful life of devices, thus increasing the amount of e-waste produced. (vi) Energy efficiency is only sought after if it provides economic benefit. There are, however, no limits on how much energy a specific device or group of devices consumes, leading to increased consumption due to rebound effects [4]. (vii) If energy production becomes cheaper, it also becomes cheaper for consumers to use electricity. This could potentially lead to consumer-side, indirect rebound effects (Income Effects) [22]. (viii) People are encouraged to buy new devices for every task. Consumerism is socially desirable, and there is no control over aggressive advertising promoting excessive consumption. (ix) Landfills are created to deal with e-waste. No proper recycling policies are enacted.

B. Scenario 2. Consistency-oriented solutions

In this scenario, most citizens know that the "greener" options are usually the better ones and many of them act accordingly. Most lawmakers are concerned with "doing the right thing", and "saving the environment" is a priority for them. The proposed measures are mostly focused on reducing the use of fossil fuels, increasing environmental corporate responsibility, and investing in recycling e-waste. This scenario could be considered to be an optimistic interpretation of present trends. In this scenario, the business model of the company is a traditional sales model.

This scenario is characterized by (i) Medium level of eco-consciousness in the population. (ii) In efforts to "transition away from fossil fuels"[2], subsidies for fossil fuels are reduced, and moderate investments are made into renewable energies and decarbonization efforts. (iii) Several standards are implemented to limit hazardous materials in the production of technology [23], facilitating recyclability while driving production costs up. (iv) Few required product warranty laws are in place. Planned obsolescence is a common phenomenon. No right-to-repair or backward compatibility laws are in place. (v) A moderate carbon tax on companies (as done in Australia [24]) promotes both the use of renewable energies and increasing efficiency. (vi) Sustainability accounting and reporting [25] is mandatory. Furthermore, companies are required to report on energy use, natural resources use, hazardous materials, and other sustainability indicators of their products. Transparency is enforced by governmental authorities. This also includes labelling digital devices with information about their environmental impact to influence customer choice. (vii) Companies are partly responsible for the environmental impact of their products. Mandatory take-back programs are implemented [26], where companies are obliged to accept old devices that customers want to throw away and ensure that they are properly recycled, in collaboration with local authorities. (viii) Investments are made at local, municipal, and national levels to properly recycle and dispose of e-waste. (ix) There is not much regulation on advertising. Targeted ads that promote buying new devices are allowed. (x) Efforts towards electrification of mobility take place. Electric vehicles and electrified public transport gradually take over combustion engines. (xi) Some ecosystem restoration projects take place (as suggested in [27]), resulting in changes in land use regulations and natural resource extraction.

C. Scenario 3. Sufficiency- and Consistency-oriented policies

After reviewing current research, the message of *sufficiency* as a requirement for sustainable development [2] (and thus possibly humanity's long-term survival) is received by politicians and lawmakers. In addition to the measures agreed upon in the COPs and recommendations from the IPCC, a set of measures for technological sufficiency are proposed and implemented. Although the primary goal is environmental sustainability, the economic side of the proposed measures is also taken into account. In this scenario, two business models will be explored, namely a traditional sales model (3a), and a device-as-a-service model (3b). In scenario 3b, the price of the subscription is set so that the time needed to amortize a device is two years[3].

This scenario is characterized by (i) Medium level of eco–consciousness in the population. (ii) In efforts to "transition away from fossil fuels", subsidies for fossil fuels are reduced, and moderate investments are made into renewable energies and decarbonization efforts. Renewable energies and recycling are prioritized over cheap electricity. (iii) Several standards are implemented to limit hazardous materials in the production of technology [23], facilitating recyclability and driving production costs up. (iv) Warranty periods are increased by law. As suggested in [2], companies are required to design electronic devices to facilitate their reparation, also if done by consumers (right-to-repair laws). Lowering maintenance costs and increasing the useful life of devices. (v) Planned obsolescence is controlled and made illegal in many cases, as it was a source of e-waste [28]. (vi) New software and hardware are required to ensure minimum backward compatibility with devices released 5 years prior. New functionalities should preferably be adapted to older devices too. This measure is based upon suggestions from [2]. (vii) Companies are responsible for the environmental impact of their products. Technology manufacturers must participate in wide-spread take-back programs [26], and ensure their products are properly recycled. (viii) Technology is taxed also based on the cost of proper e-waste treatment. A tax is introduced to compensate for some of the disposal of electronic waste. (ix) Investments are made at local, municipal, and national levels to properly recycle and dispose of e-waste. (x) A moderate carbon tax on companies (as done in Australia [24]) promotes both the use of renewable energies and increasing efficiency. (xi) To combat rebound effects in energy pricing [29], when producing electricity becomes cheaper it is taxed higher so that the final costs for consumers experience a slower increase. (xii) Standards about absolute energy expenditure are implemented, as suggested in [2]. There is a limit to the maximum energy consumption by electronic devices, which limits to some extent the development of new functionalities and more potent devices. (xiii) A one-device rule [2] is promoted both in private firms and public institutions. It is preferable to use the same computer both for work and personal activities. (xiv) Online advertising is restricted and taxed. Due to their considerable environmental impact [30], ads are also taxed based on the CO_2 emissions they produce. (xv) Advertising new technology products are heavily regulated, age-restricted, and allowed only on certain occasions, as this could potentially reduce excessive consumption and use of technology. This is similar to how certain countries regulate advertising alcoholic beverages to reduce alcohol consumption [31]. (xvi) Companies are forced to set default options that reduce the impact of their software and hardware, by aiming to reduce total usage. For instance, push notifications on social media apps would be disabled by default, and to activate them one would need to voluntarily navigate to "settings", rather than being prompted a message to activate them (as described in [2]). This reduces the usage of devices, elongating their useful life, reducing energy consumption, and showing fewer ads. (xvii) Regulation about labelling is implemented, similarly to what was suggested in [2]. Hardware products are sold with a label depicting their environmental impact. Apps must show transparently their carbon footprint due to usage, prompting the user when using high-impact features like high-quality video with suggestions to reduce their impact. This not only reduces consumption from eco-conscious people but also increases reporting trans-

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[2] https://unfccc.int/news/cop28-agreement-signals-beginning-of-the-end-of-the-fossil-fuel-era

[3] This is a similar time frame to current technology rental services such as www.grover.com.

parency, reducing greenwashing. (xviii) Promotion campaigns are regularly run to promote the sustainable use of technology. (xix) Efforts towards electrification of mobility take place. Electric vehicles and electrified public transport gradually take over combustion engines.

D. Scenario 4. Eco-centred totalitarianism

This is the final scenario, representing an extreme approach. The world is in an environmental crisis and the government has decided that the best way to tackle this situation is by immediately taking extreme measures against all the responsible actors behind climate change. This implies declaring a state of emergency to implement extreme measures that would otherwise not go through. Social and economic dimensions of sustainability are secondary. This scenario presents an extreme situation but it still may be worthwhile discussing it.

This scenario is characterized by (i) A very high level of eco-consciousness in society. (ii) Fossil fuels are immediately forbidden, and there is a very high investment in renewables. The abrupt transition also causes energy shortages, which, coupled with the costs of restructuring the power grid, greatly increase the costs of electricity. (iii) Most large businesses are taken over by the state, including all technology developers, manufacturers, and distributors. The state has a monopoly on technology sales, although some institutions (such as libraries or schools) can offer access to digital devices too. This is similar to the situation of strong alcohols in Norway, where the state has a monopoly on the sale of any alcoholic beverage with an alcohol content over 4.7%, although it is possible to buy strong alcohol in bars for immediate consumption[4]. (iv) There is no advertising needed, as the goal of the state is to cover the basic technological needs of its citizens maintaining the smallest possible consumption levels. (v) Rather than promoting private ownership, the state aims to offer an inexpensive subscription to the basic electronics that people may need, although the price may vary due to production costs. (vi) The initiative of leasing publicly owned devices is accompanied by full control over their production. The devices are produced so that they are easily repairable and recyclable. Their durability is maximized to reduce costs, both economic and environmental. These devices run on universal software that is maintained to ensure long-term backward compatibility. However, this means that the investment in developing new functionalities is very low. (vii) A mandatory one-device rule is implemented. Citizens are not allowed (in most cases) to own more than one computer, one mobile phone, etc. The same device is used for both personal and professional activities. (viii) Social media are reduced to the most basic form of interaction they provide. Features like automatic recommendations, autoplay, or infinite scrolling are forbidden. It is possible to play video, although quality is limited. (ix) Sustainability training is obligatory in every stage of education and the workplace. (x) There are strong limitations on data centres. They are expensive to use, and only certain use cases are allowed. For instance, profiling done by companies to target ads is forbidden. (xi) Strong carbon taxation, on both companies and individuals. (xii) Private ownership of petrol cars is banned in most instances. To address the crisis of mobility, the government offers a nationwide shared mobility project, electrifying the fleet of shared vehicles as fast as possible. There is heavy investment in public transportation too. (xiii) Tax revenue is heavily invested in ecosystem restoration, recycling plants (including e-waste recycling), and renewable energies.

IV. THEORETICAL FOUNDATION OF THE SIMULATION MODEL AND IMPLEMENTATION

This section describes the theoretical foundation of the modelling methodology and its implementation to simulate the scenarios described in section III.

This research is based on a simulation model, representing the interaction between three groups of stakeholders on a national level, namely the government, a large technology firm (such as Apple or Samsung), and the population of a country. The objective of the model is to simulate the interaction between these groups to understand the environmental impact of different policy scenarios, over a time frame of 24 years.

For each year, business decisions and government policies shape the values of a set of parameters. These parameters determine multiple factors, such as prices, taxes, or advertising, that affect levels of consumption and the business's revenue based on that consumption. Each year, the evolution of the number of customers, and thus of the revenue, is modelled using a dynamic simulation methodology called compartmental methods (see section IV-A). After each 1-year period, the company and the government can make adjustments and investments based on the policy objectives and the status of the market at the time. The environmental impact of technology use in each of the simulated scenarios is measured based on total CO_2 emissions and quantity of e-waste generated and not recycled.

This model is based on the following assumptions:

- The population is assumed relatively stable over the entire study period. For the model developed in this research, working with an open system does not provide additional insights.
- Businesses first attempt to pay their taxes and cover their costs, before making any investment. If no budget is left after paying for taxes and costs, no investment is possible.
- The technology company is studied in isolation, without complex dynamics, such as fluctuations in the stock market.
- Inflation is assumed to be the same in all scenarios.

A. Compartmental Methods and the Bass Model

Dating back to epidemiological studies in 1916 [32], [33], compartmental models are a modelling technique used to study dynamically evolving populations. In these models, a population is split into different groups (compartments) and the flow

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[4] https://www.helsedirektoratet.no/tema/alkohol/Act%20on%20the%20Sale%20of%20Alcoholic%20Beverages,%20etc.%20(Alcohol%20Act)%20-%20Unofficial%20version.pdf?download=false

of individuals between those compartments is modelled using differential equations. These models have been extended and applied in multiple domains, from the spread of rumours [34], [35] to modelling the evolution of digital markets [36], [37].

When studying technology adoption (as done in [36], [37]), the population is divided into users or customers, and non-users or potential customers. One approach to modelling the flow between compartments is using the Bass diffusion model [38], which can be extended to model more complex dynamics [37]. A more comprehensive description of compartmental methods and the Bass diffusion model can be found in Chapter 18 of [39].

In this study, two compartments are defined: Potential Customers (fraction of the population willing to buy a piece of technology) and Customers (fraction of the population that has bought a piece of technology recently, being unwilling to buy a new one). The sum of Potential Customers and Customers is set to 1 as they represent fractions of a relatively stable population. Thus, if the fraction of Customers is U, the fraction of Potential Customers would be $1 - U$.

To model the evolution of the fraction of Customers, it is assumed that people can acquire a piece of technology either due to individual motivations or by the influence of others (network effects [39]). It is also assumed that Customers can become Potential Customers (that is, become willing to buy a new item) after a certain period, although mainly due to individual motivations[5]. The differential equation that describes this evolution is:

$$\frac{dU}{dt} = a(1 + bU)(1 - U) - cU \ , \tag{1}$$

where $a = a(t)$ is a time-dependent parameter that modulates the flow of new customers, b is a constant representing network effects, and $c = c(t)$ is a time-dependent parameter that represents the intensity of the flow of Customers becoming Potential Customers. Figure 1 presents a diagrammatic representation of this compartmental model.

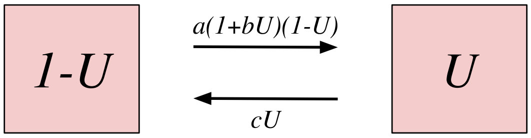

Fig. 1. Diagram of the compartmental model described by eq. (1).

B. Customer Dynamics

Despite the apparent simplicity of the model in eq. (1), its complexity lies in the definition of the time-dependent parameters $a = a(t)$ and $c = c(t)$. Their definition is based on a series of principles and assumptions, including the following dependencies:

Average level of eco-consciousness in the population (ε). This value determines the importance that environmental sustainability has for the population on average. Can be increased through governmental measures such as education campaigns. When this value is high, customers are more attentive to the environmental impacts of their actions, buying less and choosing providers that they consider more ”eco-friendly”.

Advertising level (α). This value represents presence in media and the number of ads released by a technology company. Can be increased with advertising campaigns. Higher advertising levels increase the number of sales by increasing the probability of acquiring new customers and increasing the desire of current customers to buy a new product.

Price of technology (p). Price level of the product sold by the technology company. A higher price level means more expensive technology. Potential customers are more likely to buy a cheaper item. In this model, it is assumed that the business is a large manufacturer with a relatively high level of consumer loyalty, selling relatively unique products. For this reason, it is designed in such a way that the price-demand curve is equivalent to a price elasticity of 0.7 [40].

Maintenance price of technology (m_p). This price is defined as a sum of two parameters, one independent of electricity consumption, including costs of repair and accessories, m_{p0}, and one dependent on the electricity consumption and electricity prices $m_{p,elec} \times C_{\text{elec}}$. This parameter also depends on the type of business model, as in a device-as-a-service model, the business could be responsible for repairing broken devices, thus reducing maintenance prices for consumers. These costs play a key role in the decision on whether to buy a new device or not [41].

Average level of disposable income (l). Accounts for a household's “income earned minus net taxes. When disposable income increases, other things remaining the same, consumption expenditure increases” [40]. This is an empirically proven fact [42], [43].

Level of innovation (n_0). A comprehensive parameter that accounts for the novelty following the release of new technological products or accessories (for instance, a new smartphone model or a wearable), modulated by a time-dependent function. For the modulating function, although using the Roger model for innovation diffusion [44] may seem like a reasonable option, the sale of consumer electronics presents an intrinsically distinct scenario [45], [46]. This evolution is characterized by a rapid increase in sales when a product is released for the first time and a gradual decrease over time[6].

Average life expectancy of devices (z). This parameter defines the average durability of devices (that is, the average time it takes for a device to break), depending on factors such as regulations, materials, and planned obsolescence. If a device

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[5] The assumption of small network effects for becoming a potential customer is well motivated, as the number of people that do not own yet a piece of technology is not a visible quantity, unlike the number of people that do own one.

[6] This is further evidenced by the evolution of the interest in new releases of smartphones. See, for instance, the case of the iPhone 14 https://trends.google.com/trends/explore?date=today%205-y&q=iphone%2014&hl=en. This type of interest data has been linked to the demand for a product [36].

breaks and the repair costs are too high, people will become willing to a new one.

Corporate image factor of the business (γ_0). A parameter accounting for the efforts that a business may make to appear more "eco-friendly" to consumers, such as labelling, corporate reports, publicity campaigns, or certifications. Depending on reporting and auditing regulations, this may be more or less costly. The effect of this parameter is modulated by ε.

Other policies that affect sales (K_{B0}). Representing policies, such as a one-device rule, that may influence the likelihood that people buy more or fewer devices without necessarily altering the other parameters.

Based on these parameters, the dynamic parameters $a(t)$ and $c(t)$ are defined as

$$a(t) = \frac{l\alpha}{\varepsilon p^2}(1 + n_0 e^{\frac{-t}{\Delta t}})\gamma_0^{\sqrt{\varepsilon}-1} \ , \tag{2}$$

and

$$c(t) = \frac{K_{B0} m_p l\alpha}{\varepsilon e^{-t/z}} \ . \tag{3}$$

Combining eqs. (2) and (3) with eq. (1), the equation for customer dynamics is defined:

$$\frac{dU}{dt} = \frac{l\alpha}{\varepsilon p^2}(1+n_0 e^{\frac{-t}{\Delta t}})\gamma_0^{\sqrt{\varepsilon}-1}(1+bU)(1-U) - \frac{K_{B0} m_p l\alpha}{\varepsilon e^{-t/z}}U \ . \tag{4}$$

C. Decisions, Scenarios and Parameters

This section addresses government and business decisions, the parameters that they affect, and how they change based on the scenarios. A diagram of the complete model can be found in fig. 2.

In this model, the government can make multiple decisions depending on the scenario. It can start education campaigns about sustainable use of technology, increasing the average level of eco-consciousness in the population (ε); introduce taxes, such as a carbon tax or an e-waste tax; invest in renewable energies, e-waste removal and recycling, and carbon capture; invest in energy infrastructure, making it more efficient and influencing the costs of producing electricity; change the price of electricity (C_{elec}), influencing the level of disposable income l, the maintenance price of technology m_p and some costs of the business; implement use policies, such as a one-device policy, modifying K_{B0}; modify recycling obligations, affecting the fraction of devices that the business must recycle r_f; introduce reporting regulations that require technology businesses to report on different aspects of their environmental impact, and increasing transparency in their activity, difficulting false claims and greenwashing; introduce product standards and regulations, affecting design, production, and durability of devices; give subsidies to business based on criteria such as emissions.

In the model, the business has the power to affect several of the parameters described in section IV-B. It can change the price of technology p, start an ad campaign modifying α, invest in innovation, affecting n_0, and improve their corporate image γ_0. A business can also invest in increasing production efficiency E_{ff} (reducing costs and emissions) and the efficiency of its recycling facilities E_{rff} (reducing the costs of recycling). When efficiency is increased, each consecutive improvement is more expensive than the previous one, to avoid the unrealistic limit of 100% efficiency, forbidden by the laws of thermodynamics. These increases in efficiency account for technological evolution in production and recycling. The company must also cover the costs of electricity, materials, labour, recycling, taxes, and debt. When a business cannot pay for its costs one year, it acquires debt that has to be paid back the next year with interest. When a business is in debt or unable to make a profit, it increases the prices of its products to attempt to make a profit, taking advantage of the relative price inelasticity of demand.

The parameters described in this section reflect the decisions of the government and the business across a range of scenarios. To find an adequate range of values for each parameter, identifying high and low values and an order of magnitude that produces results in accordance with the time scale used, a sensitivity analysis was performed using an OAT (One-at-a-time) approach. The results from this process, combined with the measures and characteristics of the scenarios described in section III, are the values of the parameters displayed in table I.

The `python` code for the simulation model is available in the online repository *Zenodo* [7].

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[7] https://zenodo.org/doi/10.5281/zenodo.10580298

TABLE I: Initial values of the parameters of the model in the four different policy scenarios.

Parameter	**Definition**	Scenario 1	Scenario 2	Scenario 3A	Scenario 3B	Scenario 4
Years	Number of years	24	24	24	24	24
α	Advertising level	0.1	0.1	0.1	0.1	0.1
ϵ	Eco-consciousness	1.01	1.2	1.2	1.2	2
b	Network effects	0.01	0.01	0.01	0.01	0.01
l	Level of disposable income	30	30	30	30	20
U_0	Initial customer pool	0.1	0.1	0.1	0.1	0.1
K_{b0}	Other policies that affect sales	1.5	1.2	1	1	0.5
$C_{\textbf{elec}}$	Cost of electricity	0.55	0.55	0.55	0.55	5.5
$C_{\textbf{mat}}$	Cost of materials	4	5.5	6	6.5	7.5
$C_{\textbf{lab}}$	Costs of Labour not accounting for societal wealth	0.1	0.1	0.1	0.1	0.1
r_f	Fraction of devices recycled by the company	0	0.1	0.1	0.6	0
C_{rf}	Cost of recycling e-waste	0.2	0.2	0.2	0.2	0.2
p	Price of technology	5	5	5	5	5
n_0	Level of innovation	0	0	0	0	0
γ_0	Corporate image	1	1	1	1	1
z	Life expectancy of devices	0.5	1	2.5	3	5
m_{p0}	Maintenance price without electricity	0.055	0.055	0.045	0.035	0.03
$m_{p,elec}$	Maintenance price due to electricity	0.1	0.1	0.08	0.08	0.08
T_{inc}	Income Tax	0.1	0.1	0.1	0.1	0
K_{eu}	Energy expenditure in technology manufacturing	1	1	1	1	0.8
ρ	Fraction of non-renewables	1	1	1	1	0
K_{ew}	Quantity of e-waste produced per unit of technology produced	1	0.8	0.8	0.8	0.8
K_{Tco2}	Intensity of carbon taxes	0	0.03	0.03	0.03	0
$K_{T,ew}$	Intensity of e-waste tax	0	0	0.03	0.03	0
intr	Interest rates for loans	0.01	0.01	0.01	0.01	0
n_{ee}	Factor for emissions not coming purely from energy use	0.1	0.05	0.05	0.05	0.05
fr_{ew}	Fractions of the tax money invested in recycling e-waste	0	0.2	0.3	0.3	0.3
fr_{rw}	Fractions of the tax money invested in renewable energies	0	0.2	0.25	0.25	0
fr_{cc}	Fractions of the tax money invested in carbon capture	0	0.2	0.25	0.25	0.2
fr_{ce}	Fractions of the tax money invested in energy infrastructure	1	0.4	0.1	0.1	0.2
fr_{cp}	Fractions of the tax money invested in sustainability campaigns	0	0	0.1	0.1	0.2
cost-of-corp-img	Costs of improving corporate image	1	1.5	1.5	1.5	1.5
cost-of-ads	Costs of running advertising campaigns	4	4	5	5	5
cost-of-inn	Costs of innovation	1	1.1	1.5	1.5	1

Fig. 2. Diagram of the dynamic model of customers, a large technology corporation, and the government (represented by blue rectangles). Arrows represent relationships of influence. The following colour code has been chosen for clarity: green bubbles are actions and magnitudes directly controlled by the government, purple bubbles are business decisions, orange bubbles are costs paid by the business, and blue bubbles are magnitudes indirectly affected by the stakeholders of the model. Black arrows correspond to parameters that have a direct influence on customer dynamics. Green arrows that represent government decisions are dashed to facilitate visualization.

V. RESULTS AND DISCUSSION

This section presents the final results from the simulations of the scenarios from section III, for environmental indicators in fig. 3 and economic indicators in fig. 4.

An initial evaluation of figs. 3 and 4 reveals that in the baseline scenario (Scenario 1), cheap electricity, low costs of production, low consistency standards, and constant releasing new features and devices with a short useful life lead to increased consumption and extreme amounts of e-waste and CO_2 emissions. Scenario 1 presents an inherently unsustainable system [6], based on the flawed idea of infinite growth on a finite planet. In contrast, when consistency measures are in place, these impacts are greatly reduced.

Comparing both sufficiency scenarios (3a and 3b), there is a considerable difference in outcomes. The results of Scenario 3a suggest that a traditional sales model is not compatible with a sufficiency-focused policy scenario. As the business is forced to produce highly durable devices and ensure backward compatibility, while at the same time restricting advertising of technology, once most people own a device, there are very few sales taking place each year. Without sales, the business is unable to make a profit and cover the costs, which leads to liabilities and a lack of innovation. The few devices that are left become a scarce resource as no new devices are produced. This fact, coupled with the business attempting to make a profit, results in a dramatic increase in prices as shown in fig. 4. As devices become increasingly expensive and no new features are introduced the number of customers drops, the only customers being the ones that bought a device in the early days that has not broken yet.

Scenario 3b suggests that the device-as-a-service model is a successful alternative to traditional sales, overcoming durability limitations by turning them into advantages. Durable devices yield higher profits through longer rentals and reduced maintenance. Despite the constraints in Scenario 3, this model attains a customer fraction comparable to Scenario 1's traditional sales model. Additionally, in Scenario 3, where taxes support renewable energies and e-waste management, the successful device-as-a-service strategy enables complete e-waste recycling and a full transition to renewable energy sources.

As presented in fig. 3, the greatest reduction in all environmental impact metrics is achieved in Scenario 4. However, fig. 4 presents a more nuanced perspective. Due to the extremely high energy prices and reduced level of disposable income, in Scenario 4 the number of customers is approximately 30% of the population. This result implies that extreme restrictions and abrupt transitions may have consequences that slow the adoption of technology (or even block access to it), thus negatively impacting social sustainability.

Comparing the results from all scenarios, it is evident that any type of economic restrictions, such as taxes or energy use restrictions, hinder the development of new products. However, the constant system of production and consumption of technology is unsustainable [5], [6]. The rapid turnover of smartphones, for instance, has a high environmental impact [47]. The results in figs. 3 and 4 depict, however, that the relative compromise in innovation is smaller than the environmental gains achieved by the measures, especially comparing Scenario 1 and Scenario 3b. In that case, although the investment in innovation in Scenario 3b is 30% of the investment in Scenario 1, the indicators for CO_2 emissions and generated e-waste in Scenario 3b are around 5% of the ones in Scenario 1. Moreover, in exchange for the compromise in investment in innovation, Scenario 3b was able to achieve complete decarbonization of the energy used in production and complete recycling of e-waste.

Analysing the evolution of each scenario, net-zero e-waste (removing and recycling the same e-waste that is produced in a year or more) is achieved after 6 years in Scenario 3b, and after 7 years in Scenario 4. A complete disposal of all e-waste generated since the beginning of the study period is achieved in year 17 for Scenario 3b and year 9 for Scenario 4. In Scenario 3b, full decarbonization of the technology sector's energy occurs after 17 years, while in Scenario 4, it is achieved from the start (year 0). Net-zero emissions are reached in year 13 for Scenario 3b and year 7 for Scenario 4, accounting for non-energy-related emissions. Additionally, starting from year 8, stringent land regulations and carbon capture initiatives result in the complete removal of all CO_2 generated during the study period in Scenario 4. None of the other scenarios was able to achieve these goals, suggesting that sufficiency measures may be necessary to achieve our sustainability goals, supporting the claims from the research on this matter [2], [16].

This research is limited in several ways. First, although most of its features are based on scientific knowledge, it is still based on various assumptions, as described in section IV. Moreover, the model employed is newly developed for this study and has not undergone testing with real-world data. However, the novelty of the model is a contribution due to its uniqueness as, to the knowledge of the authors, no previous model using these simulation techniques has been implemented for the case presented here. Thus, this model offers a novel perspective on a contemporary problem.

VI. CONCLUSION AND FUTURE RESEARCH

This work aims to put into practice the principle that sufficiency policies are necessary for sustainable information and communication technologies [2], by providing evidence from a simulation model. The model used is based on scientific principles and implemented using compartmental methods, to simulate the interaction between a large technology producer, the population of a country, and the government of that country in four different future scenarios.

Comparing four policy scenarios, encompassing various sustainable development approaches, leads to the conclusion that sufficiency is a crucial factor in achieving environmental objectives. All the environmental restrictions implemented have an economic impact, limiting innovation and production. However, this effect is considerably smaller in comparison

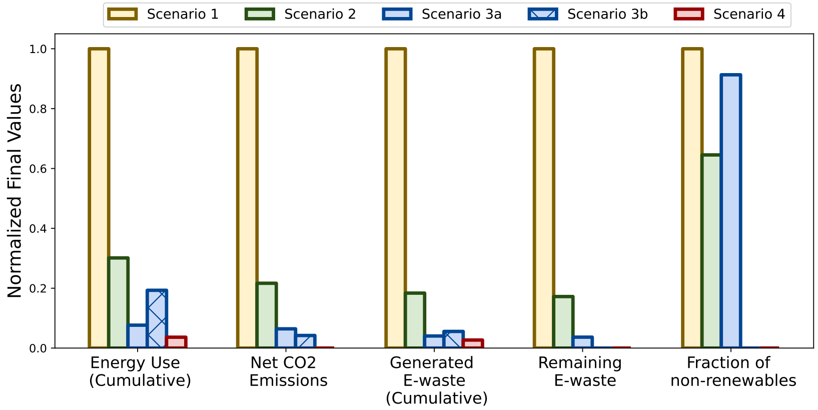

Fig. 3. Normalized final values of environmental impact indicators resulting from simulating the four different technology policy scenarios described in section III. The normalization to the maximum value is intended to facilitate relative comparison.

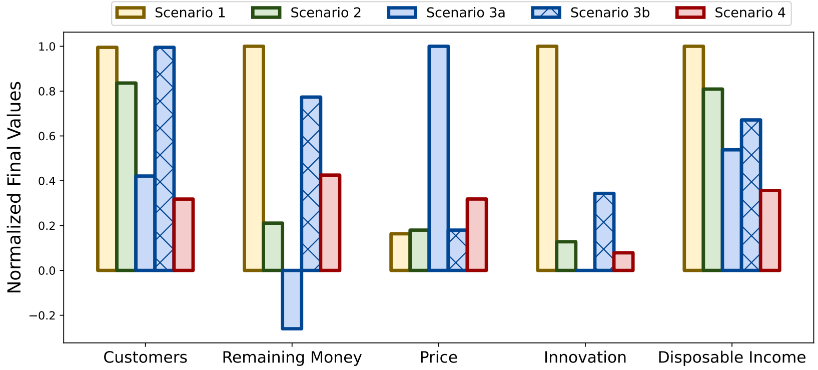

Fig. 4. Normalized final values of economic indicators resulting from simulating the four different technology policy scenarios described in section III. The normalization to the maximum value is intended to facilitate relative comparison. "Remaining money" refers to the budget that the business has for investments, after paying for taxes and costs, in the last year of the simulation.

to the environmental benefits (reduction in e-waste and CO_2 emissions) that those measures cause. Sufficiency strategies are capable of greatly reducing the environmental impact of technology, compared to a scenario with no consistency nor sufficiency measures, and a scenario with only consistency and efficiency measures. These findings underscore the importance of sufficiency measures, that should be considered by policy-makers, emphasizing their effectiveness and necessity.

This research offers insight into the future of the consumer electronics market. In a scenario where sufficiency measures and policies (e.g., limiting the total energy consumption of devices, increased durability, restrictions on advertising...) are implemented, a traditional sales business model would not succeed. In that scenario, an alternative model, such as the device-as-a-service model, would be a viable alternative because it harnesses those limitations to its advantage.

The simulation model used in this research is available in the online repository *Zenodo* [8]. and is one of the contributions of this paper. This model can be applied to other scenarios, which could be an option for future research. Based on the fact that the scenarios were developed as a set of progressive policy implements only based on literature review, testing them and developing further studies in more specific contexts is left for future research. We will seek collaboration with experts and government officials to achieve a more comprehensive and realistic set of scenarios. The results from that approach may offer valuable insights that could shape future environmental and technological policies.

There are several ways in which the model can be further developed and tested. One option is to assess the internal connections and the results with feedback from experts. Future versions of the model should be further assessed with real-world data, tuning in the parameters and the effects of those parameters to represent a real nation. The customer dynamics model could be further improved by incorporating more complex dynamics accounting for different customer types or segments, such as the PHLoQui model [36]. More comprehensive versions of the model could include the interaction of several businesses, both on a national and an international level, modelling the interaction of different governments with possibly different policies. Advanced models could also incorporate population dynamics that would be affected by

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[8] https://zenodo.org/doi/10.5281/zenodo.10580298

environmental results, such as increased mortality due to air pollution. Extensions of the model could also analyse social sustainability indicators to offer a more complete view of future scenarios.

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