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Trends characterizing technological innovations that increase environmental pressure: A typology to support action for sustainable consumption

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Technological innovation is widely recognized as an endogenous element of capitalism driving economic growth and consumption. Although technological innovations have benefited human health, quality of life, and comfort, especially in high-income countries, uncontrolled industrialization of technological innovations and mass consumption exert strong environmental pressure on natural resources and contribute to the degradation of the environment. Apart from their endogenous role in economy and consumption, these innovations are characterized by specific trends that affect the sustainability of manufactured goods and consumption patterns, such as rate of market penetration, ownership of manufactured goods, product lifespan, reparability, and recyclability. This paper aims to contribute to a theorization of the relationship between technological innovation, consumption, and sustainability. To this end, we propose a typology of trends characterizing technological innovation to constitute a coherent framework. These trends are then documented to evaluate their magnitude, drivers, and related issues, following the broad principles of integrative literature reviews through a purposeful review sampling. The following trend framework emerged with regards to technological innovations: (a) accumulation; (b) diversification; (c) substitution; (d) complexification. The work contributes to identifying and formalizing: (1) the terminology regarding each trend, (2) related concepts that should be considered to theorize the relationship between technological innovation and (un)sustainable consumption patterns, (3) the main drivers that sustain these trends, (4) interactions between these trends, and (5) societal consequences on material and energy consumption and waste management.

KEYWORDS

ownership, product accumulation, product diversification, lifespan, obsolescence, product complexity, consumption, technological innovation

Introduction

Socioeconomic metabolism, also called social or industrial metabolism (FischerKowalski and Haberl, 1997; Krausmann et al., 2018) is a branch of industrial ecology that estimates the environmental pressure exerted by society on the environment. Quantifying the energy and material inputs and outputs of society as well as the materials accumulated within it in the form of durable manufactured capital (so-called in-use stocks; Krausmann et al., 2017), documents the huge materials consumption of nations (Krausmann et al., 2009, 2018; Schandl et al., 2016; Oberle et al., 2019).

At the global level, the annual raw materials extractions were estimated at 89 Gt in 2015 (Krausmann et al., 2018). A large part, 59% (or 52 Gt/year in 2015), is used to build infrastructures and manufacture durable goods (Krausmann et al., 2018). The use of materials shows large disparities among nations. High-income countries have higher material consumption, waste stream, and in-use material flow (Dittrich et al., 2012; Wiedmann et al., 2015; Krausmann et al., 2017; Oberle et al., 2019). On a per-capita basis, the material footprint (MF) was 27 t for high-income countries in 2017, as compared to 2 t for the low-income country group (Oberle et al., 2019).

As income appears as a fundamental driver of material consumption (Wiedmann et al., 2015; Pothen and Welsch, 2019) and CO_2 emissions (Davis and Caldeira, 2010; Blanco et al., 2014), agencies such as the Organization for Economic Co-operation and Development (OECD, 2011) and the United Nations Environment Programme (UNEP; Fischer-Kowalski et al., 2011) have encouraged a decoupling of material consumption from economic growth. However, despite extensive literature, signs of decoupling are scarce (Haberl et al., 2020). When it occurs, decoupling has been only observed (1) for short periods, (2) in relative terms (the footprint increases less rapidly than GDP), not in absolute terms (the footprint decreases while GDP increases), and (3) for production-based (territorial) rather than consumption-based (footprint) indicators (Wiedmann et al., 2015; Mardani et al., 2019; Haberl et al., 2020).

In addition, the material consumption of high-income countries continues to increase, although at a slower rate than in the 1990's. This goes against some views that saturation of consumption should take place as countries become industrialized and reach a certain wealth level, a theory called the environmental Kuznets curve hypothesis (Kuznets, 1955; Selden and Song, 1994). Despite many studies and controversial results (Seppala et al., 2001; Canas et al., 2003; Bleischwitz et al., 2018), a saturation of materials consumption of high-income countries has not been put into evidence for the MF (Wiedmann et al., 2015; Plank et al., 2018; Oberle et al., 2019; Pothen and Welsch, 2019). Faced with this evidence, academics call for a profound transformation of the economic system and an abandonment of the objective of economic growth in favor of human wellbeing (Krausmann et al., 2017; Haberl et al., 2020).

At the economic level, wealth is widely recognized to sustain material consumption (Wiedmann et al., 2015; Schandl et al., 2016; Oberle et al., 2019; Pothen and Welsch, 2019). Additionally, manufactured capital determines in part the future consumption of materials and energy, as resources will be required to use, maintain, and renew existing infrastructures, equipment, appliances, and other manufactured goods (Chen and Graedel, 2015; Krausmann et al., 2017). Therefore, the increase in in-stock flows of durable goods in developed countries should be carefully considered.

Among the different drivers of consumption, technological change is well-known to be of prime importance. It may have positive effects on resource consumption, for instance by reducing the material or carbon intensity of industrial sectors or products, as well as negative effects by providing new products to purchase or inducing the so-called rebound effect (Herring and Roy, 2007). Emerging technologies may also result in waste management challenges (Lundgren, 2012).

The role of technological innovation is particularly important in developed countries since most of their activities (industrial production, health, transportation, communication, agriculture, leisure, etc.) rely on modern technologies, especially electric and electronic appliances. As emerging countries follow the same path, catching up with rich countries standards of living, income, and way of life, it is crucial to understand the role that technological change plays in societies metabolism.

Apart from the endogenous role that technological innovations play in sustaining consumption and economic growth, other factors related to technological innovation must be considered. Several trends characterizing manufactured goods can be observed, such as the increasing diversity of new devices, the elevated renewal rate of appliances, the difficulty in repairing them, and their ever-decreasing lifespan. Various dimensions have been studied quantitatively in the literature such as product ownership, obsolescence, or turnover.

A typology of these trends is proposed here to contribute to a formalization of the relationship between technological innovations, consumption, and sustainability. Four trends that influence material consumption have then been identified to characterize/analyze technological innovations: (1) the accumulation of goods, (2) their substitution, (3) their diversification, and (4) their increase in complexity.

Our primary aim is to formalize an integrate these four trends (or theoretical constructs) into a framework, and then illustrate how they characterize technological innovation. One specific objective is to synthesize the literature regarding four trends that have been preliminarily identified as playing a role in unsustainable consumption patterns and that are further inquired into. To this end, the work rests on the broad principles of integrative literature reviews as per (Snyder, 2019). As such, it does not propose nor seeks to be an exhaustive and systematic account of technological innovation and its link with sustainability. Alternately, it does seek to synthesize and to a certain extent criticize the extant literature on the topic, based on a purposeful sampling strategy, so as to draw a theoretical framework (Suri, 2011).

To our knowledge, an integrative literature review adopting this specific angle of inquiry does not yet exist in the literature and therefore constitutes an original contribution in terms of theorizing the impact dynamics of technological innovation. Such a formalized view appears necessary as societies increasingly rely on technology while technological innovations are even regarded, in some circles of society, as a unique solution to mitigate environmental crises (e.g., climate change).

After presenting the integrative literature review used as a methodology (Section Methodology), Section The environmental pressure associated with technological change is dedicated to the contextualization of the four trends under investigation and a short description of the relationship between technological change and the economy, the societal drivers of this relationship, and the ensuing impacts in terms of the four trends. Section Technological innovation trends increasing the environmental pressure provides a detailed description of these four trends, as they present themselves in the literature. A final section (Section Conclusion) summarizes the findings and underlines knowledge gaps.

Methodology

The contextualization of the environmental impact of technological change and the identification of the trends characterizing it were made previously by the authors based on the literature in the fields of sustainable development, economy, technological innovation, waste management, etc.

As stated above, the four trends were preliminarily viewed as a potential framework allowing to improve the theorization linking technological innovation, consumption, and sustainability. The objective of the present work is to validate this hypothesis and develop knowledge. We would like to answer specific questions such as: What is the amplitude and evolution of these phenomena? What are their drivers? What are their societal consequences? The objective requires a thorough literature review and analysis was necessary to document the four-trend framework (Section Technological innovation trends increasing the environmental pressure). Therefore, we carried out a purposeful sampling design which allowed targeted bibliographic research and we were able to find specific information and case studies (Snyder, 2019) related to household ownership of particular products (car, EEE), the number of products owned by households, or per capita, the substitution rate (replacement) of manufactured products, etc.

Literature search and selection process

Scientific literature searches were performed in the Web of Science database (Clarivate Analytics), including the "Science Citation Index Expanded," the "Social Sciences Citation Index," and the "Arts and humanity Citation Index." Various queries were used to encompass the four trends identified as widely as possible while looking for appropriate and relevant information. The first queries used were broad to cover the subject from a general perspective. This research step mainly provided general arguments regarding the influence of technological change on industrial goods consumption but few insights regarding the four trends under study. However, these queries helped improve the terminology subsequently used (keywords) to target individual trends.

Specific queries were then ran. Articles were selected (see below) and analyzed after each search in order to refine the survey either by using more appropriate keywords or targeting a specific topic. Table 1 highlights the search queries in the Web of Science database and the number of articles retained.

The selection of the articles was based on their relevance with regard to the trends under study. Only articles that clearly and explicitly addressed the investigated trends, their drivers, and/or that provided either quantitative annual or time-series data were selected. We noticed that even using the most precise keywords, many articles did not concern the trends under investigation and were easy to discard. Also, to help find specific data, some queries considered specific products (i.e., cars).

This process led to the selection of 103 relevant articles from a total corpus of 777. Emphasis was placed on articles published in the last 10 years. To complement this purposeful research, and consistently with a purposeful sampling, it appeared efficient to add relevant papers cited by the selected articles. The complete corpus encompasses about 200 articles. It is noteworthy that this review focuses for a large part on electric and electronic equipment (EEE), as the majority of the literature is devoted to this type of industrial goods. This is however an important sector which helps understand the consequences and manifestation of the trends related to technological innovation.

Data analysis

Data and arguments found in the different articles were categorized according to the trends, their interactions, their

TABLE 1 Details of the search queries performed.

Searches in Web of Science	Trend targeted	Number of results	Number of items retained (relevant)
"technological change" (TITLE) AND Sustainability (TOPIC)	All	41	10
technolog* (change OR rate*) TITLE AND sustainab* AND consum* AND (footprint OR impact) TOPIC	All	29	7
(impact OR footprint OR sustainab*) AND consum* AND (rate OR frequenc*) AND product (renewal OR turnover OR substitution) AND technol*	Substitution	79	3
(technolog* OR innovation*) AND turnover rate* AND sustainab* TOPIC	Substitution	44	2
"product turnover" AND consum* ALL FIEDS	Substitution	9	2
(technolog* OR innovation*) AND substitution rate AND reduc* AND sustainab* AND (footprint OR impact) AND consum*	Substitution	21	2
product substitution AND diffusion AND rate*	Substitution	143	25
household ownership TITLE AND (good* OR product*) All FIELDS	Accumulation/diversification	34	8
"per household" AND in-use ALL FIELDS	Accumulation	22	5
Product lifespan AND consumption AND technol* ALL FIELDS	Substitution	84	6
"innovation cycle" AND technol* AND product* TOPIC	Substitution/diversification	41	4
ownership AND (car OR vehicle OR automobile) AND "per capita" AND (OECD OR high-income OR industrialized OR developed) AND countries ALL FIELDS	Accumulation/diversification	48	17
product AND diversi* AND household* AND sustainab* AND consum* ALL FIELDS	Diversification	93	3
(product OR device) AND complex* AND recycl* AND sustainab* AND mater* AND review ALL FIELDS	Complexification	89	9
Total		**777**	**103**

The symbol"*" is used with words' lexical root for lemmatization purposes. The objective is to broaden the queries to consider inflected form of words and plurals.

drivers, etc., and used to build the framework presented in the manuscript.

The environmental pressure associated with technological change

Context

Technological progress is at the root of much advancement in people's life as it (1) improves life quality (health, life expectancy, food, housing, communications, mobility, comfort, etc.), (2) contributes to the increase in wealth (income), especially in developed and emerging countries, and (3) improves material and energy efficiency, product durability and recyclability, and promotes renewable energy development.

However, this progress has often resulted in material consumption and environmental degradation. Technology enhances the physical capability of Humans (i.e., allows them to explore space and increasingly exploit more inaccessible resources) and increases their industrial production capacity, thus increasing their capability to modify their environment. This remarkable capacity finds its ultimate expression in the concept of Anthropocene (Crutzen and Stoermer, 2000; Crutzen, 2002; Zalasiewicz et al., 2011). Human beings have so transformed biogeochemical and biogeophysical processes that five of the nine planetary boundaries have already been exceeded (Rockström et al., 2009; Steffen et al., 2015; Persson et al., 2022).

Endogenous relations between technological innovation and economy

To clarify the subject of this work, a distinction between technological change and technological innovation may be beneficial to the reader. Technological change is viewed as a three-step mechanism involving (1) an invention, (2) an innovation (commercialization step), and (3) its diffusion, i.e., the adoption of the innovation by the marketplace (Schumpeter, 1942; Organisation for Economic Co-operation Development, 1992; Jaffe et al., 2003). There is then a minor difference between technological change and technological innovation in that the former includes the adoption of the innovation by consumers, which exactly corresponds to what the studied trends are about. However, for simplicity reasons and because innovation designates the product that is consumed, while technological change designates the process, we focus on innovation.

The definition of technological innovation retained is based on the Oslo Manual of the (Organisation for Economic Co-operation Development, 1992) and integrates the definition of both technologically new and improved products, as follows: a technological innovation refers here to a new commercialized product, i.e., a purchasable product "whose characteristics or intended use differ significantly from previous existing products," or to an improved product, i.e., that have "higher or upgraded performances." Novelty may result from "radically new technologies, can be based on combining existing technologies in new uses, or can be derived from the use of new knowledge." Improvement can result from the "use of higher-performance components or materials, or a complex product which consists of a number of integrated technical sub-systems may be improved by partial changes to one of the sub-systems." This definition distinguishes new and improved industrial products, which are at the heart of consumption. It is then helpful in better underlying what is at stake in technological innovation.

Technological innovation and economy constitute a very effective interrelated duo to grow the economy. First, technological innovation is widely recognized as an endogenous element of capitalism driving economic growth and consumption (Schumpeter, 1939; Hasan and Tucci, 2010; Borri and Grassini, 2014; Mercure, 2015; Pesch, 2018).

Second, although technological advances generally increase the carbon or material efficiency of production, these improvements are often outweighed by the increase in resource and energy consumption induced by wealth growth. This phenomenon has been observed at national scales, notably in developed countries, where the benefits of lower domestic material intensity have been counterbalanced by an increase in consumption, resulting from an increase in GDP and imports (Schandl et al., 2016; Oberle et al., 2019). For example, despite a decrease in material intensity of 25% over the period 2000–2016, the material footprint of North America increased by 3% due to population and affluence growth (Oberle et al., 2019).

At the global scale, gains in material intensity until the beginning of the twenty-first century partially offset the increase in material consumption resulting from economic growth (Schandl et al., 2016; Oberle et al., 2019). Afterward, however, material intensity constantly raised at a global level, although it decreased for most countries. This paradox is mainly due to the increase of imports from developed countries, which shifts the production from low material intensity countries to higher material intensity ones (Schandl et al., 2016; Oberle et al., 2019).

The same conclusion has been drawn from a study, spanning over a century, investigating, with a historical perspective different world and U.S. activities such as aluminum production, electricity generation from coal or natural gas, freight rail travel, motor vehicle travel, and residential refrigeration (Dahmus, 2014). The data show that progressive advances in efficiency have not outpaced increases in the number of goods and services provided (Dahmus, 2014). A similar observation was made at the household level in industrialized countries where the benefits of technological efficiency improvements on environmental impact have been counterbalanced by the increase in demand (Duarte et al., 2013; Ryen et al., 2014).

The latter example shows that technological improvements and less material and energetic-intensive products and infrastructures may have unexpected behavioral responses which induce undesirable outcomes called the rebound effect (Jevons, 1906; Binswanger, 2001; Kohler and Erdmann, 2004; Hertwich, 2005; Zink and Geyer, 2017; Freeman, 2018). This phenomenon occurs when a decrease in material or energy intensity of processes or services is partly, completely, or more than counterbalanced by an increase in resource or energy consumption, thus leading to fewer environmental benefits or a higher environmental pressure or degradation than expected from efficiency improvements.

The rebound effect can manifest itself in different ways. As seen above, gains in material efficiency at a macroscale have been more than compensated by the increase in consumption. At the household level, a rebound occurs when an increase in product consumption or ownership, or the consumption of more resource-intensive products (larger, better performing, and more feature-laden; Herring and Roy, 2007). It has been observed in numerous sectors, including the demand for energy services (Fouquet, 2014; Havas et al., 2015), building construction (Liu and Lin, 2016), and information and communication technologies (ICT; Kohler and Erdmann, 2004; Deng and Williams, 2011). The rebound effect may also induce indirect effects. The increase in efficiency provides results in more available income, which in turn is used for the consumption of additional products or services (Herring and Roy, 2007).

Other trends related to technological innovations

In addition to these principles inherent to the current techno-scientific economic system, the industrialization of technological innovations has several specific consequences that accelerate consumption, thus multiplying the environmental footprint of goods and services. Different factors characterize consumption, including the rate at which innovations are brought to market, the longevity of manufactured products, their renewal by households, their (ir)reparability, the difficulty to recycle them, etc. The origin of these effects is technological (increased performance, miniaturization for example), but it is also strongly influenced by socio-economic, notably business decisions, competitive pressure, and consumer behavior.

As will be detailed below, there is an increase in the number of material goods per household (number of appliances of the same type, number of different appliances) in developed countries, an increase in the frequency of innovation cycles (i.e., substitution cycle and rate of introduction of new products and new technologies), while the design and physical constitution of products tend to increase energy consumption or make repairing and recycling more complex.

The various trends in technological innovations (or industrial products) can be grouped into four classes: (1) the accumulation of durable goods, (2) their substitution, (3) their diversification, and (4) their increase in complexity. These theoretical constructs are defined in Table 2. Such a typology may help formalize the relationship between technological innovation, consumption, and sustainability. This theorization rationale is described in Table 2, which contextualizes the four trends in terms of their relation to technological innovation and economy/consumption (see Figure 1).

Technological innovations are tightly linked to the economy and its underlying consumption patterns: these patterns are self-sustaining, as they contribute themselves to increasing consumption intensity and economic growth, despite, and sometimes even because of efficiency improvements (rebound effect phenomenon). Product accumulation, diversification, substitution, and complexification can thus be regarded as four interrelated manifestations or forms of counterproductive dynamics inherent in socio-technological innovation systems and, at a large scale, the global economy.

The consequences of technological trends

An increase in product ownership, diversification, and substitution, especially with more complex products, can put more pressure on the quantities and types of resources used. This issue is particularly relevant for electronic equipment as it induces some risk of shortage, especially for certain materials such as rare earth metals (Wäger, 2011) and elements of the platinum group, which are distributed quite heterogeneously across the world. This question is accentuated by geopolitical issues that may make material supply critical in the near future, and certain nations dependent and vulnerable (Friege, 2012; Greenfield and Graedel, 2013; Ciacci et al., 2018; Hache et al., 2021).

Another important potential consequence includes the intensification of waste streams and/or the appearance of new ones. In particular, the replacement of manufactured goods by new product generations can lead to new waste management and recycling difficulties. Although many of them stem from inadequate or non-existent legislation, shortcomings are accentuated by the elevated pace of technological innovations, short product lifespan, and complexification which rapidly modify the nature and/or the flows of materials intended for recycling (Althaf et al., 2019). The replacement of old technologies with new ones indeed modifies the type of end-of-life (EoL) materials, requiring sustained efforts by the recycling industry and legislation to (attempt to) adapt. Because reaction time is not instantaneous, recycling infrastructures does not necessarily exist for emerging products or obsolete ones that may end up in the waste stream.

Product diversification and complexification (miniaturization and lightweighting) lead to low concentrations of raw materials in the products and difficulty in material recovery, and therefore fragile economic sustainability (Friege, 2012; Gotze and Rotter, 2012; Lundgren, 2012). The EoL of products also involves international issues since considerable quantities of waste from developed countries are often illegally sent to developing ones (Cucchiella et al., 2015) in Asia and Africa (Friege, 2012; Lundgren, 2012; Sthiannopkao and Wong, 2013).

When recycling facilities are not available, many products are landfilled. This disposal leads to the release of toxic substances, such as heavy metals (antimony, arsenic, mercury, and lead), persistent and bio-accumulative organic chemical substances (polychlorinated biphenyls (PCBs) and halogenated flame retardants), and ozone-depleting substances, that threatens humans, biodiversity and the environment (Cucchiella et al., 2015; Bakhiyi et al., 2018). Waste streams, however, represent significant volumes of potential resources for secondary inputs, so-called urban mining (Sanchez et al., 2005; Brunner, 2011; Zeng et al., 2018); but the low recycling rates induce huge losses of materials for secondary inputs.

The links between technological innovations and other societal sectors

The economy, public policies, and social factors also influence the above-mentioned technological trends (Figure 1). The industrial competition, which promotes innovation, pushes companies to sell more products, and new products, and to target new customers. These objectives may motivate various industrial strategies including offering products with higher performance, new functions, or which are more convenient; proposing cheap products; attracting customers with marketing or easy payment; etc.

TABLE 2 Links between technological innovation and economy/consumption.

General relations	• Efficiency gains due to technological innovations • Decrease in material and carbon intensity (in relative terms) • Increase in consumption and economic growth (in absolute terms) • Rebound effects			
Specific trends	**Accumulation**	**Diversification**	**Substitution**	**Complexification**
Definitions	Increase in the number of ownerships of a given (equivalent) product	Increase in the number of different products owned	Replacement of the product by a new one (equivalent or more performant)	Increase in the complexity of product structure (heterogeneity, number of component materials)

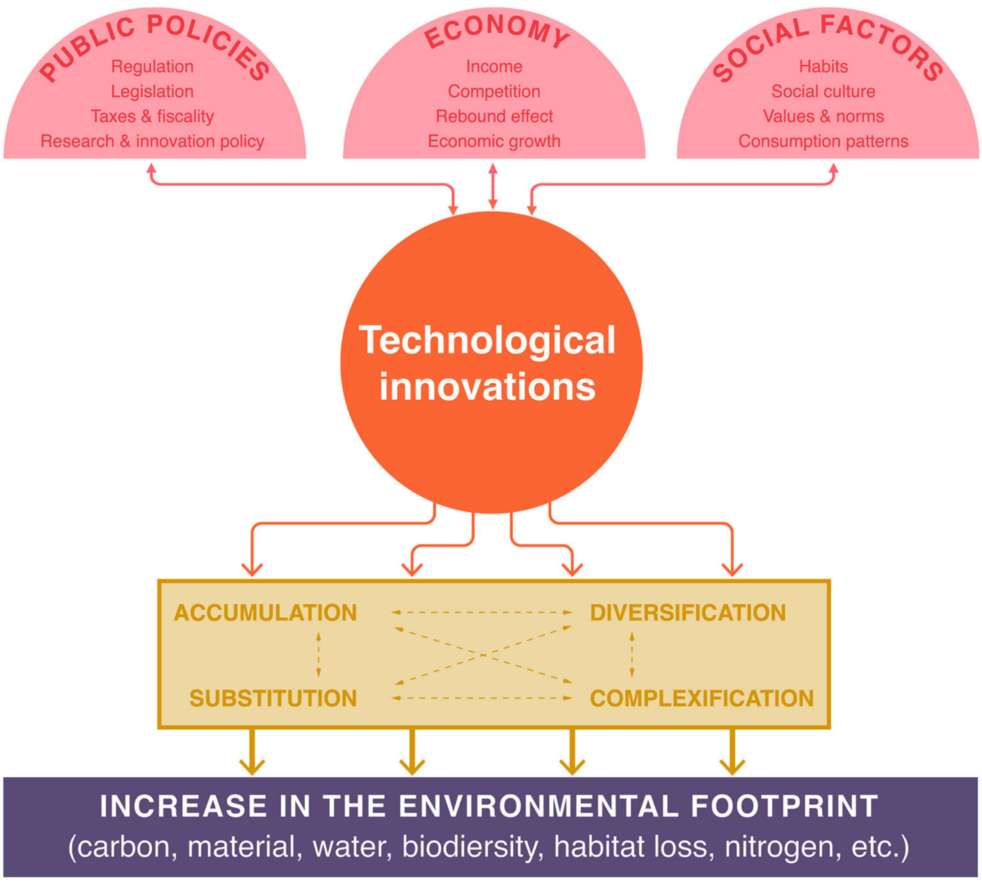

FIGURE 1
Rationalization of some trends associated with technological innovations and their societal drivers (public policies, economy, and social factors). In return, technological innovations play the role of the driver by influencing the economy, public policies, and social behaviors. The four trends identified are also interdependent as indicated by double-headed dotted line arrows.

At the social level, consumers directly influence the rate and number of product acquisitions or renewal of manufactured goods. Consumption is influenced by citizens' values (comfort level) and habits, social norms, income, culture (materialism), product accessibility (credit access, possibility of online purchase, period of store opening), store experience, and marketing. Other social factors include the citizen's perception regarding the ecological crisis (denialism, underestimation, misunderstanding, and unconsciousness) and their propensity to purchase goods (impulsive or compulsive consumers or minimalist and moderate ones; Lefèvre, 2016).

Public policies also affect how technological characteristics influence the environmental pressure of societies. Governments have various means to promote more sustainable innovations by stimulating producers' responsibility and practice changes, and modifying consumer behavior. Public policies may also reduce the impact of consumption by encouraging recycling. These political tools include among others: taxes and subsidies, laws, guidelines, and regulations. They can in particular influence product reparability, the ease of material recovery, the collection of manufactured goods, the information provided to the consumer, more sustainable innovation, etc. With politics that act further upstream, the innovation ecosystem may be reinforced by promoting collaboration and knowledge sharing between stakeholders (academics, industrials, and networking organizations) to improve the integration of sustainable innovations (Genois-Lefrançois et al., 2021).

The technology trends considered here, and their relationship with the other societal sectors, should be considered as they may explain, at least partially, the growth in material consumption in developed countries and whether they represent a break for implementing the socioecological transition that is required to allow societies functioning within the planetary boundaries. The following section is intended to better understand the different processes related to technological innovation that drives an ever-ending consumption increase in our societies.

Technological innovation trends increasing the environmental pressure

Accumulation (ownership)

Ownership [or "abundance" (Ryen et al., 2014)], is the number of a given manufactured good per household or capita (such as desktop computers, freezers, or motor vehicles), and accumulation is the increase in household ownership of a given product over time. Product ownership has to be characterized with regard to its extent, trend, and drivers since household consumption influences material, energy, water, and land use (Cabeza et al., 2014; Di Donato et al., 2015; Ivanova et al., 2016).

Ownership is often evaluated at national levels and is thus given as average values per household. Per capita indicators are provided sometimes as well. Acquisition by consumers of technological innovation as a function of time (market penetration) traditionally follows an *S*-shaped curve, also called a logistic curve, which characterizes a three-step process: initial adoption, development (growth), and saturation. This process has been observed historically for emblematic appliances such as refrigerators or washing machines, for which ownership in households eventually reached 100% in many developed countries (Cabeza et al., 2018) and in China (Liu et al., 2020). Studying the historical evolution (1800–2010) of in-use stocks of 91 products distributed among 10 U.S industrial sectors, Chen and Graedel concluded that many products or groups of products have reached or will reach saturation (Chen and Graedel, 2015).

The beginning of the expansion phase and the saturation level of a given product depends on the country and period considered (Cabeza et al., 2018). Developed countries generally acquired refrigerators or washing machines before developing countries (Cabeza et al., 2018). The most recent market penetration of computers and mobile phones is, however, almost simultaneous in many countries. Some products do not necessarily reach 100% saturation as shown by clothes dryer ownership that is still expanding in many countries (Cabeza et al., 2018). The ownership of some appliances eventually also decreases (phase-out) as they are replaced by new generations of products, as has been observed for black-and-white TV sets or video recorders (Ryen et al., 2015) or with the replacement of cathodic ray tube (CRT) TV sets by the liquid-crystal display (LCD) and plasma ones (Ryen et al., 2015; Kasulaitis et al., 2019; see also Section Substitution).

The acquisition rate and ownership of durable goods generally depend on household income (Ivaschenko and Ersado, 2008; IEA, 2018; Liu et al., 2020), with low income being a barrier to owning certain technology assets. The influence of income, however, has to be tempered since it is also context-dependent. Car ownership is a relevant example. If income seems to be a significant driver of car ownership (Wu et al., 2014; Yang et al., 2017), it applies particularly to developing countries, which undergo strong urbanization, in contrast to developed nations that are suggested to have reached saturation (Metz, 2013).

Other factors also have been considered to describe car ownership such as access to credit (Verma, 2015); urban environment (e.g., urban form, city size, population density, and availability of public transport) (Verma, 2015); demographic factors such as age and population aging (Kuhnimhof et al., 2013); lifestyles (Metz, 2013), etc. Cultural/social factors may also drive product ownership such as interest in technology in the case of electronic devices (Kasulaitis et al., 2021). As for air conditioners, climate unsurprisingly comes before income as a determinant of ownership (IEA, 2018).

Several appliances have reached ownership above 100% on average per household or in some parts of the population of developed nations. CRT TV is a representative example. Average ownership was three CRT TVs per U.S. household in 2007 (Ryen et al., 2015), 2.5 in Japan in 2005 (Cabeza et al., 2018), and 1.4 in China 2005–2010 (Liu et al., 2020). Interestingly, taking into account all types of TV sets (CRT, plasma, and LCD), the total number of TVs remains saturated at three per U.S. household between 2000 and 2010 despite the progressive phasing out of CRT TVs, which were replaced by more recent technology-based ones (Kasulaitis et al., 2019).

Another typical example is provided by mobile phones which growth rate was very rapid (around 8%) in various countries (Cabeza et al., 2018). Ownership values were around 3.5 mobile phones per household in 2010 in the U.S. (Ryen et al., 2014). In Australia, values of 5.1 in 2014 (two phones per capita; Golev et al., 2016) and 3.5 in 2017–2019 (Islam et al., 2020) have been reported. It is noteworthy that not all appliances owned by people are actually in use. It is estimated that the fraction of mobile phones kept in storage in Australia continuously increases up to 50% in 2012–2014 (Golev et al., 2016). This is due to the fact that mobile phones are frequently renewed and that the replaced item is stocked rather than resold on the secondary market.

Other examples are given by desktop computers, videocassettes, and digital cameras which ownership was 1.6, 1.7, and 2.0 per household, respectively, in 2010 in the U.S. (Ryen et al., 2014). Almost 23% of U.S. households owned two or more refrigerators in 2009 (Dahmus, 2014). It is noteworthy that ownership of some products may trigger others [Section Diversification (diversity)].

The ownership of many kinds of material-intensive appliances in a household is related to a large extent to the floor area of that household. For example, the number of TV sets and air-conditioners is partly determined by the number of rooms (Liu et al., 2020) or by second house property. Ownership may be driven simply by convenience, as consumers may want to watch TV in different settings, which implies buying several products of the same type (Kasulaitis et al., 2021).

Unfortunately, data on ownership of durable goods are scattered, incomplete and heterogeneous due to the scale and region of studies, period, and evaluation methods used. Ownership is not well-documented in all spheres of the material needs of households. While electric and electronic appliances are relatively well-documented, this is not the case for instance for kitchenware or gardening and renovation tools.

Diversification (diversity)

This section discusses the diversity of durable goods owned by households or citizens, and diversification, the arising trend of continuous increase in the variety of products owned, i.e., products that fulfill different functions. Some drivers at the origin of this trend are also addressed.

Quantification of product diversification

Diversification is obvious when considering, as an archetypal example, the uninterrupted introduction of new electronic and electrical appliances in the last decades as illustrated qualitatively in Figure 2. With ownership, diversification is a trend that increases device proliferation and its contribution to environmental impacts. This trend in high-income countries can be traced back to the beginning of the twentieth century when industrialization and mass consumption began.

Quantification of product diversification is far from being exhaustive in the literature, except for electric and electronic appliances, although even in this case it remains restricted to some countries. Chen and Graedel studied various products in three economic sectors (transportation facilities, home appliances, and electronic products) over a period encompassing one century (Chen and Graedel, 2015). They found that in-use products increase in the U.S. from two products in 1900 to nine in 1950 and 14 in 2000. This long-term trend seems to be supported by more recent works. An increase in the average total number of electronic devices owned by U.S. households has indeed been reported, from four in 1992 to 14 in 2007 (Ryen et al., 2015). According to a more recent study, the number of electronic products in stock in U.S. households increased from just over three on average in 1990 to more than 16 in 2010 (Kasulaitis et al., 2019). The latter value corresponds to 7.4 electronic products per capita. In the same study, it is evaluated that the acquisition rate of new devices increased from 0.5 per year in 1990 to 3.5 per year in 2021 on average in the U.S., i.e., a 700% increase in 30 years (Kasulaitis et al., 2019), showing the rapid increase in product diversification in households.

The time series of annual inflows show that the number and type of electronic products in the U.S. rapidly increased between 1990 and 2010, particularly due to the introduction of small mobile devices such as digital cameras, MP3 players, tablets, and mobile phones (Babbitt et al., 2017). Product consumption seems, however, to have plateaued and slightly declined since 2010 (Althaf et al., 2021). This has been related to the replacement of single-function devices (camcorders, MP3 players, digital cameras) with multifunctional ones (smartphones; Althaf et al., 2021), a phenomenon called device convergence (Ryen et al., 2014). However, it should be noted that these evaluations are based on a limited number of products and do not necessarily consider accessories and other peripheral devices (Bluetooth®/Wi-Fi headsets and speakers, dock stations, webcams, routers, chargers, power bars, etc.).

In parallel to this increase in electronic devices consumed, a lightweighting of the mean product mass has been observed (Kasulaitis et al., 2019). These two input mechanisms are at the origin of two output phenomena that impede EoL material recovery and recycling, i.e., dispersion and dilution, respectively (Kasulaitis et al., 2019; see also Section Complexification). The former mechanism results from the distribution of materials in more products, the latter from the decrease of material mass in each product.

Despite a continuous shrinking of the mean weight of individual electronic products, the corresponding total weight of material consumed has not diminished in the U.S. between 1990 and 2010. More precisely, the mass inflow of electronic products

FIGURE 2
Illustration of the introduction of new product as a function of time (not exhaustive) as illustrated by electronic devices. Colors indicate new waves of products. Note that some products progressively phase-out (CRT TVs and monitors, video recorders) and are removed for more recent years (data source: Ryen et al., 2015; Althaf et al., 2019).

increased from ∼10 kg per household in 1990 to ∼18 kg per household in 2000 and then decreased to ∼10 kg per household from 2000 to 2010. The latter observation is mainly due to the retirement of large and heavy appliances such as CRT TVs and monitors (Babbitt et al., 2017; Kasulaitis et al., 2019). This relation between mass and units of products has also been observed in Sweden for TV sets and monitors (Kalmykova et al., 2015). The decreasing mass of electronic waste (e-waste) from U.S. households since 2000 has been confirmed with more recent data covering the period 1990–2018 (Althaf et al., 2021).

Drivers of product diversification

Some technological drivers that induce diversification. It can first be driven by the ownership of other goods. For instance, a TV set is related to that of auxiliary devices such as video recorders, Blu-ray displays, decoders, game consoles, speakers, and power bars, since their use is associated with TVs. Similarly, desktops and laptops are linked to the use of printers, Internet (Wi-Fi) routers, scanners, speakers, etc. This trend may be influenced by the desire to benefit from the full potential of the device or to customize it (Déméné and Marchand, 2016). It is noteworthy that not only the acquisition of a given product can generate the acquisition of peripheral others, but it may also be for decoration reasons, at least for TV sets (new armchairs, sofas, cushions, or carpet; Déméné and Marchand, 2016). This mechanism operates as well when the consumer who needs to change a dysfunctional appliance (e.g., refrigerator), changes one or more others (cooking stove and dishwasher), still functional, in order to keep the decorative layout of the interior of the house. It also occurs when the purchase of a piece of clothing triggers the purchase of others to match the initially purchased item. These phenomena have been observed for a long time and have been called the Diderot effect (Lorentzen, 2008).

Product diversification is also related to the introduction of new functions. In the electronics domain, examples of functions are playing videos, recording images, emailing, or web browsing. Figure 2 illustrates the increase in product diversity (or functions) in recent years (Ryen et al., 2015). More quantitative analyses show that the number of product functions increases with time, from almost exclusively a single function in 1990 to multifunctional devices for 80% of all mobile products by 2000 and 100% by 2010 (Ryen et al., 2014). On average, each product provided one new function between 1990 and 2010 (Ryen et al., 2014).

There is, however, a high level of functional redundancy (Ryen et al., 2014), i.e., products that provide the same function with equivalent quality. Households are equipped with multiple devices that fulfill identical functions. For example, image recording and video playing functions can now be fulfilled by up to 12 and 15 products, respectively (Ryen et al., 2014).

Product convergence could therefore be beneficial in reducing the number of appliances necessary to perform all the functions that satisfy consumer needs and desires. The decline of specialized devices such as digital cameras, camcorders, and MP3 players is attributed to the growth of multifunctional ones, i.e., tablets, and smartphones (Babbitt et al., 2017; Althaf et al., 2019, 2021). Similarly, the regression of Blu-ray and DVD players is associated with the appearance of streaming services (although it is not a product *per se* in this case; Babbitt et al., 2017; Althaf et al., 2019). A tablet is an interesting appliance since only some of its functions are used and turns out to be a redundant device rather than a replacement (Kasulaitis et al., 2021).

Substitution

Product substitution (also called replacement, renewal, or turnover) is the mechanism by which a product is replaced by an equivalent or an improved one. Although saturation of ownership of a given device or function may have occurred, replacement of this device or function perpetuates and/or diversifies material consumption. Substitution occurs when the product no longer works, cannot be repaired, can no longer be used, or is no longer considered reparable or useful. Substitution is then strongly related to product lifespan (or lifetime) or obsolescence and is influenced by the rate of introduction of technological innovations (innovation cycle).

Lifespan, end-of-life, and obsolescence

Product lifespan is closely related to product obsolescence. Whereas lifespan refers to the period of use of a product, obsolescence can be defined as an ensemble of processes by which a product is (considered) no longer working or reparable. A typology of obsolescence has been proposed in the literature, including absolute (physical and functional), technological (or systemic), and perceived obsolescence (den Hollander et al., 2017; Zhilyaev et al., 2021). Another classification distinguishes absolute from relative obsolescence (Cooper, 2004). The former refers to non-functional products, the latter to functional ones. An exhaustive review identified the various forms of obsolescence and notes the responsibility of users and/or manufacturers (Déméné and Marchand, 2015).

Obsolescence can be driven by technological, social, or economic factors. Technological drivers of obsolescence refer to the effective end of functioning, either because the product or one of its elements is deteriorated or broken and not reparable (the device is not dismountable, spare elements are discontinued), or because it is obsolete (no more compatible with actual appliances or systems; Ropke, 2001; Longmuss and Poppe, 2017). Technological factors might include advances that make older products outmoded and to the introduction of new products that are more performant or offer new functions or other experiences, a process called generation substitution (Michalakelis et al., 2010).

An example is provided by the evolution of audio listening systems that have made several devices and supports obsolete with time, from the phonograph and wax cylinders to MP3 files/displays or streaming listening today, *via* tape cassettes, vinyl records, and CDs (Ropke, 2001; Lefèvre, 2016). Apart from replacement due to technological progress regarding the product itself (for example, from CRT to LCD or plasma TVs), replacement may occur due to the evolution of the system in which it takes place. For TV sets, this phenomenon occurred upon the introduction of HD TV sets, but also upon the transformation of broadcasting or analog transmission to digital transmission (TV cable, Internet cable, Wi-Fi; Kalmykova et al., 2015; Gusukuma and Kahhat, 2018). Obsolescence may also occur due to backdated capacity, a situation encountered particularly for computers and smartphones (Islam et al., 2020).

Social factors refer to cases where the consumer's perception accelerates product EoL, for example by lassitude, comfort need (Bedir et al., 2013), values, social comparison, fashion (new aesthetics) (Kalmykova et al., 2015), identity formation (Ropke, 2001), family structure and interactions, equity associated with a brand, attraction by products that exhibit better performance, new functions or new experiences, convenience, or simplification of everyday life (Ropke, 2001; Kalmykova et al., 2015; Longmuss and Poppe, 2017; Girard et al., 2018; Zhilyaev et al., 2021). For example, it has been estimated that 40% of LCD TV sets were discarded within 5 years of purchase while they were still functioning (Kalmykova et al., 2015). This was attributed to the premature replacement of CRT or LCD TVs, in the latter case to have a larger TV or one with new/additional features (Kalmykova et al., 2015).

Economic factors include income, product price, reparation price and accessibility of manufacturer support services or repairing services, marketing (advertising), second-hand market opportunities (Zhilyaev et al., 2021), etc. The question of planned obsolescence, i.e., defined as any practice of producers intended to accelerate the devaluation of consumer goods (Wieser, 2017), will not be covered herein because the subject is beyond the scope of this article. We will simply mention that obsolescence is a shared responsibility between manufacturers and consumers, while government decision-makers may strongly influence stakeholders' decisions and actions (Déméné and Marchand, 2015).

To illustrate the short lifetime of products, one can turn to mobile phones. In Australia, the average lifespan goes from about 6 years at the end of the 1990's to about 5 years in the early 2000's and seemed to be constant in 2014 at around 4 years. A more recent work evaluates the lifespan at 3.17 years in 2017–2019 (Islam et al., 2020). Moreover, the active use of mobile phones was estimated in the range of 2.0–2.6 years (considering the first use and reuse; Golev et al., 2016). For European countries, the U.S., and China, the average life cycle of smartphones range from 17 to 24 months between 2013 and 2015 (Baldé et al., 2017) while Korean consumers typically replace their mobile phones every 28.8 months on average (Jang and Kim, 2010).

The phenomenon of substitution is as old as the appearance of the first industrial products. It is however generally admitted that product lifespans of electronic and electric appliances in industrialized societies have steadily declined over the past decades (Karagiannidis et al., 2005; Babbitt et al., 2009; Bakker et al., 2014). For example, the lifetime of CRT for the period 1996–2014 in Sweden was 15 years while that for the more recent LCD TVs was 6 years (Kalmykova et al., 2015). At the same time, the average size of TV sets progressively increased (Kalmykova et al., 2015). In Australia, the average lifespan for a mobile phone decreased from about 6 years in the late 1990's to about 5 years in the early 2000's and then stabilized at around 4 years (Golev et al., 2016). In the educational sector, the life span of computers has been found to decrease from 10.7 years in 1985 to 5.5 years in 2000 (Babbitt et al., 2009).

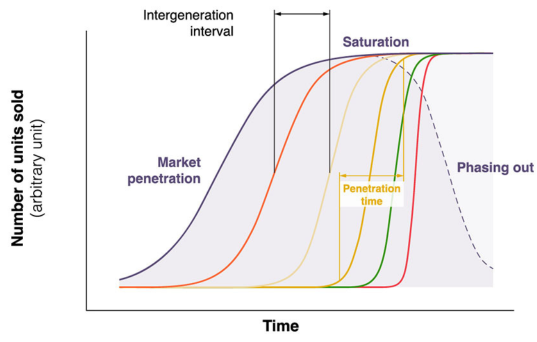

FIGURE 3
Schematic illustration of the market penetration of various products (successive innovation cycles) as represented by their logistic curves. The figure exemplifies actual trends, i.e., the decrease in penetration time and intergeneration interval over time.

The acceleration of consumption due to ever-shorter cycles of replacement has however been partially contested and has been proposed to be often taken for granted, therefore only representing one facet of the reality. The lifespan lengthening has indeed been observed for three products (plant breeding, automobiles, and mobile phones). In particular, mobile phones showed an increasing period of use in the U.K., from 12 months in 2006 to 24 months in 2016 (Wieser, 2017). Similarly, no decreasing trend was observed for several types of electronic equipment in Switzerland (Thiebaud et al., 2018). It is then inferred that, although the strategy that consists in offering products incorporating new functionalities or new performance undoubtedly works in many cases to reduce lifespan, it does not always work if the novelty that is proposed is not sufficient to justify a new purchase (Guenveur, 2017; Wieser, 2017). Then, Wieser et al. call for an empirically grounded theory that can explain both periods of extension and shrinking of lifespan (Wieser, 2017). However, the question as to whether these cases fundamentally question a more general rule of lifespan shrinking with time, at least for electronic products, remains doubtful.

Innovation cycle

This section is about successive cycles of innovations, the rate at which they follow each other (or innovation rate), and their penetration time. As mentioned in Section Accumulation (ownership) the innovation cycle is usually represented by three-step *S*-shaped curves, eventually characterized by a fourth declining step corresponding to products' phasing-out (Figure 3). These curves may be smooth or abrupt and may succeed more or less frequently.

The innovation rate can be monitored by the intergeneration frequency which refers to the rate at which successive innovations penetrate the market or the inverse parameter, the intergeneration interval, which corresponds to the time that separates two innovations. Penetration time refers to the elapsed time between the introduction of a given innovation into the market and saturation.

Studying electronics products owned by U.S. households showed that the penetration time is decreasing with time (as schematized in Figure 3). This shrinking seems to be steady and predictable (Althaf et al., 2019). Chen and Graedel (2015) indeed observed that the saturation level was reached more rapidly for more recent products such as mobile phones, flat-screen TVs, or computers than for older ones such as monochrome TVs, CRT TVs, electric ranges, or refrigerators.

Originating from technological progress and inventions by manufacturers, the innovation rate is mainly driven by the supply side of the market, although the demand represents a motivation that prompts innovation and consumption (although the ultimate decision to purchase new products is the consumer's responsibility).

The question arises as to whether the innovation rate increases with time. Empiricism and simple observation of an increase in product diversification (Section Diversification (diversity)) suggest that the frequency of technological innovations is increasing. Indeed, the time interval that elapses between the introductions of two successive generations, seems to become shorter (Michalakelis et al., 2010; see Figure 3). Although empirically obvious, quantitative validations of this hypothesis are lacking.

It is also important to distinguish innovations that prompt substitution (replacement) from those that prompt diversification (new products). While the former refers to product generations that bring an improvement in performance or additional functions, the latter underlies more radical technological transformations. For example, whereas the smartphone represents a new substitution generation of phones, the first electric telephone represents a news apparatus that accelerates communication between citizens. Breakthrough innovations are generally at the origin of new appliances (phonograph, combustion engine, CRT TV, and computer) and the result of fundamental technological changes [thermal machines, electricity, electronics, information, and communication technology (ICT)] that have far-reaching consequences on consumers' habits and way of life and on the structure of the society itself.

The revolution of so-called general technologies is however not crucial to induce product diversification, as shown by the introduction of electric devices such as yogurt makers, ice cream makers, or pressure cookers. Some substitutive innovations may also have significant effects on the general picture of home appliances. For example, the transition from analog to digital television, the transition from turntables to CD players, or the transition from landline to cell phones induced several modifications of appliances in households since, not only the product itself changed but also the peripheral products that are replaced or appear. They can also drastically change our way of life.

Complexification

Complexification is a process by which products are formed of more components and materials and have a more complex structure, to integrate additional functions and/or to be more performant, miniaturized, lighter, smarter, transportable, wearable, more connected, and/or more autonomous. The complexity is both structural and functional. The two influence each other since, on the one hand, structural complexity allows the implementation of functional complexity, while, on the other hand, functional complexity can motivate structural complexification. Functional complexity can itself be split down into several characteristics including multifunctionality, secondary functions (standby operation), autonomy (energy and responsiveness), and miniaturization and weight reduction.

Referred to by other names such as sophistication (Greenfield and Graedel, 2013) or quality increase (Chen and Graedel, 2015), challenges related to complexification had regularly been underlined (Ropke, 2001; Longmuss and Poppe, 2017; Kasulaitis et al., 2019; King, 2019; Althaf et al., 2021). As a seminal example, Chen and Graedel noted from their historical perspective an increase in the variety, quantity, and quality of manufactured goods, which leads to an increase in the number of types, numbers, and amount of materials used (Chen and Graedel, 2015). Complexification can then take many forms. As the phenomenon has not yet been rationalized, a typology of the various characteristics of manufactured goods that represent numerous manifestations of complexification is then tentatively presented below.

Functional complexity

Multifunctionality

As seen in Sections Endogenous relations between technological innovation and economy and Other trends related to technological innovations, manufactured goods tend to integrate more functions over time and several appliances provide the same or similar functions (redundancy). Multiplication of functions, and then of functional elements (devices), can further be illustrated by automobiles: besides their basic functions (drive, turn, brake, see backward, and lighting), private vehicles now incorporate numerous other devices including remote starter, on-board computer, power-steering, cruise-control, air-bags^{TM}, air conditioning, heated seats, automatic back door opening, rear camera, touch-screen display, rear-cross traffic alert, parking assistance, etc. Several of these functions, like in many appliances, are fulfilled by electronic devices which require many different materials including scarce, critical, or precious metals (Buchert et al., 2012; Cucchiella et al., 2015).

Other examples of products that have seen their functionality increase include watches that integrated calculators and refrigerators that may have water and ice dispensers. Such additional functions, like safety, lightweight, and the increase in performance or comfort, are fulfilled by more complex materials, which are more difficult to recycle than mono-constituent ones. Complexification and the multiplication of components, including accessories, make the product more likely to fail.

Secondary functions (digitalization and connection)

Many appliances contain electronic components that fulfill secondary functions. These functions include: keeping the information, measuring time, displaying information, or responding to a remote-control signal. These components remain functional even if the appliance is switched off and/or is in a low-power mode (Lawrence Berkeley National Laboratory, 2008). Many electric appliances also contain indicator lights (for example to indicate that they are in operation or that a function is activated) or LCDs that are continuously activated (for example on cooking stoves, microwave ovens, coffee makers, remote controllers, etc.). Appliances are also equipped with infrared sensors allowing remote control and the capacity to respond when they are not activated, such as for TVs, air conditioners, stereo Hi-Fi systems, etc.

In 2006, 13% of the total electricity consumption in California was due to apparatuses in "sleep" mode (Lawrence Berkeley National Laboratory, 2008). The energy required to power low-power modes is expected to increase due to the rise in the total number of appliances (Lawrence Berkeley National Laboratory, 2008). In particular, one may infer that this trend will expand further as information is, and will be, more exchanged between appliances in the future, which will be prominent with the growth of the Internet of Things (IoT). This development will indeed be concomitant with that of smart appliances which can perform new secondary functions such as sensing, monitoring, and providing information *via* the internet to mobile devices such as smartphones. This trend is in its infancy but already exists for refrigerators, thermostats, and remote control of the opening/closure of window blinds or front doors. Besides smart homes, IoT is expected to be essential for the establishment of smart cities and a connected health system as well as for industries (Nizetic et al., 2020). Not only do smart appliances offer additional functions to traditional appliances, but they are also more autonomous since they can be programed and act accordingly.

Autonomy (energetic and responsive)

Autonomy refers here to the energetic autonomy of appliances and the capacity to respond physically to specific triggers. It is essentially illustrated by the increasing number of appliances that are energetically independent (i.e., not connected to the general electric circuit or computers) thanks to batteries, a trend accentuated by the development of mobile devices and Wi-Fi and Bluetooth® technologies. Examples of autonomous appliances include laptops, mobile phones, computer mouses and keyboards, speakers, earphones, watches, etc. From a survey carried out in Northern California, it has been evaluated that 8.4 devices on average are rechargeable in a typical household (McAllister and Farrell, 2007).

Autonomous products also include robotic vacuum cleaners and, maybe in the future, cars. This type of machine can operate independently and adjust itself according to the information collected by its sensors. Robotics are expected to expand in the future, not only to perform household tasks but also in industry. The rise of self-powered devices joins the transition to electric cars in putting pressure on the minerals needed to make batteries such as lithium, cobalt, and nickel.

Miniaturization and lightweighting

Miniaturization, or compactness, is an intrinsic trend of technological innovation that is well-illustrated by the evolution of computers from the 1960's to nowadays. This observation is a manifestation of the progressive increase in the number of transistors on a microprocessor chip, leading to a continuous increase in digital performance, which is known as Moore's law (Mack, 2011; Waldrop, 2016). We have seen above that due to miniaturization, the amount of materials used in appliances has shrunk. Nevertheless, compactness represents an obstacle to recovering materials for recycling purposes. This problem has been underlined for tablets (Cucchiella et al., 2015) and for hard disk drives which compact design complexifies the separation of critical raw metals from other materials (stainless steel and aluminum; Buchert et al., 2012).

As mentioned in Section Diversification (diversity) lightweighting has been considered for electronic devices, showing a continuous decrease in their weight, from 19 kg per product on average in 1990 to 2 kg per product in 2010 (Kasulaitis et al., 2019). It should be however noted that this result is influenced by the replacement of the heavy CRT TVs with more modern and lighter LCD and LED TVs (Kasulaitis et al., 2019). It is also noteworthy that if the replacement of CRT TVs with LCD and LED TVs induced an overall decrease in the weight of electronics consumed by households, this shift occurs with the diversification of materials used and new waste burdens (Althaf et al., 2021).

Additionally, the lightweighting of electronic appliances is driven by the use of light metals such as aluminum and magnesium, while plastics increasingly replace heavier steel product casings and other structural elements (Althaf et al., 2021). As mentioned in Diversification (diversity) diversity and dilution (Kasulaitis et al., 2019), which were attributed to product lightweighting, complexify recycling (Kasulaitis et al., 2019). Some metals are even found in very low concentrations in electronic devices, thus complicating the recovery of these materials and causing problems of economic viability (Friege, 2012; Gotze and Rotter, 2012).

Structural complexity (material heterogeneity)

One powerful strategy employed to enhance materials properties (mechanical, optical, and electrical), functionality, miniaturization, and lightweighting is to make use of multicomponent (heterogeneous) materials including composites, intertwined, embedded, or multilayer organizations. For example, printed circuit boards (PCBs), ubiquitous in modern appliances, contain ceramics, plastics, and more than 20 materials, including precious metals and toxic compounds (Cucchiella et al., 2015). A smartphone incorporates 65–70 elements of the periodic table in a volume of about 100 cm^3 (King, 2019). In turn, complexification, in addition to diversification, increases the variety of materials used so that almost all elements of the periodic table are now used to capitalize on their specific properties (Greenfield and Graedel, 2013).

Besides basic materials, the design of electronic devices and their elements (displays, motherboards, batteries, casings, etc.) often induces structural complexity such as laminated components, coatings, sealants or additives which may inhibit material recovery and pose hazard risks (Gotze and Rotter, 2012; Tansel, 2017).

Alloys are also widely used, due to the innumerable properties that can be obtained by adequately mixing the appropriate elements. They are particularly important for jet engines (Greenfield and Graedel, 2013). This strategy makes however the production and recycling more complex. Thus, the existence of alternative approaches has been underlined to enhance the properties of traditional alloys by tuning the micro- or nanostructure, especially by the proper processing (Li and Lu, 2019). The authors even called for a "compositional planification" when designing materials to contribute to sustainability alternatives (Li and Lu, 2019).

Rather than relying on composite materials that are complex to recycle, material design approaches may focus on hierarchical organization such as those found in nature (Sanchez et al., 2005). Biological materials are indeed characterized by mild-conditions production (room temperature and atmospheric pressure) and by single or a moderate number of (renewable) components that are arranged in a complex structure organized hierarchically a different length scales (Egan et al., 2015; Wegst et al., 2015; Lefèvre and Auger, 2016). Biomimetic approaches have then the potential to reduce the impact of industrial products at the production, use, and EoL stages and reduce complexity while enhancing functionality (Benyus, 2011; King, 2019).

Conclusion

Outcomes

This theoretical essay categorizes and underlines diverse aspects of technological change that influence, and more often than not, increase the MF of developed countries, especially of households. The review shows that these trends contribute to the pressure exerted by material consumption on resource use, output flows, and energy demand. It provides a general view of some trends related to technological innovations that contribute to the increase and diversification of consumption, waste streams, and to the difficulty in repairing and recycling.

One of the main contributions of this work concerns the advancement of the theorization regarding the influence of technological innovation on the consumption of industrial products based on the establishment of a trend framework related to technological change. In particular, the review process allowed documenting trends related to technological innovation and reveal several important points that may contribute to formalizing the relationship between technological innovations, consumption of manufactured goods, and sustainability. These points regard:

- The specification of the terminology regarding each trend
- The identification of related concepts that should be considered with regard to the theorization of the relationship between technological innovation and (un)sustainable consumption
- The identification of the main drivers that sustain these trends (innovation social, economic, and other factors)
- The identification of interactions between these trends that contribute to consumption
- The identification of societal consequences on material and energy consumption and waste management

The main findings are summarized in Table 3. In particular, this study shows that the trend framework considered is part of a larger context that closely links economy, technology, and consumption. The trends seem to be intrinsically attached to the socioeconomic system and culture (values and lifestyle). Consequently, profound societal transformations are required and, given the ecological situation and the crossing of planetary boundaries, it requires urgent action. To be efficient, this action should target simultaneously the different societal domains concerned, i.e., economy, social aspects, and public policies.

The four trends are interdependent and influence each other. For instance, diversification can contribute to product ownership and renewal. In this respect, it is important

TABLE 3 Outcomes drawn from the integrative review.

Trend	Accumulation	Diversification	Substitution	Complexification
Other terminology	Abundance		Turnover, renewal	Sophistication, quality increase
Related concepts	Product ownership	Function convergence, Diderot effect	Product lifespan, obsolescence, lifecycle, penetration time, intergeneration interval	Multiple materials and components, heterogeneity; Secondary functions, autonomy, mobility, connectivity; Dispersion, dilution
Origin/motivation	• INNOVATION DRIVERS (NOVELTY): New function or user's experience, more performant, miniaturized, lighter, smaller, smarter, transportable, wearable, connected, digitalized, autonomous, and/or responsive • SOCIAL DRIVERS: Lassitude, comfort needs, values, social comparison, fashion (new aesthetics), identity formation, family structure and interactions, equity associated with a brand, attraction by products that exhibit better performance, convenience or simplification of everyday life • ECONOMIC DRIVERS: Income/purchasing power, consumer price index, and economic conditions (recession, inflation, and crisis) • PLACE OF RESIDENCE: Country, urban/suburban/rural location • ENVIRONMENTAL DRIVERS: Climate (air conditioners, ventilators)			
Interactions	• OWNERSHIP and SUBSTITUTION (novelty/improvement) drives DIVERSIFICATION (new peripherical products) • COMPLEXIFICATION drives innovation, in turn drives ACCUMULATION, DIVERSIFICATION, and SUBSTITUTION			
Consequences	• Increase in the consumption of products and materials • Increase in the consumption of energy (production and use phases) • Variation in the flow and type of material outputs • Complexity of the recycling processes (dispersion, dilution) • Pressure on non-renewable resources, especially critical and strategic metals			

to mention that this overview reveals that the trends are often treated separately. Finally, the data collected show that the available literature focuses mainly on electric and electronic appliances, although other industrial sectors are sometimes considered.

Knowledge gaps

The numerous, highly informative, and innovative research reviewed appear very interesting at the empirical and theoretical levels to understand lifespan, substitution, and obsolescence patterns, and their role in material inputs and waste streams. Several knowledge gaps exist, including the fact that data are scattered geographically, in both space and time (Cabeza et al., 2018). Also, some particular points need clarification. For example, many authors mention or assume the acceleration of the product lifecycle but proofs of this assertion are rather rare.

Above all, studies found in the literature mainly focused on electronics and electric appliances, while data regarding other industrial sectors (kitchenware, furniture, renovation, DIY tools, etc.) are far less documented. It may indeed be expected that similar trends are ubiquitous in all sectors. For example, the apparel area also exhibits accumulation phenomena and acceleration of acquisition rate due to discarding before the entire clothes lifecycle (Schor, 2005) whereas (more complex) smart clothes begin or are about to penetrate the market (Bin Qaim et al., 2020; Xiong et al., 2021).

Additionally, the reviewed papers mainly focused on household consumption. Although it has been the subject of less interest, one is also compelled to admit that the same technological trends are likely taking place in businesses, organizations, and institutions at even bigger scales. Gaining a more quantitative view of the impact of technological innovations across all industrial sectors and actors (consumers, industries, institutions, and organizations) in order to fill the current knowledge gaps would indeed refine our evaluation of the different contributions on the impact related to technological innovations.

Yet as this additional research would not change the main conclusion outlined above, it may very likely confine itself to tinkering at the margins or even indirectly justify political stagnation. As evidenced here, we already know that the possession, substitution, diversification, and complexification of technological innovations critically contribute to increasing consumption of goods and materials in households, and as such, result in unsustainable resource demand and unmanageable EoL challenges. Moreover, we know that unless strong action is taken at the political level, it can be expected that future waves of technological innovations will perpetuate the actual rate of product turnover, thereby maintaining the renewal of products with new functions, increasing customer experience, and exacerbating consumption.

Author contributions

TL: conceptualization, methodology, analysis, writing of original draft, writing of the corrected versions and editing, visualization, and project administration. CD: conceptualization, reading, review, editing, and analysis. M-LA: conceptualization, reading, review, and editing. PG-L and HE: reading, review, and editing. J-FM and MC: reading and review. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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