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Unsustainabilities: A study on SUVs and Space Tourism and a research agenda for transition studies

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ABSTRACT

While transitions research has pursued a successful research agenda around how to improve established socio-technical systems in terms of sustainability, it has missed out, among other things, on innovations that make, or keep, societies less sustainable. In our paper, we explore two innovations in different stages of development: Sports utility vehicles (SUVs) and space tourism. SUVs entrench an existing socio-technical system and reproduce problematic practices, while space tourism might create a whole new, unsustainable system. We make three contributions. First, we introduce 'unsustainabilities' as a new term for technologies, institutions and practices that make, or keep, societies less sustainable. With this we direct attention to developments and structures that undermine ongoing sustainability transitions. Second, we distinguish unsustainabilities associated with socio-technical configurations, socio-technical systems, and meta-structures (spanning multiple systems). Third, we argue that precautionary policies will be needed in early stages of innovation, when there is still room to avoid unsustainable transitions.

1. Introduction

Research and practice in the field of sustainability transitions has the ambition to address pressing sustainability challenges through fundamental transformations of socio-technical systems around energy, transport, agri-food or water [1–3]. So far, this agenda has been pursued with two major strategies centered around innovation and decline: supporting innovations that provide more sustainable alternatives to existing practices, and accelerating the decline of unsustainable practices and systems configurations [4,5].

Even though both strategies are important, they are not sufficient [6,7]. Scholars have argued that, in transition studies, there is too much focus on 'usual suspect' systems [8], a neglect of negative trends [6], and a bias toward the positive [9].

For example, while we focus on innovations such as renewable energies, electric vehicles or meat alternatives, hundreds of new products, services, technologies, or processes are introduced without sustainability considerations. Particularly problematic examples include disposable e-cigarettes, ultra-fast fashion, fast furniture, fracking, deep sea mining, or urban aero mobility. More generally, we are confronted with innovations (e.g., fracking, tar sands) that further entrench problematic socio-technical systems; new products based on unsustainable business practices such as planned obsolescence or high frequency product cycles; or new technologies which may spawn entire industries with questionable environmental impacts (e.g., deep-sea mining, space tourism).

The general argument of this paper is that, to adequately address grand sustainability challenges such as climate change or resource

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depletion, we also need to watch out for 'unsustainable innovations'[1] (and negative developments more broadly). Transition scholars can make important contributions here. We suggest *exploring existing and emerging 'unsustainabilities'* in a more systematic way. We coin the term unsustainabilities[2] to capture technologies, institutions and practices that make, or keep, societies less sustainable. We expect to find unsustainabilities in relation to innovations (empirical focus of this paper) but also beyond. To point to the wider realm of unsustainabilities, we introduce a map of phenomena and potential research topics in the Discussion and conclusions section.

To be sure, we do not claim that unsustainable developments are new for transition studies. Much of the early literature has addressed unsustainable socio-technical systems [5,11,12], and transition scholars have often departed from unsustainable practices and structures (typically associated with socio-technical systems) to justify why we need more sustainable alternatives [2]. However, there are still crucial gaps. For example, established, unsustainable socio-technical systems may undergo step-change transformations to the worse (e.g., fracking, SUVs), or entirely new, problematic configurations and industries might emerge (e.g., deep sea mining). The key problem is that while, as transition scholars, we are busy with a limited set of potentially more sustainable innovations, large numbers of innovations emerge every day, many of which are designed by other criteria than sustainability. Some of these innovations may counteract and potentially even dwarf our ongoing efforts to innovate and transition toward sustainability [6].

Take electric vehicles. While they receive much attention in the transition toward low-carbon transport [13,14], they may distract us from that fact that automobility at large is shifting toward sports utility vehicles (SUVs), which consume more materials in production, more energy in use and are more dangerous than smaller cars [15]. While most pronounced in North America and Europe, the trend toward larger vehicles has been almost universal, albeit with some instances of small car retention in specific markets like Japan and China. Similarly, urban sprawl continues almost unabated, increasing the overall demand for transport. These transformations happen in plain sight but do not seem to get sufficient attention in transitions research. Ironically, the transition toward electric vehicles might even help obscure the above developments for the worse.[3]

The aim of this paper is twofold. First, we want to direct more attention to unsustainabilities and how they can be analyzed from a transitions perspective. Toward this end, we study two examples of 'unsustainable innovations.' Second, we want to help chart the terrain of unsustainabilities. Toward this end, we introduce three analytical dimensions and present a broader map of unsustainabilities with first ideas for future research and policy.

The innovations we study are from different sectors and in different stages of development. The SUV case stands for a failed transition to cleaner transport in a sector with ineffective policies, influential incumbents, a car centric culture, strong dependence on automobility and unsustainable user practices [17,18]. Space tourism, in contrast, is in the early stages of development [19]. It might create new consumer aspirations and needs, like air travel from the 1960s onwards. However, there is still an opportunity to intervene before major lock-ins have emerged. In both cases we focus on climate change as a central sustainability challenge, allowing that there are many more at play (e.g., air pollution, inequality, modern slavery).

2. Theoretical background

We build on the sustainability transitions literature [2] whose conceptualization and understanding of socio-technical change is central to study the dynamics of unsustainabilities.

2.1. Key concepts and analytical dimensions

Transitions research is concerned with processes of fundamental change in socio-technical systems [5]. *Socio-technical systems* are complex, interrelated sets of actors, technologies, institutions, and infrastructures that provide key societal functions, including the provision of services, products, or materials [11,20]. Transitions are closely intertwined with the emergence and widespread diffusion of new *socio-technical configurations*[4] [21]. Socio-technical configurations include a focal technological or non-technical innovation, complementary technologies and infrastructures, as well as actors, business models, regulations, user practices and cultural norms that make this innovation work. For example: electric vehicles as a focal technology, batteries and charging stations as complementary technologies, vehicle manufacturers and charging station operators as key suppliers, emission reduction targets and support programs as key policies, and societal expectations around clean transport as cultural norms [22]. The term 'socio-technical configurations' is applicable to innovations in different stages of development, including mature stages.

While sustainability issues have played a prominent role in transition studies from the start [5,11,12], they are a central driver for the development of the field today [2], giving the increasing urgency of grand sustainability challenges such as climate change, ocean pollution, or inequality. In fact, *sustainability transitions* has emerged as an umbrella term for transitions associated with environmental or social sustainability targets [23].

Currently, there are two key strategies to address sustainability in transitions research and policy [4,24]. The first is to *foster innovations*, or socio-technical configurations, which have potential to contribute to more sustainable modes of production and consumption, by policies that target niche creation and innovation diffusion [25,26]. The second is to *accelerate the decline* of unsustainable configurations and practices, e.g., by means of phase-out policies [27,28].

However, there are at least two major shortcomings in current approaches. First, strategies to foster sustainable innovations have typically concentrated on one sustainability dimension (e.g., greenhouse gas emissions), thereby neglecting other social and environmental dimensions (e.g., poverty, resource depletion, water pollution). So, there

[1] Innovations are not sustainable or unsustainable per se, which is why we use quotation marks. See appendix. Instead, their effects depend on the associated business models, production logics, user practices, cultural meanings etc. In the conceptual parts of the paper, we use the term socio-technical configuration(s) to capture the social, cultural and economic embedding of innovations. However, we continue to use innovation as a shorthand synonym. Instead of unsustainable, we could say "potentially unsustainable" or, as we do in the conceptual part: "designed by other criteria than sustainability." The same considerations apply to other instances where we use "unsustainable."

[2] The concept of unsustainabilities parallels the 'mobilities' studies pioneered by John Urry and colleagues [10] K. Hannam, M. Sheller, J. Urry, Mobilities, immobilities and moorings, Mobilities 1(1) (2006) 1–22., and embraces both long-term, global, dynamic processes of multi-dimensional socio-ecological change and the immediacy of everyday life.

[3] One can argue that the transition to electric vehicles is, in fact, stabilizing many unsustainable elements of the existing regime around individual, car-based transport [16] J. Kester, B.K. Sovacool, G. Zarazua de Rubens, L. Noel, Novel or normal? Electric vehicles and the dialectic transition of Nordic automobility, Energ. Res. Soc. Sci. 69 (2020) 101642..

[4] This term is inspired by Rip and Kemp (1998) who write "technology is also stratified, in the sense that it is composed of materials and components, combined into devices and linkages that, in their turn, are combined into an overall working system. This is how modern technology is organized: a configuration that works." (p. 330) The term highlights that innovation is more than just a new product or practice. It is equally applicable to new configurations (e.g., SUVs, solar PV) in mature stages of development. It is therefore different from the niche concept, where protecting the innovation is central (Kemp, Schot, Hoogma, 1998).

is a risk to overlook “sustainability trade-offs” [29] such as the extraction of minerals for the batteries in electric vehicles [30], exploitation, or the (re-)creation of inequalities [31].

Second, transitions research has neglected ‘unsustainable innovations’ such as fracking or SUVs, which exacerbate existing, already problematic systems [6]. More generally, scholars have argued that the field has a bias toward the positive [9] and that negative developments should be analyzed more systematically [6,7].

Our paper focuses on the latter (but also revisits the former in the Discussion and conclusions). We introduce the notion of *unsustainabilities* for technologies, institutions, practices that make, or keep, societies less sustainable. Technologies, institutions, practices are used here as umbrella terms to include a wide range of elements such as business models, production logics, technology standards, regulations, collective expectations, social norms etc. The intention is to offer a broad definition to capture many different phenomena and dimensions. As research on unsustainabilities progresses, scholars may come up with more specific suggestions.

Our central argument is that we need to think about and analyze unsustainabilities in a more systematic way because many escape the current focus of transitions research. As a first step toward systematization, we work with three analytic dimensions (Table 1). Next to socio-technical configurations and systems, we suggest looking into *institutions and practices that span multiple socio-technical systems*. We refer to them as *meta-structures.* These include societal beliefs and values (e.g., freedom of choice, individualism, innovation as inherently positive), as well as consumption and business principles (e.g., buy a new product instead of repairing it, profit orientation, mass-production). They also include the material structures that support them such as machinery for mass-production or resource extraction. The concept embraces recent ideas around meta-rules [32,33], meta-structures [34] and industrial modernity [35].

It is important to note that the three dimensions are defined in a general way, independent of whether they are used to study sustainable or unsustainable developments. In our paper, we use them as areas where we look for features that are potentially leading to unsustainable developments.

While the dimensions may remind readers of the multi-level perspective [36], we chose more generic categories that allow for a multitude of interactions, including multi-system interactions [37]. With this we are not bound by the nested hierarchy of the multi-level perspective or the landscape concept with largely exogenous factors [38]. Meta-structures are different from landscape elements as they are constantly re-created, transformed, or even newly emerging during a transition [34].

Table 1
Key analytical dimensions and unsustainability examples.

	Definition	Examples of unsustainabilities
Socio-technical configuration	Focal technological or non-technical innovation, complementary technologies and infrastructures, actors, business models, regulations, user practices and cultural norms.	Shale gas exploration Deep sea mining Fast furniture Ultra-fast fashion
Socio-technical system	Interrelated sets of actors, technologies, institutions, and infrastructures that provide key societal functions, including the provision of services, products, or materials.	Established sectors with key unsustainable features around waste creation, resource depletion, fossil fuel use, inequalities etc.
Meta-structures	Interwoven meta-rules and material structures that span multiple socio-technical systems (and configurations)	Central features of industrial modernity such as profit maximization, linear production, exploitation, obsolescence, consumerism

Socio-technical configurations, systems and structures may have multiple interactions and they can be viewed as permeating each other. For example, a configuration (e.g., re-usable rockets) can be used in several systems (e.g., space exploration, commercial satellites, space tourism), and a system (e.g., transport) can use several configurations (e.g., cars, public transit, bikes). Similarly, meta-structures permeate the other two dimensions.

Regarding (emerging) socio-technical configurations, we want to watch out for innovations designed by other criteria than sustainability as these might generate detrimental sustainability impacts. These ‘unsustainable innovations’ will be in the focus of our empirical analysis. We expect that developments around unsustainable innovations are intertwined with system- and meta-level structures and developments.

There are further aspects of unsustainabilities in each dimension, which will be discussed in the final part of the paper.

2.2. Analysis of ‘unsustainable innovations’

The field of innovation and transition studies provides several approaches to analyze the prospects and dynamics of innovations, independent of how they fare in terms of sustainability. The technological innovation systems approach, for example, suggests a set of seven functions (e.g., knowledge development, entrepreneurial activity, legitimation, market formation) to assess how well a novel technological field performs [39,40]. A key idea behind these analyses is to identify weaknesses in the innovation system and to suggest policies to support the innovation [39,41].

Our interest in ‘unsustainable innovations’ is different and so are the implications for policy and research. We look at innovations whose innovation systems are performing sufficiently well in a traditional, economic sense (e.g., because they are backed by resourceful and politically well-connected companies) and pose a threat for sustainability if they diffuse widely. Policy makers may want to avoid that these innovations form a new socio-technical system (or strengthen an existing one) and become locked in.

Our analysis is structured along the three generic dimensions plus a fourth one on policy challenges (Table 2). The first dimension captures the basic characteristics of the innovation, including its origins and current state of development, applications, scope, level of disruption,

Table 2
Specific dimensions to analyze innovations designed by criteria other than sustainability.

	Key questions
Socio-technical configuration	**Innovation characteristics:** What is the innovation about and what is its current state of development? How disruptive is the innovation? Who are the key actors? What are key drivers and barriers? **Context:** How is it related to ongoing transitions and other context developments? **Sustainability:** What are actual and potential implications for sustainability? Which of these will be inherent, which can be avoided and how? **Needs and user practices:** How does the innovation affect user practices? What new needs and practices emerge and how persistent are they?
Socio-technical system	**Regimes:** How does the innovation relate to existing or newly emerging regimes on the production side? What regimes structures emerge and how persistent are they? Who are the influential /incumbent actors?
Meta-structures	**Societal values:** How is the innovation framed in terms of broader societal values, and how is it potentially changing these values? **Business practices:** How is the innovation driven by established business logics and practices? How does it lead to new practices?
Policy challenges	What are key challenges for policy and politics? What policies target the sustainability implications of the innovation?

key actors, context developments, and sustainability implications. We also look into the potential or actual formation of needs, which - once they have formed – make it very difficult to scale back or abandon the innovation [42,43].

The second explores how the innovation relates to socio-technical systems (existing or newly emerging). From past studies, we know that cumulative effects during the innovation process can lead to the formation new standards and lock-ins, which make later adjustments very difficult [44–47]. In parallel, new business models emerge and actors start working actively toward maintaining their interests [48,49]. When technological, institutional and actor related developments become interconnected and link up with already existing structures, a new socio-technical regime [50] might emerge (or an existing regime is strengthened). Once regimes have formed, they become very hard to change [51,52]. So, when studying potentially ‘unsustainable innovations’, it will be key to understand how they affect existing regimes or lead to the formation of new ones.

The third dimension is about meta-structures. Here, we suggest looking into the role of societal values and business practices (further aspects can certainly be added in future studies).[5] Recent work on industrial modernity provides many examples such as the belief that innovation is inherently good and value free, that there are technological solutions to complex societal problems, or that the main purpose of businesses is to create profits [35]. Similarly, it is often assumed that user needs exist prior to innovation [42,43,53] and that the task of engineers and firms is to address these needs, e.g. through new technologies [54]. However, needs are not given, independent or stable. Instead, they emerge over time and co-evolve with technology, or they are deliberately created by businesses [43,55,56].

The fourth dimension captures key policy challenges, politics and (potentially existing) policies to address unsustainabilities. Directing attention of policy makers to unsustainabilities in early stages of development will be key for devising precautionary policies, instead of the usual ‘firefighting’ once they have matured and formed fully fledged and rigid socio-technical systems.

3. Case selection and analytical approach

With our empirical analysis we want to illustrate how in general innovations can undermine ongoing transitions and why they deserve attention from research and policymaking. To address this aim, we select innovations from different fields (mobility and tourism). Moreover, we assume that innovations in an early stage of development are different from those in a later stage, as rigid system structures and lock-ins have not yet formed, which means that they can be more easily guided by (precautionary) policies. In later stages, sustainability implications are better visible (and become more pressing to be resolved), but it is more difficult to contain or reverse these.[6]

Our two exemplary cases, SUVs and space tourism, are in very different stages of development. SUVs grow out of a strong, well-established system around automobility. They have already diffused widely and needs have formed. It is therefore very difficult for policy to change the course of the ongoing transition toward SUVs with pre-emptive or precautionary policies. Alternatively, space tourism is an emerging innovation in a very early stage of development with competing ideas and designs and embryonic user needs. Arguably, there is still a window of opportunity for policy intervention and guidance toward more sustainable trajectories. For both cases, we work with a qualitative case study approach [59], and there is also a comparative element in our case selection [60].

Our empirical analysis builds on the expertise of two co-authors with substantial knowledge and experience in the respective topics.[7] We compiled discursive statements using secondary data covering the two topics in recent years, e.g., newspapers, magazines, scientific publications and industry reports. Due to the explorative nature of this study, we identified relevant sources by using a combination of relevant keywords at the Google Search engine, such as company names (e.g., SpaceX, Virgin Galactic, Blue Origin), key actors (e.g., Elon Musk), technologies (e.g., rocket, Falcon) and key terms (e.g., space tourism). Secondary sources such as newspapers and magazines are increasingly used to capture discursive dynamics in transition research, especially in emerging but contentious fields [61–63]. More specifically, actor statements reported in these sources can be interpreted as exemplary voices and perceptions on a controversial topic or an emerging challenge that requires solutions. Understanding such ‘public discourse’ therefore helps identify the sort of narratives that different actors use to legitimize their views or strategies [62].

Following an abductive reasoning approach [64], we identified elements in actor statements that can be related to the dimensions listed in Table 2. When necessary, we also checked statements by triangulating with other factual data using the similar search terms and source types. Below, we include quotes that best illustrate our arguments. For these quotes, we provide sources (i.e., hyperlinks or other references) to ensure retrievability.

4. Exploring SUVs and space tourism

4.1. SUVs

4.1.1. Socio-technical configuration

Sports utility vehicles are an example of a product innovation in a mature industry. The SUV is an incremental development from off-road or pick-up style vehicles that previously formed a niche segment for special purposes. Most SUVs or ‘crossover’ vehicles lack true off-road capability but have the styling cues, bulk, and height of genuine off-road vehicles.

A definitive example of this new normalized crossover SUV segment is the Nissan Qashqai, introduced in 2006. At the time:

> “…there were still considerable barriers to SUV ownership for many hatchback and saloon buyers… SUVs were considered too large for around-town maneuverability and general everyday usability, plus people didn't like the poor fuel efficiency and lackluster interior quality … We managed to persuade the business that we could break down some of these (consumer) barriers by taking the best bits of a family hatchback and adding the elements of SUVs that are most attractive to customers. And so, the idea of the first ‘crossover’ was born.” Peter Brown, Vehicle evaluation manager, [65]

SUVs can be sold at a premium to a large base of customers, marketed as rugged, spacious, adventurous, versatile, and at the same time ‘safer’ (for the occupants) than smaller, sedan-type family cars. In the US market SUVs and crossover cars commanded transaction prices 39–51 % higher than the equivalent saloon or hatchback, despite similar build costs [66].

SUVs have diffused quickly, primarily replacing smaller cars. In Western Europe, the market share of SUVs grew from 8 % in 2008, to around 35 % by 2018, and 46 % by 2021.[8] Global SUV market shares

[5] Note that we leave out the material aspect of meta-structures in our empirical analysis to reduce complexity.

[6] This predicament is also known as the Collingridge dilemma [57] D. Collingridge, The social control of technology, St. Martin's Press, New York, 1982. [58] A. Genus, A. Stirling, Collingridge and the dilemma of control: Toward responsible and accountable innovation, Res. Pol. 47(1) (2018) 61–69..

[7] These authors joined the team also because of this expertise, after the decision was taken to study SUVs and space tourism.

[8] https://www.best-selling-cars.com/europe/2021-full-year-europe-new-car-sales-and-market-analysis/ Accessed 26/05/23.

reached 46 % in 2022, very much driven by sales in the US, India and Europe.[9]

SUVs diffuse at times, when the automotive industry is confronted with a broad range of major structural challenges, including overcapacity, technological changes (e.g., digitalization, advances in autonomous driving, connectedness to mobile networks), and the transition to battery electric vehicles (BEVs). There are also regulatory constraints and increasing conflicts over scarce space in cities, air pollution and climate change [67].

SUVs come with an inherent increase in energy consumption as they substitute smaller cars. For example, the Nissan Qashqai 1.5 l in 2006 had a weight of about 1454 kg and average emissions of 201.0 gCO_2/km. This is 16 % heavier and 14 % more polluting than the Nissan Almera, which it replaced.

Analysis from the International Energy Agency [68] suggests that SUVs were second only to the power sector in contributing to the increase in global CO_2 emissions since 2010. Carbon emissions from SUVs grew faster than the iron and steel, cement, aluminum, commercial vehicle, and aviation industries. Despite these concerns, it is possible that electrification of SUVs makes their use more socially acceptable, despite congestion and safety concerns [78–80].

SUV users consider their vehicles to display status and affluence, to have approval in their social networks, and to be functionally better than smaller cars [69]. As SUVs are becoming the new norm, consumers have come to 'need' SUVs (e.g., for driving their kids to school) due to perceived safety benefits (e.g., keep my kids safe), no matter how erroneous that perception may be and despite the increased risk to other road users [70]. As more people drive SUVs, it becomes less safe for others not to do so.

4.1.2. Socio-technical system

Automobility is an established socio-technical system, centered around the provision of individual mobility and complemented by massive infrastructures, regulations, services, user practices and societal norms [17,71]. Multiple incremental innovations in materials, components, and whole vehicles have acted to sustain the viability of the regime [72–74].

Within the established system, the SUV is an innovation that builds on and strengthens existing structures. SUVs fit well into established business models and business practices of car manufacturers [75]. SUVs are easily accommodated within existing supply chains, manufacturing systems, distribution networks, retail structures, finance and insurance provision, consumer expectations, and service and support systems including fuel supply. SUVs fit also readily into existing regulations and road infrastructures. Finally, the SUV continues the already entrenched path dependency around individual, long-range mobility as the dominant mode of transport in numerous countries and regions [76].

At the same time, new structures have emerged that favor SUVs. One example is the labels to inform consumers about fuel efficiency and CO_2 emissions. Germany's mass-based weighing scheme has been designed to benefit heavy SUVs. As a result, a BMW X5 SUV which emits more than 150 gCO_2/km receives an A label, while a VW Golf with 114 gCO_2/km only gets a B [77]. The CO_2 emissions regulations flexibilities applied in the EU specifically use limit curves that allow manufacturers of heavier cars higher emissions than manufacturers of lighter cars.[10]

Due to these high levels of complementarities, SUVs are well on their way to become the dominant passenger vehicle. In 2020, Ford abandoned production of sedan (saloon) cars in North America to focus on SUVs and crossovers. All major auto makers now include SUVs in their model ranges. More tellingly, even niche sports and luxury auto makers such as Bentley (with the Bentayga), Lamborghini (Urus), Porsche (Cayenne), Maserati (Levante), Rolls Royce (Cullinan), and Aston Martin (DBX) now feel compelled to have models in this segment.

According to the International Energy Agency [78] p. 28:

"A key development of the past decade is the increasing share worldwide of the small SUV/pickup segment… [they] primarily replaced city cars, medium and large cars."

4.1.3. Meta-structures

Cars and automobility have long reflected wider societal values around material prosperity, personal freedom, individuality and choice, underwriting their social legitimacy despite the evident social inequalities created. In deeply entrenched socio-technical systems such as automobility, cognitive assumptions about needs are woven tightly into the fabric of everyday practices, and are all the more difficult to alter [76]. SUVs build on and extend these societal values.

The SUV concept is also associated with and driven by changes in societal values (in some places), such as more active lifestyles or adventure holidays [79]. Many activities such as water sports, off-road biking, mountain climbing, etc. have become more widely popular in recent years, and are often associated with large quantities of equipment and a desire to access more remote locations [80].

In terms of business practices, SUVs reinforce the position of the automotive industry as a pioneer in mass production, process automation, digitization, and supply chain management. Moreover, the expansion of the SUV market resonates with existing business practices and linear business models premised on material extraction, assembly, and the sale of 'mass customized' products to final consumers in which profitability is conditional upon modest product variety and high levels of capacity utilization [81].

Individual automobility more broadly also reflects deep structural assumptions that 'low carbon – high energy' futures are viable without profound change to user behaviors and practices, despite creating multiple new inequalities [82]. This is in contrast to research which suggests that achieving deep de-carbonization goals in mobility will require a combination of electrification, policy measures and, crucially, lifestyle changes [83,84].

4.1.4. Policy challenges

Progressively tightening emissions controls and a new regulatory regime for carbon emissions from vehicles in the EU, stimulated a long-run decline in average new car CO_2 emissions from 159 gCO_2/km (2007) to 118 gCO_2/km (2016) [85]. However, improvements in efficiency are counteracted by an increase in traffic and the ongoing transition toward SUVs. In Germany, for example, emissions from road transport have not decreased since the 1990s [86].

Future policy targets seek to decrease overall emissions.

> "Cars and vans produce 15% of EU's CO_2 emissions. The Parliament approved new legislation to toughen car emissions standards, introducing CO_2 reduction targets of 37.5% for new cars and 31% for new vans by 2030. … The Parliament is also calling for measures to facilitate the shift to electric and hybrid vehicles." [87]

Whether these targets will be reached is unclear. Vehicle manufacturers have lobbied against strong emission regulations for decades, with some success.[11] They favor technological solutions for carbon targets, even though these might not be sufficient without additional behavioral change [88].

[9] https://www.iea.org/commentaries/as-their-sales-continue-to-rise-suvs-global-co2-emissions-are-nearing-1-billion-tonnes Accessed 25/05/23.

[10] see https://ec.europa.eu/clima/policies/transport/vehicles/cars_en Accessed 25/05/23

[11] During the period 2020 to 2022 vehicle manufacturers selling in the EU gained 'super credits' toward their 120 gCO2/km regulated fleet average target for new vehicles, on the basis that every electric vehicle sold (zero gCO2/km) counted double in 2020, 1.67 times in 2021, and 1.33 times in 2022. In this sense, Nissan could sell more Qashqai models based on having sold more Leaf (BEV) models.

Policies targeting vehicle users and the need for automobility are more difficult and complex to implement [88]. Reversing the SUV trend would likely have to embrace the cultural framing of automobility through which needs emerge [89].

Regarding future pathways, there are overlaps between SUVs and BEVs. Many vehicle manufacturers seem determined to sell SUVs up to the boundaries set by the various regulatory regimes for carbon emission reductions. In parallel they also develop electric SUVs because the additional costs of electric battery packs and powertrain can be more readily recovered with premium segment vehicles. Finally, some automakers develop light-weight 'L-category' BEVs such as the Renault Twizy or Citroen Ami, or the BMW i3 [90], in order to achieve an efficient vehicle with a smaller battery pack that is also more suited for short-distance traffic in congested cities.[12]

4.2. Space tourism

4.2.1. Socio-technical configuration

Space tourism is currently a service innovation in the rapidly growing and transforming space sector [19]. The core idea is to send non-astronaut citizens to outer space for recreational purposes. In the future, we might also see links emerging with the tourism sector. Commercial space tourism is currently planned at the orbital or suborbital levels, but some firms also speak about lunar tours. Both the business idea of space tourism and the underlying technologies are relatively new. It is still in an early stage of development (with ultra-rich individuals as pioneering customers) but progressing rapidly.

Space tourism dates back to the late 1990s, when the American businessman Dennis Tito became the world's first space tourist visiting the International Space Station (ISS) with the Russian spacecraft Soyuz TM-32.[13] Recent developments around space tourism are driven by the rapid growth of the 'New Space' movement [91,92]. This is a wider, fundamental transformation of the space industry involving technological innovations, new actors (many of which are private firms), and commercialization (e.g., mass-launching of satellites).

In terms of actors, three large, resourceful spaceflight companies stand out. Blue Origin and Virgin Galactic are both experimenting with technologies for short suborbital tourism. SpaceX aims to send tourists on a trip to the ISS, and even around the moon. Partnering with Axiom and NASA, SpaceX successfully sent a crew of private citizens to the ISS in April 2022 – marking a new major milestone for commercial spaceflight.[14]

Space tourism benefits from technology advances in reusable rockets and the commercialization of space travel.[15] There have been rapid cost reductions. Compared to the early NASA Space Shuttle program in 1981 during which the payload cost was more than 50,000 USD/kg, SpaceX claimed in 2018 a payload cost of less than 3000 USD/kg [93].[16]

Space tourism can bring major sustainability implications especially for the Earth's climate [94]. The industry is inherently energy intensive and there are three main types of problematic emissions: Chemicals (chlorine) which lead to ozone depletion, CO_2 emissions, and soot emissions.

In terms of carbon footprint, each rocket launch would result in about 150 metric tons of carbon.[17] This makes every rocket launch equivalent to about 3 times as much CO_2 as a transatlantic flight (which also has about 50–100 times more passengers). If a firm launched once every two weeks, this would accumulate approximately 4000 tons of carbon annually just for that one firm. As of 2023, SpaceX is launching rockets every four days on average (for satellites mainly).[18]

In terms of soot (also known as black carbon), latest simulations show that emissions could significantly raise temperatures in the polar regions. Soot deposited on the surface absorbs more sunlight energy than snow or ice. Soot may also remain in the stratosphere for up to ten years, where it absorbs sunlight and exacerbates global warming.[19]

> "Due to particularly harmful 'black carbon' being emitted at very high altitudes, 1000 spaceflight launches per year would constitute an analogous contribution to climate change as currently exerted by the entire aviation industry." [19] p. 280.

> "As long as the space tourism industry is developed without the necessary cautions, it remains at risk of becoming the most anti-sustainable tourism sector, with pervasive negative impacts at the global scale." Asli Tasci, Professor of tourism.[20]

Today, space tourism still targets rich and ultra-rich individuals. It is a luxury for a few, and needs have not formed yet. However, there is a strong demand. According to Virgin Galactic, about 650 tickets (250′000 USD each)[21] were already sold before the orbital flight by Richard Branson himself in July 2021. Since then, prices for a ticket climbed to $450,000 with a waiting list of about 800 customers.[22]

If the promises and visions materialize and costs reduce significantly in the future, the demand for leisure space travel is likely to become increasingly common. Those who took a trip to space might flaunt their higher social status through extravagant leisure activities as we already observe in the tourism industry.

4.2.2. Socio-technical system

Space tourism can be viewed as a socio-technical system in the making. It currently emerges within the socio-technical system of the space industry, which is rapidly transforming due to technological progress, new (private) actors and international competition. There are no established dominant technological designs, business models, consumer expectations, or regulations related to space tourism yet. However, technological competition and business narratives in public media are developing rapidly, leading to progressive formation of visions and ideals, attracting financial investments and customers, as well as government support.

Business plans for space tourism estimate a flight rate of 1000 suborbital trips per year once space companies routinely fly passengers for leisure purposes.

> "In time, we expect to be operating a variety of vehicles from multiple locations to cater for the demands of the growing space-user community. Whether that be transporting passengers to Earth

[12] In China the 'Low Speed Electric Vehicle' is a distinct segment that claims around 20 % of total EV sales, while in the US such a segment does not exist.
[13] https://www.britannica.com/topic/space-tourism accessed April 20, 2020
[14] https://www.euronews.com/next/2022/04/07/the-international-space-station-will-welcome-its-first-all-private-crew-of-astronauts-this accessed July 8, 2022
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[21] https://www.nbcnews.com/mach/science/how-much-does-space-travel-cost-ncna919011, accessed April 20, 2020
[22] https://www.space.com/virgin-galactic-spaceship-factory-arizona accessed July 22, 2022

orbiting hotels and science laboratories, or providing a world-shrinking, transcontinental service […].” Virgin Galactic[23]

If a system with these features were to take shape, it will be very difficult to avert it from having a major sustainability footprint. One of the challenges is its close association with other spaceflight activities such as satellite launches, transporting goods and astronauts, or public-private missions to the Moon. Space-based infrastructures that rely heavily on lower launching costs are rapidly developing and have attracted enormous business and policy investments [95].

4.2.3. Meta-structures

The promotion of space tourism heavily mobilizes broader societal values. These include personal mobility, a human right of ultimate freedom, adventure and exploration, or accessibility to extravagant luxuries, despite building on deeply entrenched social inequalities.

The excerpt below shows how the space tourism industry is portrayed in a travel magazine as offering the same opportunities of bringing ‘normal people’ to places that were previously unreachable:

> “The next era of space exploration and innovation is here — and we're all invited. A billionaire space race is underway as Blue Origin, Virgin Galactic, SpaceX, and others are testing the technology to take us to places previously visited only by highly trained astronauts.” ‘Travel and Leisure magazine[24]

Space tourism has even been associated with a deep realization and appreciation of the vulnerability of our planet:

> “As space adventure will boost the economy, it likewise will increase our appreciation of how rare and valuable our own planet is. The experience of traveling out of Earth's atmosphere and looking back on the world we inhabit produces a sense of awe and respect…” Allan Fyall, Professor of tourism marketing[25]

In terms of business practices, space tourism companies follow well-established principles around profit orientation or the logic of using complementary assets such as rockets and launch sites. At the same time, they also appeal to shared values around sustainability (e.g., pointing to reusable rockets, or more ethical sourcing of raw materials), cost efficiency through mass production (e.g., by increasing the manufacturing volume for parts and components of spacecraft and rockets, achieving standard operating procedures), or even addressing inequality (e.g., by ‘reserving seats’ for people from the Global South). At the same time, the creation of new economic opportunities (e.g., by offering local jobs and industries) and resource exploitation (e.g., allowing access to outer space minerals) are used to legitimize space tourism [94].

> “Blue Origin believes that in order to preserve Earth, our home, for our grandchildren's grandchildren, we must go to space to tap its unlimited resources and energy […] our road to space opens to the door to the infinite and yet unimaginable future generations might enjoy. Paving the way starts now.” Blue Origin[26]

We therefore observe that space tourism, despite being in a nascent stage, is progressing rapidly by building on some generic societal values as well as commonly shared business principles.

4.2.4. Policy challenges

Policy challenges related to space tourism are contextualized within the space sector. Policy issues include environmental impacts such as carbon emissions, the accumulation of space debris, as well as questions around access, ownership, and control of space technologies. Resolving these policy and regulatory issues is challenging and requires a high level of international coordination. International organizations that have started to address space governance issues include the European Space Agency or the United Nations Office for Outer Space Affairs, which have been active in advocating for new institutions.

For space tourism, new policies and regulations will be needed.[27] At the moment, many aspects of private space travel are not yet regulated and national and international policies on space tourism are either non-existent or at a very early stage of development. For example, governments have not devoted much attention to regulating emissions from rocket launches. Since they were considered a matter of national security in the past, they have been largely exempted from environmental legislation. However, this perspective is changing as scientists have started to highlight the environmental consequences:

> “Until legislation is put in place, the inequality of environmental harm caused by space tourism will continue…Most of us are here on the surface dealing with the full brunt of the climate crisis…while just a tiny number of people are up there having these opportunities.” Mahir Ilgas, environmental action group 350.[28,29]

Overseeing private spaceflight activities or constraining touristic space travels seems to be challenging [94]. The industry is gaining increasing political influence, not just because of its enormous economic potential but also because space tourism targets influential customers. If successfully commercialized and scaled up with current technologies and fuel systems, space tourism will work against national and international climate targets.

4.3. Summary

Here we review both cases and summarize the main findings (Table 3). The SUV is an innovation whose widespread diffusion is in full swing, and it exacerbates long-standing issues around energy use and CO_2 emissions in individual transport. Space tourism, in contrast is a new configuration in an early-stage development spawned by an industry that is undergoing rapidly transformation. It might cause major energy and climate problems. For space tourism, consumer needs have not yet emerged, so there is still room to moderate future customer expectations. This is very different for SUVs, which have already become the norm for many users and new needs (e.g., around status and safety) have emerged around it.

Regarding system formation, the SUV case demonstrates how innovations can entrench existing regime structures, including established business models and user practices. SUV design and concepts are now also carried over to the transition toward electric vehicles. Space tourism, in contrast, is a case where system formation is only beginning. Nonetheless, resourceful actors push strong visions around a large and vibrant industry with limited concerns around sustainability issues.

In terms of meta-structures, both cases exhibit several similarities, which we will explore in further detail in the Discussion and conclusions section.

From a policy perspective, the SUV case can be viewed as a policy failure. Even though the automotive sector's sustainability issues have been under scrutiny for many years [96], the SUV transition keeps unfolding undiminished, especially in the US, India and Europe. This is an important reminder of how rigid and powerful socio-technical systems can become, e.g., with their key actors having close ties into policymaking to prevent effective climate policies [97,98]. The concurrent

[23] https://www.virgingalactic.com/vision/ January 12, 2020
[24] https://www.travelandleisure.com/trip-ideas/space-astronomy/space-tourism-is-here September 26, 2023
[25] https://www.ucf.edu/pegasus/space-tourism/ accessed January 12, 2020
[26] https://www.blueorigin.com/our-mission accessed January 12, 2020
[27] https://phys.org/news/2022-06-climate-space-tourism-urgent-mitigation.html accessed July 8, 2022
[28] https://www.digitaltrends.com/dtdesign/environmental-costs-of-space-tourism/ Accessed April 20, 2020
[29] https://350.org/about/ Accessed April 22, 2020

Table 3
Analytical dimensions and main differences across the two cases.

	SUVs	Space tourism
Socio-technical configuration	Innovation in a mature industry; Late stage, transition to SUVs in full swing; Inherent increase in energy and material consumption; SUVs created new needs around status and safety	Innovation in a rapidly growing and transforming industry; Early stage with rapid progress Inherent massive energy consumption, CO_2 and soot emissions in stratosphere; Luxury, strong demand, has not created new needs
Socio-technical system	Entrenchment of existing regime around automobility; Carry-over impacts on markets for electric cars	No system formation yet but strong visions for future developments; Interaction of space tourism with other commercial and non-commercial space activities
Meta-structures	Societal values: Personal freedom, material prosperity, mobility, adventure, active lifestyles; Business practices: Mass production, profit orientation, process automation, digitization, linear business models	Societal values: Personal freedom, prosperity, mobility, adventure, leisure, appreciation for Earth; Business practices: Profit orientation, economic opportunities, cost efficiency, reusability, resource exploitation
Policy challenges	Policy failure after decades of emission and climate regulations with enduring implications for carbon emissions; Transition to electric vehicles obscures climate challenges of SUVs	Window of opportunity for industry and environmental regulation; International coordination as a key challenge

transition to electric vehicles even helps to hide some of the negative effects of SUVs.

In contrast, space tourism has received very little attention in terms of climate or environmental policy up to now – even though its climate impacts might be substantial. While the window for policymaking thus appears to be wide open, firms and nations rather focus on the new opportunities, i.e., the race toward commercialization than on environmental sustainability considerations. Another major policy challenge is international policy coordination, as firms can do forum shopping, i.e. evading to places with less strict regulations [99].

5. Discussion and conclusions

While both cases point to several differences (as intended), there are also many similarities, especially with regard to how they interact with and reinforce existing meta-structures. Next, we start with these similarities, which point to a larger 'web of unsustainabilities' beyond our specific cases. Building on this and our initial reflections in Section 2, we then map unsustainabilities more broadly. Finally, we propose ideas for future research and policy.

5.1. Discussing similarities in relation to meta-structures

In our cases, 'unsustainable innovations' have not emerged in isolation, but they are linked to a larger array of structures and practices in established socio-technical systems and beyond. Here, we discuss the role of meta-structures.

We already established that SUVs fit well into existing business models and supply chains of car manufacturers [75]. However, they also resonate nicely with *general business practices* that reach well beyond the car industry. For example, developing and selling new products with little to no consideration about sustainability issues, re-creating linear value chains, mass-producing items to increase profits and lower costs, or creating desires and turning them into needs, so that consumers become locked in and find it increasingly difficult to explore alternatives. The emergence of space tourism works along similar logics, albeit in an earlier stage of development. Here, we also find general business principles such as profit orientation, no consideration of sustainability impacts, leverage of existing assets, and creating desires and subsequent demand for something new that did not exist before.

Both cases also speak nicely to deep rooted beliefs around technological progress, the legitimacy of pushing scientific and engineering boundaries, or seeing an inherent value in innovation. These resonate well with common business and policy targets around growth, job creation, international competitiveness, exports, creating new businesses and industries etc. In fact, both cases relate to many of the elements of what Kanger and Schot (2019) have termed *industrial modernity*: Rules of industrial societies that have formed and accumulated over centuries and "manifest themselves as particular structural features, long-term trends and persistent problems" [35] p. 10.

Our examples also point to connections between innovations and widely shared societal values around individual mobility, freedom, adventure, exploration, active lifestyles, or status. In the case of the SUV, also perceived concerns around safety and 'cocooning' come into play [18].

What we observe in both cases are acts of framing and institutional embedding in relation to both, existing socio-technical systems and meta-structures. This is very much in line with findings from earlier studies that have shown how important it is to connect innovations to 'higher level' institutional structures[30] in order to create legitimacy [61,100–102]. And this is not just a one-way relationship: Business practices and societal values are also recreated (and new ones are potentially generated) by innovations that diffuse widely while 'using' them.

It is important to note that not all meta-structures or business and consumption practices in established socio-technical systems are unsustainable per se. While some are, most can be used in different ways. Societal values such as freedom can be mobilized to e.g., strengthen human rights or political systems but they can also be used to praise SUVs and space tourism. Similarly, business principles such as profit maximization can be used to increase efficiency (e.g., reducing material consumption) but they can equally contribute to exploiting labor. Future research around unsustainabilities might want to further explore the hybrid nature of (some) meta-structures.

5.2. Mapping unsustainabilities

Next, we start mapping unsustainabilities across the three analytic dimensions (Table 4). The map includes five areas. For each, we present issues that are important from a sustainability perspective, potential research topics and examples. The idea with this map is to stimulate further research, not to be exhaustive or free from overlaps.

The first area is about innovations designed by other criteria than sustainability (as in our two cases). There are several, partly interconnected issues. First, if innovations diffuse widely, potentially problematic sustainability impacts multiply (e.g., space tourism, deep sea mining). Second, the formation of new markets and socio-technical systems can bring about new interests (businesses and consumers), including resistance to change. Third, if innovations such as fracking or tar sands strengthen existing socio-technical systems, they may counteract required transformations (e.g., the transition away from fossil fuels). Also, innovations may result in the formation of new needs, when

[30] We don't work with the conceptual repertoire around institutions and institutional logics here (even though it could be used as well) because the emerging ideas around meta-structures and industrial modernity speak more directly to unsustainabilities.

Table 4
Established and potential areas for research on unsustainabilities.

	Issues relevant from a sustainability transitions perspective	Topics for transition research	Examples
Socio-technical configurations			
1 Innovations designed by criteria other than sustainability	Potentially wide diffusion and upscaling; Formation of new markets and interest; Entrenchment of existing systems and practices; Formation of new needs Longevity of artefacts	Widen the scope to unusual suspects; Emergence of problematic innovations and businesses; Consequences for ongoing transitions; Unsustainable lifestyles	Fracking; Exploitation of tar sands; Deep sea mining; Space mining; Space tourism; Single use products (e.g., e-cigarettes); Ultra-fast fashion
2 Innovations designed to address unsustainable socio-technical systems	Problem shifting; Unwanted effects; Continued lock-ins; Delay of more fundamental transformation	Widen the scope of transition studies: multiple sustainability goals; Needs, demand side, lifestyles	Biofuels: land use, monocultures, emissions; Electric vehicles: mineral use and waste creation around batteries, contd. lock-in around individual mobility: Syn-fuels: energy efficiency, deeper transformation delayed
Socio-technical systems			
3 Socio-technical systems with major sustainability problems	Development of new systems with potential sustainability problems; Entrenchment and re-stabilization	System emergence and policy guidance in early stages; Widen the scope: beyond the usual sectors; Politics of delay	Classic sectors (energy, transport, buildings, industry); Fast food; Fast fashion; Tourism; Materials (e.g., plastics)
4 Socio-technical systems with favorable sustainability features	Increasing pressure and destabilization; Decline of sustainable technologies or practices	Rationales behind the decline of established practices	Nature based solutions; Local production of goods; Walking, active travel; Passive heating / cooling
Meta-structures			
5 Multiple systems	Diffusion of unsustainable meta-rules and meta-structures; Decline of sustainable meta-rules and meta-structures	Interplay of meta-structures, systems, and configurations; Transformation of meta-rules and structures, emergence of new ones; Post growth / degrowth	Profit orientation and profit maximization; Planned obsolescence; Strategic lock-ins (e.g., platforms); Buy new instead of repair; Prioritize quantity over quality; Convenience; Consumerism

practices turn from luxuries (e.g., exotic vacations, flying and the ‘jet-set’) into commonplace activities [103]. As it is difficult to scale back these needs, we rather see less harmful variants (e.g., synthetic aviation fuels, electric SUVs) instead of a more fundamental reorientation. Finally, the above effects may be aggravated by the longevity of artefacts, or infrastructures.

The second area is about innovations directed at sustainability challenges – a core topic in transition studies [2]. These might come with neglected unsustainabilities because we tend to focus only on one sustainability dimension and one place at a time (e.g., global North vs. South, rural vs. urban). ‘Environmental problem shifting’ [104] or ‘sustainability trade-offs’ [29] occur if one sustainability issue is addressed at the expense of another. For example, electric vehicles may help to address local air pollution and climate change but their batteries need minerals such as lithium or cobalt whose sourcing can be highly problematic [30]. Problem shifting may also occur across places, e.g., if production is moved to regions with low environmental or social standards [105]. A second issue is about unwanted or unexpected effects. In the case of bioenergy, for example, these include monocultures, competition with food production, or additional carbon emissions from soils [101]. A third issue is about the implications of continued lock-ins once more sustainable innovations have diffused widely as in the case of electric vehicles. Finally, innovations may also be used to keep unsustainable systems in place and delay more fundamental transformation (e.g., end-of-pipe approaches such as carbon capture and storage).

The third area is about socio-technical systems with major sustainability issues. While already a key topic in transition studies [2], some aspects deserve further attention. These include the emergence of new socio-technical systems as in the case of new space [106] or artificial intelligence [107]. They come with a broad array of potentially beneficial and problematic innovations, and the associated governance challenges. A related issue is about further system entrenchment and processes of regime re-stabilization, in contrast to de-stabilization [108].

The fourth area addresses socio-technical systems with specific technologies or practices that have favorable sustainability features. Examples include public transport, passive energy architecture, short-distance city planning[31] or nature-based buildings. More research is warranted into how these systems have come under pressure, perhaps even declined (e.g., for cost or convenience reasons) and how to re-stabilize and expand them. Interesting cases include the decline of the American railroad system at the beginning of the 20th century [109] or the decline of city tramways and their eventual re-introduction [110]. A related issue is the decline of specific practices such as those around short distance tourism, buying local and seasonal food, repairing goods (electronics, clothing), passive cooling or drying, or walking [43,111].

The fifth area includes meta-structures that span across multiple socio-technical systems. Many features of industrial modernity [35] can be viewed as unsustainable meta-rules. For example: business models based on growth perpetuity, fast product cycles, planned obsolescence, or mass production and consumption [112,113]. Also, the strategy of platform service providers to lock-in consumers can be viewed as a problematic meta-rule. Our cases illustrated the relevance of societal values (e.g., freedom, choice) which don't even have to be unsustainable.

5.3. Implications for research

A central intention of this paper is to direct more attention to unsustainabilities and to invite researchers in the field of transition studies and beyond to investigate them more systematically. With our cases we have just begun exploring some of the facets of unsustainabilities. The above map points to many more, some of which we discuss next.

In general, unsustainabilities call for widening the scope of transitions research. [6,8]. The first area highlights the necessity to study negative developments and innovations that are not part of the ‘usual suspects,’ but new technologies in fields such as deep sea mining,

[31] https://citymonitor.ai/neighbourhoods/what-is-a-15-minute-city, accessed June 19. 2023

geoengineering, chemical recycling, space travel, or carbon capture and storage. In addition, we might also want to study the emergence of problematic businesses practices (e.g., ultra-fast fashion, beauty and fashion influencers, fake news and disinformation services), how they affect unsustainable lifestyles, existing industries as well as ongoing sustainability transitions [106,114,115].

The second and third area have been widely studied already. However, there is certainly a need to better understand sustainability tradeoffs across sectors and places [104] and across other sustainability dimensions (e.g., unethical sourcing of minerals used for batteries or the justice dimension of the energy transition [116,117]). Also demand side and lifestyle issues require more attention.

In the third area, we might want to take a closer look at the dynamics of system formation. This includes the emergence of dominant socio-technical configurations or standards [62,118], the formation of markets [119], guidance or influence on the direction of innovation processes [47], emerging coalitions of actors [120] or changes in user practices [43,121]. While many of these aspects have already been addressed, we may want to widen the scope from the 'usual suspect sectors' to tourism, plastics, fast fashion, or other industries with extremely short product cycles. As we widen the scope, we will also be confronted with problem framings (e.g., circular economy) that challenge established transition frameworks.

The fourth area is rather new. It is vital to also understand the processes behind the decline of sustainable system features such as nature-based solutions or localized production and consumption systems. The same goes for the decline of sustainable practices (passive cooling or drying, walking, repair) or technologies (electric tramways, low-carbon building materials) [122].

Regarding meta-structures, we need to better understand how they emerge, spread across systems, and become deeply embedded into the fabric of societies and economies [35]. As a part of this agenda, we need new frameworks to capture the interplay of multiple transitions and the key processes involved [37,123,124]. We also want to understand the conditions for multiple transitions to generate cumulative positive effects, as in the case of the net-zero energy transition [21]. Another central topic is how to transform and overcome unsustainable meta-structures [125]. Can we even achieve sustainability transitions within deeply unsustainable economic systems? How to transform foundational principles such as exploitation, growth and profit orientation [125,126] to foster new and more sustainable meta-structures around circular or post growth economies [127]?

5.4. Policy implications

Research on unsustainabilities is still in early stages and so are our implications for policy. Juxtaposing economic rationales for policy-making and those of transition studies, scholars have pointed to a set of general transition policy principles [4]. These include i) transformation orientation, ii) prioritizing effectiveness over efficiency, iii) stimulating radical innovation (plus putting pressure on unsustainable practices), iv) tailoring policies to local and sectoral contexts and v) addressing the politics, e.g., by creating supportive coalitions.

Venturing into the study of 'unsustainable innovations' provides additional policy recommendations. A first is about *precautionary innovation policies* – as a response to 'innovations designed by other criteria than sustainability.' Decision makers may want to guide and constrain potentially problematic innovations early on to avoid more politically difficult interventions later, when they have diffused widely, when new needs have emerged and influential business interests have formed.[32] Precautionary principles already exist in fields such as chemicals policy or environmental policy, but they could also be expanded to climate policy, for example.

A second recommendation relates to the principle of transformation or mission orientation [128–130]. It is about *expanding the scope*, to include multiple sustainability dimensions instead of just one. The European Green Deal [131] can serve as an example in this regard as it does not only include climate policy issues but also biodiversity, toxic substances and justice concerns. With an expanded scope, we make sure to address unsustainabilities such as problem shifting, raised in the second area of Table 4.

Finally, policymaking might also want to look into tackling meta-structures, including some of the fundamental principles of established capitalist economic systems [125] or industrial modernity [132]. While these are typically pervasive and very hard to change, we see in current politics around (de-)globalization, security and (national) independence, that changes are possible, e.g., because of crises. At some point in time, sustainability issues may rise to a level of importance in the (national and international) policy agenda that even long-hold principles might be put into question - similar to what Schot and Kanger refer to as the second deep transition [32,35].

5.5. Conclusion and outlook

With this paper, we have explored a new area for sustainability transition studies. First and foremost, it is a call to not only focus on the positive but to also watch out for adversary developments. Given the extent and urgency of many sustainability challenges, we need to work on all fronts to counter not only established but also emerging practices that are unsustainable. The policy challenge will be to develop precautionary transition policies and strategies to identify, assess, guide and potentially constrain developments that exacerbate grand sustainability challenges instead of mitigating them. The research challenge will be to develop concepts and frameworks that cover the underlying complexities (e.g., multiple transitions, unsustainable meta rules). Topics around unsustainabilities open a new strand of important research in the field of transition studies. It is high time to address the associated challenges.

Declaration of competing interest

There are no competing interests.

Data availability

No data was used for the research described in the article.

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Appendix A. Appendix

Challenges when dealing with (un)sustainability

There are several challenges when it comes to assessing whether an innovation is sustainable or not. These include uncertainty, values, multi-dimensionality, scope and use issues [133,134]. We briefly discuss these below to flag that there are longstanding debates around these issues. At the same time, it is not within the scope of this article to address them in greater detail.

First, innovations are inherently uncertain. In early stages of innovation, we just know very little about the potential benefits and

[32] This is the general argument of TA and precautionary policy making – just with a broader focus on sustainability.

shortcomings of an innovation [57,58]. For example, who would have thought that the innovation of computer-to-computer communication at DARPA would result in one of the most central technologies of our time, including Facebook and millions of people uploading pictures of their cats or dinner? There might also be unwanted effects such as the competition of biomass use for energy with food production or conservation of forests.

Second, sustainability issues are a matter of values and preferences. Different societal groups or constituencies carry different values when it comes to e.g., climate change, clean water, air pollution, security etc. Also, these values are socially constructed and might change over time. One way to address this dilemma in technology assessment studies is to make the influence of values on outcomes transparent and to leave the decision to political decision makers, instead of technology experts [133].

A related issue is multi-dimensionality. In sustainability (transitions) research, we often tend to focus on one sustainability dimension such as climate change. However, there are many other dimensions such as those listed in the 17 sustainable development goals [135]. Often, there are trade-offs between different sustainability goals [42]. For example, both wind and nuclear power are low-carbon technologies. While wind has negative impacts on nature and landscapes, nuclear power plants produce highly problematic waste, bear the risk of dramatic accidents and can be used to arm atomic weapons.

A fourth issue is the scope of analysis. Whenever we draw boundaries, e.g., around a sector or country, there is a risk of 'environmental problem shifting' [104]. A selected sustainability problem is solved within these boundaries (e.g., Western countries) while other places are confronted with additional problems. Take electric vehicles, which reduce air pollution and GHG emissions but require problematic resources for their batteries such as cobalt, which – partly – is produced by artisanal mining and child labor in the Democratic Republic of Congo [136]. Similar issues apply to sectoral boundaries.

The temporal scope is closely related to this. For example, an innovation can be more sustainable in the short run but generate bigger problems later on. Re-usable rockets are clearly an innovation that generates sustainability improvements (less waste and pollution) in today's space industry. In the future, however, they may turn into a problematic technology, when they enable dramatic cost reductions and become the steppingstone for space tourism (see below). In the long run though, we can also envision a future, in which space tourism is again the steppingstone for reaching out beyond Earth, the sustainability implications of which we can hardly grasp.

Finally, there are many different ways of how technologies can be used. Developing reusable rockets for scientific missions can be viewed as sustainable, using them for touristic purposes is less sustainable. Pattern recognition can be used to identify faulty products in a production system, or to track political activists in a totalitarian state. The use issue is related to the temporal scope and to uncertainty.

We extract three major lessons from this. First, whether an innovation should receive policy support (or should rather be abandoned) for sustainability reasons is a political decision by a specific constituency in a specific context at a specific time. Second, unfolding transition pathways are laden with uncertainties and unwanted effects. Third, all innovations come with a variety of sustainability effects on a variety of dimensions.

When we suggest focusing on unsustainabilities, we want to direct attention to the risk that policy making might overlook systemic sustainability problems in early stages of development, thereby missing the window of opportunity for intervention and re-orientation.

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