Unsustainabilities – A new area of research for transition studies

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1 Introduction

Research and practice in the field of sustainability transitions has the ambition to address pressing sustainability challenges such as climate change, waste or resource depletion, through fundamental transformations of socio-technical systems around energy, transport, agri-food or water (EEA, 2019; Köhler et al., 2019; Victor et al., 2019). So far, this agenda has been pursued with two major strategies: supporting innovations that provide more sustainable alternatives to existing practices and guiding system transformation, including the decline of unsustainable practices and technologies (Smith et al., 2010; Markard and Rosenbloom, 2020b).

While both strategies are important, they are not sufficient. As we focus on developments for the better, we tend to miss those that do the opposite (Antal et al., 2020; Markard et al., 2021b). Below, we will argue that in order to adequately address grand sustainability challenges, transitions research should also *explore emerging 'unsustainabilities.'* We coin the term *unsustainabilities* to capture the broad range of structures, practices and developments that make or keep societies less sustainable. In this way, unsustainabilities point to opposite directions as the ones favored by sustainability transitions. The concept of unsustainabilities parallels the 'mobilities' studies pioneered by John Urry and colleagues (Hannam et al., 2006), and embraces both long-term, global, dynamic processes of multi-dimensional socio-ecological change and the immediacy of everyday life.

Examples of unsustainabilities can be found everywhere: fast food, fast fashion, consumption-based lifestyles, high frequency product cycles, planned obsolescence, urban sprawl, mass tourism but also fracking, tar sands, deep sea mining, etc. To be sure, the point is not that there are unsustainable products or practices but that they *continue to expand and new ones keep emerging*, even in parallel with sustainability transitions. In fact, unsustainable developments counteract and potentially even dwarf the current efforts to innovate and transition toward sustainability.

Take electric vehicles. While they receive much attention in the transition toward low-carbon transport (Henderson, 2020; Kotilainen et al., 2019), automobility at large is shifting towards vehicles, which consume more materials in production, more energy in use and are more dangerous than smaller cars (Taylor, 2020). Also, 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 towards electric vehicles might even help to obscure the above developments for the worse.

The aim of this paper is to direct attention to unsustainabilities, to help chart the terrain and to show how transitions research can contribute. As a first step we reflect on gaps in existing research and present a typology of unsustainabilities. We also introduce three analytical dimensions, regime formation, needs and politics, we consider useful when studying unsustainable developments.

A second step is to detail what exploring unsustainability means for the agenda of transition studies; here we present two illustrative cases on SUVs and space tourism. The SUV case stands for a failed transition to cleaner transport with ineffective policies, a car centric culture, strong dependence on automobility and unsustainable user practices (Mattioli et al., 2020; Wells and Xenias, 2015). Space tourism, in contrast, is in the early stages of development (Spector et al., 2017). It might create new consumer aspirations and needs, similar to air travel from the 1960s onwards. However, there is still an opportunity to intervene before major lock-ins have emerged. In both examples 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). We conclude with implications for research and policy.

2 Theoretical background

We build on the sustainability transitions literature (Köhler et al., 2019) whose conceptualization and understanding of socio-technical change is also helpful to study the dynamics of unsustainabilities.

2.1 Sustainability gaps in transitions research

Transitions research is concerned with processes of fundamental change in socio-technical systems (Smith et al., 2010). Core frameworks such as the multi-level perspective or technological innovation systems were developed independent of sustainability considerations (Carlsson and Stankiewicz, 1991; Geels, 2002; Rip and Kemp, 1998). Also, early empirical studies had no particular interest in sustainability (Carlsson and Jacobsson, 1994; Geels, 2002; Geels, 2005).

Since around the 2000s, however, sustainability issues have become increasingly prominent in transitions research (Smith et al., 2005; Smith et al., 2010) and today, the intention to *foster sustainable system transformations* is a central driver for the development of the field. The concept of transition management is inherently linked to sustainability issues (Loorbach, 2010; Rotmans et al., 2001) and *sustainability transitions* (Markard et al., 2012) has emerged as a focal term for transitions associated with environmental or social sustainability targets.

The scope of sustainability transitions research has widened over time. For many years, scholars have studied the interplay between, on the one hand, path-dependence and resistance at the level of established socio-technical systems (or regimes), and, on the other hand, radical innovations, which emerge in niches and challenge existing regimes (Kemp et al., 1998; Smith and Raven, 2012). In this line of research, the central sustainability strategy is to *foster innovations,* which have a potential to contribute to more sustainable modes of production and consumption.[1] Solar or wind energy are typical examples in this regard. Research has made much progress to better understand processes and actors that delay innovations, and how to overcome resistance (e.g. Bergek et al., 2008; Lauber and Jacobsson, 2016; Meckling et al., 2015). Policy suggestions have concentrated on how to support experimentation, innovation and diffusion (Hoogma et al., 2002; Jacobsson and Bergek, 2011; Sengers et al., 2019).

More recently, scholars have started to explore a second sustainability strategy: *accelerating the decline* of socio-technical system configurations or practices that cause particular sustainability problems (Markard et al., 2021a; Rinscheid et al., 2021; Turnheim and Geels, 2012). Examples are incandescent light bulbs, coal power plants or internal combustion engines (Meckling and Nahm, 2019; Rosenbloom, 2018; Stegmaier et al., 2014). Phase-out policies, technology bans or carbon pricing have been suggested to accelerate decline (Kivimaa and Kern, 2016; Rosenbloom et al., 2020; Rosenbloom and Rinscheid, 2020).

These two approaches (quadrants 1 and 3, Figure 1), are currently central strategies for research and policy advice in transition studies. While this was a useful start, it has created at least two blind spots. These include innovations that have been designed by other criteria than sustainability (quadrant 2) and the decline of practices and system configurations that are more sustainable than the ones that replace(d) them (quadrant 4). We will discuss these in detail below.

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[1] Note that innovations are not sustainable or unsustainable per se, which is why we use quotation marks. Instead, their effects depend on how they are used. See appendix.

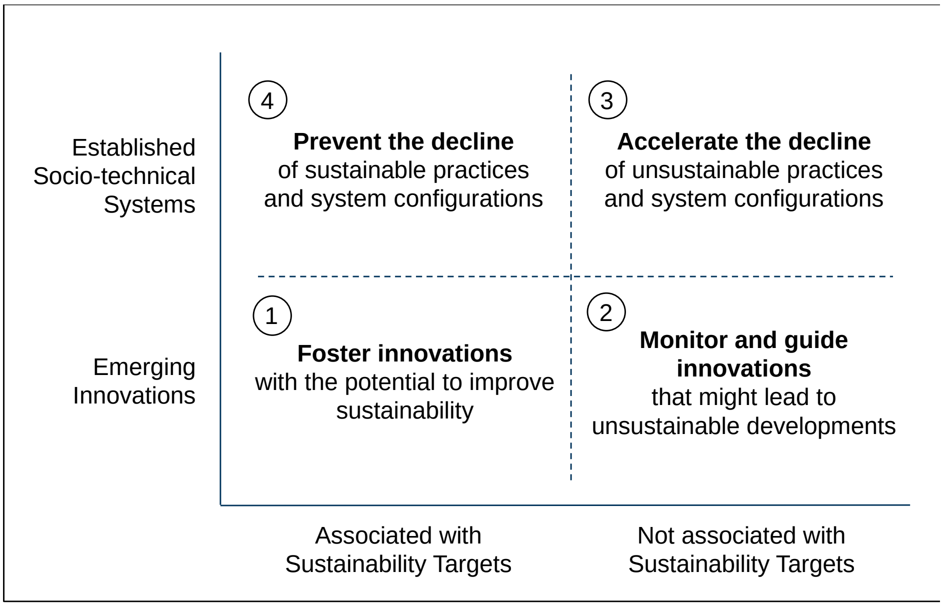

Figure 1: Established (dark grey) and neglected (ligh grey) strategies to improve sustainability through socio-technical change

2.2 Mapping unsustainabilities

There is large terrain of unsustainable developments, which remains to be charted from a transitions perspective. Our typology of future research areas builds on Figure 1 and adds a fifth category with meta rules that reach across multiple socio-technical systems (Table 1). Our intention is to provide guidance and inspire further research. The typology is not meant to be exhaustive and there will be overlaps between the research areas.

There are three levels of aggregation. The innovation level is about emerging novelties; it provides the opportunity to watch out for and guide sustainability in early stages of development. The level of socio-technical systems is where larger transformations unfold and lock-ins become particularly problematic. Sustainability considerations have a wider impact here and missed opportunities are much harder to correct. At the highest level of aggregation are meta rules or infrastructures that impact multiple socio-technical systems (Schot and Kanger, 2018). At this level, unsustainabilities are particularly problematic because they are pervasive and often persistent.

Next, we discuss critical issues, examples and topics for transition research for each of the five areas. The first area is about innovations that are designed by other considerations than sustainability (e.g., to reduce costs or create new markets). While at best they don’t create much harm, at worst they do. There are several, partly interconnected issues that are relevant from a transition studies perspective. First, if innovations diffuse widely, their impacts multiply. This can lead to the formation of lock-ins or new socio-technical regimes. A related issue is that innovations may result in the formation of new needs as in the case of SUVs. It will be very difficult to scale back these needs; the default is often to fulfill them with less harmful alternatives (e.g., electric SUVs). Third, if innovations spawn new markets, industries and entire socio-technical systems, as perhaps in the case of reusable rockets, this leads to the formation of business and political interests and resistance to change. Fourth, if they entrench existing (unsustainable) systems, they may effectively counteract ongoing sustainability transitions. This is the case for fracking or the exploitation of tar sands, which undermine the transition away from fossil fuels. Finally, the above effects are moderated by the longevity of artefacts, or infrastructures, related to the innovation.

The second area is about innovations to address sustainability challenges. While this is a classic topic in transition studies, it also comes with (often neglected) unsustainabilities. One of these is about 'environmental problem shifting' (van den Bergh et al., 2015), which occurs 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 cobalt whose sourcing may be highly problematic (Sovacool et al., 2020). Problem shifting may also occur across places, e.g., if production is moved to regions with low environmental or social standards (Kabir et al., 2018). A second issue is about unwanted or unexpected effects. In the case of bioenergy, these include monocultures, competition with food production, or additional carbon emissions from soils (Markard et al., 2016). A third issue is about the implications of renewed lock-in once sustainable innovations have diffused widely.

Another area for further research is related to socio-technical systems with major sustainability issues. While already a key topic in transition studies, some unsustainabilities might deserve further attention. The first is about new and potentially problematic socio-technical systems emerging as in the case of space tourism. Second, transition research may want to widen the scope from the 'usual suspect sectors' such as energy or transport, to food and agriculture (Hebinck et al., 2021), tourism, plastics, fast fashion or other industries with extremely short product cycles. As we widen the sectoral scope, we will also be confronted with contexts and problem framings (e.g., circular economy) that challenge established transition frameworks. A third issue is about further entrenchment (e.g. through innovations such as fracking), increasing influence and power, or growing resistance to change (Unruh, 2000).

Table 1: Established and potential areas for research on unsustainabilities

	Critical issues	**Topics for transition research**	**Examples**
Innovations			
1 Innovations designed by criteria other than sustainability (Q2)	Potentially wide diffusion and upscaling Formation of new needs Spawning of new markets and systems Entrenchment of existing systems and practices Longevity of artefacts	Processes of regime formation / entrenchment Needs and lifestyles; how to potentially scale them back Formation of political interests around new business opportunities	Numerous examples: SUVs; flying cars Space tourism Fracking; exploitation of tar sands Deep sea mining Widespread use of hot tubs
2 Innovations designed to address unsustainable socio-technical systems (Q1)	Problem shifting Unwanted effects, e.g. rebound effects, new socio-economic and geographic inequalities New lock-ins Delay and greenwashing	Widen the scope of transition studies: multiple sustainability goals, needs and demand side issues Incumbent actors and politics of delay	EV batteries (minerals, waste) Biofuels (land use, monocultures) Energy efficiency technologies
Socio-technical systems			
3 Socio-technical systems with major sustainability problems (Q3)	Emergence of new problematic systems / regimes Increasing entrenchment and resistance	Dynamics of regime formation and early destabilization Beyond the 'usual suspects'	Classic sectors (energy, transport, buildings, industry) Fast food / fast fashion Tourism Materials (e.g. plastics)
4 Socio-technical systems with favorable sustainability features (Q4)	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
Macro level structures			
5 Meta rules and infrastructures	Diffusion of unsustainable meta rules and structures Decline of sustainable meta rules and structures	Changes in meta rules and how to conceptualized them	Cheap vs. durable, replace vs. repair, obsolescence, convenience, carbon intensive lifestyles, consumerism

The fourth area is related to socio-technical systems with specific technologies or practices that have favorable sustainability features. More research is warranted into how these systems come under pressure (e.g. for cost or convenience reasons) and potentially destabilize. Interesting cases include the decline of the American railroad system at the beginning of the 20th century (Roberts, 2017) or the decline of city tramways since around the 1950s and their eventual re-introduction (Turnheim and Geels, 2019). A related issue is the decline of specific practices such as those around heating or cooling (e.g., passive vs. air conditioning), drying or personal hygiene (Shove and Walker, 2010; Walker et al., 2014).

The fifth area includes infrastructures and meta rules. Meta rules include general principles, norms, values or practices that are widely shared across socio-technical systems (Kanger and Schot, 2019) but also across related fields such as finance, education, news reporting etc. Examples of problematic meta rules include business models based on fast product cycles, planned obsolescence, or mass production and consumption (Bocken and Short, 2021; De Graaf, 2002). From a transitions perspective, more research is warranted on why they are so persistent and how to change them.

At all levels, we distinguish developments associated with sustainability targets and those that are not. While the latter obviously deserve attention from a sustainability perspective, the former may be problematic as well.

2.3 Regime formation, needs and politics: Three focal issues when studying unsustainabilities

Concepts and frameworks in the field of transition studies apply a *systemic view* on the dynamics of socio-technical change (Köhler et al., 2019). This means that actors, institutions, technologies and business and consumption practices change in a co-evolutionary way when innovations emerge and socio-technical systems transform (Geels, 2014a). Here, we briefly discuss three insights from transition studies we regard as relevant starting points when studying unsustainabilities.[2] While these three will guide our empirical analysis, they are not meant to be exhaustive.

The first issue is about lock-in and the formation of socio-technical regimes (Kemp et al., 1998; Unruh, 2000). Cumulative effects can lead to the formation of rigid structures, in which one socio-technical configuration becomes dominant and the actors, business models and user practices associated with this configuration become more influential than others. Once regimes have formed, they are very

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[2] Note that we do not engage with the issue of how to assess whether an innovation is sustainable or not. See Appendix for further explanation.

hard to change (Geels, 2014b; Fuenfschilling and Truffer, 2014). When studying unsustainable developments, it is key to understand how they affect (e.g., strengthen) existing regimes or lead to the formation of new ones. Regime formation makes the impacts of unsustainabilities even worse.

A second issue is about (technology) users, needs and practices (Kemp and van Lente, 2011; Shove and Walker, 2010, van Lente, 2014). It is often assumed that needs exist prior to innovation and that the task of engineers and firms is to address these needs, e.g. through new technologies (van Lente, 2019). However, needs are not given, independent or stable. Instead, they emerge over time and co-evolve with technology (Pinch and Bijker, 1984; Shove, 2003; Shove and Walker, 2010). They may also be deliberately created by businesses (Box 1). Another path for the formation of needs is when practices turn from luxuries (e.g., exotic vacations, flying and the 'jet-set') into commonplace activities (Lie and Sørensen, 1996; Sørensen, 2006). The formation of needs is key for emerging unsustainabilities. Once new needs have emerged around an unsustainable practice, it may be very hard to change it.

Companies know that creating new needs is central to the success of new technologies, which is why budgets for R&D and marketing are often about the same. Business scholar Peter Drucker stated: "There is one valid definition of business purpose: to create a customer" (Drucker, 1954, 37). The history of technology provides many examples such as the success of the Kodak photo camera (Utterback, 1994). At the end of the 19th century, photography was a cumbersome activity for specialists. Eastman Kodak's idea was to make photography a low-threshold activity using celluloid instead of glass, which allowed rolling up light-sensitive layer. The roll was put in a closed box and users could send the entire device to the manufacturer, who would return the developed photos with a new, empty roll in the box. Eastman presented photography as a simple activity ("you push the button, we do the rest"), not only for the crucial moments of life but also for daily use. Indeed, photography became ubiquitous and today, it is an inseparable part of everyday life.

Box 1: Early photography as an example of creating new needs

A third issue is related to contestation and politics (Jacobsson and Lauber, 2006; Roberts et al., 2018). New as well as established socio-technical configurations are supported by actors that benefit from it. As a result, transitions are characterized by struggles of competing groups of actors. These struggles can be observed in many instances, including the creation of markets, the formation of technology standards (Yap and Truffer, 2019) or the design of public policies (Hess, 2014;

Markard and Rosenbloom, 2020a). With regard to unsustainabilities, it will be key to analyze how public policies can be used to mitigate unwanted developments. It will also be key to understand how politics and political interests play into this, e.g. which groups of actors seek to push unsustainabilities despite their detrimental effects.

3 Case selection and analytical approach

With our empirical analysis we want to illustrate how unsustainabilities can undermine ongoing transitions and why they deserve attention from policymaking. Our focus is on innovations that were designed by criteria other than sustainability as outlined in section 2.2. We assume that innovations which are in an early stage of development show substantially different characteristics of unsustainabilities than those in a later stage; for instance, that they can be more easily guided by (precautionary) policies. In later stages, the sustainability implications are more clearly visible but it is more difficult to control or reverse these.[3]

We work with a qualitative case study approach (Yin, 2016) that includes two exemplary cases: SUVs and space tourism. We selected socio-technical innovations with repercussions for climate from different fields (mobility and tourism) to obtain a broader variety of insights. There is also a comparative element in our case selection (Bartlett and Vavrus, 2017), given that both innovations are in very different stages of development. SUVs grow out of a strong, well-established regime 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.[4] 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.

Our empirical analysis builds on the expertise of two co-authors with substantial knowledge and experience in the respective topics.[5] In addition, we compiled secondary data from a broad range of sources that have been published in recent years, primarily including news media, scientific publications and industry

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[3] This predicament is also known as the Collingridge dilemma (Collingridge, 1982; Genus and Stirling, 2018).

[4] In some places, SUVs have already formed a formidable regime, which means that the SUV case is touching upon research areas 1 and 3 (Table 1).

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

reports. From these sources, we also included quotes to illustrate some of the arguments.

Concept development and empirical analysis in this paper follow an abductive reasoning approach (Bell et al., 2018). Both our typology and our analytical dimensions were first derived deductively based on the transitions literature and subsequently refined inductively drawing on our emerging empirical insights. We also adapted the structure of our empirical analysis accordingly. This process was repeated until our final conceptualization matched our empirical findings, and vice versa.

Our analysis is structured along five key aspects, or dimensions (Table 2). Dimensions three to five are those introduced above, while one and two are more generic. The first captures the basic characteristics of the innovation, including its origins and current state of development, actual and potential applications, scope and level of disruption, important drivers and barriers, or how it is related to sectoral and spatial contexts. The second dimension covers actual and potential implications for sustainability. It also touches upon some of the critical issues mentioned above, e.g. risks due to widespread diffusion or the formation of new markets and industries.

Table 2: Dimensions to analyze innovations designed by criteria other than sustainability

	Key questions
Basic characteristics and context	What is the innovation about and what is its current state of development? How disruptive is the innovation? What are key drivers and barriers? How is it related to ongoing transitions and other context developments?
Sustainability implications	What are actual and potential implications for sustainability? Which of these will be inherent, which can be avoided and how? What are critical issues?
Regimes and path-dependency	Does the innovation relate to existing regimes? At what pace are new path-dependencies emerging and how persistent are they? What is the risk of path-dependencies?
Needs and practices	How does the innovation affect user practices? Are new needs emerging and how what are the risks (e.g. persistence)?
Policy challenges and politics	What are key policy challenges? What are the key actor groups involved and their interests?

4 Exploring SUVs and space tourism

4.1 SUVs

4.1.1 Basic characteristics and context

Sports utility vehicles (SUVs) 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. 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 crossover SUV segment is the Nissan Qashqai. Introduced in 2006, this model was hugely successful, prompting other incumbent vehicle manufacturers to offer similar models. 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, Nissan, 2017)

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 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 (Snyder, 2017).

According to the International Energy Agency (IEA, 2019a: 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."

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 45.5% by 2021.[6]

The transition to SUVs is happening at times in which the auto industry is confronted with a broad range of major structural challenges, some exacerbated by the SARS-CoV-2 pandemic. These include over-capacity, weak demand,

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[6] https://www.best-selling-cars.com/europe/2021-full-year-europe-new-car-sales-and-market-analysis/

technological changes such as digitalization and the increasing relevance of software, advances in autonomous driving, connectedness to mobile networks, and the beginning transition from internal combustion engines to battery electric vehicles (BEVs). The auto industry is confronted with regulatory constraints and increasing conflicts over scarce space in cities, air pollution and climate change (Bordovskikh, 2020).

Several of these developments are disruptive for incumbent firms, as they threaten their core business model, entail an entirely different view on the automobile (computer device vs. assemblage of hardware), or require new competences, e.g., in software development, electric drive trains or battery system optimization.

For vehicle manufacturers, SUV vehicles are an ideal segment to develop and market many of these novel technologies. With BEVs, larger vehicles can hold larger battery packs, enabling performance and range expectations created by internal combustion engine vehicles to be met. According to the IEA, about half of all BEV models globally in 2021 were SUVs (IEA, 2022)

4.1.2 Sustainability implications

SUVs come with an inherent increase in energy consumption as they substitute smaller cars. For example, the Nissan Qashqai 1.5 liter in 2006 had a weight of about 1,454kg 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 (IEA, 2019b) 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. As a significant incremental change in the existing automobile regime, SUVs are almost ‘hiding in plain sight’ from more high-profile instances of CO_2 emissions growth.

4.1.3 Regimes and path-dependency

Automobility is an established socio-technical regime, centered around individual automobility and complemented by massive infrastructures, regulations, services, user practices and societal norms (Geels, 2018; Mattioli et al., 2020). Multiple incremental innovations in materials, components, and whole vehicles have acted to sustain the viability of the regime (Cohen, 2012; Wells and Nieuwenhuis, 2012; Pel et al., 2020).

Within the established regime, the SUV is an innovation that builds on and strengthens existing regime structures. For example, SUVs fit readily into many existing regulations and road infrastructures, thereby benefiting from these complementarities. 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. The SUV also continues the already entrenched path dependency around individual, long-range mobility as the dominant mode of transport in numerous countries and regions (Hoffmann et al., 2017).

At the same time, new regime structures have emerged that favor SUVs. One example are labels to inform consumers about fuel efficiency and CO_2 emissions of cars. 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 (Haq and Weiss, 2016). 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.[7]

In 2020, Ford abandoned production of sedan (saloon) cars in North America to focus on SUVs and crossovers. All major auto makers include these vehicles 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.

4.1.4 Needs and practices

In deeply entrenched socio-technical systems such as automobility, needs are woven tightly into the fabric of everyday life and lifestyles, and are all the more difficult to alter (Hoffmann et al., 2017). In this sense the uptake of SUVs is latest manifestation of the generic condition of car dependence (Mattioli et al., 2020). Extant research suggests that to achieve deep de-carbonization goals in mobility will require a combination of electrification, policy measures and, crucially, lifestyle changes (Brand et al., 2019; Marsden et al., 2020). The latter includes issues such as where to live and work, whether and how to commute, whether and how often to drive children to destinations, or whether the car is viewed as a status symbol.

SUVs are linked to many of these issues. For example, the SUV concept is supportive of more active lifestyles and adventure holidays (Jensen and Guthrie, 2006). Many activities such as windsurfing, 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 (Dunn, 2008).

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[7] see https://ec.europa.eu/clima/policies/transport/vehicles/cars_en

As SUVs have become the new norm, consumers have come to ‘need’ SUVs, e.g., for perceived safety benefits, no matter how erroneous that perception may be and despite the increased risk to other road users (Wells, 2006). As more people drive SUVs, it becomes less safe for others not to do so.

These old and new needs drive SUV usage, despite that SUVs may even be inconvenient, especially in cities with increasing congestion and greater concerns for the safety of other road users (Monfort and Mueller, 2020; Salisbury, 2020). It is possible that electrification of SUVs makes their use more socially acceptable.

Policy challenges and politics

For decades, public policies have targeted transport in general and automobility in particular to reduce air pollution and CO_2 emissions. Along with more stringent emissions controls and a new regulatory regime for carbon emissions from vehicles in the EU, there had been a long-run decline in average new car CO_2 emissions from 159 gCO_2/km (2007) to 118 gCO_2/km (2016) (ICCT, 2020). 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 (Gössling and Metzler, 2017).

Future policy targets seek to decrease overall emissions, notably many countries and the EU have adopted ‘end of sale’ dates for petrol and diesel cars or hybrids thereof. Typically, 2035 is posited as the end date for all such new car sales.

Alternatively, policies could target vehicle users and reduce the need for (and the generic dependence on) automobility, but are more difficult and complex to implement (Whittle et al., 2019). Policies to reverse the SUV trend would likely have to embrace the cultural framing of automobility through which needs emerge (Sovacool and Axsen, 2018).

With regard to future pathways, there are interesting overlaps between the transition toward SUVs and the transition toward BEVs. Many vehicle manufacturers - in the EU and elsewhere - seem determined to sell as many conventional SUVs as possible, up to the boundaries set by the various regulatory regimes for carbon emission reductions. At the same time, 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’ EVs such as the Renault Twizy or Citroen Ami, or the BMW i3 (Sovacool et al., 2019), in order to achieve an efficient vehicle with a smaller battery pack that is also more suited for short-distance traffic in congested cities[8].

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[8] 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.

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> "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." (European Parliament, 2019)

Whether these targets will be reached is unclear. By and large, past policies have not yet disrupted the dominant pathway towards more cars and larger vehicles. Vehicle manufacturers have lobbied against strong emission regulations for decades, mostly with success.[9] They favor technological solutions for carbon targets, even though these might not be sufficient without additional behavioral change (Whittle et al., 2019).

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

automakers develop light-weight 'L-category' EVs such as the Renault Twizy or Citroen Ami, or the BMW i3 (Sovacool et al., 2019), in order to achieve an efficient vehicle with a smaller battery pack that is also more suited for short-distance traffic in congested cities[10].

4.2 Space tourism

4.2.1 Basic characteristics and context

Space tourism is a service innovation in the rapidly growing space flight industry (Spector et al., 2017). The core idea is to send non-astronaut citizens to outer space for recreational purposes. Commercial space tourism is currently planned at the orbital or suborbital levels, although some firms even speak about lunar tours. Both, the idea and the underlying technologies are radically new. The business rationale is to create attention and to use the profits for further technology development. Space tourism is still in an early stage of development (with ultra-rich individuals as pioneering customers) but progressing rapidly.

The history of space tourism can be dated 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.[11] The service was offered as a means to generate income for the maintenance of the aging Russian space station. Later, a Virginia-based firm, in collaboration with the Russian space agency, sent eight tourists to the ISS on flights lasting ten or more days.[12] Tickets were sold at 20 Mio USD in 2001 and 35 Mio USD in 2009.[13]

The recent developments around space tourism are driven by the rapid growth of the so-called 'New Space' movement (Clormann, 2021; Robinson and Mazzucato, 2019). While in the past space activities primarily took the form of missions led by national governments, activities today are increasingly led by private firms complemented with support from public space agencies. Progress in space tourism has in particular benefit from the technology advance in reusable rockets and the commercialization of space travel.[14] Space companies such as Virgin Galactic (with

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[10] 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.

[11] https://www.britannica.com/topic/space-tourism accessed April 20, 2020

[12] https://www.nbcnews.com/mach/science/how-much-does-space-travel-cost-ncna919011 accessed April 20, 2020

[13] https://www.nbcnews.com/mach/science/how-much-does-space-travel-cost-ncna919011 accessed April 20, 2020

[14] https://www.airbus.com/public-affairs/brussels/our-topics/space/new-space.html accessed November 18, 2020

Boeing as minority shareholder), Blue Origin, and SpaceX present highly ambitious visions, racing to be the first to offer commercial space tourism services. Billionaire entrepreneurs such as Richard Branson and Elon Musk back these ventures financially and herald recreational space travel as an individual human right for ultimate freedom.

Space tourism is embedded in the context of the larger space sector, which also includes the launch of satellites and the transport of astronauts or goods, e.g. to the ISS. To improve the reliability and costs of their technologies, many space companies exploit the synergies between these different markets.

4.2.2 Sustainability implications

Although space tourism may be a cornerstone of large-scale space exploration in the future, scaling up leisure space travel is likely to have major consequences for the Earth's climate (Spector et al., 2020). Space tourism is inherently energy intense and there are three main types of problematic emissions: Chemicals (chlorine) which lead to ozone depletion, CO_2 emissions, and soot emissions. The latter two can severely contribute to climate change.

In terms of carbon footprint, each rocket launch would result in about 150 metric tons of carbon[15]. This makes every rocket launch equivalent to about 3 times as much CO_2 as a transatlantic flight (with about 50-100 times more passengers). Following the goal of companies like SpaceX to launch once every two weeks, this would accumulate to approximately 4,000 tons of carbon annually, just for one firm.

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 (Chapman, 2015).

The sustainability impacts of space tourism may multiply in the near future. Business plans for space tourism estimate a flight rate of 1,000 suborbital trips per year once the space companies routinely fly passengers for leisure purposes. The excerpt below shows the ambitious plans of companies to scale up the business in the future:

> "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 orbiting hotels and

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[15] https://www.smithsonianmag.com/science-nature/spacex-environmentally-responsible-180968098/ accessed April 22, 2020

> science laboratories, or providing a world-shrinking, transcontinental service […].” Virgin Galactic[16]

There is an increasing number of voices in the field that call for more attention to the sustainability implications of commercializing space tourism:

> “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.” (Spector et al., 2017, p. 280).

> “If we understand rocket emission now, while their impacts are still smaller than aviation’s impacts, then proper guidelines and metrics could be established that encourage space industry growth…If we wait until rocket impacts are large, then such actions might be a burden.” Martin Ross, The Aerospace Corporation.[17]

> “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.[18]

4.2.3 Regimes and path-dependency

Space tourism can be understood as an ‘emergent’ socio-technical regime, without specific regime structures or configurations. The industry is still in an early stage of development with no dominant technological designs nor business models. However, technological competition and business narratives in public media develop rapidly, leading to progressive formation of visions and ideals, attracting financial investments and customers, as well as gaining government support.

Configurations for space tourism potentially rest in two forms. On one hand, Blue Origin and Virgin Galactic are both experimenting their technologies, i.e. the New Shepard rocket system the SpaceShipTwo respectively, for short suborbital tourism. On the other hand, SpaceX aims to send tourists on a trip to the ISS, and even around the moon. SpaceX focuses on developing its Dragon spacecraft and the Falcon Heavy (or Falcon 9) rocket. Partnering with Axiom and NASA, SpaceX successfully sent a crew of private actors to the ISS in April 2022 – marking a new

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[16] https://www.virgingalactic.com/vision/ accessed January 12, 2020

[17] https://www.digitaltrends.com/dtdesign/environmental-costs-of-space-tourism/ accessed April 22, 2020

[18] https://www.ucf.edu/pegasus/space-tourism/ accessed April 22, 2020

major milestone for commercial spaceflight.[19] Progress in the nascent space tourism industry is largely attributed to rapid cost reduction. Compared to the early NASA Space Shuttle program in 1981 during which the payload cost was more than 50,000 USD/kg, SpaceX claimed a payload cost of less than 3,000 USD/kg in 2018 (Jones, 2018).[20]

If the emergent regime of space tourism matures in the future, it might be too difficult to destabilize it, given the strong path-dependency it potentially anchors into the sector. As mentioned, private spaceflight and transportation play an increasingly prominent role in fueling the majority of space activities today (e.g., satellite launch, transporting goods and astronauts, or even public-private missions on the Moon). In particular, space-based infrastructures -- rely heavily on lower launching costs -- are rapidly developed and promoted for sustainability purposes (Yap and Truffer, 2022) and have attracted enormous business and policy investments (McKinsey, 2022). Disrupting a successful regime formation of space tourism in the future, therefore, is not just about limiting private leisure in space but could mean disrupting multi-dimensional path-dependencies of almost the entire space sector. The regime formation of space tourism, in parallel of other space developments, may therefore be seen as shaping emerging meta rules of the space sector, political struggles and impacts of which might be huge and irreversible.

4.2.4 Needs and practices

As of today, space tourism still targets rich and ultra-rich individuals. For a flight to the ISS, a few people paid between 20 and 35 Mio USD in the past (see above). Tickets for several hours in zero gravity are expected to be much cheaper. 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 grew up to $450,000 with a waiting list of about 800 customers.[22] This shows a growing demand for space tourism and that certain people are ready to pre-pay tickets, thereby financing missions, the concept of which still needs to be proven.

Although it is early to say that space tourism will form a new need, the progress made may rapidly turn the vision of a few into a reality for many. The promotion

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[19] 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

[20] https://www.nasa.gov/mission_pages/shuttle/flyout/index.html, accessed June 20, 2020

[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

of space tourism – built upon future imaginaries and hope - has intensified over time while visions seem to converge around a common set of ideals or ideographs. Firms appeal to shared values such as sustainability, rights for freedom, a better future, or democracy, to legitimize space tourism (Spector et al., 2020).

An excerpt below shows an example of a marketing narrative framed around sustainability concerns for Earth:

> "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[23]

In other instances, narratives framed around benefits for future generations could be found, presenting space tourism as almost necessary:

> "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[24]

If the promises and visions materialize and cost reduces significantly in the future, the demand for leisure space travel is likely to become increasingly common among the wealthy. Those who aspire a trip to space might associate space tourism with human rights and personal freedom, or flaunt their higher social status through extravagant leisure activities. This might eventually lead to new kinds of lock-ins around emerging needs such as the 'necessity' of new adventure, new perspectives, and lifetime experience even at the expense of environmental sustainability.

4.2.5 Policy challenges and politics

Policy challenges related to space tourism are contextualized within the broader, changing space sector. These include environmental issues such as the carbon emissions of rockets, 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 such as the European Space Agency (ESA), United Nations Office for Outer Space Affairs (UNOOSA) have been active in advocating for new institutions.

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[23] https://www.ucf.edu/pegasus/space-tourism/ accessed January 12, 2020

[24] https://www.blueorigin.com/our-mission accessed January 12, 2020

With regard to space tourism, policies and regulations are needed to address the increasing repercussions for climate change and broader sustainability issues.[25] 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. Governments have not devoted much attention to regulating emissions of rocket launches. Since rocket launches in the past were considered a matter of national security, they have been largely exempted from environmental legislation. However, this perspective has changed since scientists began to question 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.[26,27]

Overseeing private spaceflight activities or constraining touristic space travels seems to be challenging (Spector et al., 2020). 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 is inherently unsustainable if and when space travel becomes an established practice.

4.3 Summary

Here we review both cases and summarizes the main findings (Table 3). The SUV is an incremental innovation in an established industry. Its diffusion is in full swing and it exacerbates long-standing issues around energy use and CO_2 emissions. Space tourism, in contrast is a radical innovation in an emerging industry in an early stage of development. It might cause major energy and climate problems (Spector et al., 2020).

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[25] https://phys.org/news/2022-06-climate-space-tourism-urgent-mitigation.html accessed July 8, 2022

[26] https://www.digitaltrends.com/dtdesign/environmental-costs-of-space-tourism/ Accessed April 20, 2020

[27] https://350.org/about/ Accessed April 22, 2020

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

	SUVs	Space tourism
Basic characteristics and context	Incremental innovation in automobile industry; Late stage, transition in full swing; Driven by profitability and complementarities	Radical innovation in the rapidly developing space flight industry; Early stage; Driven by new technologies and the commercialization of space travel
Sustainability implications (energy and climate)	Inherent increase in energy consumption, conventional engines: above average CO_2 emissions	Inherent, massive energy consumption, CO_2 and soot emissions in stratosphere
Regimes and path-dependency	Strengthens industry incumbents and established business models; increases path-dependency; Carry-over impacts on markets for electric cars	No regime structure or path-dependencies yet; but strong visions for future industry and resourceful players to push the development
Needs and practices	Reproduces existing practices around individual automobility; Creates new needs around status, and safety	Luxury for the ultra-rich; emerging demand but no established needs or practices yet
Policy challenges and politics	Policy failure after decades of emission and climate regulations; in conflict with low-carbon transport pathways	Under-regulated sector; window of opportunity to shape future pathways; international coordination as a challenge

The SUV case shows how innovations can entrench existing regime structures, including established business models and incumbent actors. 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 still in flux with many uncertainties in terms of future pathways. Nonetheless, resourceful actors push strong visions around a large and vibrant industry with little to no concerns around sustainability issues.

For space tourism, needs have not yet emerged, so there is still room to shape and moderate the expectations of future customers. If policies for sustainable space tourism were developed soon, we would expect little to no resistance from potential users. This is very different for SUVs: they have already become the norm for many users (e.g., for driving your kids to school) and new needs (e.g., around status and safety) have emerged around it. In fact, SUVs fit well into the existing 'car-dependent transport system', where infrastructures, lifestyles, urban sprawl and a car-centered culture have co-developed and reinforced each other (Mattioli et al., 2020).

With regard to policy and politics, the SUV case is a very interesting example because the automotive sector was not somehow overlooked by policy. On the contrary, the sector's sustainability issues have been under scrutiny by scientists, environmental NGOs and policymakers for many years (Geels et al., 2012). That the SUV transition unfolded nonetheless can be viewed as a blatant failure of at least two decades of emission and climate policy in transport. It is also an important reminder of how rigid and resistant to change socio-technical regimes can become, e.g., with their key actors having close ties into policymaking to prevent effective climate policies (Skeete, 2017; Wells et al., 2013).

In contrast, space tourism has received very little attention in terms of climate or environmental policy up to now even though sustainability repercussions might be substantial. While there is still room to guide the emerging developments into a more sustainable direction, or to constrain them (Matignon, 2019), more and more firms and nations are focusing on the new opportunities and there is an ongoing race towards commercialization that might leave environmental sustainability considerations behind. Another major policy challenge is international policy coordination, as firms can evade to those places where regulations are less strict (Yuan, 2021).

5 Discussion and conclusions

In this paper we outlined a new area for transitions studies: unsustainabilities. We began charting the territory, developed a typology and explored two exemplary cases, which show that innovations may not only negatively affect ongoing sustainability transitions but also cause new sustainability problems. Below, we discuss implications for transitions research and policymaking.

5.1 Implications for research

Even though we are only beginning to explore unsustainabilities from a transition studies perspective, we can already identify promising issues for research.

The first is about *widening the scope of research* in the field of sustainability transitions. This includes the innovations and sectors we study: here, we want to go beyond the 'usual suspects' to explore topics that have been overlooked so far but are still highly relevant from a sustainability perspective (Antal et al., 2020; Kanger, 2020). However, a wider scope also includes studying sustainability tradeoffs across sectors and places (van den Bergh et al., 2015) and across other sustainability dimensions as in the case of minerals used for batteries or the justice dimension of the energy transition (Johnstone and Hielscher, 2017; Sovacool et al., 2016).[28]

A second topic centers around the *interaction of multiple transitions*. There are at least two issues here, the increasing complexity and cumulative effects. With regard to the former, we have to adapt existing or develop new frameworks to capture the interplay of multiple transitions and the key processes involved (Andersen and Markard, 2020; Rosenbloom, 2020). The deep transitions approach can certainly offer some insights here even though it was developed to study very long-term patterns of change, in particular on the generation of new, unsustainable meta rules and the consequential influences on meta regimes (Kanger and Schot, 2019). With regard to the latter, we need to better understand the conditions for multiple transitions to generate cumulative effects in terms of sustainability, instead of conflicts and trade-offs. This will be a central topic for the net-zero energy transition, where we expect transitions in electricity, buildings, transport and industry to support and reinforce each other (IEA, 2021).

A third research topic is about the dynamics of *regime formation*. This includes the emergence of dominant socio-technical configurations or standards (Heiberg et al., 2022; Markard and Erlinghagen, 2017), the formation of markets (Dewald and Truffer, 2012), guidance of innovation processes (Yap and Truffer, 2019), emerging coalitions of actors (Hess, 2019) or changes in user practices and the formation of needs (Shove and Walker, 2007; Shove and Walker, 2010). While many of these aspects have already been addressed in transition studies with the interest to support more sustainable alternatives and to destabilize established regimes, the new research agenda will also have to address how to prevent potential lock-ins or slow-down the formation of new regimes.

A fourth promising topic for future research relates to the *meta rules* that guide most innovation activities and also the workings of socio-technical systems more broadly (Kanger and Schot, 2019). With a specific focus on unsustainabilities, we want to understand, question and ideally transform key principles of our economies that are associated with mass consumption, continuous growth, profit orientation, or waste production (Feola, 2020; Kemp et al., 2018). A better understanding of how to foster new and more sustainable meta rules or even the emergence of new meta regimes may help identify opportunities and challenges to building post-growth or degrowth economies (Cosme et al., 2017).

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[28] See also research area 2 in Table 1 in this regard.

5.2 *Policy implications*

To address transitions toward sustainability in an encompassing way, policymaking needs to address all different kinds of unsustainabilities (Table 1) and even navigate across them. This policy agenda goes beyond sustainability issues of established socio-technical systems, which have been traditionally on the political radar, and also beyond potentially problematic innovations, which were in the focus of this paper.

With regard to innovations such as SUVs and space tourism, we suggest developing *precautionary innovation policies*, which can identify and tackle sustainability issues in an early stage of development before novelties have diffused widely, regimes have formed and wants have sedimented into needs. Such policies have to assess innovations as to whether they potentially jeopardize established policy targets such as those formulated in the European Green Deal (European Commission, 2019). When developing precautionary policies, we might want to engage with the literatures on innovation and transition policy (Haddad et al., 2022; Kivimaa and Kern, 2016) but also with environmental governance which has adopted a more anticipatory perspective towards unsustainable developments (Muiderman et al., 2020; Muiderman et al., 2022).

Precautionary innovation policies complement but also differ from established innovation and transition policy approaches. They contrast with innovation policies from the past, which were primarily serving an economic growth narrative associated with the principle of 'the more innovation, the better.' Instead, they complement mission-oriented innovation policies that target specific kinds of innovations to address grand societal challenges such as climate change or inequality (Mazzucato, 2018). At the same time, precautionary policies go beyond mission-oriented policies because they seek to guide and restrain innovations that might undermine the mission targets. Precautionary policies also complement contemporary sustainability transition policies (Rosenbloom et al., 2020), which largely follow a 'firefighting' approach as they seek to ameliorate sustainability issues of established socio-technical systems instead of seeking to prevent such systems to emerge in the first place.

Policies to guide sustainability transitions are already complex. They have to address innovation and decline processes, accommodate for different transition phases and the particularities of different sectors, and carefully manage the associated politics (Kern et al., 2019; Kivimaa and Kern, 2016; Rosenbloom et al., 2020). Adding precautionary policies increases the complexity even more and makes the design of transition policy mixes a daunting task (Lindberg et al., 2019; Rogge and Reichardt, 2016). A particular challenge is that these new policies come on top of already existing policy structures (Flanagan et al., 2011; Flanagan and Uyarra, 2016).

Finally, policymaking aiming to prevent or address unsustainabilities should also deal more explicitly with cross-departmental policy coordination (Markard et al., 2020; Peters, 2018), long-term policy orientation (Guston, 2014), or strengthening trustworthy institutions at the science-policy interface (Lacey et al., 2018). This overall allows better management of tradeoffs and more comprehensive policymaking to guide societal transition and transformation toward sustainable futures.

5.3 Conclusion and outlook

With this paper, we have explored a new area for sustainability transition studies. First and foremost, it is an appeal 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. It is a call for policy and research. 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.

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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 (Ely et al., 2014; Pope et al., 2004). 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 shortcomings of an innovation (Collingridge, 1982; Genus and Stirling, 2018). 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 (Ely et al., 2014).

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 (Sachs et al., 2019). Often, there are trade-offs between different sustainability goals (Kemp and van Lente, 2011). 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' (van den Bergh et al., 2015). 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 (Sovacool, 2019). 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.