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Inhalt
In the context of research on long-run transformations, such as the low-carbon energy transformation, research interest is growing on how to define and measure human well-being meaningfully. The working paper provides a thorough discussion of the literature on well-being and human needs in the context of energy consumption and confronts this scientific discourse with the concept of energy services, or functionalities. Based on a thorough literature review and a comprehensive stakeholder consultation process, we show, that energy services represent the crucial link between energy use (and related GHG emissions) and human need satisfaction.

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1. Introduction

Against the backdrop of a changing geopolitical landscape climate policy faces fundamental challenges: the need for reducing greenhouse gas emissions (GHG) rapidly to be on track of the (≤)2° target compared to pre-industrial levels; the task to acknowledge and connect to the Sustainable Development Goals (SDGs); and the emerging fundamental economic transformations triggered by breakthrough technologies. The *EconTrans* research project offers an integrated perspective to these challenges by embedding climate policy into the broader context of these emerging long run transformations of our economies.

In the context of long run transformation research (see e.g. WBGU 2011; Göpel 2016) interest is growing on how to operationalize (i.e. define and measure) human well-being meaningfully and in a way that respects planetary boundaries (Diener et al. 2009; Jackson 2009; Rockström et al. 2009; Stiglitz, J.E. and Fitoussi 2009; Raskin et al. 2010; Helliwell et al. 2013). In this working paper, we take up this strand of research and situate the concept of *well-being generating energy services (in some publications called 'functionalities')* in the broader discussion of human well-being and climate change mitigation (Lamb and Steinberger 2017) by observing other intrinsically linked transformational challenges, such as the Sustainable Development Goals (SDGs) (United Nations General Assembly 2015) and potentially disruptive technological changes.

The working paper is structured as follows: Section 2 presents the interlinked transformational challenges in the context of climate policy. Section 3 introduces the most relevant theories of human-wellbeing in the context of climate change mitigation and identifies 'A Theory of Human needs' as the most promising one to be employed within the EconTrans project. Section 4 then presents a conceptual framework, based on the concept of well-being generating energy services (functionalities), to link energy use (and GHG emissions) to human need satisfaction. Section 5 discusses the role of breakthrough, low-carbon technologies in the context of sustainable energy transitions, before section 6 concludes.

2. Transformational challenges to sustainability policy

Climate change poses fundamental challenges to modern society through catastrophic events and impacts today but even more so in the future (Gough 2015). Even if anthropogenic GHG emissions cease, climate change will continue for a long time due to the inertia in the climatic system. According to projections, global warming and ocean circulation could approach equilibrium on the millennial timescale, but other climate change effects like the thermal expansion of the ocean, ice sheet melt and their contributions to sea level rise will continue (IPCC 2014a). Hence, climate change puts policy makers under high pressure to act towards a transformation of the present socioeconomic system.

Furthermore, consequences of climate change overcome borders and will be felt across generations. This requires a multinational and multilevel governance response to climate change.

However, the obstacle of "free riding" or the lack of an effective control institution is a strongly limiting factor (Gunningham 2012). Hence, the task of establishing a global agreement under the United Nations Framework Convention on Climate Change (UNFCCC), with its ultimate goal to "*prevent dangerous anthropogenic interference with the climate system''* (United Nations 1992), imposes a great challenge. In 1996 the EU Environment Council defined for the first time a global mean temperature target. This limit to not exceed an increase of 2°C above pre-industrial levels was based on the second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), published in 1995 (IPCC 1995). This upper limit was taken up by the Group of Eight (G8) in 2009. In the same year at the UNFCCC Copenhagen Conference (COP15), around 100 countries called out for an even lower temperature limit, 1.5 degrees (Munasinghe 2012). With the Paris Agreement at the 21st Conference of Parties of the United Nations Framework Convention on Climate Change (COP21) a further step towards 1.5°C was taken: "*Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change.*" This has been scientifically investigated by the IPCC's special report on impacts of global warming of 1.5°C above pre-industrial levels (SR15). (United Nations 2015; de Coninck et al. 2018a; Masson-Delmotte et al. 2018).

In the EU's current climate policy plans to reduce GHG emissions by at least 55% until 2030 compared to 1990, which is in line with the Green Deal, the European Emissions Trading System (EU ETS) as a flagship climate policy instrument is complemented by other policies which need to be aligned to the new emissions target agreed on in December 2020.

These decarbonization targets require far-reaching transitions in the energy and infrastructure sectors (Masson-Delmotte et al. 2018). The pathways given by the IPCC's Special Report on 1.5°C combine different technology mixes, which allow GHG emission mitigation and net zero emissions in 2050 (Masson-Delmotte et al., 2018). Technological innovation plays a crucial role to move towards a 1.5°C world (de Coninck et al. 2018a). The enhancements of general-purpose technologies[1] (GPTs) can contribute significantly to GHG emission reduction. Nevertheless, the potential environmental, social and economic impacts of new technologies are highly unknown and come with uncertainty. GPT may even result, though more efficient, in higher emissions, by augmenting economic activities (de Coninck et al. 2018a).

Simultaneously with the Paris Agreement global governance is setting up a framework for sustainable development. The 17 Sustainable Development Goals include 169 targets on a global scale, which seek sustainable development in all three dimensions: economic, social and environmental (United Nations General Assembly 2015). They present an overall framework for sustainable development and comprise the following 17 dimensions (1) no poverty, (2) zero hunger, (3) good health and well-being (4) quality education, (5) gender equality, (6) clean

[1] A General purpose technology (GPTs) is a technology that has the potential to affect the entire economy with far-reaching changes.Typical GPTs are the steam engine, electricity or computer.

water and sanitation, (7) affordable and clean energy, (8) decent work and economic growth, (9) industry, innovation and infrastructure, (10) reduced inequality, (11) sustainable cities and communities, (12) responsible consumption and production, (13) climate action, (14) life below water, (15) life on land, (16) peace, justice and strong institutions and (17) Partnerships to achieve the goals. The SDG's show many interlinkages between the individual goals and present a broad and universal policy agenda and thereby also tackle the challenges brought about by climate change. This is done on the one hand indirectly, in almost every single target, and on the other hand directly through Goal 13 "Take urgent action to combat climate change and its impacts" (United Nations General Assembly 2015). Energy access and the design of energy systems are central to any society and are directly related to climate change.

The World in 2050 Initiative prepared a report in which six transformations pathways/options are presented/developed which try to illustrate "*how the objectives of sustainable development within planetary boundaries can be met*." The approach aims to combine all possible domains affected and to focus on their trade-offs and co-benefits (TWI2050 2018). Figure 1 visualizes these six transformations: Human capacity and demography; Consumption and production; Decarbonization and energy; Food, biosphere and water; Smart cities; and Digital revolution. The transformation options cover almost entirely the global regional, and local dynamics and describe major drivers of future changes (TWI2050 2018).

Figure 1: The six transformations as identified in the TWI2050 Report

Source: (TWI2050, 2018).

3. Theories of well-being and climate change: Eudaimonic versus hedonic understanding of well-being

While the previous section has presented the transformational challenges to sustainability policy imposed by anthropogenic climate change, we aim to connect these to relevant theories of human well-being. 'Human well-being' has become a catch-all term for measuring and stimulating 'good lives' embedded in a 'good society' (Lamb and Steinberger 2017). While there are many schools of thought providing characterizations of well-being, the two most often used theories of well-being are the *hedonic* and *eudaimonic* ones.

In hedonic theories of well-being, dating back to Epicurus, the goal of life is experiencing the maximum amount of pleasure (balanced over pain), enjoying life and feeling good. Thereby individual happiness is equivalent to well-being. In this mental account, well-being is a subjective concept that can be operationalized via a bottom-up empirical approach and on the expectancy approach (well-being is a function of expecting to attain) (Ryan and Deci 2001). In this sense **hedonism interprets limits to consumption as limits to human well-being**. If the consumption of a good or service is limited due to climate change related reasons (although there is plenty of it available), this limits the hedonists goal of experiencing the maximum amount of pleasure. This thinking leads to **consequences for sustainability**. Nevertheless, hedonists argue that influencing personal behavior with policy instruments (thus convincing a human being that he can seek pleasure within this action or gain elsewhere more) could lead to sustainable actions (Brand-Correa and Steinberger 2017). By **focusing on the subjective pleasure** hedonism **lacks the possibility of an evaluation of intergenerational factors**. Thus, hedonism gives a static view of well-being (Brand-Correa and Steinberger 2017).

Eudaimonic well-being, referring to the central concept of Eudaimonia in Aristotelian thought, is derived from 'flourishing' (Lamb and Steinberger 2017) and differs from a state of pleasure or happiness. In this understanding actions, content and processes of an individual's life matter. Focusing on activities, abilities or 'functionings' (rather than material goods), an individual's life is perceived well-lived when she can reach her highest potential within the society (Doyal and Gough 1991). Eudaimonic thinking approaches well-being from a non-individualistic perspective. Within the eudaimonic school of thought a wide range of theoretical approaches have evolved, like the Human Needs Theory of Max-Neef (Max-neef et al. 1992), the capabilities approach of Nussbaum and Sen (Sen 1999; Nussbaum 2000) and A Theory of Human Need by Doyal and Gough (Doyal and Gough 1991). While being diverse in their details, these eudaimonic approaches share certain commonalities: They (1) incorporate diverse intercultural views on what constitutes a good life by arguing that a core set of objective basic human needs (Max-Neef and Doyal and Gough) or fundamental capabilities (Sen and Nussbaum) can be defined, but the particular ways in which we satisfy these needs ('satisfiers') or achieve a flourishing life ('functionings') remain open to personal and cultural preferences; (2) perceive human well-being and the enabling 'satisfiers' or 'functionings', respectively, as multidimensional (comprising physical, social as well as psychological aspects); and (3) do not hierarchically rank these multiple dimensions and consider them non-substitutable (Lamb and Steinberger 2017).

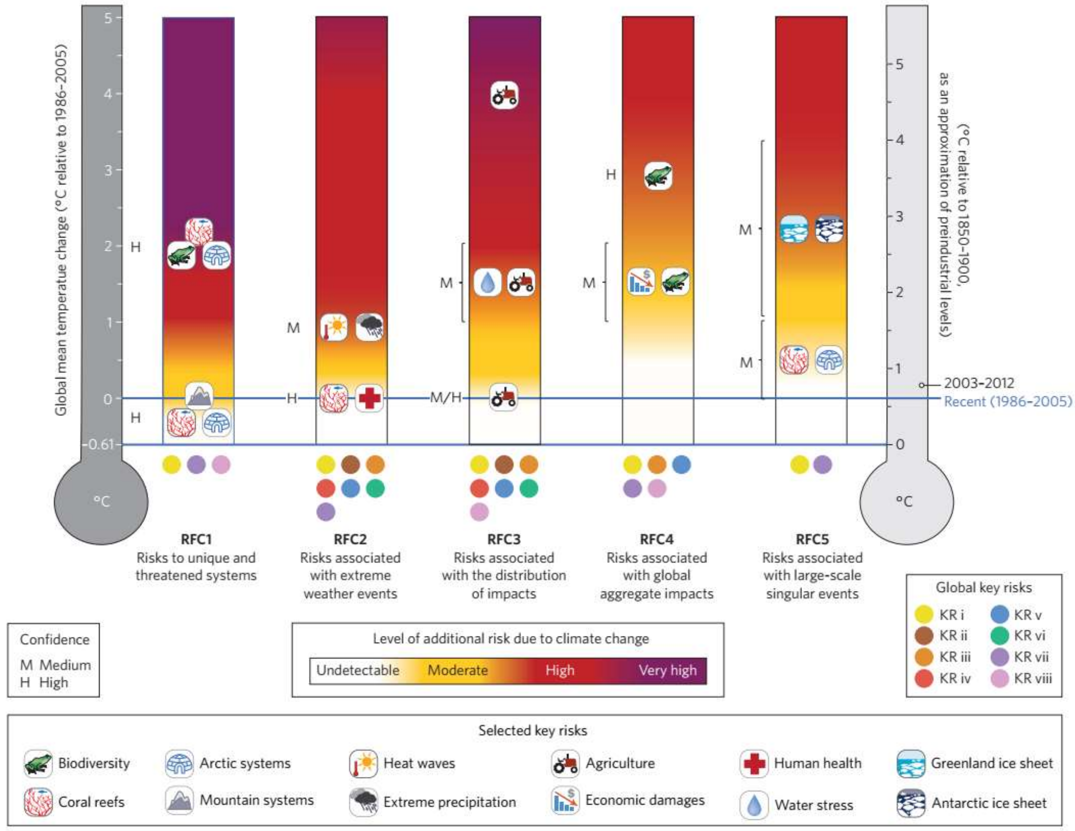
Since climate change threatens human well-being across the globe already now and even more so in the future, we argue for an eudaimonic understanding of well-being in the Econ-Trans project (Brand-Correa and Steinberger 2017). In particular, we build on the specific Theory of Human Need (THN) eudaimonic approach by Doyal and Gough (1991). It has been identified to be of great relevance in the face of threats from climate change and to be more fundamental than the capabilities approach by Sen and Nussbaum (Gough 2015).

3.1 Employing 'A Theory of Human Needs' to Climate Change

The human needs concept moves hierarchically from universal goals, through basic needs to intermediate needs (also called universal satisfier characteristics) (Gough 2015). The universal goal of this theory is the **avoidance of serious harm**. Doyle and Gough (1991, p. 50) define serious harm as the '*fundamental disablement in the pursuit of one's vision of the good, whatever that vision is*'. Thus, a direct **connection to the threats from climate change, today and in the future,** is given. At the same time the possibility of a non-impaired social participation is regarded a key cornerstone of the human needs approach. The personal goals one follows must be achieved based on successful social interaction. In each cultural group and at each time and place human beings act in it. This aspect acknowledges the social character of human action (Gough 2015). Thereby the objective approach of this theory **considers also intergenerational factors**, by acknowledging that human needs are the same for present as for future generations. Therefore, we deem this theory well suited for operationalizing human well-being in our research project and in the context of long run transformation.

Climate change is already imposing serious harm to people living today and will do so even more in the future (IPCC 2014b). The scientific understanding about risks in relation to varying levels of climate change is communicated by the reasons for concern framework of the IPCC. The framework aggregates global climate change risks into five categories as a function of global mean temperature change. An enhanced version by O'Neill (O'Neill et al. 2017) shows already for today a moderate level of additional risk due to climate change for some of the categories in Figure 2. While the 2015 Paris Agreement aims at limiting global temperature increase to well below 2°C above preindustrial levels, even this level of warming could lead to high levels of additional risk and eventually to intolerable impacts for some of the most vulnerable nations. According to the IPCC's SR15, risks for natural and human systems are higher for 1.5°C global warming than at present, but lower than at 2°C (Masson-Delmotte et al. 2018). However, the actual global mean temperature change based on the current Paris pledges will amount to 2.6°C to 3.1°C (Climate Action Tracker 2018), leading to potentially very high additional risks due to climate change across the five categories visualized by the IPCC reasons for concern framework.

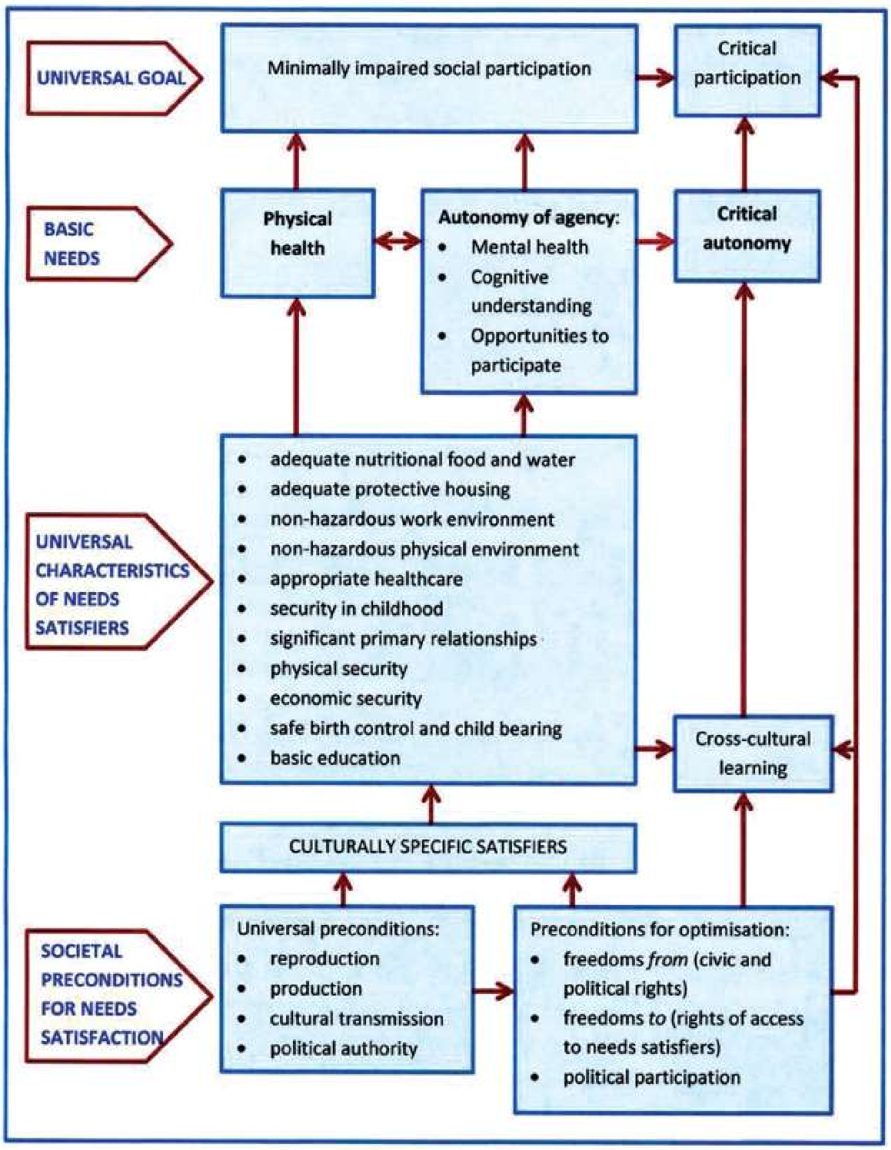
Figure 2: The enhanced burning embers diagram, providing a global perspective on climate-related risks



Source: O'Neill et al. (2017).

Within the THN well-being approach (see Figure 3), basic needs are defined as universal pre-conditions for a non-impaired participation in society. They are divided in **autonomy** (ability to make competent informed choices about what should be done and how to go about doing it) and **physical health** (Doyal and Gough 1991). While basic needs (and needs overall) are defined as being universal; goods, services, activities and relationships to satisfy them are culturally and temporally available. In this distinction the THN follows the concept of Max-Neef (Max-Neef et al. 1989) and **distinguishes needs and satisfiers**. For example, the basic need for food exists in each culture and in time, but how this need is satisfied varies, meaning the culturally distinctive cuisines (satisfier) are diverse (Max-Neef et al. 1989; Doyal and Gough 1991).

Figure 3: A visual outline of the THN



Source: Gough (2015).

As a bridging concept between basic human needs and the culturally specific satisfiers, the THN introduces '**intermediate needs'**, also called '**universal satisfier characteristics (USC)'**. Needs are a very abstract concept and a common critique is that needs are too abstract for implementing them in policy choices or applying them to real human dilemmas. USC offer to build a bridge between needs and satisfier and offers a starting point for measuring human needs. USC are defined as '*[…] those properties of goods, services, activities and relationships* *that enhance physical health*[2] *and human autonomy in all cultures. For example, calories per day for a specified group of people constitutes a characteristic of (most) foodstuff which has transcultural relevance*.'[3] (Doyal and Gough 1991). Hence, USC can be regarded as inputs that lead (in a positive way) to the output of individual health and autonomy in all cultures. Each intermediate need has a material base which is identifiable in terms of biomedical understanding. Another important point is that the categories of USC will be the same for future generations and the present one (Gough 2015).

USC can be regarded as ends for which culturally specific satisfiers can act as the means. In this sense they provide a secure foundation on which to establish a list of derived or second-order goals (Gough 2015). Intermediate needs, or USC, comprise according to Gough (2015):

- physical health: adequate nutritional food and clean water, adequate protective housing, a non- hazardous work environment, a non-hazardous physical environment, appropriate health care
- autonomy: security in childhood, significant primary relationships, physical security, economic security, appropriate education, birth control and child-bearing (see e.g., Brown and Harris (1978))

To identify the USCs, a causal relationship to the two basic needs, physical health or autonomy, and the numerous factors affecting them has to be defined. Moreover, anthropological knowledge about practices in the numerous cultures and sub-subcultures, states and political systems in the contemporary world needs to be gathered. Taking in consideration these two scientific pillars on which intermediate needs are built on, the concept remains open to continuous improvements and empirical application.

4. The link between human well-being, energy use and GHG emissions

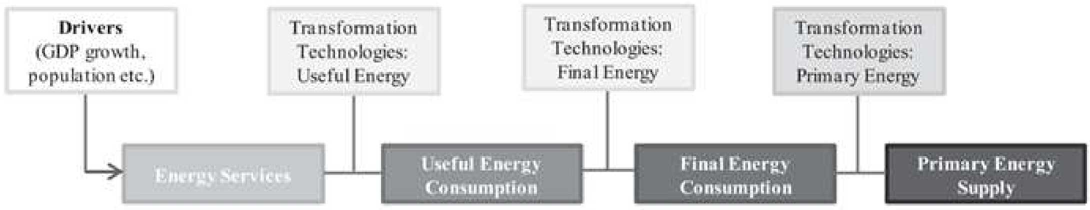
EconTrans addresses the link between human well-being, energy use and GHG emissions, by focusing on "energy related functionalities" which we use as synonyms for the term energy services (Köppl et al. 2016; Köppl and Schleicher 2018)**.** This relationship is represented by a complex system of inter- and intra-connected variables (Ortiz et al. 2017). Nowadays and in most EU countries living a 'good life' comes with high (fossil) energy usage. Many activities which improve individual human wellbeing, like air conditioning, heating, refrigeration, cooking, hot water access or lighting are highly energy consuming. It has been evaluated that activities like heating or air conditioning have become unquestioned standard in less than one generation (IEA 2020; Shove 2003; Waite-Chuah 2012).

[2] The Theory of Human Need also includes mental health (Doyal and Gough 1991).

[3] Doyle and Gough (2015) identify a 'minimum optimorum', a *minopt* threshold. "*In principle, (need) satisfaction is adequate when, using a minimum amount of appropriate resources, it optimises the potential of each individual to sustain their participation in those constitutive activities important for furthering their critical interests.*" (Gough 2015).

The **link between human well-being, energy use and GHG emissions can be established through the energy chain** (Figure 4) (Brand-Correa and Steinberger 2017; Köppl and Schleicher 2018). Traditional energy models analyze the energy system starting from the supply of primary energy flows (e.g. crude oil), followed by secondary energy/energy conversion (e.g. oil at refinery) to final energy (e.g. gasoline, electricity) and useful energy (e.g. heat, work/ mechanical drive, light, food). In a final step, useful energy delivers energy services (Jochem et al. 2000). This final step can be termed 'passive system'. Here no further conversion processes occur, only energy dissipation according to the second law of thermodynamics (Cullen et al. 2011). Since energy services constitute the ultimate objective of an energy system and the energy supply chain (Brand-Correa and Steinberger 2017), we suggest to turn around the standard direction of the energy chain and put energy services at the starting point of any energy system analysis (Köppl et al. 2014, 2016). The desired energy related functionality defines the previous steps in the energy chain – useful, final, primary energy – as well as the respective transformation technologies.

Figure 4: Structure of the energy chain

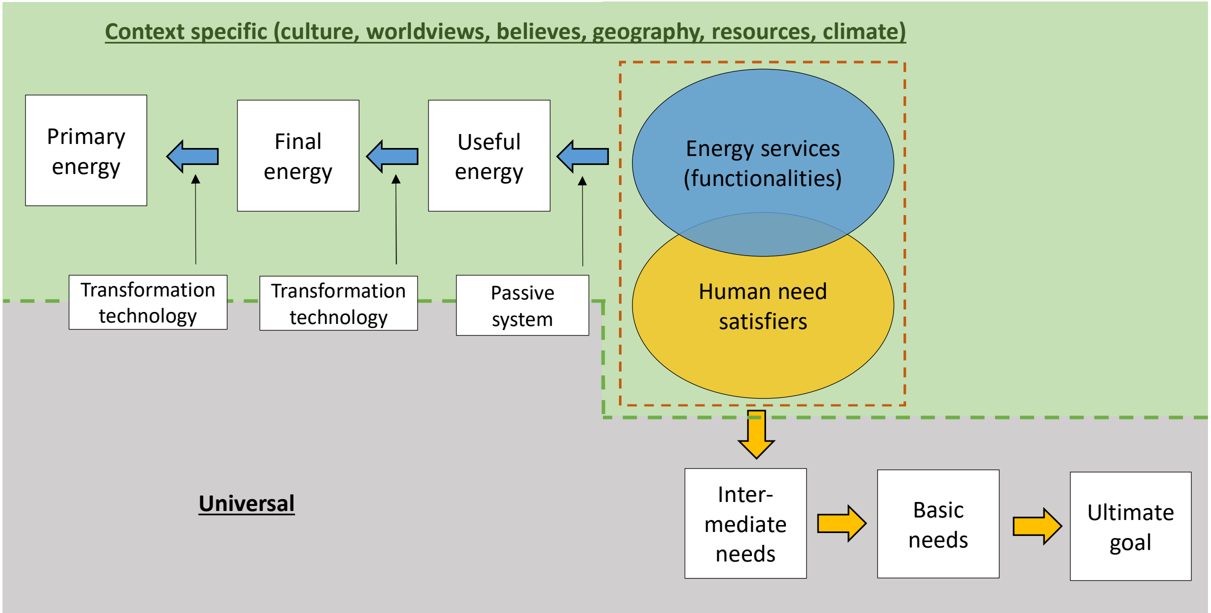


Source: Köppl et al. (2014).

Moreover, by changing the focus from energy flows to energy services one can assess the potential for reducing energy flows while keeping the used energy services and thereby human well-being constant (Köppl et al. 2014). Hence, **energy services represent the crucial link between energy use (and related GHG emissions) and human need satisfaction** (see Figure 5). **Energy services, not flows (e.g. expressed in kWh) of useful, final or primary energy, are used as satisfiers of human needs** (Brand-Correa and Steinberger 2017).

Examples for an energy service are *mobility* and *shelter*. Mobility understood as a service means to provide people with access to various activities, goods and services and to fully participate in society. This service can be provided in different ways, each with different energy requirements: walking, driving by car, using public transport or telecommunication. The same holds true for shelter, which can be provided with different qualities of capital stocks.

Figure 5: The conceptual framework for establishing the link between energy use, GHG emissions and human need satisfaction



Source: Own visualization.

4.1 Stakeholder consultation on well-being and functionalities

The concept of human well-being as well as the focus on functionalities with respect to the energy system are the starting point for our research in the EconTrans project. In order to understand how these concepts found in literature meet with a broader perception, we consulted with Austrian stakeholders where they see the link between energy use (and related GHG emissions) and human need satisfaction and functionalities. We conducted 26 semi structured interviews with stakeholders from policy, practice, and science. Since qualitative samples tend to be purposive rather than random as for quantitative data, the selection of the interviewee sample depends strongly on the respective research questions. In the present study, we applied a reputational case selection approach. The first interviewees were chosen based on consultations within the research group. This first group of interviewed experts was then asked for further recommendations of possible additional interview partners. The overall goal of the selection process was to have a sample as comprehensive as possible across scientific disciplines, policy and practice. Our results of the interview analyses show that while the group of scientists also identify energy services as the crucial link between human need satisfaction and GHG emissions, a third of the interviewed practitioners perceive the primary energy source as the most important link. Politicians emphasized that the whole energy chain matters and highlighted the importance of the energy services concept along the energy chain.

Table 1: Row percentage words coded per stakeholder group

	final energy useful energy energy service	primary energy	entire chain matters
policy	29,25%	0%	70,75%
practice	37,73%	37,39%	24,89%
science	58,2%	0%	41,8%
company	74,45%	8,52%	17,03%

Source: Own visualization with NVivo4.

Most of the experts linked human well-being and energy at the point of final, useful energy or at the point of energy services (see Table 1). This is essentially consistent among all the stakeholder groups. Stakeholders from practice nevertheless emphasize primary energy supply and the entire energy chain equally important for well-being. Representatives from companies emphasize especially the final conversion point, i.e. energy services, whereas stakeholders from the policy level underline the importance of the entire energy chain. These results align with the theoretical approach of our project. The relevant point of the energy supply chain – the energy services – are the ultimate goal of the energy conversion chain. Nevertheless, the entire energy chain is indirectly affecting human well-being. Thus it is always the entire energy chain that needs to be analyzed, regardless of whether energy services or the supply of primary energy is taken as starting point. Experts from practice, especially regional managers underline the problem, that citizens do not notice the environmental impact of energy production, as they do not directly feel or see the conversion steps.

4.2 Mapping energy services and intermediate human needs and indicators for measuring energy-related functionalities

Analogous to satisfiers of human needs, energy services and in particular their socio-technical provision systems can be seen as culturally specific[5]. Cullen and Allwood (2010) identified eight final energy services that can be measured using physical data.

These thermal, mechanical and specific electric energy services can be mapped (Figure 6) to the list of intermediate needs (or USC) presented above (Gough 2015) and may be interpreted as energy related specific human need satisfiers. The mapping was done jointly by the EconTrans project team according to the question "Which energy services are needed to satisfy a specific intermediate need (USC)?". The map visualizes the complexity of the connections between the energy related functionalities and intermediate needs. The size of the symbols for energy services reflects their relative importance as satisfiers for intermediate needs.

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[4] NVivo is a software-package for qualitative data analysis: https://www.qsrinternational.com/nvivo-qualitative-data-analysis-software/home

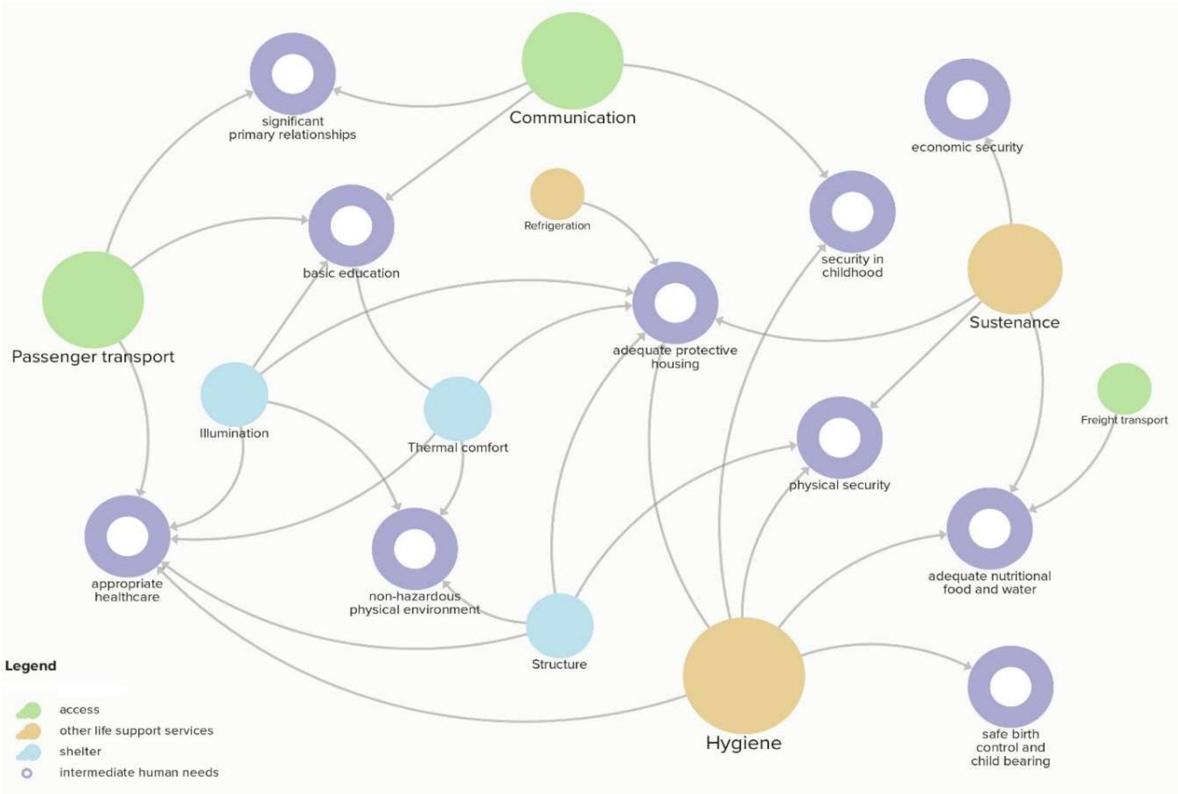
[5] Along the energy supply chain the properties of primary, final and useful energy as well as the respective transformation technologies may be context specific, varying due to differences in e.g. culture, worldviews, believes, geography, resources, and climatic conditions.

The list of “thermal, mechanical and specific electric energy services can be summarized under the heading of functionalities” (Köppl and Schleicher 2018, p. 4) and employed to specify the three classes of functionalities listed in the EconTrans proposal (shelter, access, other life support services):

- **Functionality ‘Access’**
    - passenger transport
    - freight transport
    - communication
- **Functionality ‘Shelter’**
    - structure
    - thermal comfort
    - illumination
- **Functionality ‘Other life support services’**
    - sustenance
    - hygiene

The presented concept so far calls for a more concrete operationalization and measurement of human well-being of energy-related functionalities. We therefore identified a set of indicators for the thermal, mechanical, and specific-electric energy services (Table 2).

Figure 6: Mapping energy services (also called functionalities) to intermediate needs



Source: own visualization with kumu[6].

Table 1: Preliminary list of indicators for measuring energy services

Energy services	**Indicators**
Passenger transport	passenger-km
Freight transport	tonne-km
Communication	bytes
Structure	Volumetric heat capacity [MJ/m³K]; m²/person
Thermal comfort	°C
Illumination	lumens
Sustenance	calories; litres of water; % undernourished; % no access to drinking water
Hygiene	access to toilets; clean drinking water
Refrigeration	°C

Source: own illustration based on a literature review.

[6] Kumu is a software-package for organizing complex data into relationship maps: https://kumu.io/

This indicator list was on the one hand informed by literature and on the other by the semi-structured interviews of the stakeholder consultation where stakeholders recommended indicators suitable to capture energy services and functionalities(Table 2).

Table 2: List of indicators for measuring energy services

Energy services	Indicators
Shelter	
illumination	Lumens per square meter
thermal comfort	Temperature humidity; temperature (°C), access to electricity; energy poverty; electrification
Access	
communication	Connection to infrastructure; access to communication; social contacts
freight transport	Availability; transportability; storability; amount of freight transports; local supply in the community; prices of goods, export levels
passenger transport	Walkability; access/distance to public transport; passenger kilometers; dependence on motorized individual transport; modal split; cycling infrastructure
Other life support services	
sustenance	Energy per kilogram of food (in one culture); energy needed to deliver nutrients needed; access to food
hygiene	Amount of medicine available per person; electrification; health indicators (e.g. number of sick persons, productivity of people)

Source: own illustration derived from stakeholder interviews.

The list of indicators in Table 2 and Table 3 show some similarities. It is noticeable that the suggestions by the stakeholders are more diverse than the summary from the literature. Overall, the step towards operationalization requires in particular the provision of corresponding data as well as their use and establishment in empirical research.

5. The role of disruptive technologies

In the context of climate change mitigation policy, many researchers and practitioners perceive **technological innovations - in particular so-called breakthrough technologies - as a glimmer of hope** (Nordhaus 1973, 1977, 1992; Edenhofer et al. 2011)**. At the same time, the**

feasibility and environmental effectiveness of their large-scale deployment is widely discussed and, in some respects, unknown (de Coninck et al. 2018b).

Different definitions and examples **of such groundbreaking technological innovations**[7] exist in the literature, comprising both currently available technologies as well as potential future technologies. However, **definitions** and usage of the term 'innovation', 'breakthrough' or 'disruptive' are **often unclear and vary from one source to another**. The Oxford dictionary defines *innovation* as "*the change of something established by the introduction of new methods, ideas or products*" (Kramer 2018). Kramer (2018) argues that in our age, innovation has become something strongly desirable. For disruption it is different. Going back again to the dictionary definition, disruption is a 'serious alteration or destruction of structure', from the Latin *disrumpere*, to break apart (Kramer 2018). The term 'breakthrough' on the other hand is defined as "*a sudden, dramatic, and important discovery or development*" (Oxford Dictionary 2018).

Additionally, and more important in our context of the EconTrans project and the need to decarbonize our economies and societies, disruptive technologies deeply influence modern societies and may eventually lead to large-scale sustainable energy transitions. The term 'transition' is defined as a "*passage from one state, stage, subject, or place to another*" or "*a movement, development, or evolution from one form, stage, or style to another*" (Elzen et al. 2004; Webster Dictionary 2019).

Innovation was not always a prominent topic for social science (Fagerberg 2018). The Austrian-American economist Joseph Schumpeter (1942) was one of the first who saw innovation as the driving force of long run economic and societal change (Fagerberg 2018). Already in 1942 Schumpeter (1942) recognized that innovation comprises several dimension, covering not only technological but also organizational characteristics.

In this chapter we will therefore outline and compare different theories on technological innovation (Freeman and Perez 1988; Geels 2002), including theories on disruptive innovation (Christensen 1997; Wilson 2018), by focusing on the role of low-carbon technologies. Starting with a summary of the historical analysis of technological change by Perez (2016), different innovation theories in the context of low-carbon technologies will be introduced; first Christensen's (1997) theory on disruptive innovation with the focus on company failures; then the socio-technical system perspective by Geels (2002) and finally Wilson's (2018) theory, which focuses on low-carbon innovation.

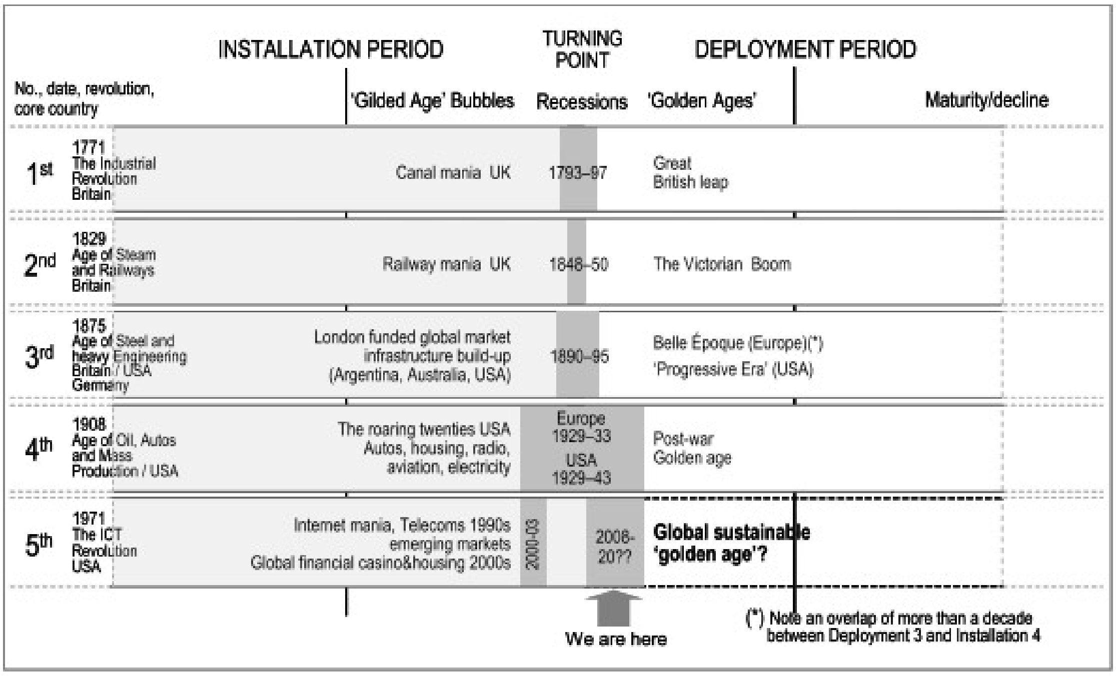
Based on this literature review, we will present a working definition which links up to the previously outlined concept of human well-being.

[7] https://www.technologyreview.com/lists/technologies/2018/
https://www.mckinsey.com/~/media/McKinsey/Business_Functions/McKinsey_Digital/Our_Insights/Disruptive_technologies/MGI_Disruptive_technologies_Full_report_May2013.ash

5.1 A historical perspective on innovation – A Global Sustainable 'Golden Age'[8]

Perez (2016; 2018) sees technological change through a historical lens. Her (2016) historical analysis shows that since the first industrial revolution in 1771 five technological revolutions have occurred. Each revolution was different in its technical characteristics and even had distinct historical or political factors. However, there are certain common features among them (see Figure 7). Each revolution is characterized by two phases, the 'installation' and the 'deployment' period.

Figure 7: "The historical record: Bubble prosperities, recessions and golden ages"



Source: Perez (2016).

The first period ('installation') is characterized by wild turbulences and Schumpeterian 'creative destruction'. The process is driven by financial capital. Entrepreneurs and innovators invest and explore the possibilities of new technologies. Government action is characterized by laissez faire trends. In addition, the installation of new technologies leads to displacement of the before prevailing skills, polarization between the old and the new, and to difficult social disruption and adaptation (Perez 2016).

[8] A Smart Green European Way of Life: The Path for Growth, Jobs and Wellbeing by Carlota Perez was written as a chapter in Europe 2050: Rethinking Europe. This publication was edited by the Austrian Council for Research and Technology Development (Perez and Leach 2018).

Every 'installation' period ends with a big bubble, which is followed by a major crash. The following second period, 'deployment' is indicated by harmonious growth. In this phase, often the government steps in and plays an active role providing enabling policies and leading to 'Golden Ages' (Perez 2016).

The revolution, in which we are today is the ICT (information and communication technology) revolution (see Figure 7). This shift started in the 1970s, with the emergence of ICT. At the same time, another group of people, a movement of hippies and other outsiders, were striving for a return to nature. Beyond that, the awareness of environment and climate issues, resource scarcity, environmental degradation and climate change, rose (Perez and Leach 2018).

According to Perez (2016) (see arrow in Figure 7) we are currently at a point after a wild period of Schumpeterian creative destruction. According to her theory this is a phase, in which something new has to occur to foster investment, employment and innovation.

This phase is often accompanied by a change in lifestyles: "*a new aspirational 'good life', underpinned by the new technologies and fostered by government policy*" (Perez and Leach 2018). A revolution provides a new inter-related set of life-shaping goods and services and therefore has its origin often in niches. These niches are to be found at the top of the income scale or/and in radical outsiders. Often such changes are adopted by the younger generations (Perez and Leach 2018). This coupling of products and lifestyles cause a systemic change, which affects the service economy and the production economy. "*The car as both status symbol and practical mode of transport, for example, needs not just the innovation of the automobile, but petrol stations, mechanics, car insurance and traffic reports*" (Perez and Leach 2018).

For today, Perez (2016, 2017; 2018) proclaims a 'smart green' lifestyle as the direction for innovation which could lead to a 'Global sustainable golden age'. "*The EU is in a key position to promote future investment and well-being in a smart green direction*" according to Perez and Leach (2018). Italy, for example, successfully combined a new technology with a new 'niche' lifestyle and European and national directives. By doing so they encouraged industrial synergies and realized a legislation, which restricted consumers to use long-life reusable carrier bags or biodegradable, compostable bags. This not only led to a significant (50%) reduction of disposable bag use, but even decreased greenhouse gas emissions by about 30% (tied to disposal actions) (Perez et al. 2016).

The important role of lifestyle change in innovation and economic growth should not be underestimated and is shaped by businesses, government policies as well as consumer values. The requirements for a golden age are threefold:"*(a) consistent with the potential of the technological paradigm; (b) mutually compatible and reinforcing; and (c) a positive-sum game for all participants*" (Perez and Leach 2018).

Focusing on the different stages of technological innovation one can distinguish: incremental innovation, radical innovation, new technology systems and changes of techno-economic paradigms (Freeman and Perez 1988).

a) Incremental innovations occur continuously and comprise engineering or production process improvements. Often, incremental innovations may pass unnoticed and unrecorded.
b) Radical innovations are discontinuous and result out of research and development at companies or universities. At long time distance they may bring about a radical impact and thereby structural change, however considering their economic impact they are relatively small and localized.
c) Changes of technology systems are based on the combination of radical and incremental innovations and lead to the rise of entirely new sectors. They affect several branches of the economy (larger scale). They come in combination with organizational and managerial innovations, which affect more than one company.
d) Changes in techno-economic paradigms are 'technological revolutions. These changes in technology affect the behavior of the entire economy. A vital characteristic is that also another branch of the economy is affected; it is a meta-paradigm

5.2 Sustaining versus disruptive innovation

The term 'disruptive innovation' was first introduced by Christensen (1997) regarding the long-term success of companies in management studies.

Christensen (1997) found that although **leading companies** manage to consistently develop and commercialize new technologies and develop enormous improvements regarding existing technologies in their existing markets, they **often fail to commercialize new technologies that** do not initially meet the needs of mainstream customers and **only satisfy small or emerging markets**. For example, Intel's 32-bit 386 microprocessor instead of the 16-bit 286 chip didn't create a new market, but satisfied the already existing need of existing costumers (Christensen 1997; Christensen and Overdorf 2000). **Eventually, these incumbent companies will be replaced by an emerging company**. The reason for this phenomenon is that the existing companies or industries stay too close to their current customers. Hence, customers will reject a disruptive product in an application they already know and understand. New companies with the new technology enter the market and launch new models, which initially are only interesting to a small group of costumers. Managers of the leading companies see themselves in a position where they have two choices: invest in an up-market with sustaining technologies whose profit margins are high or take interest in a down-market whose profit margins are low. Often, **they stay close to their current costumer interests and stay with the upmarket** (Christensen and Bower 1995; Christensen 1997; Christensen and Overdorf 2000; Christensen and Michael 2003).

Intel is an example for a sustaining technological innovation. A new technology is defined as "**sustaining**" if the innovation makes a product or a service better in a way that the customers in the prevailing market value. These breakthrough innovations provide a product or service better than it had been before. **Disruptive innovations** create new markets, which will at some point replace the (before) prevailing market (Christensen and Bower 1995; Christensen 1997). In this sense disruptive innovations have a strong potential to (re)shape economic structures and may have a substantial impact on the energy and emission system (Köppl and Schleicher 2018). An example for a disruptive innovation are the early personal computers around 1980 which replaced the minicomputers produced mainly by the company Digital (Christensen and Overdorf 2000).

Nelson and Winter (1982) confirm that the central competitive asset of large (prevailing) firms is the organizational knowledge they possess (Fagerberg 2018). This is visible in a set of routines. But this implies that large firms are path-dependent. Large firms are "*much better of the tasks of self-maintenance in a constant environment than they are of major change, and much better in changing in the direction of "more of the same" than they are at any other kind of change*" (Nelson and Winter 1982, pp. 9–10). Established firms incorporate established routines, which are questioned by new market entrants but at the same time very difficult to be broken up (Fagerberg 2018).

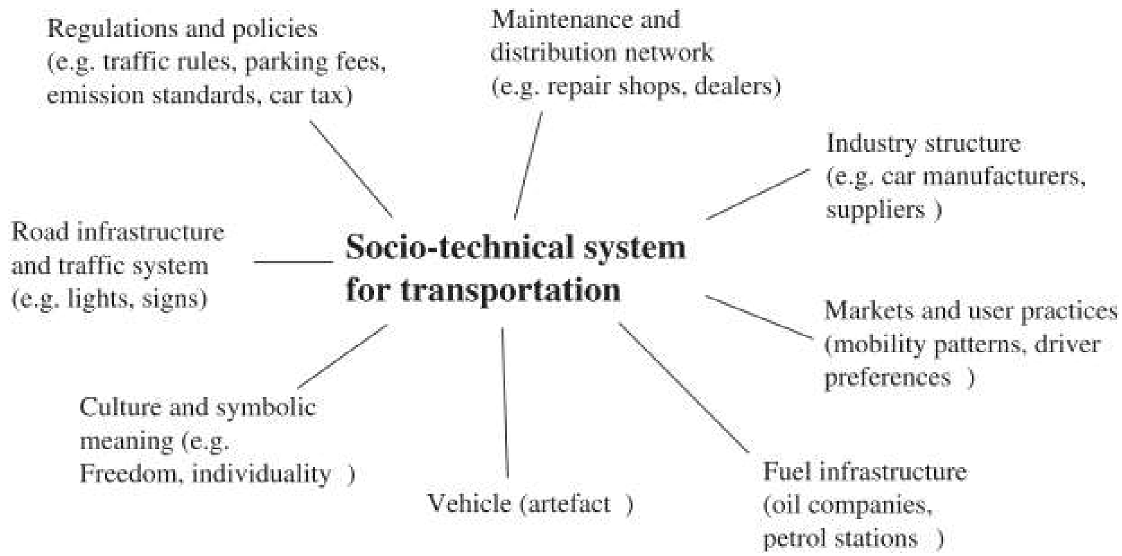
5.3 Changing systems - Technological transitions as system innovations

Technologies support and enable important societal functions, such as communication, transportation, housing or feeding. For this it is important to notice that: (a) technology is heterogeneous and (b) its functioning claims linkages between these heterogenous elements (Geels 2004).

Therefore, innovation should be studied from a socio-technological systems perspective (see Figure 8 as an example for the transportation sector). In this broader conceptualization, technological innovation is studied from a system transition perspective. Hence a disruptive innovation can trigger a transition towards a new level of societal functions. These transitions lead to changes in socio-technical systems. Further if a transition then provokes a change *from one socio-technical system to another, that is a system innovation*" (Elzen et al. 2004).

A system innovation builds on "*three sub-processes: (i) emergence of new technologies, (ii) diffusion of new technologies, (iii) replacement of old by new technology*" (Geels 2004). The second sub-process regards coevolution. Specifying a system innovation does not only consider technological substitutions, but even changes in "*user practices, regulation, industrial networks, infrastructure, and cultural meaning*" (Geels 2004). The third sub-process (replacement of old by new technology) is where new functionalities emerge (Geels 2004).

Figure 8: "Socio-technical system for modern car-based transportation"



Source: Geels (2004).

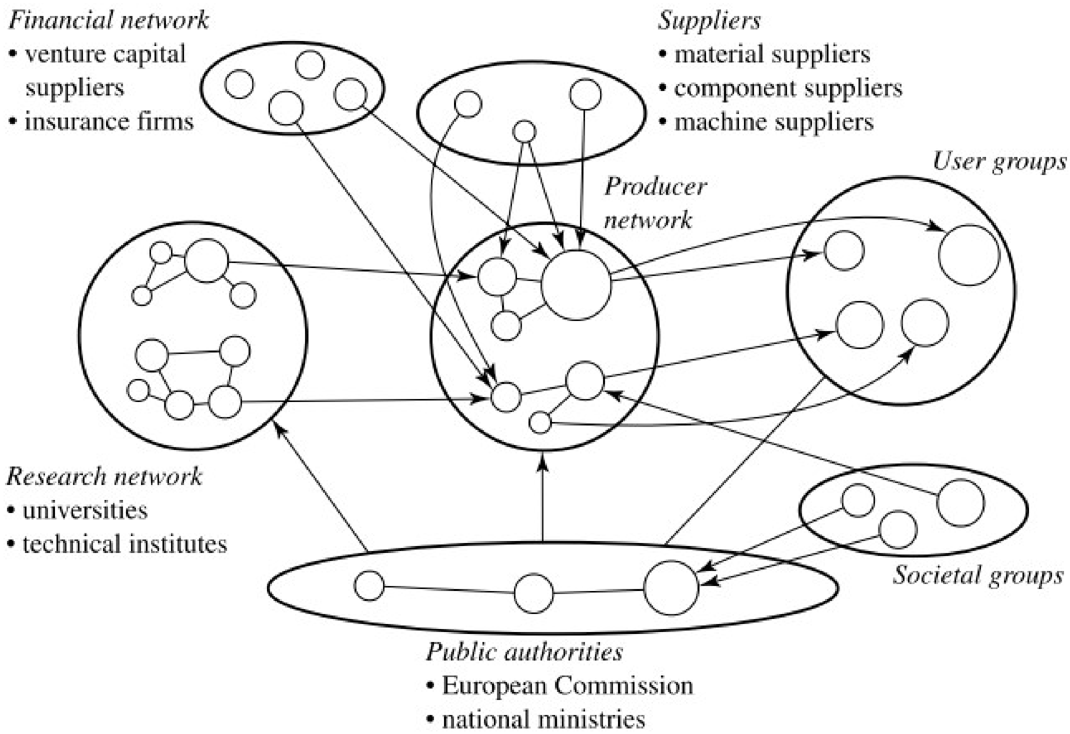
Thus, a new technology can cause a large-scale transformation, thereby leading to a system innovation. "*System innovations are defined as large-scale transformations in the way societal functions such as transportation, communication, housing, feeding, are fulfilled*" (Geels 2004).

Considering this broader viewpoint, a conceptualization is needed, which integrates different approaches and combines sociology of technology and evolutionary economics. Hence three levels are distinguished, which are analytical and heuristic concepts to understand the complex dynamics of socio-technical change (Geels 2004).

(a) socio-technical regimes

Geels (2002, 2004) uses the term *socio-technical regimes* to characterize a set of semi-coherent rules, which are used by different social groups. The elements and linkages in a socio-technical system are created by the different actions of social groups which (re)produce them. Not only engineers shape as social groups the socio-technical regime. *Technological trajectories* are also shaped by users, policy maker, societal groups, scientists, etc. (see Figure 9).

Figure 9: "The multi-actor network involved in socio-technical systems"



Source: Geels 2004.

(b) socio-technical landscape

The *technological trajectories* are embedded in a *socio-technical landscape* (see Figure 9). The socio-technical landscape "*contains a set of heterogeneous, slow-changing factors such as cultural and normative values, broad political coalitions, long-term economic developments, accumulating environmental problems growth, emigration*" (Geels 2004). At the same time, it not only contains this relative stability but also shocks and surprises, like wars or sudden price spikes. It is important to note that landscape factors are difficult to change in contrast to regimes (which can be changed to some extent) (Geels 2002, 2004).

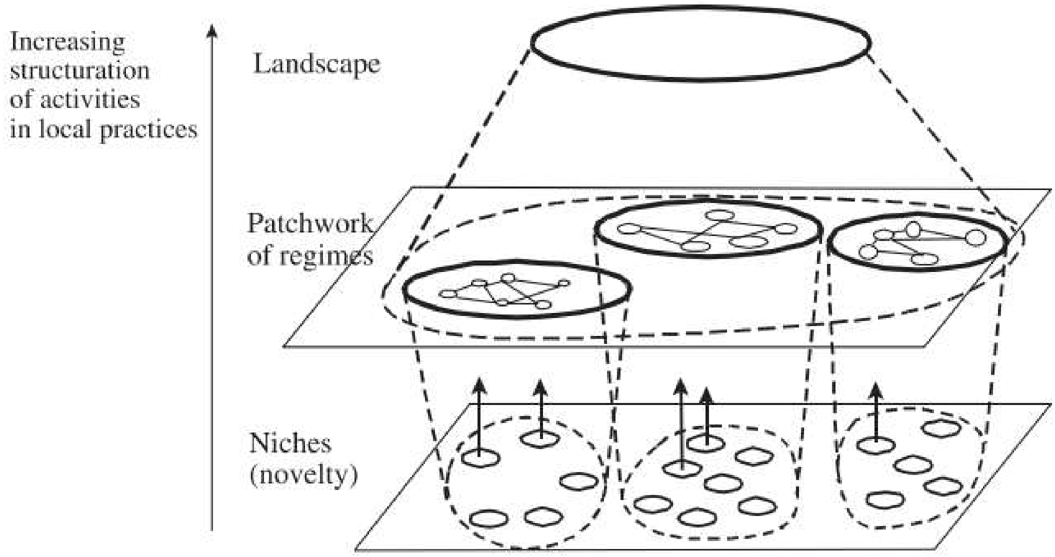
(c) technological niches

In regimes, incremental innovations are created. A radical innovation on the other hand is generated in niches. These niches are somehow separated from conventional market selection (Geels 2004). They can be considered as "*incubation rooms for radical novelties*" (Schot 1998). Radically new technologies need protection from the conventional market selection, because they usually have a low technical performance and are at the same time cumbersome and expensive. An example for a niche is the army. This niche helped the emergence of new technologies in their early phases, like the digital computer, jet engines, radar. Furthermore, such niches provide social networks for changing experiences and locations for learning processes (Rosenberg 1976; Lundvall 1988; Von Hippel 1988; Geels 2002, 2004).

These three levels have a different kind of structure. Whereas *technological niches* are loose and vague in their structuration, *regimes* are structured much stronger. Further, *socio-technical landscapes*, like material environments and widely shared cultural beliefs are even harder to deviate from (Geels 2004).

The relationship between these three levels is described as a nested hierarchy (Figure 10). They are connected to each other; *regimes* are embedded within *landscapes* and *niches* within *regimes* (Geels 2002, 2004).

Figure 10: "Multiple levels as a nested hierarchy"



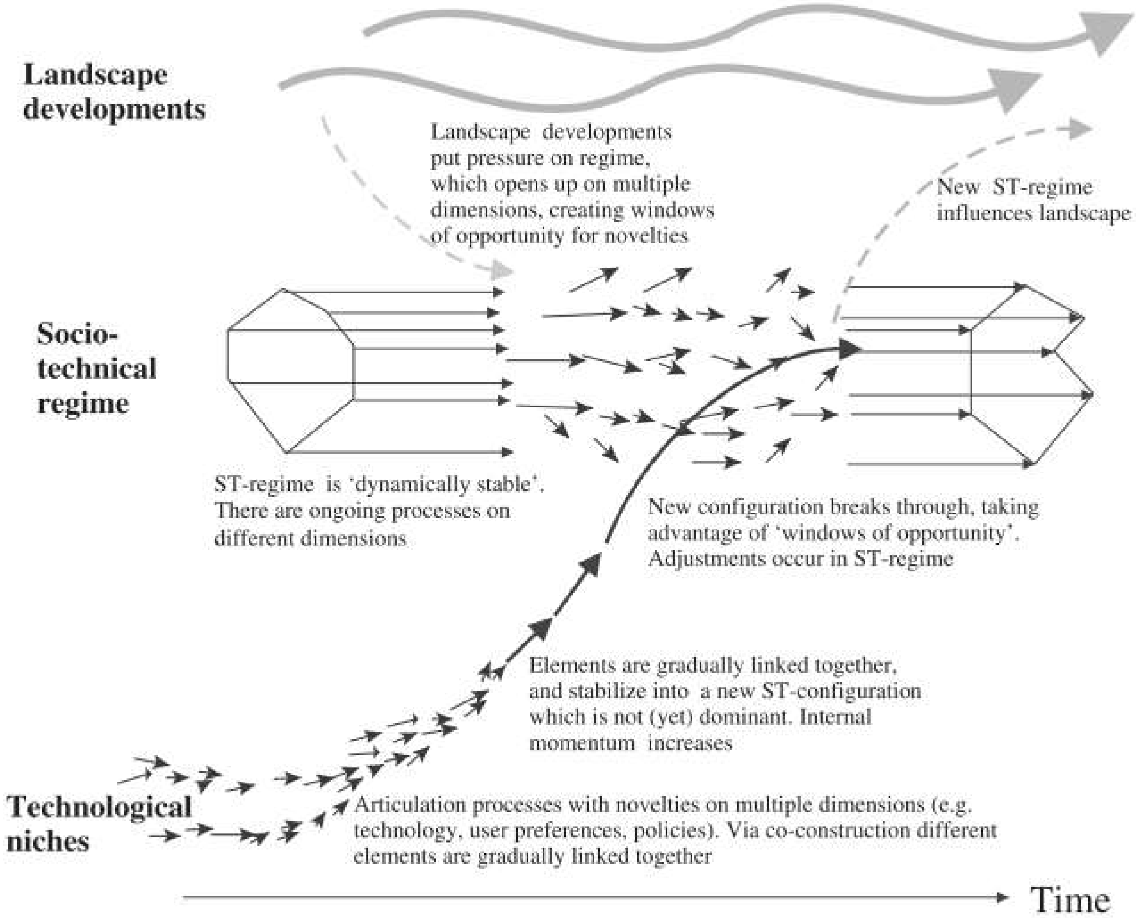
Source: Geels 2002.

Promoters of a new technology, developed in a niche, hope that this novelty will be used alongside or will even replace the regime in the above layer. This is not easy, as the prevailing regime is entrenched in institutions, organizations, economy and culture. Further, a radical novelty has a mismatch with the existing regime (Freeman and Perez 1988), preventing their breakthrough (Geels 2004).

Niches are crucial for the multi-level perspective, as in technological niches novelties emerge initially within the old prevailing framework (Freeman and Perez 1988). However, the radical potential of a novelty is not always clear at the beginning. They may even start insignificantly, as simple contribution to solving problems in the existing regime (Geels 2004). As the direction is not clear at the beginning and no dominant design has emerged, multiple processes on multiple dimensions, like user preference or policies occur. As a dominant design emerges elements are linked together, and a new socio-technical-configuration stabilizes (Geels 2004).

Geels (2004) defines breakthrough and innovation of a new technology as the product of linkages between developments at the three different levels. An innovation can emerge – break out – of its niche, when external circumstances are right. This means that a window of opportunity is created at the level of *regime* and *landscape*. If the innovation breaks through and enters mass markets, it is in competition with the existing regime and perhaps may even replace the existing "old" regime. This change will provoke changes in other dimensions of the socio-technical regime. A system innovation may also trigger changes in regulation, infrastructure and so on. Further the new regime could also cause wider *landscape* changes (see Figure 11).

Figure 11: "A dynamic multi-level perspective on system innovations"



Source: Geels (2004).

A system innovation is provoked not only by a single radical technology, but by interlinkages of several technologies. The multi-level perspective of Geels (2004) is seen as an explanation of two kinds of directions considering system innovation: a) external circumstances and b) internal drivers.

- External circumstances are reasons for destabilization created by tensions between elements in the regime; for example, climate change; or internal technical problems which create opportunities for novelties; negative externalities; changing user preferences; competition between firms.
- Internal drivers can also stimulate diffusion of innovations and technological substitution. These are in an economic perspective improvement in price and performance or in a socio-technical perspective increase of linkages between heterogeneous elements (= diffusion process) (Geels 2004).

Four phases of transition are proposed by Geels (2004) and (Rotmans et al. 2001).

First phase: *emergence of novelty in an existing context*. The novelty is born in technological niches and small market niches. There is a lot of uncertainty about design or functionality. The existing regime shapes the novelty in design and functionality. In this phase "*technological add-on* and *hybridization*" occurs. This means, that a novelty links up with an existing technology as an auxiliary to improve the prevailing "old" technology. This leads to a certain kind of symbiosis. An example is the steam engine, which at the beginning only supported sailing ships, when there was no wind.

Second phase: *technical specialization in market niches and exploration of new functionalities*. Actors in the niches interact with each other and build experiences and diffusion based on their new gained knowledge. Also, users interact with the new technology and explore new functionalities.

Third phase: *wide diffusion, breakthrough of new technology and competition with established regime*.

The diffusion of a new technology depends on a window of opportunity and gives a higher visibility to the novelty.

Fourth phase: *gradual replacement of established regime, wider transformation*. This replacement happens often in gradual fashion. Reasons for this are, cost-performance ration of a new technology, different market niches with different selection criteria, changes in the socio-technological regime take time, incumbents tend to stick to old technologies, because of investment insecurity or vested interests.

5.4 Technological change and GHG emissions - Wilsons's disruptive low-carbon innovation

Often novel goods and services are being made available with the hope of eventually reducing overall anthropogenic GHG emissions. Even though these innovations may have low or even zero direct GHG-emission, they may not reduce overall GHG emissions if the custom before was non-use. This raises the conflict, that no social benefit is being generated regarding emissions reduction. Thus, low-carbon outcomes of an innovation depend on:

a) the emission profile of the before prevailing technology, which is to be replaced.

b) the changes in market demand and products in the background of the disruptive innovation (Wilson 2018).

Additionally, low carbon innovations have the characteristic that they offer a more efficient or lower carbon substitute than the prevailing technology. This leads to the question: how can consumers be convinced to switch from one service or good to another, if the needs satisfied stay the same? **Low-carbon innovations have a limited consumer appeal** (Wilson 2018). This implies that a low-carbon innovation provides the same function to the end-user as the prevailing high-carbon technology.

Wilson (2018) distinguishes between disruptive low carbon innovation (DLCI) and low carbon innovation (LCI). A DLCI, in contrast to a low carbon innovation, offers novel attributes to the consumer and emits far less emissions than the prevailing technology. The innovation is initially attractive in a market niche, subsequently a wide diffusion may occur. Furthermore, a DLCI is characterized as a radical technological breakthrough which improves exponentially and reduces GHG emission if adopted at scale. As an example: Solar photovoltaics (PV) produced by using perovskite as a novel material may be radical, using improved silicon techniques incremental, but neither of these low carbon technological improvements may be considered disruptive (Wilson 2018). This is because the PV application system itself for the end-user remains the same, though at lower cost and/or higher efficiency (Wilson 2018). Otherwise, shifting to a comprehensive decentralized PV system, involving battery storage systems and electricity trading, can be considered as potentially disruptive. This design offers the end-users novel system attributes, for example an active consumer role. Hence this novel decentralized PV system can be defined as a disruptive low-carbon innovation (Wilson 2018).

Wilson (2018) conducted a literature survey, covering more than hundred sources (sectoral reports, economic reports, modelling studies, scenarios, case studies, synoptic views) to identify potential DLCI's in four different domains: mobility, buildings & cities, food and energy supply & distribution. The focus was on new attributes for users and on the emission-reduction potential if adopted to scale. The result for mobility is given in Table 3. The table gives an overview of the DLCI which could be applied in a certain type of innovation or strategy. The third row lists the incumbent form of mobility which is being displaced.

Table 3: Potentially disruptive low-carbon innovations (DLCIs) relating to mobility

type of innovation or strategy	potentially disruptive low carbon innovations (DLCIs)	displaced incumbent
alternative fuel or vehicle technology	electric vehicles (EVs)	internal combustion engine (ICE) vehicles
	fuel efficient ICEs	ICE vehicles
	hydrogen fuel cell vehicles	ICE vehicles
	advanced biofuels	ICE vehicles
alternative form of auto-mobility	autonomous (self-driving) vehicles	ICE vehicles
	car clubs, car sharing	car ownership & use
	mobility-as-a-service (MaaS)[a]	car ownership & use
	ride-sharing	car ownership & use
alternative to auto-mobility	e-bikes	bikes, motorbikes, cars
	neighbourhood EVs	walking, bikes, cars, public transport
reduced demand for mobility	telecommuting, video- or teleconferencing	commuting
	interactive virtual reality[b]	commuting, teleconferencing

[a] *Mobility-as-a-service* (also *inter-modality*) refers to integrated scheduling, booking and payment systems for multiple transport modes (ride-sharing, bus, train) through a single gateway or account (typically via a mobile app).

[b] *Interactive virtual reality* can be used for immersive interaction by remote (e.g., currently used in medical diagnosis or surgery).

Source: (Wilson 2018).

5.5 Summary of similarities and differences between different theories

Table 4 summarizes the similarities and differences between the previously outlined theories.

Table 4: Summary of similarities and differences

	Field of application	Source of innovation	How is the end-user affected? (Connection to human well-being)
Technological revolutions in history (Perez)	Historical analysis	Has its origin often in niches, which are at the top of the income scale or/and in radical outliers.	A revolution provides a new inter-related set of life-shaping goods and services. Coupling products and lifestyles causes a systemic change.
Disruptive innovation which lead companies to fail (Christensen)	Management studies	New technologies are created and adopted at large scale by not prevailing companies.	A new technology targets previously excluded user.
System transition (Geels)	System transition	Radical innovation is generated in niches – which are "*incubation rooms for radical novelties*." Niches are crucial, as the existing regime is preventing the radical novelty from their breakthrough. The innovation breaks through when a window of opportunity is created.	A system innovation builds on three sub-processes. In the third sub process the old technologies is replaced by the new. This is where new functionalities emerge.
Disruptive low carbon innovation (Wilson)	Value of low-carbon innovation	An innovation emerges initially in a market niche then a wide diffusion may occur.	A disruptive low carbon innovation offers novel attributes for the end-user.

Source: own adaptation.

Christensen's definition of 'disruptive innovation' is built upon "*[…] repercussions of the social redefinition of a technology, for example by targeting excluded users*" (Tyfield and Jin 2010).

Hence this theory recognizes, although focusing on management studies, the social aspect of a new technology. A link can be seen from Christensen's (1997) research to the socio-technical system perspective of Geels (2004). First, they both recognize the potential of social redefinition through a technology, for example by targeting excluded users (Tyfield and Jin 2010). Second, they both highlight new functionalities or capabilities for users. Third, comparing the four phases of transition of Geels (2004) to the disruptive innovation by Christensen (1997) shows some coherence between those theories (see Table 5). However it is important to notice, a disruptive innovation is not alone responsible to produce a system transition (Tyfield and Jin 2010).

Table 5: "Comparison of system transition and disruptive innovation"

Stage	Systems transition (Geels)	Disruptive innovation (Christensen)
1	Emergence of novelty in an existing context	Disruptive step, social redefinition of a technology through targeting previously excluded markets and users
2	Technical specialization in market niches and exploration of new functionalities	A novel sustaining innovation trajectory improves functionalities, but in different directions, developing new capabilities
3	Wide diffusion breakthrough of new technology and competition with established regime	Wide diffusion as prior markets and users migrate to the new innovation, creating completion with incumbents
4	Gradual replacement of established regime, wider transformations	Gradual replacement of established trajectory and firms

Source: (Tyfield and Jin 2010).

Like Geels (2002), Perez and Leach (2018) state, a revolution has the characteristic to provide a new inter-related set of life-shaping goods and services. For these qualities to develop niches are necessary. These niches are found at the top of the income scale or/and in radical outliers. Yet, lifestyle changes are often adopted by young people. These changes are perceived as 'novel' and often out of reach for the majorities (Perez and Leach 2018). The decisive role of niches is also supported by many other scholars, like Wilson (2018). Although Christensen (1997) doesn't mention niches explicitly, he recognizes that most innovations emerge in non-prevailing small firms.

All considered theories agree that niches are a crucial breeding ground, as the existing regime is preventing the radical novelties from their breakthrough. The diffusion and breakthrough of a technology, according to Geels (2002) is facilitated by a window of opportunity. It is important to notice, that a new technology alone does not lead to a system innovation. A system innovation is about linking multiple technologies and does not only influence technology and market share, but shapes also regulation, infrastructure, symbolic meaning and industrial networks (Geels 2004).

Focusing on low-carbon innovation has been a recent focus in the scientific literature (Smith et al. 2005; Sauter and Watson 2007; Willis et al. 2007; Tyfield and Jin 2010; Wilson 2018). In a low-carbon transition changing user behavior or generating completely different uses is a prerequisite for a transition (Shove 2004; Tyfield and Jin 2010). Hence low-carbon innovation considers strongly the social aspect of a new technology.

As stated in section 5.4, low carbon innovations have the characteristic that they offer a more efficient or lower carbon substitute than the incumbent form of technology for energy production, distribution or use (Wilson 2018). In the thinking of Christensen's (1997) disruptive innovation theory, one may deduce that these low-carbon innovations are in fact a sustaining technology. They do in fact not improve the incumbent technology nor do they offer new services or attributes to the users. Translated to the thinking of EconTrans: the *energy service* and *functionality* remains the same, but the underlying new specific technology to provide this service changes the related flow of energy and GHG emissions change. The difference to the incumbent technology is that the low-carbon innovation has reduced carbon emissions by offering higher energy productivity and/or by using non-fossil fuel-based energy carriers.

The remaining question is: how can consumers be convinced to switch from one service or product to another low-carbon one, if the *energy service/functionality* stays the same? This implies that a low-carbon innovation satisfies the same needs of the end-user as the prevailing high-carbon technology. In this case it becomes important to assess technologies throughout their whole lifetime, as potentially higher investment costs must be compared to substantially lower operation and maintenance costs.

Contrary to that a *disruptive* low-carbon innovation does offer new services to end-users and enhance them to a different, more active, consumer-role. An example already given in section 5.4 is a decentralized PV system.

Wilson's (2018) definition of disruptive low carbon innovation (DLCI) allows us to connect human well-being to innovative socio-technical provision systems of energy services and eventually to GHG emissions. Hence, we adopt it as the working concept for low carbon breakthrough technologies in the EconTrans project.

6. Discussion and conclusion - Linking technological innovations to human well-being, energy consumption and GHG emissions

Based on a comprehensive literature review and expert interviews we conclude that it is essential for a better understanding of the well-being implications of the intrinsically linked transition processes to focus on the ultimately expected well-being generating energy services (summarized under a set of functionalities) to serve intermediate and eventually basic human needs (Köppl and Schleicher 2018). We have shown, based on a thorough literature review and a comprehensive stakeholder consultation process, that energy services represent the crucial link between energy use (and related GHG emissions) and human need satisfaction.

Technological innovations and changes in prevailing structures may serve as supporting link between well-being and low emission structures. We discussed that disruptive low carbon innovations (DLCIs) have the potential to drastically reduce GHG emissions of energy services (or energy related functionalities) as human needs satisfiers. However, market and behavioral feedback mechanisms may eventually lead to rebound effects and thus even higher GHG emissions than before the introduction of the technology. Thus, while individual well-being may indeed increase due to DLCIs, overall human well-being might even be negatively affected by higher GHG emissions and relate to more severe climate change impacts. Wilson (2018) argues, that non-use would most often be the most direct way to lower or eliminate GHG emissions, since the introduction of a new incremental (sustaining) technology or of a completely new product or service due to a disruptive innovation may eventually result in higher GHG emissions linked to a specific energy service (or functionality) than before. "*The acquisition of new energy services […] is net detrimental for emissions even if beneficial for material wellbeing and development*" (Wilson 2018). Thus, according to Wilson (2018), low-carbon outcomes of (disruptive) low carbon innovations depend on (1) emissions of the incumbent technology and (2) the dynamic background of change in market demand and products, which are themselves shaped in addition by disruptive innovation.

In consultation with experts from practice it was underlined, that also for disruptive technologies the rebound effect plays a crucial role in determining the eventual energy use and thus GHG emissions– even if using a more efficient technology. Nevertheless, they play a crucial role for transforming society to less carbon intensive structures. Hereby, the interviewed experts underline that DLCIs must be affordable and reliable. Without people changing behaviors and lifestyles, and without becoming aware of how their choices and their demand affects the environment it is unlikely that innovation will decrease GHG emissions.

Hence, the disentanglement of human well-being, energy use and GHG emissions, the role of low carbon technological innovations – incremental/sustaining or disruptive – is not straight forward. Without considering dynamic market feedback effects, the introduction of new technologies that improve individual well-being could end up in generating new socio-technical provision systems for existing energy services or create even new additional energy services that both could lead to net increases in energy use and GHG emissions.

A deepened structural approach to modeling energy services (functionalities) represented by context specific techno-economic setups, i.e. combinations of stocks and flows (Köppl and Schleicher 2018), which is the objective of the modelling exercise in the EconTrans project, will add a valuable improvement to the operationalization and assessment of energy related human need satisfiers and potential DLCIs.

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References

Brand-Correa LI, Steinberger JK (2017) A Framework for Decoupling Human Need Satisfaction From Energy Use. Ecol Econ 141:43–52. doi: 10.1016/j.ecolecon.2017.05.019

Brown GW, Harris T (1978) Social origins of depression: A study of psychiatric disorder in women. London

Christensen CM (1997) Innovator's Dilemma. Harvard Bus Sch Press Bost. doi: 10.1007/978-3-8349-7188-3_4

Christensen CM, Bower JL (1995) Disruptive Technologies : Catching the Wave. Harv Bus Rev

Christensen CM, Michael ER (2003) The Innovator's Solution: Creating and Sustaining Successful Growth. Harvard Business School Press, Boston

Christensen CM, Overdorf M (2000) Meeting the Challange of Disruptive Change. Harv Bus Rev 1–20. doi: 10.1002/rwm3.20019

Climate Action Tracker (2018) Temperatures. Adressing global warming. https://climateactiontracker.org/global/temperatures/

Cullen JM, Allwood JM (2010) The efficient use of energy: Tracing the global flow of energy from fuel to service. Energy Policy 38:75–81. doi: 10.1016/j.enpol.2009.08.054

Cullen JM, Allwood JM, Borgstein EH (2011) Reducing Energy Demand: What Are the Practical Limits? Environ Sci Technol 45:1711–1718. doi: 10.1021/es102641n

de Coninck H, Revi A, Babiker M, et al (2018a) Strengthening and Implementing the Global Response. In: Global Warming of 1.5C. An IPCC special report on the impacts of global warming of 1.5C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, s. In Press, p 132

de Coninck H, Revi A, Babiker M, et al (2018b) Chapter 4: Strengthening and implementing the global response. Glob Warm 15C an IPCC Spec Rep impacts Glob Warm 15C above pre-industrial levels Relat Glob Greenh gas Emiss pathways, Context Strength Glob response to Threat Clim Chang 132

Diener E, Lucas R, Schimmack U, Helliwell J (2009) Well-Being for Public Policy. In: Series in Positive Psychology. Oxford. Oxford University Press, Oxford

Doyal L, Gough I (1991) A Theory of Human Need. The Guilford Press, New York

Edenhofer O, Madruga RP, Sokona Y, et al (2011) Renewable energy sources and climate change mitigation: Special report of the intergovernmental panel on climate change

Elzen B, Geels FW, Green K (2004) System Innovation and the Transition to Sustainability. Theory, Evidence and Policy. Edward Elgar, Cheltenham, UK; Northampton, MA, USA

Fagerberg J (2018) Mobilizing innovation for sustainability transitions: A comment on transformative innovation policy. Res Policy 47:1568–1576. doi: 10.1016/j.respol.2018.08.012

Freeman C, Perez C (1988) Structural crises of adjustment: business cycles. Tech. Chang. Econ. theory. London Pinter 38–66

Geels FW (2002) Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study. Res Policy 31:1257–1274. doi: 10.1016/S0048-7333(02)00062-8

Geels FW (2004) Understanding system innovations: a critical literature review and a conceptual synthesis. In: Elzen B, Geels FW, Green K (eds) System Innovation and the Transition to Sustainability. Theory, Evidence and Policy. Edward Elgar, Cheltenham, UK; Northampton, MA, USA, p 315

Göpel M (2016) The Great Mindshift. How a new economic paradigm and sustainability transformation go hand in hand. Springer International Publishing

Gough I (2015) Climate change and sustainable welfare: the centrality of human needs. Cambridge J Econ 39:1191–1214. doi: 10.1093/cje/bev039

Gunningham N (2012) Confronting the challenge of energy governance. Transnatl Environ Law 1:119–135. doi: 10.1017/S2047102511000124

Helliwell JF, Layard R, Sachs J (2013) World Happiness Report 2013. UN Sustainable Development Solutions Network, New York

IEA (2020) Cooling, IEA, Paris https://www.iea.org/reports/cooling

IPCC (2014a) Climate Change 2014 Impacts, Adaptation, and Vulnerability. Cambridge University Press, Cambridge

IPCC (2014b) Climate Change 2014: Mitigation of Climate Change. Summary for Policymakers and Technical Summary

IPCC IP on CC (1995) Climate Change 1995: A report of the Intergovernmental Panel on Climate Change

Jackson T (2009) Prosperity without growth. doi: 10.1111/j.1530-9290.2009.00213.x

Jochem E, Sathaye J, Bouille D (2000) Society, behaviour and climate change mitigation. Kluwer Academic Publishers

Köppl A, Kettner-Marx C, Schleicher S, et al (2016) Modelling Low Energy and Low Carbon Transformations The ClimTrans2050 Research Plan. Wien

Köppl A, Kettner C, Kletzan-slamanig D, et al (2014) Environment mitigation wedges. Energy Environ 25:

Köppl A, Schleicher S (2018) What Will Make Energy Systems Sustainable? Sustainability 10:2537. doi: 10.3390/su10072537

Kramer GJ (2018) Energy scenarios—Exploring disruption and innovation. Energy Res Soc Sci 37:247–250. doi: 10.1016/j.erss.2017.10.047

Lamb WF, Steinberger JK (2017) Human well-being and climate change mitigation. Wiley Interdiscip Rev Clim Chang 8:e485. doi: 10.1002/wcc.485

Lundvall BA (1988) Innovation as an interactive process: from user-producer interaction to the national system of innovation. In: Dosi G, Freeman C, Nelson R, et al. (eds) Technical change and economic theory. London: Pinter. Pinter, London, pp 349–369

Masson-Delmotte V, Zhai P, Pörtner H-O, et al (2018) Summary for Policymakers. In: Global Warming of 1.5C. An IPCC special report on the impacts of global warming of 1.5C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, s. World Meterological Organization, Geneva, Switzerland, p 32

Max-neef M a., Hopenhayn M, Hamrell S (1992) Human Scale Development: Conception, Application and Further Reflections, Volume 1

Max-Neef M, Elizalde A, Hopenhayn M, Sears R V (1989) Development Dialogue

Munasinghe M (2012) Millennium Consumption Goals (MCGs) for Rio+20 and beyond: A practical step towards global sustainability. Nat Resour Forum 36:202–212. doi: 10.1111/j.1477-8947.2012.01451.x

Nelson RR, Winter SG (1982) An Evolutionary Theory of Economic Change. Harvard University Press, Cambridge, Mass

Nordhaus W (1973) The allocation of Energy Resources. Brookings Pap Econ Act 529–576. doi: 10.1080/19390459.2015.1036617

Nordhaus W (1977) Economic growth and climate: the Carbon Dioxide problem. Am Econ Rev 67:341–346

Nordhaus W (1992) An optimal transition path for controlling greenhouse gases. Science (80-) 258:1315–1319

Nussbaum MC (2000) Woman and Human Development The Capabilities Approach. Cambridge University Press

O'Neill BC, Oppenheimer M, Warren R, et al (2017) IPCC reasons for concern regarding climate change risks. Nat Clim Chang 7:28–37. doi: 10.1038/nclimate3179

OCED/IEA (2018) Global Energy and CO2 Status Report 2017

Ortiz MA, Kurvers SR, Bluyssen PM (2017) A review of comfort, health, and energy use: Understanding daily energy use and wellbeing for the development of a new approach to study comfort. Energy Build. 152:323–335

Oxford Dictionary (2018) Oxford Dictionary. Oxford Dict.

Perez C (2016) Capitalism , Technology and a Green Global Golden Age : The Role of History in Helping to Shape the Future

Perez C (2017) Is Smart Green Growth the Solution ? Lessons from History. BTTR WP 2017–01:

Perez C, Leach TM (2018) A Smart Green "European Way of Life": the Path for Growth, Jobs and Wellbeing

Perez C, Vellinga P, Hudson C, et al (2016) Changing gear in R&I: green growth for jobs and prosperity in the EU. Report of the European Commission Expert Group "R&I policy framework for Green Growth & Jobs". Brussels

Raskin PD, Electris C, Rosen RA (2010) The century ahead: Searching for sustainability. Sustainability 2:2626–2651. doi: 10.3390/su2082626

Rockström J, Steffen W, Noone K, et al (2009) A safe operating space for humanity. 461:

Rosenberg N (1976) Perspectives on Technology - Nathan Rosenberg. Cambridge University Press, New York

Rotmans J, Kemp R, Asselt M van (2001) More evolution than revolution: transition management in public policy. In: Foresight, 1st edn. MCB UP Ltd, pp 15–31

Ryan RM, Deci EL (2001) On Happiness and Human Potentials : A Review of Research on Hedonic and. Annu Rev Psychol 52:141–166

Sauter R, Watson J (2007) Strategies for the deployment of micro-generation: Implications for social acceptance. Energy Policy. doi: 10.1016/j.enpol.2006.12.006

Schot J (1998) The usefulness of evolutionary models for explaining innovation. The case of the Netherlands in the nineteenth century. Hist Technol 14:173–200. doi: 10.1080/07341519808581928

Schumpeter JA (1942) Capitalism, Socialism and Democracy. Harper, New York

Sen A (1999) Development As Freedom

Shove E (2004) Sustainability, system innovation and the laundry. In: Elzen B, Geels FW, Green K (eds) System Innovation and the Transition to Sustainability. Theory, Evidence and Policy. Edward Elgar, Cheltenham, UK, pp 76–94

Shove E (2003) Converging Conventions of Comfort, Cleanliness and Convenience. J Consum Policy. doi: 10.1023/a:1026362829781

Smith A, Stirling A, Berkhout F (2005) The governance of sustainable socio-technical transitions. Res Policy. doi: 10.1016/j.respol.2005.07.005

Stiglitz, J.E. A Sen, Fitoussi J-P (2009) Report by the Commission on the Measurement of Economic Performance and Social Progress

TWI2050 (2018) Transformations to Achieve the Sustainable Development Goals. Report prepared by the World in 2050 initiative. International Institut for Applied System Analysis (IIASA), Laxeburg, Austria

Tyfield D, Jin J (2010) Low-carbon disruptive innovation in China. J Knowledge-based Innov China 2:269–282. doi: 10.1108/17561411011077909

United Nations (1992) United Nations Framework Convention on Climate Change. Fccc/Informal/84 1:270–277. doi: 10.1111/j.1467-9388.1992.tb00046.x

United Nations (2015) Convention on Climate Change: Climate Agreement of Paris. Paris Agreement. United Nations, Paris

United Nations General Assembly (2015) Transforming our world: The 2030 agenda for sustainable development. https//sustainabledevelopment.un.org/content/documents/7891Transforming%20Our%20World pdf 1–5. doi: 10.1007/s13398-014-0173-7.2

Von Hippel E (1988) The Sources of Innovation. Oxford University Press, Oxford

Waite-Chuah S (2012) Living in the comfort zone: At what cost? Sustainability 5:386–390. doi: 10.1089/SUS.2012.9909

WBGU (2011) World in Transition: A Social Contract for Sustainability. Summary for Policy-Makers. WBGU-German Advisory Council on Global Change, Berlin

Webster Dictionary (2019) Webster Dictionary. Webster Dict.

Willis BR, Webb M, Wilsdon J (2007) The Disrupters: Lessons for low-carbon innovation from the new wave of environmental pioneers. Technology 1–48. doi: 10.1002/adom.201600649

Wilson C (2018) Disruptive low-carbon innovations. Energy Res Soc Sci 37:216–223. doi: 10.1016/j.erss.2017.10.053