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Abstract

The paper reflects the hypothesis that those technological and institutional innovations survive which extend the *safe operating range (SOR)* of the Humans-Technologies-Institutions (HTI) system (e.g. companies, cities, regions and countries). The multidimensional SOR of a country comprises in particular safe livelihood, quality of life, security, monetary stability, supply security and quality of the environment. A "mechanism of progress" is described involving the search for higher safety and independence of constraints. With innovation and learning in a key role, the mechanism leads to a relative decoupling of resource use and economic value added and a growing share of knowledge generation in the economy. Competition of HTI systems for scarce resources may lead to independence strategies such as enhanced resource efficiency. It may also lead to cooperation of competing HTI systems facilitated by new institutions thus forming an HTI system at higher level of complexity. While the consortium could coordinate their resource consumption within the boundaries of safe operating space, the partner HTI systems would further expand their SOR. Data is provided that net resource importing countries have developed higher material productivity thus increasing their independence from resource supply, and countries with such capability have gained higher innovation capacity.

Key words: eco-innovation, resource efficiency, decoupling, technology assessment, institutions, sustainable resource management

1. Introduction

This article conveys considerations in search of a universal mechanism of innovation and its effect on the use of natural and man-made resources. While the current debates on resource use focus either on supply security or on resource efficiency and reduction of the consumption towards sustainable levels, often with diverging policy implications, it seems worthwhile to have a closer look at the underlying basic motives. Understanding what humans and various actors finally search might allow to better align policies, and to evaluate and plan innovations with regard to their effect.

Since Schumpeter it is widely acknowledged that technological innovations have been an important element in the historic development of human societies and a constituent of economic growth. Basic technologies have shaped a sequence of industrial revolutions and led to a wave-like or cyclical development of the socio-economic system (see overview in Freeman and Louca 2001). Technical innovations do not happen in isolation but depend on the social and institutional environment (e.g. Perez 1983). Kline and Rosenberg (1986) had introduced the term "social-technical system", stating that "the process of innovation must be viewed as a series of changes in a complete system not only of hardware, but also of market environment, production facilities and knowledge and the social context of the innovation organization." The economic factors influencing innovations and its path dependency have often been described (e.g. Grübler et al. 2002). In the general absence of environmental considerations in markets, public policies have been the main trigger for eco-innovation and the establishment of substantial eco-industries in European countries (Ekins 2010). Success factors for environmentally sustainable product innovations have been derived in a comprehensive review by de Medeiros et al. (2014), comprising (1) knowledge on markets, law and regulation, (2) "interfunctional collaboration", (3) innovation-oriented learning, and (4) R&D investments. The Eco-Innovation Observatory of the EU Commission (EIO 2013) defined that an "eco-innovation" would need to contribute to higher material and energy efficiency. The observatory monitors¹ the inputs, activities, outputs and outcomes of member state performance, including the decoupling of GDP from materials, energy, and land use and GHG emissions, as well as socio-economic indicators like employment.

The intention of this article is to bring those success factors, preconditions and outcomes into a systematic and more coherent picture. Deductively, an outline and key elements of a

¹ <http://www.eco-innovation.eu/>

theoretical model may emerge which can explain past developments and can be used to model future developments. It is written from a multi-disciplinary, systems analytical perspective as outlined by (Scholz 2011) and compatible with observations on evolutionary self-organization (Bossel 1998).

The central hypothesis reflected within this paper states that the desire for both safety and independence from constraints is a basic driver of innovation. As a consequence, those technological or institutional innovations will survive or persist, resp., which provide its user group with greater independence from constraints which limit their growth, persistence or dispersion, and contribute to the expansion of their safe operating range.

As user group and unit of human evolution or selection in the sense of differing chances to grow, persist and disperse, *Humans-Technologies-Institutions (HTI)* systems (HTIS) are considered such as companies, households, cities, regions and countries as well as groupings thereof. Technologies as well as economic and political institutions (as organisations or norms) seem to act as kind of protective clothing without which the group of human beings in their social context could hardly survive.

For the purpose of the paper, the term "safety" is used in a way comprising the meaning of "shelter" and "security". Enhancing the safety of HTIS implies that the current way of living and working has a higher chance to be continued for a longer period of time or elsewhere. A greater independence from constraints which are determined by the environment of HTISs (including other HTISs) implies that growth, survival or persistence, resp., and/or dispersion has become less limited. Both higher safety and greater independence result from innovations, and the article will argue that the "success" of innovations is manifested in an expansion of the "*safe operating range*" (SOR) of the user group in space and time. The SOR may be defined as *actual* capability of HTISs to survive physically and economically in a decent manner under acceptable conditions (incl. a livable environment) over time and at certain locations (defining the mobility range). As will be discussed subsequently, what is "decent" and "acceptable" may change over time. The SOR is multi-dimensional and comprises components such as safe livelihood, quality of life, security, monetary stability, supply security and quality of the environment. In contrast to SOR, the safe operating space (SOS) as defined by Rockström et al. (2009), comprises dimensions only relating to environmental resources in a wider sense (absorption capacity for GHG emissions, cropland use etc.), and

reflecting the boundaries for potential low risk development given by the earth system. This paper argues that the SOR of countries may continue to expand in various domains while keeping the overall resource use within the SOS. This might require further institutional development to foster the independence of that constraint.

The focus of this article is on the mechanism which seems to direct innovations to the effect of a stepwise, although continuous expansion of the SOR of HTISs (which otherwise fall behind and disappear). The search of higher safety and independence of proximate constraints, together with continuous learning is central for the proceeding transformation which leads to higher complexity of HTISs with a further expansion of SOR of the overall system.

The following sections start with an overview on the SOR of HTISs such as countries and societal strategies for safety and independence of risks and constraints. Then, the expansion of the SOR by technical and institutional innovations is discussed based on historical examples. It will become clear that progress towards higher independence of constraints can vary significantly depending on the status of development. As central piece, the article describes a "mechanism of progress" which leads to a decoupling of economic value added and natural resource use, and which may favour transition from competition towards cooperation of HTISs. The proximity principle is described as which requires that constraints at close range in time and space are overcome next. As a consequence, the formation of country consortia – in particular for global sustainable resource management – need to provide opportunities for an enlarged SOR within the participating countries themselves. Empirical data show that net importing economies which are more constrained in resource supply than net exporters, have developed higher material productivity which led to higher independence of material supply. Moreover, those economies with higher material productivity also developed higher innovation capacity. The paper will finally summarize the consequences for technology assessment, innovation evaluation and policy design for sustainable resource management.

2. Societal strategies for safety and independence

This section introduces main aspects of a safe living which can be used to operationalize the safe operating range. It looks at the country level and describes strategies which either try to control, or to become independent of constraints and risks for a decent living. The focus then

will be on policies for decoupling of wealth and the use of natural resources. If not stated otherwise, this article will refer to the use of "natural resources" as in the form of abiotic and biotic raw materials.

The method employed have been conceptual considerations against the background of numerous publications on indicators of sustainability (which are not referenced, as the definition and selection of the indicators used as examples are not relevant for the argumentation of this article). Links to relevant similar concepts are given below.

Safety and independence of constraints can be discerned for individuals and groups, including complex HTISs such as whole countries. Indicators on the quality of living, individual and social life, security and safety of capital, as well as supply security and the quality of the environment, can be used to measure the performance of living conditions with regard to safety in the broader sense of this article (Table 1). Although not identical, the selection of those aspects corresponds to earlier concepts on basic human needs by Maslow (1943) and Max-Neef (1992).

Safe living is under risk and certain constraints may limit the chance to continue with business as usual. There seem to be two basic policy patterns to cope with these challenges: (a) strategies to react on entered risks and tangible constraints, and (b) strategies to prevent those risks and avoid or become independent from those constraints. For instance, the health system of a country may react on infections caused by poor hygienic conditions to cure people, while early education may enable people to practise a low risk behaviour. Employment agencies may try to bring unemployed back towards existing jobs, while education might enhance to chance to get and keep a job. The table shortlists a couple of more examples for each aspect of safe living which shall not discussed in detail but outline the general pattern.

The double interest in both safety and independence is also reflected in actual policies. At the EU level, the raw material initiative (EC 2008) comprises three pillars where two are aiming to secure supply, whereas the third aims to increase resource efficiency and thus enhances independence from further supply. The Flagship initiative for a resource efficient Europe 2020 (EC 2011a) and the roadmap for a resource efficient Europe (EC 2011b) underpin the importance of the independence strategy.

Table 1. Strategies to extend the safe operating range of countries

Aspects of safe living	Indicators (examples)	Risks or constraints for safety (examples)	Strategies to react on constraints or entered risks (examples)	Strategies to become independent from constraints or prevent the risks (examples)
Livelihood	Life expectancy	epidemics	health system (curative)	hygienic education
	population not undernourished (%)	famines, climate change, global population growth	higher agricultural production, distributional policies	consumption policies, education
Quality of life	population not homeless (%)	increasing social disparities	distributional, social policies	education
	population above poverty income (%)			
Quality of life	employment rate	International competition	blocking mobility of capital and people	innovation policies, education
	share of non-employment work or time (%)	Inflation	financial policies	individual search for rewarding non-economic activities
	memberships in parties, NGOs	ageing society, social disintegration, growing selfishness, terrorism	legal system and constitutional rights	new forms of social networks, education
	Donations		gratuitousness	
	population with health insurance (%)		health insurance	
	population with pension insurance (%)		pension funds	
	populations receiving an award (%)		individual awards	
successfully integrated former criminals	(often lacking)			
Security	criminal statistics (negative status) Days of year without military killings	growing disparities (poor vs. rich) Acute supply shortages (ev. through climate change)	Security forces enhancement Building military force and economic power to control other regions	Education Decoupling policies, multilateral policies of peace and cooperation
Monetary stability	inflation rate below critical level	Uncontrolled financial institutions	finance policies; monetization of human and natural capital	Non-market activities, measuring human and natural capital in terms of their functions
	Losses at exchanges	greed	code of conducts	
Supply security	share of domestic resource use (%)	higher competition over resources through globally growing demand	supply contracts	decoupling policies
	renewables (%)	climate change leading to reduced biomass availability; physical growth of technosphere storing future recyclables	supply contracts, certification	decoupling and consumption oriented policies, urban mining policies
	spread of imports over many supply countries	international security depending on global governance development	traditional foreign and military policies	foreign aid (cooperation) and decoupling policies
Quality of the environment	air quality	Economic growth and rising extraction of resources, expansion of agriculture and forestry, climate change	traditional environmental policy	decoupling policies, economy-wide sustainable resource management, waste prevention policies, international cooperation
	water quality			
	conserved nature			
	climate stability, global atmospheric temperature	Climate change through enhanced green house gas emissions (fossil fuel use, deforestation, ruminants etc.) associated with economic growth and rising demand	adaptation policies (e.g. building higher dams against increased flooding; reinforced infrastructures to withstand storms)	decoupling policies (energy efficiency), international cooperation (Kyoto and post-Kyoto)

Source: own elaboration

Policies for *decoupling* of economic performance and welfare from the use of natural resources play an important role for lowering the dependence of resource supply constraints. Since a couple of years, the issues of "resource efficiency" and the objective to increase "resource productivity" were adopted at the highest policy level and are gaining momentum to

become mainstream perception. The first ideas towards this end were formulated by researchers at the beginning of the 1990s who sought an effective strategy to provide increasing wealth for a growing world population against the background of limited natural resources. It was the consideration of normative standards such as the equity principle which lead Schmidt-Bleek (1992) demand for a factor 10 increase in resource productivity in industrial countries, and Weizsäcker et al. (1995) to call for a factor 4. The idea of "factor X" was adopted by various governments in the form of concrete targets with Germany and Japan in the forefront (Bahn-Walkowiak et al. 2008). The European Resource Efficiency Platform EREP (2014) recommended the EU "to set a target for a substantially increased decoupling of growth from the use of natural resources, in order to improve competitiveness and growth as well as quality of life. The target should aim to secure at least a doubling of resource productivity as compared with the pre-crisis trend. This would be equivalent to an increase of well over 30% by 2030".

Those ideas would have remained in the noble mind, if there were not two aspects motivating actors in industry, governments and NGOs to adopt those strategies. *First, the constraints* must become visible and close enough: with regard to resource use, the first concerns of the protagonists like Schmidt-Bleek calling for a factor X increase in resource productivity and more recent reports of the International Resource Panel (UNEP 2011) were about the detrimental environmental consequences of increased resource use and the associated inequality at a global level; although they sought to build the bridge to the economy, the alluded risks seemed still rather distant from business. The price spikes of raw materials in the first decade of the 21st century were much more closer and gave rise to concern that attracted attention in the business community (e.g. PwC 2011), and prepared their readiness to search for alternatives (e.g. Robecosam 2014).

Second, alternative strategies will only be adopted if the *opportunities* of getting independent from constraints became tangible. For business, the supply of materials is associated with costs, and reducing the need for material supply provides options to reduce costs, and thus become more competitive (McKinsey 2011). Scarcity of supply is seen as business opportunity (Carbon Trust 2014). It is those arguments which find themselves in the forefront also of the policy documents outlining policy programmes for resource efficiency, for instance, in Japan (MoE 2008) and Germany (BMUB 2012). The observation that material and energy efficiency increases may lead to absolute decline of resource use and thus a real

reduction of environmental burden at various scales, is a well-received possible side-effect so far.

As an interim observation, strategies for "decoupling" are aiming at an increased independence of resource constraints, and thus higher supply security and improved quality of the environment. One may assume that any implementation of policies towards this end will be accepted only, if other aspects of a safe living as indicated in table 1 are not being compromised, and those measures will be preferred which provide progress also in those other dimensions (within the country). This intention is basically implemented in the form of ex ante impact assessments of policies, e.g. for the 7th Environmental Action Programme (EC 2012, EU 2013) which also lays emphasis on resource efficiency. Against this background, the question arises whether those observations could fit into a general theoretical framework.

3. Expansion of the safe operating range

This section outlines the concept of safe operating range (SOR), and distinguishes it from the safe operating space (SOS). Historical examples indicate how SOR has been continuously expanded by means of technological and institutional innovations which led to higher independence of (resource) constraints. As a consequence, the measurement of such independence depends on the state of development.

The methods applied are theoretical considerations deduced from the observations described. The observations are usually well-known (therefore references for the historical examples seem obsolete). The suggested underlying pattern may, nevertheless, be helpful to explain the preconditions for "key innovations".

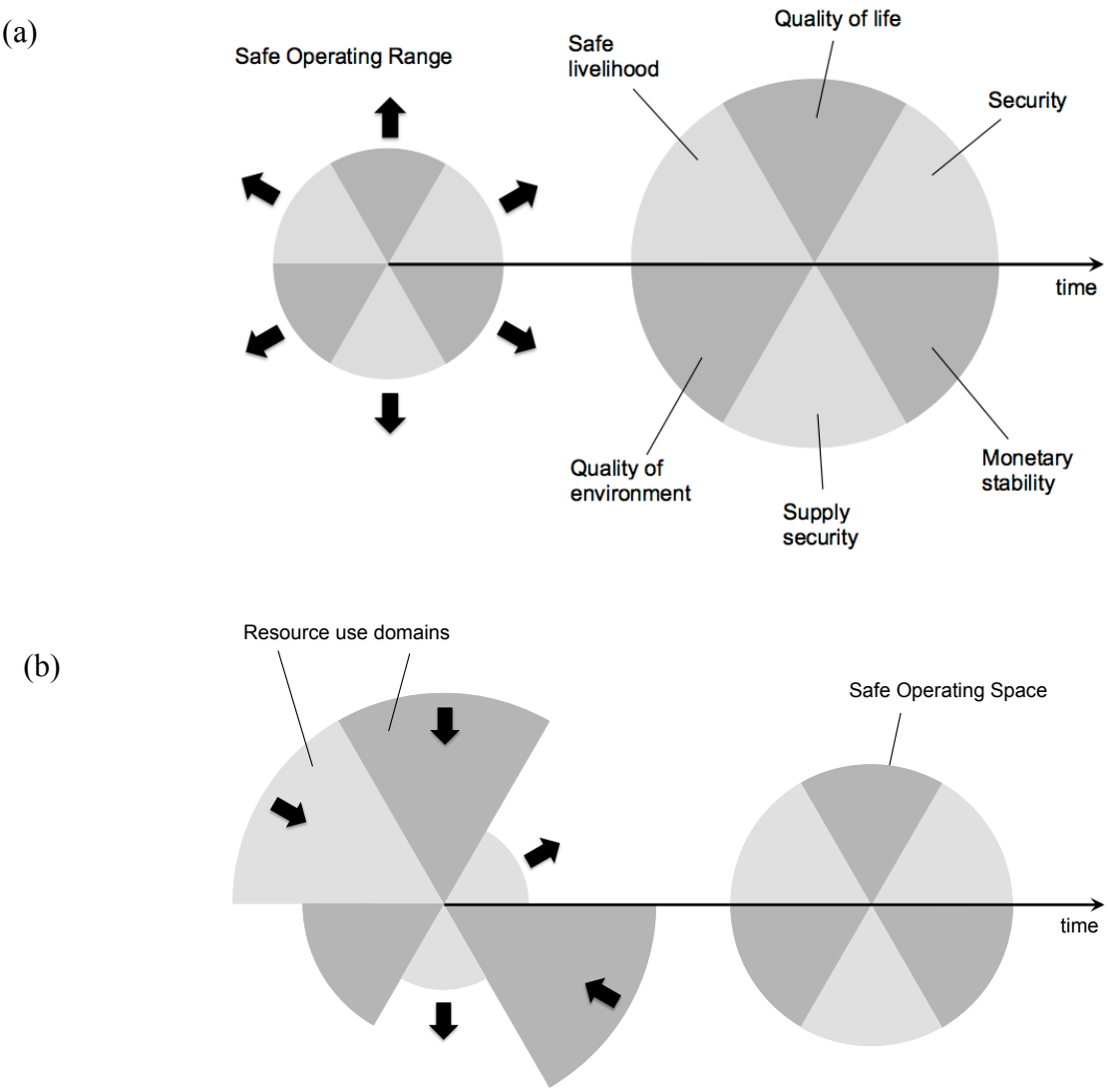
3.1 Safe operating range and safe operating space

In the course of human development, the safe operating range of societal groups and humanity as a whole was tremendously expanded, both in space and time, through technological and cultural innovations. Controlling light and temperature in buildings, taking precautions against seasonal variations of food availability, developing countermeasures against floods, droughts, epidemics, criminals, warfare, and financial crises, all led to safer living and working conditions.

The SOR of a HTIS can be defined by its performance with regard to the six key aspects or domains of a safe living (described in table 1 and shown in Figure 1a). The SOR expands over time, and also spatially (not indicated in the figure). When survival or decent living

conditions can be upheld not only over weeks but decades, the SOR has been extended temporally. When the more favourable conditions – e.g. labour safety precautions, indoor air conditioning, water quality standards – become available at more locations, and/or HTISs are enabled to settle in new regions, then their SOR has been extended spatially. It seems to be a fundamental characteristic, that HTISs, like all living organism, have the inherent tendency to disperse and get inhabited – not necessarily "colonize" – in widening circles, constrained by limiting external conditions (such as arctic temperature) or limited technology options (e.g. if in lack of vehicles). Mobility options are part of adequate quality of life conditions.

Figure1. a) Extension of the domains of the Safe Operating Range (SOR)
 b) Resource use develops into the Safe Operating Space (SOS)



Source: own elaboration

The SOR is the multifunctional "safety" room *actually* realized by a HTI. In contrast, the safe operating space as defined by Rockström et al. (2009) is a *potential* of a low risk use of the natural environment specified by key components or subdimensions of resource use in a wider sense such as green house gas (GHG) emissions, nutrient emissions, land use (Figure 1b). The determination of a SOS involves normative assessments on the acceptance of environmental change and associated risks. It is scale dependent as discussed by UNEP (2014) for the subdimension of land use. When defined for the global scale, the countries need to be attributed their fair share (usually done on a per person basis) in order to know whether they perform within their SOS or beyond.

The SOR seems to expand in all aspects. While there may be some trade-offs between domains, e.g. restricted mobility and thus reduced quality of life due to higher security precautions, on the long run progress may be expected in every domain. In contrast, resource use or pressure to the environment may expand sustainably, if the SOS threshold is not yet reached, or need to be constricted, if exceeding that limit.

The "doughnut" concept of Raworth (2012) defines minimum requirements for safe living conditions visavis maximum allowance of environmental use defined by SOS. This is compatible with the SOR concept, as the adoption of those minimum standards by a higher share of the population would represent an extension of the SOR of that country. As discussed below, the minimum standards are not fixed but depend on the state of development. It seems important to note that the concept foresees that SOR might grow further in its domains, while development is kept within SOS boundaries. In other words, it is assumed that quality of live and safety of living conditions can be improved (within and between countries) while keeping resource consumption within environmentally safe limits.

As a precondition of the widening of the safe operating range, craftsmanship, science and technology have tremendously expanded sensation beyond the biological capacities. Telescopes receive signals from the edge of the universe, and physics have discovered quantum parts forming atoms. Not only the spatial dimension of perception expanded, also the forward looking capacities and the ability to ensure survival over time. Today, life expectancy is longer than any time in the past, and science and research are able to simulate past and future developments for decades to millenia. Although at different speed and with

high variation between HTISs such as countries and societal groups the overall development so far seems to be characterized by an expansion of the SOR, including its functionality for the group members. This expansion has been linked to technical and institutional innovations.

3.2 Technical innovations

In the past, the progress of human development was marked by a sequence of historical milestone innovations. Table 2 provides some selected examples.

Table 2. The role of technical key innovations in history

Technical innovation - examples -	User group	Proximate constraint	Independence from constraint	Improved living and working - extended SOR	Consequences
Weaving loom (7th millennium BC)	Women	Limited clothing	Greater independence from hunting for leather;	More and better clothes (from wool and plant fibres)	Basic technology, continuously refined, and later - with steam engine - made much more efficient, subsequently automated with computers
Wheel (4th millennium BC)	All individuals, households, warriors	Limited transport capacity for freight and soldiers	Greater independence from carrying by hand	More and farther transport of various items	Basic technology for machine based mobility; used for traction by humans, animals, steam engines and e-cars
Wheelchair (15th century)	Frail and handicapped people	Limited mobility	Greater independence of the individual	Safe movement and extended mobility	Established technology, later equipped with motor
Steam engine (18th century)	Manufacturers	Limited power of machines	Greater independence of human and horse power	Significantly higher productivity, cost savings	Coupling with various machines led to new products and markets; new dependence on fuel supply
Electric bulb (19th century)	Cities, firms, households	Activities mostly limited to daylight conditions	Greater independence for many activities over the day, and within buildings	Better lighted living and working rooms and city spaces	Became established technology; dependent on power supply; recently superseded by more energy efficient LED
Personal Computer (middle of 20th century)	Scientists, firms, households, administrations	Capacity for calculations and text writing limited	Greater independence from sliderules and typewriters	Significantly increased capacity for data storage and management; incl. simulation of future options	Integration with into existing technologies led new products and markets; changed social behaviour (in particular in connection with internet)
Internet (2nd half of 20th century)	All individuals with access; science, industry, households, administrations	Access to stored information limited to libraries and private documentation; exchange of data and information limited by mail and conventional wire transfer	Access to information any time from any location (with access)	Use of all information stored publicly, worldwide, cost savings, new services	New markets, new technologies, new institutions
Cell phone (end of 20th century)	Potentially all individuals	Telephone calls were limited to fixed-line end stations	Communication as well as access to the internet any time from any place (provided mobile network access)	Easy communication worldwide; access to all information stored publicly, cost savings, new services	New markets, new technologies, new institutions

Source: own elaboration

From the ancient weaving loom to the cell phone, each of the inventions allowed to overcome a proximate constraint and expand the safe operating range, from rather close range time savings of women producing clothes for the tribe, to far range communication at global scale

at any time today. Getting independent from the proximate constraints led to an improvement of living and working conditions. Moreover, the combinations of those mile stone techniques subsequently led to new innovations, the speeding up of technology development and the opening of new markets. Mechanical weaving looms driven by steam engines lead to a boom of textile industry with plenty of new products. The combination of computer chips with cell phones and the use of the internet opened up a completely new "continent" or literally a "second world" where activities mirrowing the real world can be played through, new products and services arise with tantamount expectations of capital rents.

None of those innovations occured out of the blue, from sudden imagination, or enlightening; while few other findings like the use of penicillin and X-radiation sprang from serendipity, instead, most milestone innovations have resulted of a stepwise learning, with improvements of and building on what has been reached earlier. The stepwise development of the electrical light bulb was nicely described by Abernathy and Utterback (1978). They also point to the analysis of White (1978) who suggested that dominant innovations "can be recognized in the early stages of their development if they will more likely display one or more of the following qualities: (1) Technologies which lift fundamental technical constraints limiting prior art while not imposing stringent new constraints; (2) Designs which enhance the value of potential innovations in other elements of a product or process; and (3) Products which assure expansion into new markets." The first criterion already captured a key aspect, while his second criterion corresponds to the aspect of improved living and working conditions to which the innovative design must contribute as otherwise no value would be generated.

Technical innovations also led to new constraints, although usually more distant in space and time. For instance, the availability of coal made the use of steam engines much more efficient. While the SOR of the industries and their employees expanded in terms of higher income and quality of life in the early days (compared to the rural population), the growing coal incineration led to high air pollution and subsequent health impacts, and contributed to todays climate problem. Again, innovations were generated to shift the constraints farther away: new institutions of environmental governance.

3.3 Institutional innovations

Societal "progress"² not only depends on technical but also on institutional innovations. Both types of innovations are also interlinked and may reinforce each other. The origins of institutional innovations through practise of social movements, religious groups, businesses community and professional organisations are plenty, from medieval management of 'the commons', to social rules and taboos enforcing hygiene. Here the focus will be on governmental institutions. The history of environmental governance institutions in a country like Germany provides interesting insights (TABLE 3).

Environmental protection started as health protection at close safe operating range. One of the first water management authorities was founded in the Ruhr at the end of the 19th century. It improved the hygienic situation in the cities significantly, however, at the expense of flushing the pollution farther away into the river Emscher which became the main open sewage canal of the region with treatment plants installed before its outlet into the river Rhine. The innovative authority ("Emschergenossenschaft") became an institutional model for sewage management institutions in other regions, and it set technology standards for sewage treatment. Similar milestone institutions followed with the air cleaning act, – still triggered by a proximate health issue.

Waste policies started in the 1980s with prescriptions on safe deposition. The widening of the waste law to the Waste and Recycling Act was a further milestone. For the first time, a regulation aimed to make a good out of a bad, and to request savings of waste. It then became obvious that reduced wastes would also mean savings of natural resources for the production of what had become waste. Moreover, the increased recycling could provide secondary raw materials which can substitute for natural resources. In the 1990s, also triggered by findings and suggestions of research institutes advocating a factor X resource efficiency revolution, governments established facilitating institutions. The Efficiency Agency in Northrhine-Westphalia ("efa") was founded by the minister for the environment. It helps SMEs to analyze their consumption of energy, water, materials and the generation of waste and waste water, and to find and implement options for savings. The institution works quite successfully and was taken as model also for the federal German Material Efficiency Agency (DEMEA).

² The term "progress" here is used in the sense of "process" and "proceeding", not implying a masterminded or teleological meaning

Table 3. The role of innovations of environmental governance in Germany.

Institutional innovation - examples -	User group	Proximate constraint	Independence from constraint	Improved living and working - extended SOR	Consequences
Emscherogenossenschaft (Regional Waste Water Management authority of the Ruhr) (1899)	Cities, industry, households	Flooding of polluted water caused illness and epidemics	Channeling of sewage and waste water discharges and central sewage treatment provided independence from floods	Improved water quality and hygienic conditions	The institution was taken up as model by other communities, set technical standards for sewage treatment; local problems were solved, however, at the expense of converting a river into an open sewage canal
Bundes-Immissionsschutz-Gesetz (BImSchG) (Federal law for the protection against air pollution) (1974)	Industry, households	Unhealthy air pollution in particular in centres of industrial production	Mandatory emission thresholds for production plants, power plants, and other incineration plants were introduced; directly removing constraint, getting independent from prevailing winds	Significantly improved air quality	Model for other countries and the EU as a whole; trigger for technological innovations (filter techniques) and institutional development (decentralized control)
Kreislaufwirtschafts-Abfallgesetz (KrWafG) (Recycling and Waste Management Law) (1994)	Public administration, manufacturers, households	Rising waste deposition and related costs and environmental problems	Starting point to turning bads into goods; thus reducing the constraint	Final waste disposal was subsequently effectively reduced and recycling industry became a big business	Model for other countries like Japan; new market development; trigger for technological innovation (recycling technologies) and institutional development (for separate collection; such as Green Dot System)
efa - Efficiency Agency Northrhine-Westphalia (1998)	Manufacturers (SME)	Lagging competitiveness; costs for waste and waste water management, material and energy supply	Greater independence through higher resource efficiency and savings in material, energy and water input	Higher profitability and competitiveness of the companies	Model for the federal state and other countries; trigger of technological and organisational innovation
Ecological Tax Reform in Germany (1999)	Refineries, car drivers, manufacturers	Ancillary wage costs (impeding international competitiveness) and climate change due to high fossil fuel consumption	Gasoline and diesel price was increased in several steps, the revenues used for social insurance of employees and reduced compensation of employers's costs; greater independence from fossil fuel use by higher energy efficiency	Social insurance costs of employers were reduced thus increasing profitability of business; fuel consumption of car fleet was slightly reduced	Additional trigger of technological innovation (higher fuel efficiency of cars), reinforcing the effects of long-term rising oil price
Programme for Resource Efficiency (ProgRes) in Germany (2012)	Industry, households, public administration	Spiking prices in particular of metal in the first decade of the 21st century; costs of material supply for manufacturing; science based information on global resource constraints and environmental degradation through growing resource use	Higher independence from external resource supply by higher resource efficiency and material savings in particular in manufacturing, and through increased recycling	Intended goals: higher competitiveness of industry, contribution to more sustainable and internationally fair consumption of global resources	Expected trigger for technological and institutional innovation

Source: own elaboration

The most recent institution which aims at the increase of resource efficiency for the whole economy is the German Programme for Resource Efficiency (ProgRes) (BMUB 2012), as the national pendant of the EU's Roadmap for Resource Efficiency (EC 2011b). Here, the proximate constraints are clearly more distant. Having flushed the pavements next door, defecated the rivers nearby, cleaned the air to get a blue sky again, having controlled waste

deposits of the communities, and getting more efficient within companies, the next proximate challenge is to get the economy as a whole more efficient in order to improve its competitiveness on the global market. In addition, political culture has advanced to a stage where countries also feel obliged to respect consequences of own actions to other regions, and that problem shifting to other countries should be avoided.

Altogether, the development of environmental governance started at close distance of proximate constraints, and introduced institutions which contributed essentially to enlarge the safe operating range from cities to regions to countries, and from immediate to long-term requirements. Thus, the proximate constraints were shifted into a distance where they cannot be directly sensed by humans, but scientific modelling, and monitoring by statistics are required to unveil the "hidden flows" or "footprints" of countries bearing on other regions.

3.4 Measuring independence depends on the state of development

For many people on the planet, poverty is the proximate constraint rendering life unsafe. In developing as well as industrial countries living below the poverty line means that the work of the day is not sufficient to allow for an adequate livelihood. Most of the time is devoted to the search of food, fire wood, drinking water, or for shelter for the family. The need to care about the survival overrides any chances to invest time and money into education and thus poverty keeps the people in a vicious circle of dependence. The "poverty line" in terms of income is no globally universal measure, rather it is a relative measure on a certain proportion of per capita income in a country. Meanwhile, measuring the per capita purchase power and income distribution as an indicator of safe living conditions is more or less regularly practised by statistical services and international institutions.

Material products are often the emblem of wealth and the symbols of a successful conquest of poverty. In rich countries, though, they may have become much less desired possessions, if not a clog. An outstanding example are cars. Since their invention, cars have enlarged the mobility range of individuals significantly. Nowadays, however, the situation, in particular in large cities is often different. Highways, bridges, tunnels, side streets are congested and parking lanes are fully packed. Mobility comes to a stand as a consequence of too much of a originally good thing. The average kilometre travelled by car declines in Japan, Britain and France, stabilized in the US; in USA, Germany and Netherlands, young people are significantly less interested in an own car then decades before (Davis et al. 2012, Economist 2012, Jorritzma and Berveling 2014). Nevertheless, they are more mobile than their parents

have ever been. They make use of car sharing and switch smartly between different modes (car, train, bus, bike). This has become possible due to the widespread availability of the mobility hardware and associated services.

The list of such examples might grow in the future, when "leasing" in terms of renting becomes more popular (Fischer et al. 2012) and the desired function or service can be provided by different means (Stahel 2010). Besides cars, copying machines and tools, it might also comprise apartments and real estate. When infrastructures and the built environment has reached a certain stage, it might be more comfortable and provide a higher degree of independence for the consumer not to own and be responsible for more and more hardware but make use of its functions and utilities. Because the service provider might be interested in long-term functioning and low maintenance costs of the hardware, this tends to contribute to a further decoupling of resource use and economic value generation. Service orientation and the generation of higher individual independence from constraints (e.g. technical and/or human assistance for handicapped and frail elderly people) can lead to an increase of well-being. Individual happiness may further flourish with the experience of decoupling from economic subsistence, although at different levels, and presumably and hopefully determined by ones own decision of what material possessions are deemed sufficient, without political force or societal prescription, – to allow for higher individual independence.

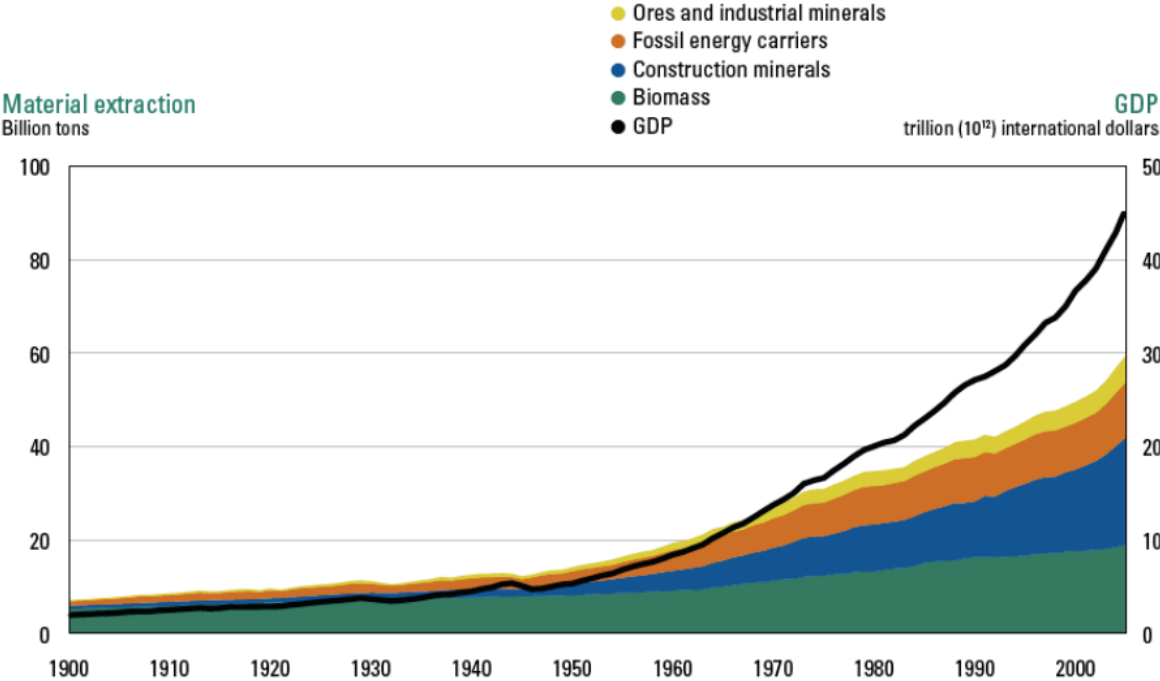
What does this mean for measuring independence? Simple accounting of nominal income or material products available in households may be misleading, as it depends on the context and status of development whether this leads to more or less degrees of freedom. Therefore, income level above the poverty line was not included in Table 1 (which conveys a nevertheless non-exhaustive selection of indicators to measure the SOR of countries).

Measures need to distinguish between economic and functional performance. An interim step is the distinction between economic and physical parameters, in particular between the flows and stocks of capital versus material flows and stocks. Whereas a growing economic capital may be associated with higher socio-economic safety (while growing disparities in its distribution represent rather growing risk), a growing stock of materials in the form of buildings and infrastructures will sooner or later meet certain saturation. For instance, the floor area per person in the Netherlands (Müller 2006) and Norway (Bergsdahl et al. 2007)

has reached the upper zone of a sigmoid curve indicating that it is not far from final saturation, although at different level, while the development in Beijing seems to be in an earlier phase indicated by lower level and still rising trend (Hu et al. 2010).

Another important distinction is between stocks and flows. Whereas the former represent a potential for possible resource use (by mobilizing capital or materials for recycling), the latter are linked to the current supply (with income or natural resources). A growing independence from material supply may be indicated when income grows faster than material use.

Figure 2. Decoupling of worldwide use of natural raw materials from economic value generation (UNEP 2011 after Krausmann et al. 2009).



Worldwide, the use of natural raw materials grew along with GDP until the 1970s (FIGURE 2). Afterwards, the world GDP increasingly decoupled from material extraction and harvest, although the latter further increased. Still, developing countries in an early phase of infrastructure built-up as well as resource exporting countries often exhibit a close coupling of GDP and the use of natural materials. In most of the richer countries, however, direct material input and domestic material consumption have either stabilized or are growing significantly less than GDP (Giljum et al. 2014). A closer look at the total material requirement (Bringezu et al. 2004) and the material footprint (Wiedmann et al. 2013) of those countries often reveals that the decoupling is less significant or even non existing when considering the upstream material flows. Obviously, highly industrialized countries have shifted resource intensive

processes towards the resource exporting countries. This development goes along with both an increase of resource efficiency within industries and a structural change of final demand towards less intensive products in regions like the EU (EEA 2013) and thus may be assumed to result from innovations in the industrialized countries rather than active translocation of old established process technologies to other regions (which also happened in singular cases (Kahn and Landler 2007)).

Thus, while all countries still significantly depend on material supply and natural resources, and in most cases, the absolute amount of material consumption still increased, the growth of material productivity indicates that countries became somewhat less dependent from the direct more proximate use of material and natural resources to generate peoples' income.

This leads to the question how the proceeding decoupling of economic value generation from the use of natural resources can be explained, as policies intended to foster the decoupling economy-wide still had been in an infant stage or not yet existing at all in most countries? Is there an inherent mechanism which leads to decoupling, possibly to sustainable resource use?

4. The mechanism of progress

This section describes a mechanism which leads to the expansion of the SOR and thus also to increased independence – or decoupling – from natural resource use. The mechanism may reduce the burden of competition for resources through cooperation and the formation of institutional innovations to form HTI at higher level. It basically works on the principle of proximity.

The method applied are theoretical considerations which try to bring well-known observations in context with underlying motivations, and to apply this in a multi-level framework. This shall allow to draw some conclusions, for instance, on the preconditions of international collaboration towards global sustainable resource use.

In the course of socio-economic development, milestones of technical and institutional innovations had effected systemic changes addressed as "progress" which provided higher independence from constraints, led to a continuous extension of the SOR and thereby also to a

decoupling of economic growth and resource use. In the following some key elements of a causal mechanism are outlined.

At the centre of the mechanism of progress is the HTIS which functioning is going to be improved by innovation (Figure 3 and 4). The HTISs comprising human beings, the technologies they use and the institutions developed to organize their living and working are considered as both subject and object of innovation (i.e. inducing activities which result in innovation and taking the effect of the innovation). These Humans-Technologies-Institutions (HTI) systems seem to be units of survival ("success") which strive for both higher safety and more independence from proximate constraints. Examples of HTISs may be companies, households, cities, regions and countries. More complex HTI such as whole countries consist of less complex HTI subsystems with a higher homogeneity of technologies in use and institutions involved.

The progress mechanism comprises three elements:

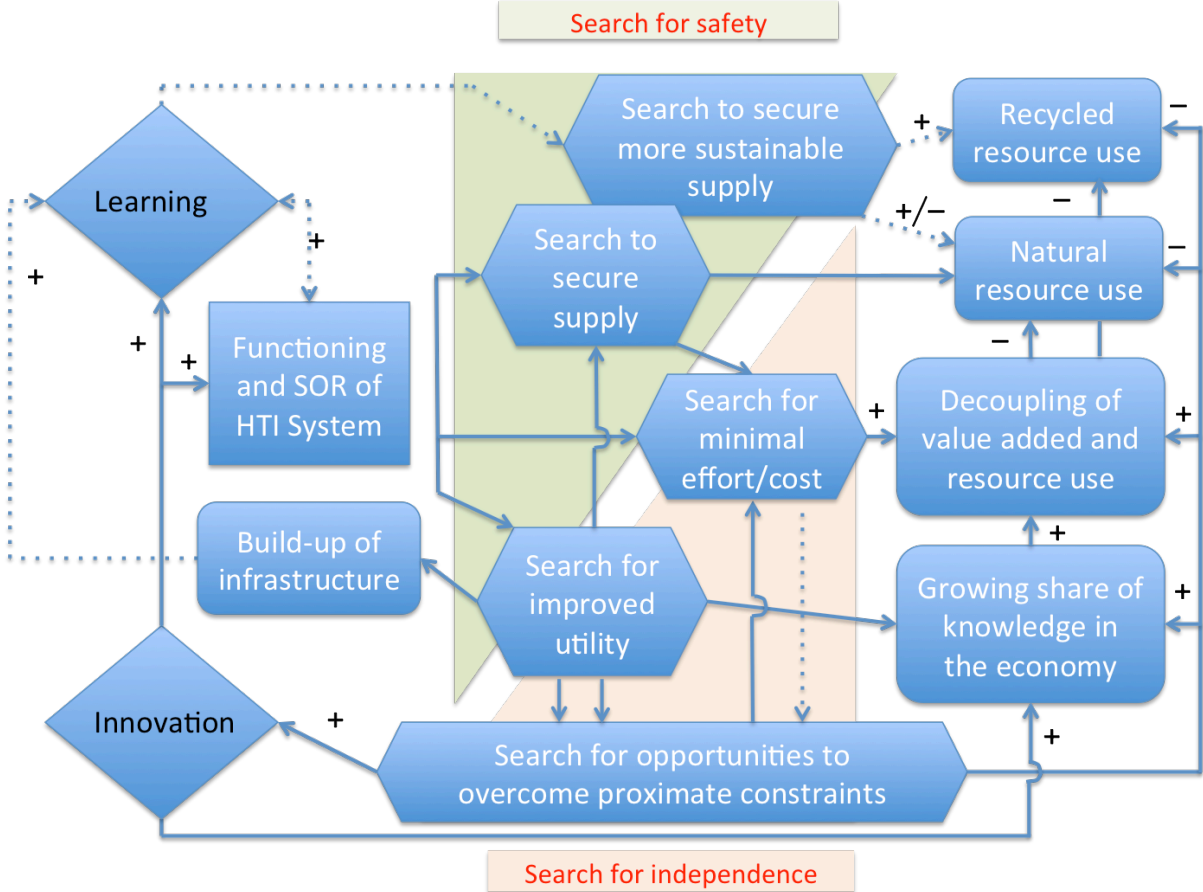
1. the innovation mechanism: the search for both safety and independence from constraints lead to innovation for improved supply security on the one hand, and the decoupling of utility provision (and generation of economic value added) and resource use on the other hand; learning and growing knowledge further support the search for enlarging the SOR and an more sustainable supply;
2. competition avoidance: cooperation of HTISs can relieve the burden of competition; this leads to more safety and independence at a higher level of complexity;
3. the proximity principle: eluding the proximate constraint first allows stepwise proceeding into the direction of higher independence of that and subsequent constraints, a development which leads to continuous expansion of the SOR.

4.1 The innovation mechanism: driven by search for safety and independence

HTISs have a certain capacity to manage and improve their functioning (Figure 3). The search to secure supply, in particular with raw materials, semi-manufactures and final products, has the tendency to uphold and increase the use of natural resources. At the same time, engineers and economists are in continuous search for opportunities of cost savings which tend to increase the efficiency of resource use and enhance resource savings in a way that more value added is produced with less resource use. The search for cost savings (in both a narrow and a

wide sense, considering internal and externalized costs, resp.) is a central momentum for the decoupling of value added and resource use.

Figure 3. The mechanism of innovation and its effect on resource use. "+" , "-" indicates an increasing or decreasing causal effect, resp.; the dotted line indicates subsequent effects of earlier searches.



Source: own elaboration

HTISs also search for improved utilities, i.e. better or additional functions to support living and working, in particular in the domains of the SOR (secton 3.1). This is usually implemented by an innovative combination of technologies and institutions. Examples may be online purchasing, mobile care services, etc., and in general all product-service systems. An essential component of those utilities is a growing share of services and know-how in the overall provision of goods. This, in turn tends to increase the share of the service sector in the overall economy as well as the share of information in industry products. As services always involve also some hardware, a growing demand for those utilities tend to enhance the search to secure supply, which may lead to higher resource use and trigger further search for cost

savings. Both searches for cost savings and improved utility then lead to an extended search also for opportunities to overcome proximate constraints (which determine the costs of supply, the need for supply and utilities etc.). This search will further trigger innovation and learning. It will increase the knowledge base of the economy. As such it tends to further push the decoupling of value added and resource use. As long as either the use of natural or recycled resources represent a constraint (and in terms of costs they always represent a certain constraint, whether proximate or distant) the search for higher independence will find further opportunities to get less dependent from such use.

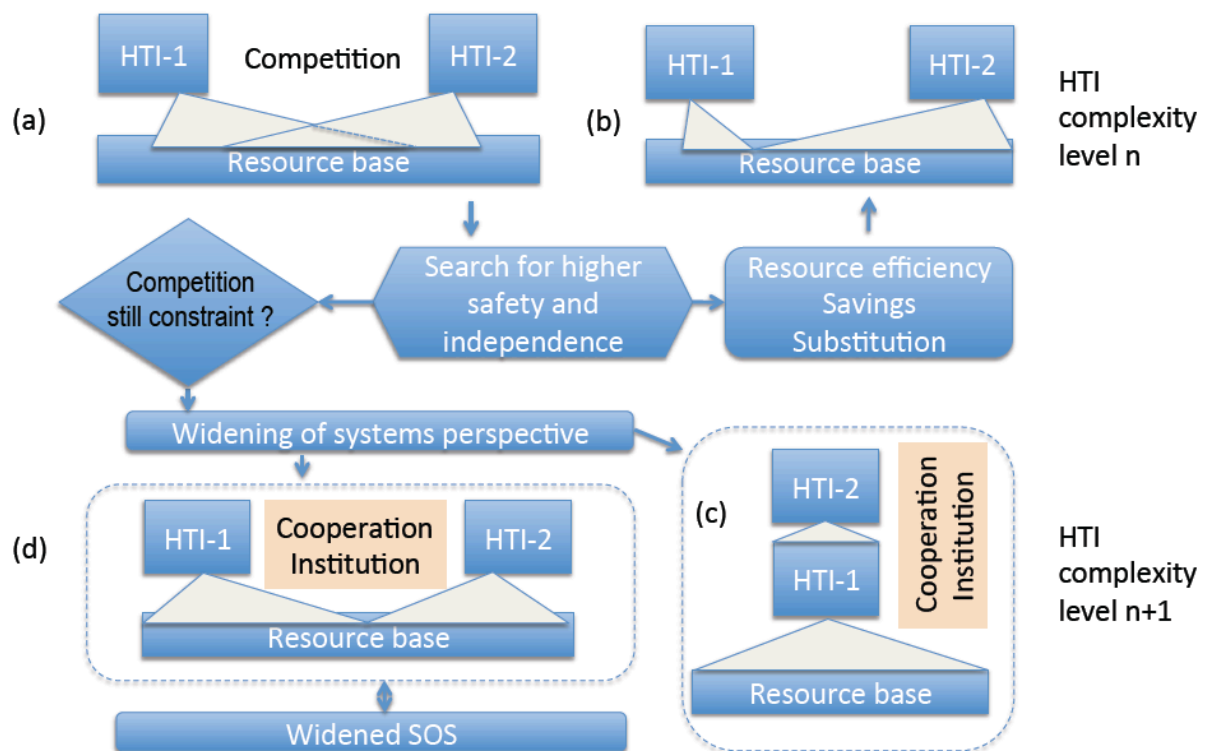
In the course of development, the infrastructure for the provision of utilities will grow and improve, thus also contributing to further learning. The learning process is key for the progress mechanism as it filters the effective and efficient options to secure supply, implement cost savings, improve utility functions and become more independent. The learning leads to an expansion of the SOR, and thus the quest to secure immediate supply will be superseded by the search for also long-term supply which can be upheld under sustainability conditions (i.e. within the SOS).

Thus, while the search processes of the HTIS may lead to an increased use of natural resources, mainly for secured supply and improved utilities, the search for cost savings, and for independence from proximate constraints, together with continued learning can be expected to at least foster a proceeding relative decoupling of economic performance and natural resource use, as well as a shift towards regenerated resources (e.g. by technical regeneration, i.e. recycling). Whether and how far the mechanism will also lead to an absolute reduction of natural resource use by all involved HTISs will depend on their competition for those resources.

4.2 From competition to cooperation: safety and independence at a higher level

As HTISs are competing for resources, the further progress towards more sustainable resource use will depend on the development of strategies to avoid competition and on the development of institutional innovations at higher levels of complexity (FIGURE 4).

Fig. 4. Competition of Humans- Technologies- Institutions (HTI) systems may lead to higher resource efficiency and cooperation



Source: own elaboration

When resources are becoming scarce and thus a more proximate constraint, usually competition results. In natural systems, a continuum between two basic forms can be observed (Lomnicki 2009). "Scramble competition" occurs when competitors have the same access to the resource, while "contest competition" allows for monopoly. Scramble leads to overuse of the resource and retarded development of the competitors (Figure 4a). Human forms of scramble competition may be observed with regard to strategies for securing resource supply using military power. "Contest competition" represents a smart way of either dominating or escaping the direct confrontation. For instance, woodpecker birds with a longer beak are capable of reaching deeper for prey. Technological innovation in oil extraction also aimed at drilling deeper. As soon as those technologies become available for all competitors, the competitive advantage fades. An effective independence of constrained oil supply would be enabled only by innovations which reduce the use of oil, like policy programmes which limit the consumption of heat energy of buildings and fuel consumption of car fleets (which will increase innovations on energy efficient technologies etc.). In general, a country with

higher resource efficiency could minimize the competition with other less efficient countries, while still drawing on the same resource (Figure 4b).

If the competition on the scarce resource remains to be a constraint, other opportunities will be explored. The competing HTISs may agree on a cooperation in order to use the scarce resource in a shared manner (Figure 4c,d). For that purpose, an institutional setting can be arranged such as a contract, and the facilitation of the establishment as well as the monitoring of the conduct will usually also be managed by a new institution. A prerequisite for the agreement is that the competing HTISs perceive the limitation of the resource and the constraints arising from the competition, as well as the opportunities of a cooperation (such as reduced transaction costs for military or other security measures). The result of the cooperation is the formation of a HTIS at a higher level (comprising the former HTI-1 and HTI-2 and the new institution). The new HTI_{n+1} system can be regarded as an agent of its own because it may become active on behalf of the consortium and negotiate, for instance, with other HTI systems aiming to use the same resource, or for completely different purposes (for instance, because the cooperation triggered an exchange on technologies which then lead to new innovations). The cooperation of the HTISs may be arranged "vertically" along the resource extraction, manufacturing, use and recycling chain (Figure 4c). For instance, product certification and guarantees along the production chain represent one basic mode of cooperation. In addition, cooperation may also be arranged "horizontally" between HTISs which make parallel use of the same resources, while agreeing on certified shares. An example is the emission trading scheme for GHG. Other examples exist on the management of water along rivers, when upstream users as a consequence of a new dam – a technical innovation to enlarge the SOR of that HTI – reduce the availability for downstream users. For instance, Ethiopia, Sudan and Egypt have agreed to solve their dispute on Nile water use in tripartite consultation³. The reader will note that combinations of both vertical and horizontal cooperations are possible which together with a growing number of participants would extend the cooperation network and the complexity of the resulting HTIS considerably.

Multiple HTISs exist often nested and with competing interests also across levels. For instance, companies and their industry branches have different interests (priority domains to enlarge their SOR) than NGOs. The government of the country represents the institution at a

³ <http://www.middleeasteye.net/news/egypt-ethiopia-settle-dispute-over-nile-dam-677531603> (accessed 10 Jan 2015)

higher level which draws its legitimacy of taking care not only of balancing the interests but – ideally – to enhance the SOR of the member groups (HTISs at lower level).

Regarding competition between countries, one may assume that the scramble strategy to secure access to scarce resources by military or political force is costly and therefore any innovation which effectively enables a higher independence from such scarce resources and burdensome strategies may provide a competitive advantage. On the long run, this might lead to the success of those HTISs which adopt innovative strategies, products and services which are less dependent on material supply in general, and on scarce natural resources in particular. As a consequence, also those technological and institutional innovations might succeed – "survive" – which enable the HTISs to expand their SOR and reach higher independence from proximate constraints.

4.3 The proximity principle: addressing closest constraints first

The principle of proximity implies that constraints are overcome from the close to the distant border of the SOR which is thus gradually and continuously extended. The principle applies to HTISs and groups thereof. Only if its proximate safety is guaranteed (i.e. progress reached in the domains of the SOR (Figure 1a) is not compromised), a group would be willing to consider the safety interests of other groups and be open to reflect cooperations which make the group itself more independent from constraints such as risky conflicts, and provides the opportunity of higher safety in the future. Farther cooperation depends on close safety.

For instance, a company at the verge of bankruptcy would hardly be open to start a programme for producer social responsibility, while the latter may be a part of a long term strategy of a well-established company to enlarge and consolidate its social rooting, thus contributing to enhance ultimate safe operation of its business. If the working and living conditions are characterized by severe pollution and health hazards, the employees and managers might have a prior interest to improve their proximate environment, before becoming engaged in the life-cycle-wide impacts of their products.

The assessment of proximity of certain constraints may change over time. After the Fukushima accident in Japan, Germany decided to phase out nuclear power, in order to avoid the risks and enhance safety. The substitution by coal shortly afterwards led to somewhat higher GHG emissions (climate change effects seem more distant than a potential super accident in a power plant near by). The use of renewable energies increased earlier and was further pushed. Biofuels and bioenergy improved the income security of farmers within

Germany, but its growing use within the country induces higher GHG emissions and losses of biodiversity in other world regions (Bringezu et al. 2009). The same is true for the EU as a whole (Bringezu et al. 2012). Substituting resources, the SOR is enlarged by overcoming close constraints, while creating new constraints, although farther away in space and time.

It is the countries with a high standard of living such as Japan and Germany who successfully managed to protect or regain a high quality of their domestic environment, who are now becoming engaged in the worldwide consequences of their resource consumption. While they have started to make themselves more independent from resource imports from other regions, still quite resource and pollution intensive processes are part of the supply chain, although "hidden" elsewhere. On the other hand, resource extracting countries still often depend on the income of those exports, and their policies to support extractive industries will only be changed with the realization of other business and income opportunities which would make the country more independent from squandering their natural capital.

At the global level, the current situation of the use of natural resources is characterized by growing demand and predominantly competing relations between countries. Cooperation on the use scarce resources has only started to become institutionalized. For instance, in the Antarctica treaty⁴ countries agreed not to use the region for resource extraction, and the UN Convention on Biological Diversity⁵ laid down principles and established instruments aimed to halt the global loss of biodiversity in the terrestrial and ocean ecosystems, i.e. within country territories as well as international waters. With regard to a globally sustainable use of natural resources an international convention is still lacking (Bringezu and Bleischwitz 2009). Suggestions were made to include sustainable resource management into the upcoming Sustainable Development Goals (IRP 2014). The ongoing debate is still characterized by uncertainty on the risks of looming scramble and on opportunities and obstacles to grow in the domains of the SOR – representing the "development agenda" – and to do so within the SOS of resource use – the "environment agenda". While developing countries still struggle to improve their narrow SOR, and therefore emphasize the need for socio-economic enhancement, industrial countries want to enlarge their wider SOR even further trying to sustain their global sourcing of resources. Institutions such as the International Resource

⁴ http://www.ats.aq/index_e.htm

⁵ <http://www.cbd.int/>

Panel⁶ are expected to contribute to improved knowledge and widened public perception of the constraints and possibilities to combine both agendas, in particular by fostering decoupling at the country level and below.

The establishment of an institution facilitating cooperation on global sustainable resource management, would again require two preconditions: (a) the constraints of business-as-usual must become visible to the countries, and here more research is required on the determination of SOS levels; and (b), opportunities for becoming independent from those constraints – while ideally growing in SOR domains – must become seizable. Whereas those countries who are highly depending on resource imports have started policy programmes to foster resource efficiency and become more independent from supply constraints, exporting countries would need to become aware of opportunities to extend their SOR while becoming less dependent from resource exports. While the world's remaining forests and mineral deposits are located within only a limited number of large countries, all countries may develop their interest in using those resources in a safe, fair and efficient manner; it would provide an association of net consuming and net producing countries with a competition excluding and potentially symbiotic⁷ effect if they help each other to increase their independence from natural resources and the related constraints further while enjoying the benefits of contained nature reserves for higher safety and living conditions on this planet.

As interim conclusion, the search for safety and independence seems to be at the core of the innovation mechanism which involves learning and leads to decoupling of value added and resource use. As the proximate constraints are tackled first, countries with a larger SOR have a higher interest to use resources more sustainably in farther space and time, while countries with smaller SOR strive to fulfill minimal social requirements. Cooperation between countries to enhance global sustainable resource use requires to reveal the opportunities for each country to grow its SOR while keeping resource use within SOS. A motivating argument could be that countries remaining in a resource intensive, competition stricken mode fall behind, while others who have acquired higher capabilities of decoupling are in a better position to further enhance innovation and expand their SOR.

⁶ <http://www.unep.org/resourcepanel/>

⁷ The exclusion of competition is no symbiosis yet; nevertheless, the formation of a cooperating consortium is often a basis for further exchange and joint search processes which tend to lead to further innovations (and if those innovations are beneficial for the consortium partners one may regard the effect as "symbiotic").

5. Learning to use natural resources efficiently further enhances innovation capacity

This section contains an empirical analysis showing that the innovation capacity of countries increases with decoupling of material resource use and economic growth (i.e. rising material productivity), and that material productivity grows with net import of material resources.

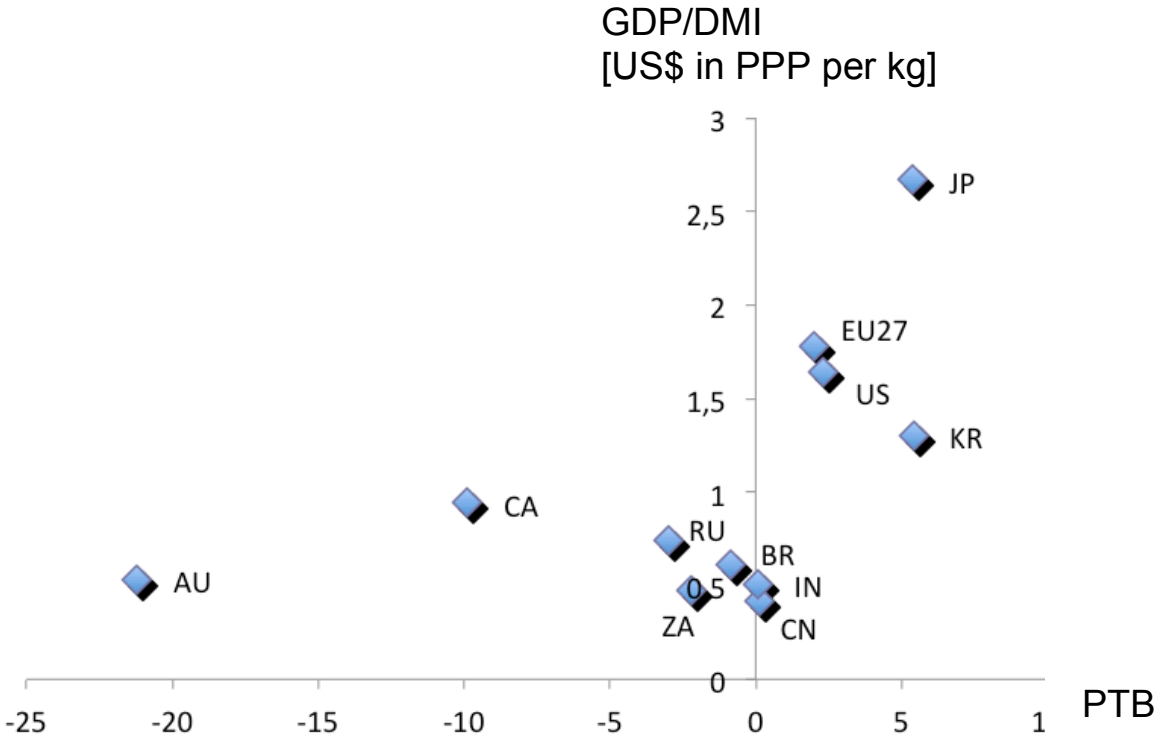
Regarding the method, the work and data from Hollanders and Es-Sadki (2014) who provided the Innovation Union Scoreboard (IUS) 2014 was taken as a starting point. They distinguish various factors (and their indicators) in support of innovations: enablers covering human resources (new doctorate graduates, population completed tertiary education), open, excellent and attractive research systems (international scientific co-publications, most cited scientific publications), and finance and support (R&D expenditure in the public sector); and firm activities covering firm investment (R&D expenditure in the business sector), linkages and entrepreneurship (public-private co-publications), and intellectual assets (PCT patent applications, PCT patent applications in social challenges (environment related technologies, health). These indicators were adopted in this article to determine an index of innovation capacity (IC) by the median of relative performance in comparison to the EU-27 (100%) based on the scores for those indicators referring to a performance in 2010/2011 (Annex G of the IUS; indicators of their third group were not considered as these may be regarded more as outcomes of innovation). The higher the score across the various indicators the higher seems to be the innovation capacity of those countries. The international comparison covered Australia (AU), Brazil (BR), Canada (CA), China (CN), India (IN), Japan (JP), South Korea (KR), Russia (RU), South Africa (ZA), USA (US) and EU27. As a next step, the physical trade balance per person and the material productivity (GDP in PPP per Direct Material Input) for those countries was determined (based on data from Eurostat, ComExt and the materialflows.net database). The parameters were related by simple rank correlation analysis.

There is ample evidence that countries with a high endowment of natural resources were often retarded with regard to their socio-economic and political development. This is known as "resource curse" (Humphreys et al. 2007). The focus on extractive industries and easy money for the elites, often coupled with corruption, lead to a retardation of technological

development. Qualified employees are bound to the use of comparatively old business models and dinosaur technologies, and no incentives effectively lead to system innovation.

If there is a resource curse, one may conclude that vice versa there is a "blessing of resource constraints". Indeed, at least beyond a certain level, the material productivity of countries is growing with their dependency of foreign resources (FIGURE 5a). A significant correlation turned out (both for year 2000 for which data are shown and 2007). Thus, the more material resources countries are importing from others, the better they have learned to make more value out of less. With the increase in material productivity they decoupled their people's income⁸ from material use and in doing so increased also their independence from foreign supply.

Figure 5a. Material productivity grows with physical trade balance (PTB).
 $p_{\text{Spearman}} < 0.001$

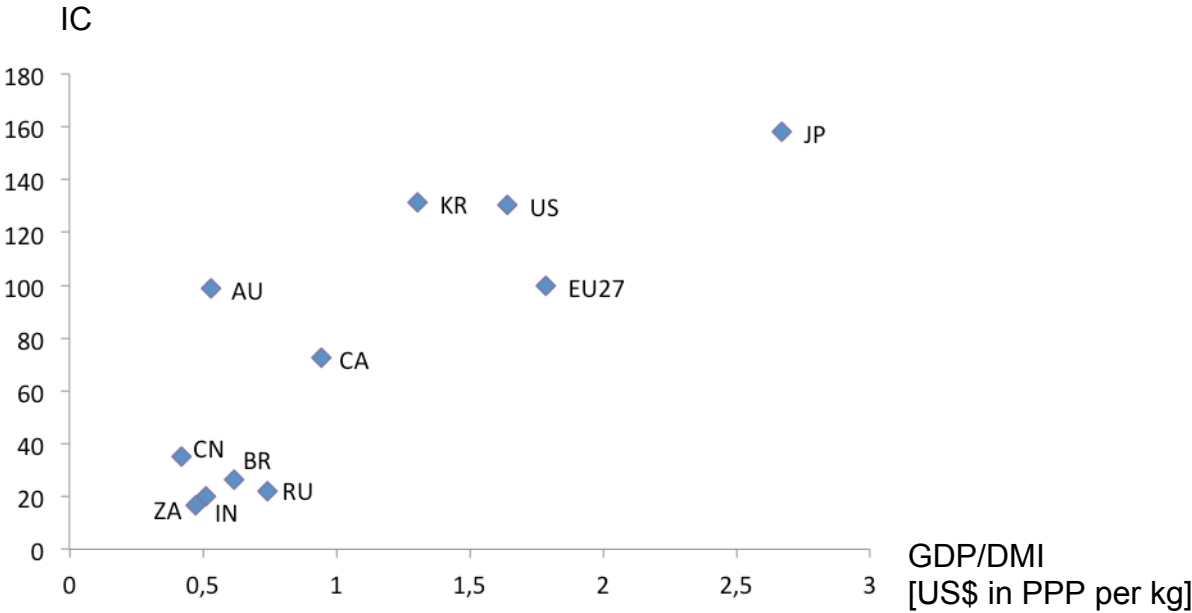


Source: own elaboration based on data from Eurostat, ComExt and materialflows.net

⁸ Taking GDP/person as independent variable no significant correlation resulted with IC. This corroborates the finding that whether a country is a net importer or exporter of resources depends more on natural endowment and population density rather than on income level (Dittrich et al. 2012).

Furthermore, the innovative capacity of countries is positively correlated with their past material productivity (Figure 5b). Certainly, one must be careful in interpreting these correlations, as they may not indicate direct causal relationships, and the indicators used for the IC cover only selected aspects of the innovation capacity of countries. Nevertheless, it seems that the capacities of countries which enable them to use materials more efficiently – which certainly required innovations – are favourable to enhance innovations even further.

Figure 5b: Innovation capacity index in 2010/11 vs. material productivity GDP/DMI [US\$ in PPP per kg] in 2000. $p_{\text{Spearman}} = 0.001$
 IC index for EU-27 = 100



Source: own elaboration based on additional data from Hollanders and Es-Sadki (2014)

Dosi (1988, p. 223) already observed that "it is generally the case that the probability of making technological advances in firms, organisations and often countries, is among other things, a function of the technological levels already achieved by them." The empirical data provides further evidence also with respect to whole economies.

The findings shown in figure 5 indicate that a high material productivity is not only going along with a higher independence of economic performance from the use of (natural) materials. More material efficient economies also seem to have higher innovative capacities. These innovative capacities are built up with the knowledge on how to manage, store, increase, and use information for the benefit of HTISs, - providing them with higher

independence of their proximate constraints. The advanced knowledge will provide an even better basis for extending their SOR further.

6. Conclusions for technology assessment, innovation evaluation and policy design

As a conclusion, the success of innovations depend on their contribution to higher safety and independence of the users. The users are different types of groups, comprising humans, technologies and institutions in specific combined settings. The advantages of the innovation will come into full play only if the user group can enjoy those benefits, while the continuous and wider application by the group constitutes the spreading and "survival" of the innovation.

When planning innovative approaches to products, services, technologies and institutions for target groups such as companies, cities, regions and countries, the following questions may guide the way forward:

1. Which are the proximate constraints of the target group (implying risks to safe living or business conditions or limiting growth, persistence or dispersion)? Which domains of the SOR are particularly underdeveloped?
2. Does the innovation help to increase the independence from the proximate constraints?
3. Which institutions would be required to enhance and make better use of existing or innovative technologies?
4. Which forms of cooperation between groups could contribute to a higher safety and independence of constraints for the consortium, taking into account available and innovative technologies and institutions?
5. Does the innovation altogether help to extend the safe operation range of the target group within its HTIS or via a cooperation within a larger HTIS?

Altogether, technical and institutional innovations may not be analysed or designed in isolation. The full HTI complex and the context of that user group and its status of development needs to be considered, as certain groups and societies as a whole may have expanded their safe operating range to a different extent. As a consequence, different proximate constraints need to be overcome when designing adequate technologies and institutions, including policy programmes and measures. In particular, the more basic

infrastructure and utility systems have been already developed in physical terms, the more services and knowledge oriented innovations may be expected to expand the SOR further.

With regard to country policies on resource use, the strategy to enhance decoupling of economic performance and resource consumption reflects a basic motivation to become independent from constraints. The strategy, however, does not seem sufficient to guarantee a future global development which keeps the overall resource use within the boundaries of SOS. For that purpose, net resource exporting countries must be enabled to realize opportunities to extend their SOR in the less resource demanding dimensions. Only then will they agree on a cooperation to use global resources sustainably. This could be facilitated by an institutional innovation such as an international resource convention and a preparatory process to elucidate the opportunities of countries if embarking towards a more sustainable resource use. Only if there are chances to increase (or at least not compromise) safe livelihood, quality of life, security, monetary stability, supply security and quality of the environment for their citizens, countries will be willing to design policies for more sustainable use of global resources.

Technical and institutional innovations reinforce each other, and the more knowledge an HTIS, whether a company or a country, has gathered to use its resources efficiently the higher the capacity for future innovations leading to more safety, higher independence and more cooperation at a larger scale. Following the principle of proximity, the outlined mechanism of innovation and its effects could essentially contribute to develop a worldwide complex of HTISs which enhances stability and resilience, supports a more sustainable use of the global resources and makes humankind less dependent from its earthbound constraints.

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