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The Sociometabolic Transition in India

An Exergy and Useful Work Analysis 1971-2012

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Zusammenfassung

Indien befindet sich auf dem Weg eine der größten Wirtschaftsmächte des 21. Jahrhunderts zu werden. Der rasante ökonomische Aufschwung des Landes wird aufgrund seines damit verbundenen steigenden Energie- und Ressourcenbedarfs und dessen Umweltauswirkungen zunehmend kritisch betrachtet. Im Zusammenhang mit Indiens enormer Bevölkerung und deren Abhängigkeit von großteils ineffizienten (fossilen) Brennstoffen wird dieser Umstand besonders im Hinblick auf den Klimaschutz evident. Ein genaues Verständnis des Entwicklungspfades, den das Land beschreitet, ist deshalb von großer Bedeutung für die internationale Gemeinschaft.

Diese Arbeit befasst sich anhand einer *exergy* und *useful work* Analyse mit den Mechanismen und Veränderungen, die die sozialmetabolische Transition Indiens vom Agrar- zum Industrieregime vorantreiben. Diese Methode ermöglicht es, die komplette Energieumwandlungskette von Primärenergie bis zum Endnutzen zu untersuchen, sowie die Perspektive konventioneller Energieflussanalysen um die Ebenen der technischen Effizienz und der Energiedegradation zu erweitern.

Um Ähnlichkeiten und Unterschiede zu identifizieren, werden die Entwicklungsmuster von Ländern im Übergang von Agrar- zur Industriegesellschaften mit denjenigen post-industrieller Dienstleistungsökonomien verglichen. Die Analyse enthüllt, wie sich Indien innerhalb kurzer Zeit von einer hauptsächlich auf Biomasse basierenden zu einer auf fossile Brennstoffe angewiesenen Gesellschaft entwickelt hat. Dies spiegelt sich in einer Verdoppelung der aggregierten Exergieeffizienz wieder. Obwohl Indiens Energiekonsum im Großen und Ganzen dem Beispiel der Industriestaaten folgt, zeichnet die Sektorenanalyse ein anderes Bild: Ein großer, von fossilen Brennstoffen betriebener Industriesektor existiert neben Millionen von Haushalten, die nach wie vor auf traditionelle Energieträger wie Feuerholz angewiesen sind, um z.B.: Kochtätigkeiten zu verrichten. Des Weiteren impliziert die Analyse der Energie-Endnutzung, dass die Steigerung der aggregierten Exergieeffizienz nicht alleine auf technologische Innovation, sondern auch auf eine strukturelle Verschiebung in Richtung effizienterer Industriezweige (z.B. Eisen- und Stahlerzeugung) zurückzuführen ist.

Abstract

India is on course to becoming one of the economic power houses of the 21st century. While the country strives to develop, concerns arise about the local and global environmental impacts of India's growing energy demand. Given its enormous population and its dependence on inefficient (fossil) fuels, this is especially evident in the light of climate change mitigation. Therefore, it is crucially important for the international community to understand which development path the country is following.

In response, this work explores the mechanisms and trajectories which drive the Indian socio-ecological transition from agrarian to industrial regime, using the *exergy* and *useful work* analysis framework. This method can be used to examine the whole energy conversion chain from primary input to energy end-use, broadening the view of conventional energy analyses towards technical efficiencies in energy transformation, as well as energy degradation.

In order to identify similarities and differences, the development patterns of countries in transition are compared to the well-known trajectories of post-industrial service economies. The analysis reveals that India has experienced a rapid transition from a mostly biomass based to a fossil fuel dependent society, resulting in a doubling of aggregate exergy efficiency. While by and large, India's energy consumption patterns are following into the footsteps of industrialised countries, sectoral decomposition reveals a different picture: A large industrial sector, powered by fossil fuels, exists beside millions of (rural) households which depend on traditional fuels such as firewood, for e.g. cooking purposes. The end-use analysis indicates that overall efficiency improvements might not stem from technological innovation alone but also from a structural shift towards higher efficiency end-uses in branches of industry such as iron & steel production.

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Abbreviations

MEFA	Material and Energy Flow Analysis
HANPP	Human Appropriation of Net Primary Production
MFA	Material Flow Analysis
EFA	Energy Flow Analysis
IEA	International Energy Agency
FAO	Food and Agricultural Organisation
CO_2	Carbon dioxide
MJ	Megajoule (= 10^6 Joule)
GJ	Gigajoule (= 10^9 Joule)
TJ	Terajoule (= 10^{12} Joule)
PJ	Petajoule (= 10^{15} Joule)
EJ	Exajoule (= 10^{18} Joule)
HTH	High Temperature Heat
MTH	Medium Temperature Heat
LTH	Low Temperature Heat
Kcal	Kilocalories
Cap	Capita (heads)
TPES	Total Primary Energy Supply
MW	Megawatt
GDP	Gross Domestic Product
GK$	Geary-Khamis Dollar (international dollar)
t	Metric ton
Kg	Kilogram

1 Introduction

In the second half of the 20^{th} century, public awareness about the negative effects of human interventions into natural systems arose. It became apparent that economic growth based on the exploitation of finite resources could not continue forever. Classical growth theories, rejecting "external" (environmental) problems, were not regarded to be appropriate anymore for accurately describing the dynamics in a globalising world facing severe threats to the environmental (Boulding, 1966; Costanza, 1995; Jackson, 2009). This has set the scene for the emergence and public acceptance of interdisciplinary research crossing the border between natural and social sciences in order to address environmental problems (Fischer-Kowalski, 1998). In this respect, disciplines like e.g. ecological economics have critically discussed classical growth theories and pointed out the importance of integrating natural physical constraints into economic theories (Serrenho, 2013).

Social Ecology is one of the disciplines concerned with and addressing anthropogenic environmental problems (e.g. deforestation, desertification, resource depletion, soil erosion, etc.) by studying the interrelations between human societies and nature. Social metabolism, one of the main theoretical frameworks of Social Ecology, forms the intellectual basis for analysing these interactions. This interdisciplinary approach draws both from natural as well as social sciences, and provides the theoretical foundation for the thesis at hand. Social metabolism focuses on societal systems and their use of materials and energy across time and space, as well as the environmental pressure socio-economic activities put on nature (Fischer-Kowalski, 1998, 2003; Fischer-Kowalski and Hüttler, 1998; Fischer-Kowalski and Weisz, 1999; Haberl, 2001a; Haberl et al., 2004, 2016a; Krausmann et al., 2008a). The Material- and Energy Flow Analysis (MEFA) framework is an appropriate tool to empirically investigate social metabolism and its evolution over large timeframes (Ayres and Kneese, 1969; Ayres and Simonis, 1994; Fischer-Kowalski and Hüttler, 1998). The method used in this thesis builds on this framework.

Already at the beginning of the 20^{th} century, Wilhelm Ostwald proposed that societal activities could be analysed from an energy perspective and stated that the aim of societal development is ultimately to be more energy-efficient (Fischer-Kowalski, 1998). Nicolas Georgescu-Roegen, one of the founders of ecological economics, elaborated how energy and material flows and the laws of thermodynamics are irreplaceable necessities to fully understand economic production (Ayres and Warr, 2005). Since then, many other scientists, e.g. Bejan and R. Errera, (2017), Saslow, (1999), Sousa and Domingos, (2006), Ayres and Warr, (2009), to name just a few, have studied the connection between energy use, thermodynamics, and economic growth. Analysing these connections is but one of the topics the exergy and useful work approach can address:

Energy flow analyses focus "only" on the energy potentially available. In contrast, exergy accounts calculate the energy actually providing a service to society. Analyses based on exergy account for energy degradation along the total societal energy throughput by considering losses in energy transformation as well as losses in final energy use. This is achieved by including thermodynamic efficiency coefficients, which act as proxies for end-use technologies. Exergy is the theoretically available maximum amount of work nested within natural resources. It can be used as a uniform measure for assessing the amount of productive energy wasted throughout the energy conversion chain. In other words, exergy accounts estimate how (in-) efficiently societies use energy (Serrenho, 2013; Wall, 1986).

Although there exists a number of exergy studies focusing on industrialised countries (e.g. Ayres, 2003; Serrenho et al., 2014; Warr et al., 2010), developing countries are rarely targeted. The crucial role of energy as a key element for sustainable development, affluence, poverty reduction, etc. has been recognised globally and implemented in international agreements such as the Millennium Development Goals (Srivastava and Rehman, 2006). While economies like the United States, Japan, or the European Union do have access to sufficient quantities and qualities of energy, almost a third of the global population is excluded from the use of "modern" energy sources (e.g. electricity) (Srivastava and Rehman, 2006). In order to reduce inequality and poverty, and improve standards of living, "developing" countries need to provide their citizens with access to modern energy sources (Pachauri and Jiang, 2008). It has been argued that large and densely populated countries like India, which experienced exceptional economic growth during the last decades, will most probably emerge as the economic power houses of the 21st century (Schaffartzik and Fischer-Kowalski, 2017). What types of energy carriers and technologies societal systems in transition use to achieve economic progress and whether they follow the pathways of the industrialised countries are critical questions of our time. While "developing" countries must without a doubt escape poverty, achieve energy security, as well as environmental justice, concerns arise among scientific communities about the rising material and energy demand of these countries and the possible impacts this will have on climate change mitigation and the global environment (Singh et al., 2012).

This thesis addresses these questions by combining the theoretical framework of Social Metabolism (chapter 2) with the Exergy and Useful Work Approach (chapter 3). A first time long term exergy analysis of India (chapter 4) is conducted. The results are then put into a wider context (chapter 5), as the ongoing sociometabolic transition in India is compared to that of China, the other "emerging giant", and the post-industrial service economies of the US, UK, Japan, and Austria, from an exergy and useful work perspective. The analysis is based on the following underlying research question:

> In what way has the ongoing sociometabolic transition from agrarian to industrial regime in India from 1971-2012, considering technological progress, changed the composition of the energy mix and useful work supply, and which conclusions can be drawn in terms of exergy efficiency?

Additional discussion points: What insights for the on-going sociometabolic transitions of developing countries can be gained from the exergy and useful work perspective? What are the roles of renewable (especially biomass) and non-renewable sources of energy in India? Which useful work categories emerged as the main drivers for (fossil) resource demand? How does the transition from an agricultural into an industrialised society effect the demand for certain types of energy, like e.g. oil or electricity? What characteristics can be identified for the Indian case in comparison to China, and fully industrialised nations like the US or Japan?

2 Theoretical background

2.1 Social Metabolism

In a rapidly globalising world, the effects of climate change (e.g. rising sea-levels, desertification, extreme weather events,…), social injustice (e.g. global division of labour and outsourcing of resource exploitation by industrial nations, often in disadvantage of “the global south”,…), and environmental pollution (e.g. toxic, and climate-affecting emissions,…) are presently some of the most critical challenges for mankind. Understanding the complex consequences, feedbacks and impacts our socio-economic activities have on the environment has become more important than ever. The concept of “sustainable development”, defined for the first time in the Brundtland Report of 1987 (Haberl, 2000), has coined the debate about future socioeconomic progress, and has been proposed as a possible solution for the global crisis (Fischer-Kowalski, 1997a). In order to meet the goals of sustainable development[1], it is necessary to identify and analyse society-nature interactions and specify which of their biophysical processes act as drivers for (global) environmental change (Fischer-Kowalski, 1997a; Haberl, 2000).

Social Ecology aims to explore society-nature interrelations from an interdisciplinary approach, combining theories and methods of social and natural sciences, such as sociology, cultural anthropology, (ecological) economics, biology, physics, and chemistry, among others

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[1] The core foundation of sustainable development, as defined in the Brundtland report, is to connect the social, economic, and ecological dimension of global and regional development (Brand, 1997). Specifically, the goals of sustainable development are to: ‘*1) End poverty in all its forms everywhere 2) End hunger, achieve food security and improved nutrition and promote sustainable agriculture 3) Ensure healthy lives and promote well-being for all at all ages 4) Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all 5) Achieve gender equality and empower all women and girls 6) Ensure availability and sustainable management of water and sanitation for all 7) Ensure access to affordable, reliable, sustainable and modern energy for all 8) Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all 9) Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation 10) Reduce inequality within and among countries 11) Make cities and human settlements inclusive, safe, resilient and sustainable 12) Ensure sustainable consumption and production patterns 13) Take urgent action to combat climate change and its impacts 14) Conserve and sustainably use the oceans, seas and marine resources for sustainable development 15) Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss 16) Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels 17) Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development*’ (United Nations, 2015, p. 14)

(Fischer-Kowalski, 2003, 1998; Fischer-Kowalski and Erb, 2006). The concept of social metabolism, one of the principal theoretical paradigms of Social Ecology (Fischer-Kowalski and Erb, 2006), offers a methodological framework for analysing material- and energy use across time, and related environmental impacts of industrial as well as non-industrial societal systems (Ayres and Kneese, 1969; Ayres and Simonis, 1994; Fischer-Kowalski, 1997b, 1998; Fischer-Kowalski and Erb, 2006; Fischer-Kowalski and Hüttler, 1998; Fischer-Kowalski and Weisz, 1999; Haberl et al., 2016a; Kneese et al., 2015; Krausmann et al., 2008a; Krausmann and Fischer-Kowalski, 2010).

The theoretical basis of the socio-ecological model is based on, inter alia, work by Luhmann, (2015), Boyden, (1992), Sieferle, (1997), and Godelier, (1986). Human society, as defined by the Viennese school of Social Ecology, is basically a closed system regarding communication, but open to material and energy flows (Fischer-Kowalski et al., 2011a; Fischer-Kowalski and Erb, 2006; Fischer-Kowalski and Weisz, 1999; Haberl, 2001a). The conceptual model (Figure 1) illustrates a unit of two spheres, the '*natural*' and the '*cultural sphere of causation*' (Fischer-Kowalski and Weisz, 1999, p. 241), partly overlapping and constituted by three main elements: Culture, nature, and population (as well as biophysical components attributable to population, as explained below), influencing each other.

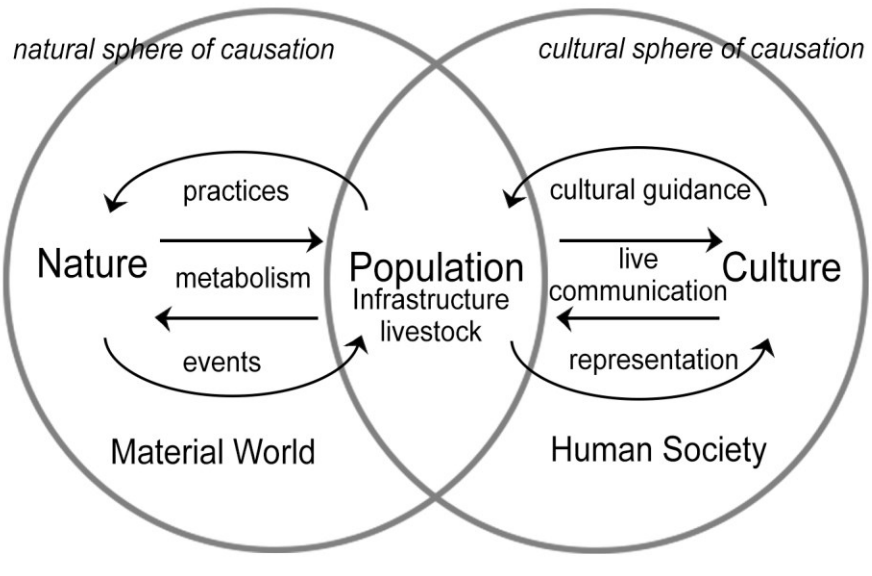

Figure 1: Conceptual model of society-nature interactions as developed by the Viennese School of Social Ecology

Own graphic adapted from Haberl et al. (2016a, p. 21)

It is crucial to mention that the interconnections between these elements contain recursive characteristics: The model describes a '*self-referential dynamic with the selective forces being contingent on the internal selection pressures of the* [societal and natural] *systems coevolving*' (Haberl et al., 2016a, p. 22). Culture refers to the symbolic realm of the model, which '*must* (…) *regulate parameters of the environment in order to be able to reproduce itself*' (Fischer-Kowalski and Weisz, 1999, p. 241). It contains, for example, sets of rules, traditions, restrictions, regulations etc. (Fischer-Kowalski and Erb, 2006), which '*lead to physical alterations in natural processes that, in turn, may or may not lead to new forces, intended or unintended, exerted from nature upon society. These changed forces might become culturally represented in one way or another (or even pass unregistered) and may or may not modify cultural guidance/programs for future action upon nature*.' (Haberl et al., 2016a, p. 22). Nature represents, simply spoken, '*all material elements* (…) *except humans*' (Sieferle, 1997, p. 38), but does, together with humans, comprise the natural realm. Population is the biophysical component of human society, linked with nature through its social metabolism, and linked with culture through communication (Sieferle, 1997). Specifically, this applies also to livestock, and other artefacts (such as buildings, electronic devices, infrastructure, cars, etc.). Therefore, as society is situated in the intersection of the symbolic (or cultural) and the physical/material realm, and connected with both spheres, it is considered to be a hybrid entity (Fischer-Kowalski et al., 2011a; Haberl et al., 2016a). In order to reproduce itself by cultural and biophysical means, human population draws materials and energy from natural systems.

The term "metabolism", in a biophysical sense, refers to the process of inputs and outputs to and out of living systems, or the need of living organisms to consume nutrients in order to maintain their bodies' biological functions and dispose the remainder into their surroundings (Fischer-Kowalski, 1998). Social Ecology applies the concept of metabolism to the level of human societies, thus describing '*a metabolism that at least equals the total metabolism of their human members*' (ibid., p. 63). It analyses the *'biophysical stocks, flows and—as we are gradually beginning to better understand, certainly in analogy to organic metabolism—the mechanisms regulating these flows.*' (Haberl et al., 2016a, p. 36). Beyond the basal biophysical requirements for survival of humans and livestock (nutrition), materials and energy required to build up and maintain biophysical structures - also referred to as material stocks (e.g. buildings, infrastructure, etc.) - are recognised by the concept of social metabolism. All materials and forms of energy used by an anthropogenic community, the modes of extraction, (re-)production, and consumption are considered (Grünbühel et al., 2003). At the same time, population produces outputs (wastes and emissions), which are dissipated back to the environment. Population and culture are affected by impacts induced by these interactions with nature, and vice versa (Fischer-Kowalski, 1997a; Fischer-Kowalski and Weisz, 1999; Haberl et al., 2016b). Culture is indirectly addressed by unwanted environmental side effects (e.g. floods, mud-slides, nuclear catastrophes, etc.) through alterations affecting material stocks (Haberl et al., 2016a, 2004). Flows of materials and energy used by a society, as well as its material stocks are looked upon in physical units, as if this society was an ecosystem compartment (Haberl et al., 2004). This allows us to use '*basically the same concepts and methods* (…) *to deal with social and natural systems*' (Fischer-Kowalski and Rotmans, 2009, p. 6). Interactions between society and nature continue to change in scope and composition as societies discover new resources and evolve. Additionally, to maintain these flows, natural systems are transformed into forms more useful to human society than their original state was – this refers to the concept of "colonisation of nature" (Fischer-Kowalski et al., 2011a):

For centuries, human societies have modified the environment they live in to their own advantage in divergent modalities, both intentionally (e.g. cultivation) and accidentally (desertification, soil erosion, etc.). Colonisation of a natural system means the modification of its processes in an organised manner to increase its usefulness for mankind, and, in order to guarantee for its functionality, the maintenance of the desired state through inputs of labour, energy and materials (Fischer-Kowalski and Erb, 2006). Agriculture is a popular example for the colonisation of natural processes: Humans clear the vegetation to enable the cultivation of various crops. By investing human and animal labour and time, artificial systems are created and maintained. In this way, nutritional levels of agricultural societies, compared to hunter and gatherers societies, can be increased (Fischer-Kowalski et al., 2011b; Krausmann and Fischer-Kowalski, 2010). Therefore it is possible to feed more individuals, leading to the establishment of permanent settlements and further inventions, such as the written word, windmills, etc. Of course, this phase of growth is not infinite and reaches its (narrow) limits sooner or later (Grünbühel et al., 2003; Krausmann and Fischer-Kowalski, 2010): The production of surplus relies on the size of cultivated land and on the investment of work and energy[2]. Area in traditional agrarian societies is limited, and intensification of agricultural work

[2] Energy return upon investment (EROI) (Hall et al., 1986). For a further socio-ecological elaboration of this topic see Winiwarter (2006)

soon reaches a point where it produces only little, uneconomical surplus. Furthermore, biomass based societies are also restricted by spatial boundaries: Mode of transportation, unless adequate water ways are available, is dependent on human and/or animal physical work. This does not allow for mass transportation of materials over long distances, given the fact that both the food/feed biomass as well as the traded goods need to be carried (Krausmann and Fischer-Kowalski, 2010; Schaffartzik and Fischer-Kowalski, 2017; Sieferle et al., 2006). In the framework of Social Ecology, colonisation of nature is addressed empirically by analysing land-use change, e.g. by calculating the "Human Appropriation of Net Primary Production" (HANPP) (Haberl et al., 2001; Vitousek et al., 1986). Although this is not the subject of this thesis, it must be noted that land-use (change) is one of the most important drivers for global change (Haberl et al., 2004).

Crucial aspects of certain modes of social metabolism and colonisation of nature are the sources and availability of energy (Fischer-Kowalski, 2011; Fischer-Kowalski et al., 2011a, 2014; Fischer-Kowalski and Schaffartzik, 2015; Haberl et al., 2016b; Krausmann et al., 2008a; Krausmann and Fischer-Kowalski, 2010). The utilisation of energy in qualitative and quantitative terms is the most elementary way to specify and define to what extent the socioecological system in question is able to modify its natural surroundings and where its "limits to growth" are (Krausmann and Fischer-Kowalski, 2010). Different stages of societal development can be identified. They occur independent of time and geographic location – the process of industrialisation, for example, took place in different regions at divergent points in human history under varying prerequisites (Fischer-Kowalski and Schaffartzik, 2015).

Nevertheless, the various phases of societal development always show recurring aspects: Each stage is defined by its energy system (sources of energy and conversion technology), patterns of consumption, social organisation, forms of population and settlement, amongst other characteristics (Fischer-Kowalski, 2011; Krausmann et al., 2008a; Krausmann and Fischer-Kowalski, 2010). In the theoretical framework of social metabolism, these stages have been termed "sociometabolic regimes" (Fischer-Kowalski, 2011). Throughout human history, at least three major sociometabolic regimes can be defined: hunter and gatherers, the agrarian, and the industrial regime. Historically, human interference, depending on the available form of energy, extended from hunting and gathering to cultivation of land, and further to extracting fossil fuels, which triggered the foundations of industrialisation in the 17th century in the United Kingdom (Grübler, 2003; Krausmann and Fischer-Kowalski, 2010; Krausmann and Schandl, 2006).

2.2 Sociometabolic Regimes

The following description of the three sociometabolic profiles draws from Schandl et al. (2009), and Fischer-Kowalski and Schaffartzik (2015).

Hunter & Gatherers: the main energy source is solar energy, which is used indirectly (or uncontrolled); the natural products of photosynthesis (plants) and wild animals, which feed on plants, are used by societies and thus extracted from the environment. Population is limited to low density and low per capita material and energy use. Typically, hunter & gatherers live a nomadic existence in order to deal with and overcome local natural limits.

Agrarian societies: Land is directly and intentionally modified by cultivation. A controlled solar-based energy system allows for increased yields, thus enabling greater population densities. Biomass (mostly timber wood & crops) is the main natural resource used, providing material for construction, nutrition and manufacturing. Energy usage is bound to and limited by land as well as human and animal labour. Additional energy inputs (e.g. by wind & water (transportation and mills), at quite low levels) might occur. Growth is only possible within narrow limits. Per capita material and energy use as well as inputs of human and animal labour force are much higher than in hunter & gatherer societies.

Industrial societies: Limited non-renewable fossil fuels (first coal, later oil, and gas) are used intensively. Complex and far-reaching interventions into natural systems occur. Industrial technology, enhanced mobility and decoupling of the energy-system from land are, amongst others, characteristics of industrial metabolic regimes. These societies are typically defined by high per-capita material and energy consumption. Some of the inherent growth and limitation problems of agrarian regimes (such as diminishing returns of cultivated land in agriculture) can be resolved to a certain extent by the application of new energy carriers, at the same time leading to new environmental problems (e.g. acid rain, soil erosion, etc.).

Table 1: Typical metabolic rates for sociometabolic regimes

based on Haberl et al. (2011, p. 2)

	Hunter & Gatherer	Agrarian	Industrial
Material use in tons/cap/year	0.5-1	3–6	15–25
Energy use in gigajoules/cap/year	10-20	40–70	150–400

It has become apparent from analysing past flows of material and energy of industrialised countries, that historic transitions to different metabolic regimes were always accompanied by a substantial increase in both material and energy consumption rates (Fischer-Kowalski and Rotmans, 2009; Haberl et al., 2004) - as visible in Table 1. However, the numbers in Table 1 are derived from historic examples. Therefore it must be noted that societies do not "automatically" transform into "higher" stages of development once they've reached a certain level of material and energy consumption. Transitions between regimes can be characterised by other aspects, as elaborated in the next chapter (2.3).

In recent years, it has been argued that the classification "regime" for industrial societies is yet to be questioned. On the one hand, their energy systems are strongly dependent on finite resources. On the other hand, their immense outputs exceed the sink-capacities of the natural environment. Hence, the ability of such systems to sustain for longer time periods may be doubted (Krausmann et al., 2008a). Instead, as some authors argue, the unsustainable character of industrialised societies may lead to the assumption that this stage of societal development itself is a transitory, temporary phase, leading to a new, yet unknown state (Fischer-Kowalski, 2011).

2.3 Sociometabolic Transitions

In Social Ecology the shift from one regime to another is termed sociometabolic transition. This is usually caused by a revolution: In the history of mankind, the "Neolithic Revolution" can be identified as the transition from hunter & gatherer to agrarian regimes (Fischer-Kowalski and Rotmans, 2009). As described above, agricultural cultivation enabled societies to use solar energy actively and hence more effectively, enabling communities to grow beyond their previous expansion limits. The shift from agricultural to industrial regimes is characterised by the use of fossil fuels. This leads to dramatic changes of society-nature interactions, and allows for rapid economic growth for a limited timeframe (Krausmann et al., 2008a; Krausmann and Fischer-Kowalski, 2010). Accelerated use of coal in combination with the introduction of steam engines (among other inventions) triggered a series of innovations and events, which '*ultimately transform*[ed] *most features of society*' (Schandl et al., 2009, p. 270), and became known as the "Industrial Revolution" (Fischer-Kowalski and Rotmans, 2009; Krausmann and Fischer-Kowalski, 2010). Oil enabled the production of fossil based fertilisers, as well as the mechanisation of agriculture ("Green Revolution"), thus emancipating agricultural production from the bounds of area (as explained in section 2.2). The use of fossil fuels (foremost oil) enabled brisk technological innovation (e.g. automobiles, air-planes, petro-chemical industries,…), and per-capita material and energy consumption far exceeded previous levels (see Table 1) (Fischer-Kowalski, 2011, 1997b; Krausmann and Fischer-Kowalski, 2010; Krausmann and Schandl, 2006; Schandl et al., 2009).

It is important to note that transitions, from a socio-ecological point of view, are not defined simply as a substantial increase of material and energy consumption rates, although this is usually a consequence of the transition process (Krausmann et al., 2008b; Krausmann and Fischer-Kowalski, 2010). Rather, sociometabolic transitions are understood as fundamental change in '*societal organization, in the economy* (…) *and in society-nature interactions*' (Fischer-Kowalski and Haberl, 2007, p. 31). These alterations are, among other aspects, attributable to changes in the society's energy system, which is a core aspect of sociometabolic regimes (Fischer-Kowalski and Haberl, 2007, p. 31). In the theoretical framework of Social Ecology, transitions are not regarded as linear, constant processes (Fischer-Kowalski, 2011). Schandl et al. (2009), and Fischer-Kowalski et al. (2011b) formulate that if a critical mass of the aspects of a certain metabolic regime (as mentioned in section 2.1 and 2.2) goes beyond the possibly "allowed" fluctuations of that system, a new stage of development with different characteristics and limitations can be achieved (usually this is triggered by the introduction of new sources of energy). Nevertheless, this pathway must, by no means, unavoidably lead to a "higher" level of societal development. In contrast, it might even (through external or internal pressures or feedbacks) lead to the collapse of that system or result in a set-back to a prior state. As a consequence, neither the result nor the direction of a transition process is pre-determined. Additionally, some elements of a sociometabolic regime may depend upon different energy systems at the same point in time: Traditional agriculture (based on draught animal and human labour) may exist within the same societal system containing industrialised urban centres (based on fossil fuels). Further, transitions may appear within a sociometabolic regime itself, for example, an industrial sociometabolic regime might shift from a coal based to an oil based energy system (Fischer-Kowalski, 2011).

A lot of previous studies about historical transitions from agricultural to industrial sociometabolic regimes focused on industrialised countries, e.g. the United Kingdom (Schandl and Schulz, 2002), Austria (Krausmann, 2004; Krausmann and Haberl, 2002; Sieferle et al., 2006; Krausmann and Haberl, 2007), etc. Globally, '*almost half of the world's population still lives in rural areas on subsistence agriculture, gathering, hunting and fishing*' (Fischer-Kowalski et al., 2011b, p. 147), while at the same time '[t]*he majority of the world's regions and economies are still in early phases of an ongoing industrial transformation*' (Krausmann et al., 2008a, p. 638). Therefore, from the end of the 20th century onwards, transitions in developing countries captured the attention of researchers from all over the world (Fischer-Kowalski and Schaffartzik, 2015): For example, Leach (1992), as well as Pachauri and Jiang (2008) analysed household energy transitions in developing countries; Schandl et al. (2009) studied the sociometabolic transition from agrarian to industrial regimes in several developing countries in Asia, focusing on energy, agricultural modernisation and urbanisation; Fischer-Kowalski et al. (2011b) analysed the sociometabolic transitions of four subsistence communities (Trinket Island, India; Campo Bello, Bolivia; Nalang, Laos; Sang Saeng, Thailand).

Transitions from biomass to fossil fuel based energy systems in "emerging economies" like India and China play a key role in the future global sociometabolic development (Fischer-Kowalski and Schaffartzik, 2015; Krausmann et al., 2008a). Whether or not these countries follow the same development paths of the nowadays industrialised nations is of particular interest for sustainability sciences.

2.4 Material and Energy Flow Accounting Framework

Within the context of increasing environmental awareness, there has been an extensive debate over operationalisation of sustainability (Fischer-Kowalski, 1998, 1997a; Gong and Wall, 2001; Haberl et al., 2011, 2004; Kates and Parris, 2003; Wall and Gong, 2001). How can we empirically identify socioecological transitions, and describe sociometabolic profiles of communities? How can we know what impacts human actions have on the environment? What effects do these impacts have on society? Which activities have the most significant consequences for natural systems?

The vast amount of environmental impacts evoked by different human actions (e.g. extinction of species, emission of greenhouse gases, depletion of natural resources etc.) makes it very complicated to define common criteria for assessing (potential) harmfulness of these activities (Fischer-Kowalski, 1997a; Haberl, 2000; Haberl et al., 2016b, 2004). The well-established "Material- and Energy Flow Accounting" (MEFA) framework[3] (Ayres and Kneese, 1969; Ayres, 1989; Ayres and Simonis, 1994; Fischer-Kowalski, 1998; Fischer-Kowalski and Hüttler, 1998; Haberl et al., 2004; Kneese et al., 2015) offers a consistent methodological tool to empirically '*observe societies, natural systems, and their interaction over time* (…) *by tracing socio-economic materials and energy flows and by assessing changes in relevant patterns and processes in ecosystems related to these flows'* (Haberl et al., 2004, p. 200) on an aggregate level. This is done '*in a way that can link socio-economic dynamics (e.g., monetary flows, lifestyles or time allocation) to biophysical socio-economic stocks and flows and these, in turn, to ecosystem processes*' (Haberl et al., 2004, p. 201). In other words, MEFA analyses the extraction of materials[4], their use and eventual transformation into other forms (of material and/or energy), and the disposal of the remains of the used materials back to nature (Fischer-Kowalski, 1998). The method enables societies to observe their own social metabolism (via e.g. aggregate proxies such as the total societal throughput of bulk materials) and is compatible with established economic and social statistics (Haberl, 2001a; Haberl et al., 2004).

Although prior to 1970 most studies about social metabolism focused on energy flows, in recent decades, Material Flow Analysis (MFA), which accounts for materials in metric tons, was in the centre of methodological development and empirical application (Haberl, 2001a). The idea of social metabolism as a driver for global environmental change is nowadays widely accepted by a growing number of governments, decision makers and institutions, and has led to the implementation of MFA into official national statistics of e.g. the European Union and Japan (Europäische Kommission, 2001; Fischer-Kowalski and Erb, 2006; Haberl et al., 2004; Weisz et al., 2015).

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[3] Since the 1970ies, a large amount of material- and energy flow analysis have been undertaken (Fischer-Kowalski and Hüttler, 1998). The greatest part of these studies focused on industrialised societies (ibid.) examining '*the whole of the materials and energy flows going through the industrial system*' (Erkman, 1997, p. 1). Therefore, the term "industrial metabolism" (Ayres, 1989) has been commonly used for these analysis. However, due to the focus of this thesis on a country in transition from an agricultural to industrial metabolism, the wider term "social metabolism" is used (Haberl, 2001a).

[4] In contrast to societal metabolism studies, water and oxygen are normally not considered in material- and energy flow accounts (Fischer-Kowalski, 1998).

Stocks and flows are the key units within the MEFA framework. Stocks are defined as '*quantity per point in time*' (Weisz et al., 2015, p. 11) while flows are defined as '*quantity per time period*' (ibid., p. 11). By conceptually linking stocks with flows, it is possible to define the system boundaries of the social system in question e.g. a village, firm, region, nation,… (Haberl et al., 2016b). Stocks are the biophysical features of society, e.g. human population, livestock, buildings, etc. Flows connect the biophysical compartments with the natural systems (as explained in section 2), thus they are influencing each other. Therefore, the '*same concepts and methods can be used to deal with social and natural systems*' (Fischer-Kowalski and Rotmans, 2009, p. 6). Material and energy flow analyses, as the name already suggests, focus on flows. In order to build (or breed and feed in the case of e.g. livestock), use, and maintain stocks, material and energy flows are required. Therefore, stocks are accounted for in flow analyses as "stock changes", which refer to flows of material and energy into, and out of biophysical stocks.

MEFA can be applied on various spatial and temporal scales and provides, in accordance with the theory presented in chapters 2, 2.2 and 2.3, a practical framework for analysing sociometabolic regimes and transitions across space and time. It is applicable on single year basis or spanning over long-term timeframes, usually decades to centuries. The method has been applied to numerous countries, regions, and even on local levels - from macro to micro scale - although it must be noted that the most common scope is the nation level (Fischer-Kowalski and Hüttler, 1998).

2.4.1 Energy Flow Accounting

Energy Flow Accounts (or Analyses) (EFA) assess energy flows through economies. They are based on energy balances, which are derived from energy statistics, as provided by e.g. the International Energy Agency (IEA) or EUROSTAT. The sum of all inputs and outputs of these balances must equal zero, meaning that all sectors of an economy and the energy flows between them must be considered, thereby respecting the first law of thermodynamics [5]

[5] The first law of thermodynamics defines the basic characteristics of energy conservation and treats work, heat and energy equally. However, there is only a limited possibility of transforming heat into work. The Carnot cycle defines the maximum amount of the ability of a thermodynamic engine to convert heat into work (Zahoransky and Allelein, 2013).

(conversion of mass and energy) (Ayres and Warr, 2009). Within the economic energy supply chain, different stages can be distinguished, namely primary, final, and useful energy[6].

Since the 1970ies, most studies about societal metabolism have focused on flows of bulk materials (MFA) (Haberl, 2001a). Helmut Haberl (ibid.) pointed to the importance of human energy use for sustainability sciences, by elaborating that EFA should be an intrinsic part of the research tools used to fully understand social metabolism. Although energy in its primary form is indeed often considered in Material Flow Analysis, Haberl (ibid.) argued that the whole energy throughput should be considered instead. This in particular refers to the inclusion of biomass providing nutritional energy for humans and animals. Energy is, as mentioned in the previous chapter, a fundamental factor for building and maintaining the material stocks of societies. It provides useful energy for end-users (e.g. light, heat, electricity,…), it is used to enhance the productivity of materials (e.g. yield in agriculture), it "fuels" economies by providing '*work and heat that activates capital and labor*' (Serrenho, 2013, p. 7), etc. Haberl (2001a) argues that energy and material flows are '*two different aspects of the same process*' (ibid., p. 13).

Furthermore, the author points out that '*the energy throughput is at least as closely related to a wide variety of environmental problems as society's material throughput is*' (Haberl, 2001a, p. 14): Obviously, energy use (as well as material use) entails negative side effects. Various environmental impacts happen at different stages of the energy conversion chain. This includes not only CO_2 emissions caused by the burning of fossil fuels like coal and oil. A lot of problems can be associated with the utilisation of Nuclear power (e.g. the permanent disposal of radioactive waste etc) but also with renewable energy: For example, large hydropower dams may endanger aquatic ecosystems, etc. (Jager and Smith, 2008), and often evoke adverse social impacts on communities such as forced resettlements etc. (Cernea, 1997). Hence, socioeconomic energy throughput (from primary to the useful stage), as Haberl (2001b) proposed, '*is a better proxy for the aggregate environmental pressures* (…) *exerted by a given national economy than conventional measures of energy use derived from energy statistics*' (ibid., p. 82), such as the primary energy input.

[6] Final energy is defined as energy at the point of final use, after all transformational and distributional processes. Primary energy, in contrast, is the form of energy embodied in resources as they extracted from nature. Useful energy is the fraction of energy actually available for human use (Grubler et al., 2014; Haberl, 2001a; Serrenho, 2013).

Reduction of socioeconomic energy throughput is a crucial part of the idea of sustainable development, for which Energy Flow Analysis provides useful indicators (ibid.). EFA can be used to follow the energy flow all the way from primary to useful energy. However, it accounts only for energy potentially available, not for transformation losses from final to useful energy. On an aggregated level, methodological difficulties occur when accounting for useful energy because this stage is '*not available for all countries, and even where available, it is generally based on random sampling surveys and technical extrapolations of low accuracy*' (Haberl, 2001a, p. 18). This is where the merits of the Exergy and Useful Work Analysis come into play.

2.5 Exergy Approach

As elaborated in the previous sections, MEFA traces stocks and flows of natural resources quantitatively in terms of mass (tons) and energy (joules) units. Instead of measuring "potential energy", as energy accounts do, Exergy and Useful Work Analyses differ from and enhance this method by including technological conversion efficiencies, hence measuring flows of energy as "potential work" (both quantitatively and qualitatively) (Ayres and Warr, 2009). In this way, losses in all transformation processes, as well as in final energy use can be accounted for. Therefore, exergy accounts reflect how much energy is actually "consumed" and how much is "wasted" (Wall and Gong, 2001). Before further distinguishing the exergy approach from conventional energy analysis in detail and highlighting the benefits of the methodology, definitions of exergy and useful work are given in the next section.

2.5.1 What is Exergy? Concept and Definition

In the context of this thesis, it is vitally important to distinguish between the terms energy and exergy from hereon. Energy, as a consequence of the first and second law of thermodynamics[7], can never be generated or destroyed – it can only be converted from one form into another and is therefore conserved (Zahoransky and Allelein, 2013). Why then, do we talk about "consuming" energy? From an exergy perspective, it becomes obvious that the usable, qualitative part of energy is in fact never conserved, but "used up" or "destroyed" (degradation of energy quality), while the remainder is dissipated as unusable heat (Wall,

[7] The second law of thermodynamics defines the first law more precisely. It introduces entropy generation and describes the direction of energy transformation, thus treating heat, work and energy differently. Entropy of thermodynamic systems in a thermodynamic process always increases. In short, the second law defines that heat can never be transferred from a cold reservoir into a warm reservoir without work being applied (Zahoransky and Allelein, 2013).

1986): Exergy is, by definition, the '*maximum amount of work a subsystem can do on its surroundings as it approaches thermodynamic equilibrium reversibly*' (Warr et al., 2010, p. 1904). Simply spoken, it is the part of energy contained within an energy carrier (termed natural resource exergy or simply exergy hereafter) that can perform (potential) work, which is finally converted into useful work via transformation processes. Thus, it is usable for human (energy) needs and is being destroyed (or "consumed") as it fulfils the desired purpose. Part of natural resource exergy is always dissipated into frictional heat (increase of "disorder", or "entropy", a consequence of the second law of thermodynamics) during transformation processes and is therefore not anymore usable for humans. The amount of natural resource exergy being lost depends largely on the technologies used for the above mentioned transformation processes and the so called end-use devices (such as lamps, cars, televisions, fans, etc.), which provide the actual energy service (e.g. illumination of a room, movement, cooling, etc.) (Warr et al., 2008).

A simple case of a transformation process and the conversion of natural resource exergy into useful work is the burning of coal. Combustible fuels are being transformed from one state to another via chemical processes, one example being '*the spontaneous recombination of hydrocarbons* (…) *with atmospheric oxygen*' (Ayres, 2003) or, in simple terms, oxidation. As stated before, a given fuel, be it wood, gas, coal etc. can never be totally converted into the desired form of use without a fraction being lost due to technological inefficiency, frictional losses etc. In the example of coal combustion, the natural resource exergy of a given amount of coal is the part of its total energy content which can be turned into heat when it is burned. Heat can be used for different end-uses: It can be consumed for direct heating purposes or used for further transformation processes (e.g. petrochemical processes, driving prime movers etc.). The remaining fraction of the total energy embodied in the fuel is transformed into frictional heat, therefore becomes unavailable to perform work and is ultimately lost. If one talks about consuming or wasting energy, exergy is the term that should actually be used (Ayres, 2003).

Exergy, which can be obtained from natural resources, theoretically exists in a highly useful form. Societies use exergy, embodied in combustible fuels as well as alternative sources of energy (such as hydro-, geothermal or solar power) to satisfy their energy needs. Unfortunately, every anthropogenic transformation process (as described above) degrades the amount of available exergy further to the point where it is of no (human) use at all. Once all transformation processes are finished, and final exergy “enters” an end-use device, it can provide a certain energy-service for societies. Only a very small fraction of the full amount of the initial exergy is really usable to provide energy-services. This share is termed useful work. Examples for the transformation of final exergy into useful work are the combustion of gas, coal etc. to provide space heating, burning of gasoline in an internal combustion engine to keep a car in motion, or the electricity to operate air conditioners, tablet computers, etc. Energy services, corresponding to the above mentioned examples are: Warmth, motion/transport, cooling, or computer programs operated on electronic devices (Brockway et al., 2015; Serrenho, 2013). Pachauri and Jiang (2008) stated what consumers want is not energy “per se” but rather the services derived from it. They further point out that ‘*energy services cannot be measured in energy units; they require many other things than energy carriers*’ (ibid., p. 18). It must be noted that this analysis stops at the stage of useful work, meaning that the amount of useful work which can provide energy services is measured. However, accounting for the actual energy services is beyond the scope of this study.

2.5.2 The Difference between Energy and Exergy Analysis

According to Serrenho (2013), “conventional” energy analyses embody several consistency problems: When examining sociometabolic systems from an energy perspective, although flows from various sources can be accounted for in homogenous units of energy (joules), these flows are only accounted for quantitatively. No statements about the quality of energy from different sources and the amount of energy wasted in transformation processes until it reaches the point of useful energy can be made. Most (but not all) energy analyses usually focus on one of the different stages (primary, final, useful) of the total energy flow within a socioeconomic system (Wall, 1986). For example, at the primary stage, only the unprocessed energy carriers entering the socioeconomic system are accounted for. In this case, neither do we know about the efficiency of transforming raw materials into forms of energy that are actually available for human use, nor can any assumptions about the efficient usage of energy in end-use devices be made.

Even when the entirety of all three stages (that is, the complete energy throughput) as Haberl (2001a) suggested, is examined from an energy perspective, various consistency problems arise: At the primary stage, energy from sources other than fuels (e.g. renewables) needs to be accounted for in a special manner (Serrenho, 2013): Primary energy from hydro power plants, for example, refers to the energy content of the resource used to generate electricity, in this case the potential energy of water driving the turbines. Primary energy from wind power stations is the kinetic energy used to move a rotor, etc. (Warr et al., 2008). Another problem arises at the final stage: final energy from divergent sources and carriers needs to be reported in different thermodynamic potentials, e.g. food and feed - internal energy; combustible fuels – enthalpy (or the product of internal energy, pressure and volume) (Serrenho, 2013). From an energy perspective, as mentioned before, the useful stage is often difficult to analyse in a consistent way, mainly due to limited data availability on technological specifications (Haberl, 2001a).

The utilisation of exergy solves these consistency problems. Exergy is not limited to describing heat transfers only, it is applicable to any form of energy, no matter what stage of conversion (primary, final, useful energy) or source of energy is considered (Zahoransky and Allelein, 2013). Ultimately, it distinguishes work from heat by measuring only potential work. Therefore it is possible to analyse the whole energy flow across all stages and energy carriers by using a single measure, namely, exergy. Consequently, the use of different thermodynamic potentials is obsolete, enabling the equal treatment of fuels and other sources of energy. Work is accounted for in a qualitative way (Ayres and Warr, 2009). In other words, exergy analyses consider the degradation of energy quality (Rosen et al., 2008; Serrenho, 2013; Wall, 1986; Wall and Gong, 2001). Therefore, the exergy paradigm is in concordance with the second law of thermodynamics. This is achieved by applying so-called "second law efficiencies" (as elaborated later in sections 2.5.1, 3.1, and 3.3), technical values representing the efficiency of given technologies to transform final exergy into useful work (Serrenho, 2013).

From a methodological point of view, the use of exergy and useful work, opposed to the energy perspective, enables us to consider technological change and transformation losses from the primary to the useful stage. Hence, one can estimate the deviation from the ideal state of the system in question, or vice versa, the potential for efficiency improvements within a socioeconomic system (Warr et al., 2008). This is a crucial point in the context of sustainability sciences: Reducing the energy throughput of societies and therefore potentially decreasing their environmental impacts is one of the main goals of policies obliged to sustainable development (Haberl, 2001b). As Rosen et al. (2008) and Rosen and Dincer (2001) pointed out, the exergy approach is a very useful concept in this respect as it offers '*a measure of the departure of the state of a system from that of the environment*' (Rosen et al., 2008, p. 132). Therefore, exergy can be used to assess, or at least provide a basis for the assessment of the environmental impacts certain technologies or energy carriers may cause. Rosen and Dincer (2001) emphasise that the concept is highly useful for interdisciplinary research, as it is applicable to a large number of scientific fields and objectives, among others sustainability sciences, ecological economics, industrial ecology, "green" technology assessment, etc.

By analysing energy flows within a socioeconomic system from an exergy perspective, the actual amount of usable (and vice versa, lost) energy for societies becomes visible (Ayres and Warr, 2009; Brockway et al., 2014a; Rosen et al., 2008; Serrenho, 2013; Warr et al., 2010; Warr and Ayres, 2010). Relating the exergy input of a national economy to its useful work output enables us to test hypotheses about whether it uses and transforms natural resources into usable energy in an efficient way or not. Further, the patterns of its overall energy use, reflecting societal states and sociometabolic transitions, as described in sections 2.2 and 2.3, can be examined.

Additionally, it has been suggested that the exergy and useful work framework acts as much more appropriate for interpreting and forecasting economic growth, instead of explaining economic development with traditional production functions (Wall, 1986; Ayres, 2003; Warr et al., 2008; Ayres and Warr, 2009; Warr et al., 2010; Serrenho, 2013). Neoclassical growth theories ignore the problem of quality degradation of energy, although the laws of physics, in particular thermodynamics, impose indisputable limits to economic transactions (Ayres and Warr, 2009). However, the link between economic growth and exergy and useful work is not a particular topic of this thesis.

2.5.3 On the History of Exergy & Useful Work Research, and State-of-the-Art

Research on exergy and useful work has a long tradition. There is a wide range of applications of the concept in various scientific fields ranging from complex system analysis over technical engineering to cryogenics, life-cycle assessments, and agricultural research. The origins of the concept of exergy lie in the nowadays entitled field of classic thermodynamics and lead back to Nicolas Léonard Sadi Carnot (1824) work about heat-engines (early steam-engines). Exergy research about technical efficiency therefore dates (at least) back to the 19th century. Years later, Josiah Willard Gibbs (1873) was the first to mention the term "available work" and to derive a concept of exergy (although it was not termed this way by then). Many different concepts and definitions have been proposed since these early pioneers but it took until the late 1960ies to formulate a mature theory. The definition used nowadays has already been mentioned in section 2.5.1. From the 1970ies on, the number of applications of the exergy concept has steadily increased. Today, there is a vast amount of literature on exergy research, from theoretical applications, efficiency measurement, sustainability research, to development of design tools, etc. (Sciubba and Wall, 2007).

A small but growing number of scientific work in the field of sustainability sciences, such as ecological economics, has been based on the concept of exergy (and useful work). Single year analyses of various economies were undertaken by different authors, among others, for the United States (Reistad, 1975), Canada (Rosen, 1992), Norway (Ertesvag, 2005), and Turkey (Seckin et al., 2012). Wall (1990, 1987) and Wall et al. (1994) conducted exergy analyses for Japan, Sweden, and Italy. In recent years, scientists have published exergy studies covering longer periods: Ayres (2003) and Ayres and Warr (2005) conducted research about the US 1900-1998, and the United Kingdom 1900-2000 (Warr et al., 2008). A comparison of Austria, Japan, UK and the US from 1900-2000 was published by Warr et al. (2010). Williams et al. (2008) examined long term exergy conversion trends for Japan from 1914-1998. Nakićenović et al. (1996) presented estimates of regional and global exergy-efficiency patterns. A twenty years analysis about resource consumption for the Chinese society based on exergy has been conducted previously by Chen and Chen (2007). Extended exergy-based ecological accounting for China 2000-2007 was conducted by Dai and Chen (2011). More recently, long term studies have been carried out for Portugal 1856–2009 (Serrenho et al., 2016), the EU-15 from 1960-2009 (Serrenho et al., 2014), and 1970–2012 (Voudouris et al., 2015), again UK and US 1960-2010 (Brockway et al., 2014a) as well as the Chinese Society from 1971-2010 with model projections until 2030 (Brockway et al., 2015). Robert Ayres and Benjamin Warr (Ayres, 2003; Ayres and Warr, 2005; Ayres and Warr, 2009; Warr and Ayres, 2010; Ayres et al., 2013), as well as Serrenho et al. (2014), among others, have undertaken a series of extended researches about the correlation between exergy, useful work and economic growth. The authors proposed that exergy instead of energy consumption acts as a productive driver for economic growth, because a large share of energy, as explained, is wasted and is hence not used productively.

2.5.4 Goals and Relevance of this work

While there exists an increasing number of studies using the exergy and useful work approach to analyse industrialised countries, only a handful of researchers have focused on so-called “developing” and/or “emerging” economies (as mentioned in section 2.5.3) e.g.: (Brockway et al., 2015; Chen and Chen, 2007; Dai and Chen, 2011). In the light of the global environmental crisis (some of the corresponding problems have been named in chapter 2), examining and understanding the transitions of these countries is of significant relevance. Observing past transitions offers important insights for both the dynamics of current socioeconomic systems as well as their further development, and provides data for future energy use model projections. In the context of sustainable development, high-density "developing" countries like India, China, etc. are of particular interest: Due to their enormous populations their future material and energy demand is expected to increase significantly, evoking severe global environmental impacts (Schandl et al., 2009; Singh et al., 2012).

The thesis at hand presents, to the author's knowledge, the first long-term exergy- and useful work analysis of the sociometabolic system of India, specifically, on the macroeconomic (national) scale. Therefore the system boundaries of this study equal the country borders. The focus of this work is to examine patterns of energy end-use as well as technological and efficiency changes within the socioecological regime. Furthermore, India's development path towards an industrial regime is analysed and compared to that of industrialised countries, and another emerging economy, China, in order to identify specific characteristics of the ongoing Indian sociometabolic transition. The sources of energy used by societies define the sociometabolic regime, according to the theories introduced in sections 2, 2.2, 2.3. The methodology is based on contemporary exergy and useful work research by Serrenho (2013) for Portugal and the EU-15, and by Brockway et al. (2015) for China. Both authors contributed to the standardisation of the exergy accounting approach based on work by Ayres and Warr (2009).

India is not a new target for researchers concerned with sustainability. There is a range of studies about this country with divergent scopes and angles. For example, Singh et al. (2012) conducted a MEFA of the biophysical economy from 1961-2008. Schaffartzik and Fischer-Kowalski (2017) compared the development paths of India and China by means of interrelations between social revolutions and energy transitions. Pachauri and Jiang (2008) and Pachauri and Spreng (2002) investigated household energy usage and transitions, also in comparison to China. By linking the concepts of social metabolism, sociometabolic regimes and transitions (sections 2, 2.2, 2.3) to the exergy and useful work approach (which is based on the MEFA framework, see 2.4), this thesis adds a new perspective to the sociometabolic research about India and fills this gap in exergy and useful work analyses. Insights into the development of exergy usage from input to final consumption to the useful work stage over a period of 41 years, as well as into technological development are revealed. Studying the entire flow from primary input to the useful stage addresses the problem of energy degradation within the socioeconomic system. Furthermore, it enables one to formulate assumptions about the efficiency improvements of conversion technologies, but also possible “rebound” (or “efficiency dilution”) effects: This refers to the phenomenon that efficiency gains of ‘*individual technologies* (…) [are] *being overtaken by using increasing amounts of less efficient processes*’ (Brockway et al., 2015, p. 893). Useful work figures represent the part of exergy available to be used for actual energy services and serve e.g. as a proxy for changing lifestyles in India. In comparison with industrialised nations, as well as with the other “emerging giant”, China, similarities and deviations in development trajectories are examined. Above all, the analysis investigates what implications can be drawn from analysing the sociometabolic transition in India from an exergy and useful work perspective.

3 Methodology & Data

3.1 Exergy and Useful Work Accounting

The methodology of this thesis is based on the before mentioned studies by André González Cabrera Honório Serrenho (2013), and by Paul Brockway et al. (2015). Both works stem from original research by Göran Wall (1990, 1987, 1986); Wall et al., (1994), and Robert Ayres and Benjamin Warr e.g.: (Ayres, 2003); (Warr et al., 2010, 2008); (Warr and Ayres, 2010); (Ayres et al., 2011), among others. André Serrenho (2013) developed a common framework for exergy and useful work mapping for International Energy Agency (IEA) data in his PhD thesis. Brockway et al. (2015), and Serrenho (2013) made further advances to the above mentioned methodology by Ayres and Warr for the mapping of electricity usage and mechanical drive applications. This scheme has been adopted for this work. Where in-country data was available, the mapping was modified to represent specific Indian end-uses. Brockway et al. (2015) methodology was used to calculate muscle work figures, as well as some of the second law efficiencies (explained in section 3.3 and Appendix 8.2). Remaining 2nd law efficiencies have also been adopted from Brockway et al. (2015).

The analysis comprises of five main steps:

1. Conversion of final energy data to primary exergy values via exergy conversion factors (see Table 2)
2. Allocation of the exergy flows of each source of energy to transformation & energy sector, and further to main economic sectors (final consumption): industry, transport, “other sectors” (agriculture, commercial & public, residential, and non-specified sector)
3. Allocation of final exergy inputs from fossil & renewable fuels to main end-use categories: Heat, Mechanical Drive, Light, Electricity, (Human and animal) Muscle Work), and respective task-levels (further subdivision of end-use categories, e.g. Heat in Low Temperature Heat, Medium Temperature Heat etc.; Mechanical drive in diesel/coal engines etc.), where possible

4. Calculation (depending on data availability) or adaption of second law efficiencies, representing technological end-use devices
5. Estimation of useful work by applying thermodynamic second law efficiencies

3.1.1 Energy Sources

Energy carriers considered here are coal, oil, natural gas, combustible renewables (& waste), electricity[8], and food & feed. Non-energy uses are not considered (Serrenho, 2013). For the full detailed mapping of final exergy from all energy commodities subsumed under each energy carrier to end-use categories derived by Serrenho (2013), see Appendix 8.1.

Sources of (non-combustible) renewable energy are solar thermal, solar photovoltaics, geothermal, hydro, wind and tide, wave and ocean. Except for solar thermal, all sources of renewable energy are used to generate electricity. The same usage was found for nuclear heat (IEA, 2015).

3.2 End-use categories & data sources

National energy supply data (production, imports, exports, stock changes, statistical differences, transfers and losses) for each energy carrier and for each economic sector of India have been obtained from the IEA for the period 1971-2012. This data set is highly consistent, easily accessible and enables good comparability with other studies/countries (Brockway et al., 2014a). It acts as the main data source for this analysis. Data from the IEA (2015) are usually available in the form of final energy and are already converted into units of Terajoule (TJ).

Human population and livestock data have been obtained from the Food and Agriculture Organization of the United Nations (FAO) (2015a) and the World Bank (2016) and replenished with national census data (Krishi, 2003). Food & Feed are the sources of energy for human and animal muscle work. However, for the calculation of exergy and useful work from food & feed, the procedure was more complicated than for the remaining energy carriers, where a straight-forward allocation of IEA data is possible. The detailed procedure is described in section 3.2.1.5.

[8] Figures of electricity can, by definition, only be reported in the form of final energy. This energy carrier comprises of all the electricity generated from various other energy sources within the transformation sector, which is then delivered to the point of final use (e.g. lightning, mechanical drive etc.) (IEA, 2004).

To calculate exergy values from final energy data, exergy conversion factors obtained from Brockway et al. (2014a) were applied to each source of energy:

Table 2: Exergy conversion coefficients

(Brockway et al., 2014b), References adapted

Energy source	Exergy inflow coefficient	Notes & References
Coal & coal products	1.088	Taken from (Ayres and Warr, 2009) Table 3.1 expanded from (Szargut et al., 1988)
Natural Gas	1.04	
Oil & oil products	1.07	
Combustible renewables (e.g. traditional biofuels)	1.15	
Nuclear	1.00	• (Warr et al., 2010, p. 1910 Table 2) – this is the assumed coefficient to convert uranium into nuclear fuel. • IEA data assumes 0.33 conversion from electricity to starting TPES energy value. • Power station conversion loss factor (~0.33) occurs after this point, so nuclear fuel to electricity factor [is]~0.33
Hydro	0.85	• (Warr et al., 2010, p. 1910 Table 2) – this is the assumed coefficient to convert inflow of energy sources into electricity, delivered to point of use • IEA data assumes 1.00 conversion from renewable electricity to starting TPES energy value. • Hydro - Pumped storage taken as same factor as natural flow hydro, as energy to pump water re-appears in energy used by own sector
Geothermal	0.35	
Solar photovoltaics	0.07	
Solar thermal	0.10	
Tide, wave and ocean	0.07	
Wind	0.15	
Other sources	0.10	

3.2.1 End-use classes

Exergy flows from each economic sector are then allocated to five main end-use classes, according to the end-use mapping done for China by Brockway et al. (2015), which is a modified version of Serrenho's (2013) original IEA mapping. Where possible, specific national data was used to derive Indian end-use data, provided mostly by the Tata Energy Research Institute (2006).

3.2.1.1. Heat

Heat is subdivided into 5 different sub-categories: High (HTH), Medium 1 (MTH1), Medium 2 (MTH2), Low 1 (LTH1) and Low Temperature Heat 2 (LTH2). This is a common procedure in exergy and useful analysis and arises because of the fact that temperature of the environment surrounding the system in observation has a significant influence on second-law efficiencies (Serrenho, 2013).

High Temperature Heat is used for industrial purposes requiring temperatures of 550°C and above (Krishan et al., 2013). These processes occur mainly in the Iron & Steel industry. Medium Temperature Heat category (MTH) is divided into two sub categories: MTH1 is used in industry mainly as process heat (ammonia production/petrochemical industry, coal coking etc.) and ranges from 250°C to 550°C (Krishan et al., 2013; Energy and Resources Institute New Delhi, 2009). Medium Temperature Heat 2 (MTH2) is ranging from 100 up to 250°C, with a majority of thermal processes requiring a maximum of 150°C within various industry sectors such as paper & pulp, food processing, dairy, textile industry, hotels, (marine) chemicals, bulk drugs, distilleries and breweries etc. In these sectors, heat is provided mainly by boilers in the form of either steam or hot air (Energy and Resources Institute New Delhi, 2009). The last heat category is Low Temperature Heat, further subdivided into 2 subcategories: Low Temperature Heat 1 (LTH1; 100°C) is used mainly for cooking purposes (e.g. heating water) and Low Temperature Heat 2 (LTH2; 20°C) for space heating. Due to India's hot climate the fraction of exergy used for LTH2 is almost negligible (Brockway et al., 2015; van Ruijven et al., 2011).

3.2.1.2. Mechanical Drive

All exergy inputs to mechanical work end-uses are subsumed under this group. Sub-categories are distinguished by type of engine, vehicle and input (e.g. coal for steam locomotive, diesel for cars, electricity for electric trains). Derived from the IEA-end use mapping framework by Serrenho (2013) and Brockway et al. (2015), replenished with in-country data from Tata Energy Research Institute (2006), the following categories were used: diesel /petrol/LPG/biodiesel/biogasoline ground vehicles, steam powered trains, diesel trains, electric trains, diesel boats, diesel tractors, aviation/jet fuel engines, stationary industrial diesel motors, and stationary industrial electric motors and agricultural pumps.

3.2.1.3. Lighting

The category light consists of all exergy inputs (oil and electricity) used for illumination purposes. Nowadays, in industrialised countries lighting is provided by electricity in the majority of cases. Oil products for illumination were used up until the beginning of the 20th century (Serrenho, 2013). However, for most developing countries these data do not fit. Besides electricity there is still a large portion of Indian households relying on kerosene as primary fuel for lighting, especially in rural areas. Although 87.6% of urban households use electricity for lightning, the percentage of all Indian households (urban and rural) is only as high as about 56%. In rural areas, nearly 60% use kerosene for lighting (Bhattacharyya, 2006).

3.2.1.4. Electricity

According to Serrenho (2013), this category includes all electric end-uses other than mechanical drive, lighting and process heat that occur in the industrial, transport, agricultural, commercial & public, as well as residential sector. Exergy from electricity for lighting, process heat, and all mechanical drive uses (Static motors and pumps of all types) were allocated to the respective end-use categories (Heat, Lighting, and Mechanical drive) (ibid.). The allocation of the remaining, in this thesis termed "direct" electricity end-uses, was more complex than for the other categories. This category includes the following end-use devices: cooling/heating appliances (fans, air coolers, space heaters, and related technologies), air-conditioners, refrigerators, and "other electric uses" (including entertainment devices such as TVs, stereos and related, as well as Computers and telecommunication tools, and other electronic equipment) (Boegle et al., 2010; Nadel et al., 1991).

Due to the growing importance of electricity (McNeil et al., 2008; McNeil and Letschert, 2008), especially in the residential sector, and the divergent efficiencies of appliances, electricity uses have been further divided into different sub-categories for each sector, when 2nd law efficiencies where available. For example, refrigeration, air-conditioning, and others, have been disaggregated separately for each sector in which they appear (Tata Energy Research Institute, 2006; Brockway et al., 2015; de la Rue du Can et al., 2009).

3.2.1.5. Muscle Work

The last category represents the ability of humans and draught animals to convert exergy embodied in food and feed into useful manual (mechanical) work. For this category, the approach was different than for previous useful work categories.

In contrast to industrialised countries, manual work (especially from draught animals) still plays a crucial role in India (Serrenho, 2013; Ayres and Warr, 2009). In the 1980ies, animal still provided 99% of the power used in Indian agriculture sector (Ramaswamy, 1998). As stated by Vaidyanathan (1986) almost 80% of activities in agricultural production in the late 1980ies could be accounted for under manual labour (such as ploughing, harvesting, weeding etc.).

Agriculture is still the biggest sector of employment in the Indian economy (Roy, 2002). Although there has been a shift in employment away from agriculture to services (rather than to manufacturing), still more than 50% of all workers in India are engaged in agricultural activities and almost 20% in industry (including mining & quarrying, construction, manufacturing, electricity, gas and water) (Mitra, 2008; Bosworth and Collins, 2008).

Due to absence of detailed numbers on actual manual labour population, statistical data from World Bank's online data base on employment in agriculture and industry were obtained. The World Bank (2016) defines as '*persons of working age who were engaged in any activity to produce goods or provide services for pay or profit, whether at work during the reference period or not at work due to temporary absence from a job, or to working-time arrangement*'.

The agricultural sector is defined as comprising of '*activities in agriculture, hunting, forestry and fishing, in accordance with division 1 (ISIC 2) or categories A-B (ISIC 3) or category A (ISIC 4)*' (The World Bank, 2016).

Industry, as defined by the World Bank, consists of following activities: '*mining and quarrying, manufacturing, construction, and public utilities (electricity, gas, and water), in accordance with divisions 2-5 (ISIC 2) or categories C-F (ISIC 3) or categories B-F (ISIC 4)*' (The World Bank, 2016).

Unfortunately, data for employment in agriculture and industry were only available for the years 1994, 2000, 2005, 2010 and 2012 (The World Bank, 2016). Missing data have been estimated using simple linear interpolation (see equation 1):

$$Pn = P_1 + (P_2 - P_1) * \frac{(x_{1+t} - x_1)}{x_2 - x_1}$$

x_{1+t} *... time in years elapsed since base year*

Pn *... estimated population*

x_1 *... base year*

x_2 *... end year*

P_1 *... population at base year*

P_2 *... population at end year*

Equation 1: Manual labour - linear interpolation for missing years

For the remaining years 1971-1994, data have been extrapolated according to equation 2.

$$P_{t+x} = P_t * (1 + \frac{r_{t,t+n}}{100})^x$$

x … difference between base point of observed period $_t$ and extrapolated period $_{t+x}$ in years

P_t … population at base year of observed period

P_{t+x} … population at end year of extrapolated period

$r_{t,t+n}$ … annual rate of change of observed period

Equation 2: Manual labour - extrapolation of population for missing years

(Giffinger et al., 2011)

Given the dimension and importance of manual labour in India and taking into account evidence from literature (especially in agriculture) (Ramaswamy, 1998), this procedure seemed more exact and plausible than simply basing the manual labour share on overall working population figures (including service sector). However, it must be noted that this approach cannot depict reality as good as detailed data on manual labour could, as Brockway et al. (2014a) used in their study. Calculation of exergy input and useful muscle work for humans follows Brockway and colleagues' (2014) approach for US & UK (see Equations 3a) & b) below).

a) $$Exergy\ input\ (TJ) = \left(\frac{M*A}{P*F}\right) * (Y * P) * 1000$$

b) $$Useful\ work\ output\ (TJ) = Ay * E * C * M * 1000$$

M… Manual labour population

P … Total population

Y … Total appropriated phytomass for South & Central Asia (GJ/cap/year)

*F … Total daily food supply (kcal/cap/day) * food wastage factor*

A … Additional calorie intake for manual work (kcal/cap/day)

Ay … Additional energy intake/year for manual work (GJ/cap/year)

E … Gross energy from food end use to metabolisable energy ratio

C … Conversion efficiency from exergy input to useful work output (13%)

Equation 3a) and b): Manual labour exergy input and useful work output

(Brockway et al., 2014a), edited

Manual worker population (**M**) is based (as described above) on employment figures in the primary and secondary sector plus estimated values (as described above). Total population (**P**) has been obtained from Food and Agricultural Organisation (FAO, 2015b). Total appropriated phytomass (**Y**) is taken from Wirsenius (2000): 30.24 GJ/capita for South & Central Asia. (**F**) represents the Total Food Intake/Capita with data from FAO (2015a), multiplied with wastage factor evolving from 0.9 in 1960 to 0.65 in 2010 from Wirsenius (2000) and Ayres and Warr (2009). Additional calorie intake for manual workers (**A**) is 500 kcal/day, resulting in an additional energy intake (**Ay**) of 0.76 GJ/year. Values for food end use per capita conversation ratio for gross energy to metabolisable energy (**E**) for South and Central Asia (in MJ/cap & day) were again obtained from Wirsenius (2000, Table 3.3): Metabolisable energy 9.9/gross energy 11.4 = 0.8684. The conversion efficiency of humans to transform food into useful muscle work (**C**) is 13%, based on Smil (2002). Statistical data on draught animal population was obtained from the Department of Animal Husbandry, Dairying & Fisheries (Krishi, 2014, 2010, 2005, 2003). Draught animal census in India has been conducted every five years until 1997, afterwards in varying timeframes, resulting in available data for the years 1972, 1977, 1982, 1987, 1992, 1997, 2003, 2007, 2012. Missing data have again been interpolated using equation 1. Species used for agricultural work are Cattle, Buffaloes, Yaks and Mithuns (also known as Gayals), Horses, Ponies, Mules, Donkeys and Camels (Singh, 1999). Draught animals in India perform manual work in various tasks such as field work (pulling ploughs), transportation (as pack animals e.g. cart carrying, sledge pulling), as power providers for prime movers (for water pumps, cane and seed crushers, electricity generators), and forestry (e.g. moving of timber) (Ramaswamy, 1998).

Calculation of exergy input (feed) and useful muscle work output from draught animals required several steps: First, energy input figures in form of species-specific feed intake per head and day were calculated, based on the number of working animals, body weight and daily energy inputs in kilocalories (kcal) (Henriques and Lunds universitet, 2011). Animals used for field work in India vary strongly in size, fodder requirement and work output compared to e.g. European draught animals. For example, Indian cattle and buffaloes are smaller in size and are treated poorly in terms of feed quality and quantity (Ramaswamy, 1998), hence their feed requirement as well as power output is less than that of draught animals in industrialised countries (Singh, 2000; Smil, 1994). Average weight values for Indian working animals from different sources are presented in Table 3.

Table 3: Species in Indian Agriculture used for muscle work, and their average body weights

Species	Average Weight (rounded)	Source
Cattle	450 kg	(Phaniraja and Panchasara, 2009)
Buffaloes	450 kg	(Phaniraja and Panchasara, 2009)
Yaks	286 kg	(Wiener et al., 2003), (Bakari et al., 1999)
Mithuns	368 kg	(Bhusan et al., 2005)
Donkeys	275 kg	(Smil, 1994)
Mules	475 kg	(Smil, 1994)
Camels	600 kg	(Khanna et al., 2004)

Next, aggregation of exergy inputs and useful work outputs from divergent animals required conversion of different species into equal units. Henriques and Lunds universitet (2011) estimated the primary energy consumption (feed) of various species in daily fodder units by converting all animals into “horse equivalents” (E.g. 1 mule = 1 horse, 1 ox = 2/3 horse, etc.) (Kander and Warde, 2011). Table 4 presents the daily metabolisable energy of draught animals (adjusted for India) in fodder units:

Table 4: Daily fodder units, related to body weight in horse equivalents. 1 daily fodder unit = 3000 kcal

(Henriques and Lunds universitet, 2011), modified for India

Weight (kg)	Cattle/Buffaloes/Yaks/Mithuns	Horses/Mules/Camels	Donkeys
300	4,2	4,7	3,5
400	5,6	6,2	4,7
500	7	7,8	5,9
600	-	9	6,8

Due to their similar feed requirements (Dikshit and Birthal, 2010) and (daily) work performance (Anne Pearson, 1989), cattle & buffaloes were combined in one category. Yaks and Mithuns were, in the absence of detailed data on feed requirement, and taking their physical and evolutionary similarities (Wiener et al., 2003) into account, also subsumed under cattle & buffaloes. Intake of camels was assumed to be equal to horses and mules, according to Dikshit and Birthal (2010) procedure. Fodder units (Table 4) for working animals have been converted into kcal/day. The average number of working days per year for draught animals varies greatly among the publications listed below, since seasonal climatic fluctuations and the rural/urban split have a significant effect on average numbers. Thus, published figures from Brockway and colleagues’ (2015), Phaniraja and Panchasara (2009), Copland (1987), Pearson and Dijkman (1994), Ramaswamy (1998) were weighted, resulting in an average of

130 working days per year. Feed requirement for the remaining 235 idle days was calculated using data from Pearson and Dijkman (1994). Based on Henriques and Lunds universitet, (2011) and Serrenho's, (2013) formulae, equation 4a for feed input for working animals has been derived:

$$Feed\ exergy\ input = \left(130_d * h_s * \left(\frac{kcal}{day_{sw}}\right)\right) + \left(235_d * h_s * \left(\frac{kcal}{day_{si}}\right)\right)$$

d ... *days*

h_s ... *heads of animal s*

$kcal/day_{sw}$ ... *energy requirement of working animals per day based on species and body weight*

$kcal/day_{si}$ ... *energy requirement of idle animals per day based on FAO feed data*

Equation 4a: Feed exergy input of draught animals per year and species

(Henriques and Lunds universitet, 2011), (Serrenho, 2013)

The next step was to calculate useful work muscle output. Feed to useful work conversion efficiency factor of draught animals is 4%, according to Ayres and Warr (2009). This factor has been applied to the aggregate feed exergy input for working animals for 130 working days, producing equation 4b (derived from equation 4a). Results have been converted into units of terajoule via kilocalorie to kilojoule conversion factor of 0.238, provided by the IEA (2004).

$$draught\ animals\ useful\ work = \left(\left(130_d * h_s * \frac{kcal}{day}_{sw}\right) * c\right)$$

d ... *days*

h_s ... *heads of animals per species*

c ... *feed to useful work conversion factor (Ayres and Warr, 2009)*

$kcal/day_{sw}$ ... *energy requirement of working animals per day based on species and body weight*

Equation 4b: Useful work output of draught animals per year and species

Derived from Equation 4a; (Henriques and Lunds universitet, 2011), (Serrenho, 2013)

3.3 Second law efficiencies

Useful work figures for all end-use categories except muscle work can be calculated if one takes into account time-dependent technological efficiency values. These so-called second law efficiencies reflect the ability of end-use devices to transform final energy into useful work. As described in section 2.5.1, useful work is the small fraction of total exergy available for human use.

Since technologies differ dramatically throughout world regions, efficiency values need to be adapted to the development status of the country (or any other unit of analysis) in question. In recent exergy and useful work publications (e.g. Brockway et al., 2014b; 2015; Serrenho et al., 2014; 2016; Warr et al., 2008; 2010), authors have either used published figures or estimated own efficiencies. For this thesis, a mixed approach has been chosen: First, the most important end-use categories have been identified. Then, depending on the availability of in-country data, specific 2nd law efficiencies for these end-uses have been calculated. Remaining efficiencies have been obtained from Brockway and colleagues' (2015) China study.

Several studies by the IEA, and by Indian and international authors provide a limited amount of information on efficiencies on various scales, ranging from whole sectors to end-use devices: Unfortunately for this study, only heat efficiencies (High, Medium Temperature 1 & 2, and Low temperature heat 1) have been estimated, due to data availability. Nevertheless, given the huge similarities in China’s and India’s development path, adopting Chinese values seems to be a legit approach.

For a full list of second law efficiencies, and in-country modifications and references, see Appendix 8.2.

4 Results

This section starts with an overview of the total primary & final exergy figures, followed by a description of the transformation sector & own energy use in the energy sector. Next, detailed results of the exergy inputs and respective fields of application for each energy carrier & other sources of energy are presented. The final section gives insights into useful work figures according to the five end-use categories, as well as the respective, and aggregate exergy efficiencies.

4.1 Primary Exergy Input - Overview

The IEA (2015) provides detailed data on energy supply from natural resources (domestic production, imports, exports, statistical differences, international bunkers, transfers, losses), as well as a sector-wise breakdown of all energy flows within a socioeconomic system. Total Primary Energy Supply (TPES), an indicator commonly used in the MEFA framework (see section 2.4), comprises of the sum of domestic extraction (production) and imports, transfers, and stock changes, minus exports, international marine, and aviation bunkers (IEA, 2004). It normally covers all energy carriers except (food & feed) biomass, and is usually applied on the country-level (Fischer-Kowalski et al., 2014).

Total Primary Energy Supply is the starting point for this analysis. Exergy coefficients (section 3.2) were applied to the energy flows reported by the IEA (2015) in order to gain primary exergy inputs. Additionally, food & feed inputs for muscle work by humans and draught animals were calculated according to the methodology elaborated in chapter 3.2.1. Figure 2 covers the total amount of primary exergy supplies differentiated by source of energy. In the next step these supplies are delivered to the transformation sector as well as to final consumption, which is differentiated by main economic industries, households, public sectors etc., as defined by the IEA (2016): own use in the energy sector[9], industry (iron & steel, chemical and petrochemical, non-ferrous metals/minerals, machinery, mining and quarrying, food & tobacco, paper, pulp and printing, wood and wood products, construction, textile and leather, non-specified industry), transport (road, rail, pipeline transport, domestic

[9] Exergy inputs into the energy sector represent the amount of exergy that is used within the energy industry for providing its energy services that is for purposes other than electricity generation. These inputs can be allocated to end-use categories according to section 3.2.1, e.g. providing light and heat as well as other purposes. Therefore, in the total energy balance, exergy used in the energy sector can be added to final consumption categories.

navigation/aviation), and "other sectors" (agriculture & forestry, commercial and public services, residential, and non-specified other). The results describe aggregate exergy inputs available for transformation & final (human) energy consumption in India. Energy sector's own use, and exergy required for transformation processes and electricity production within the transformation sector are analysed in detail in section 4.2.

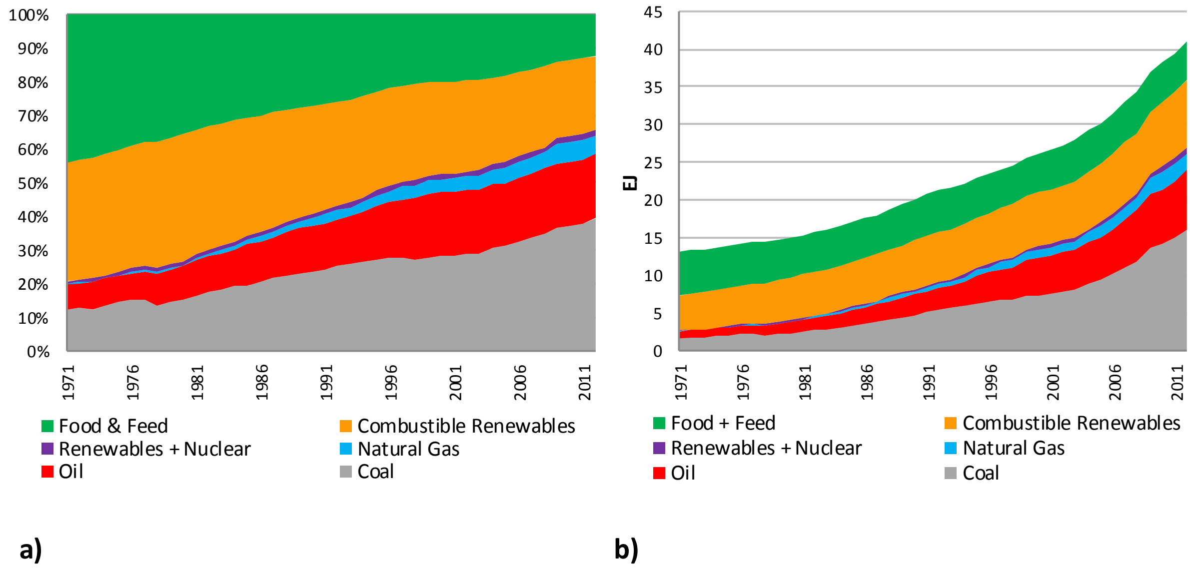
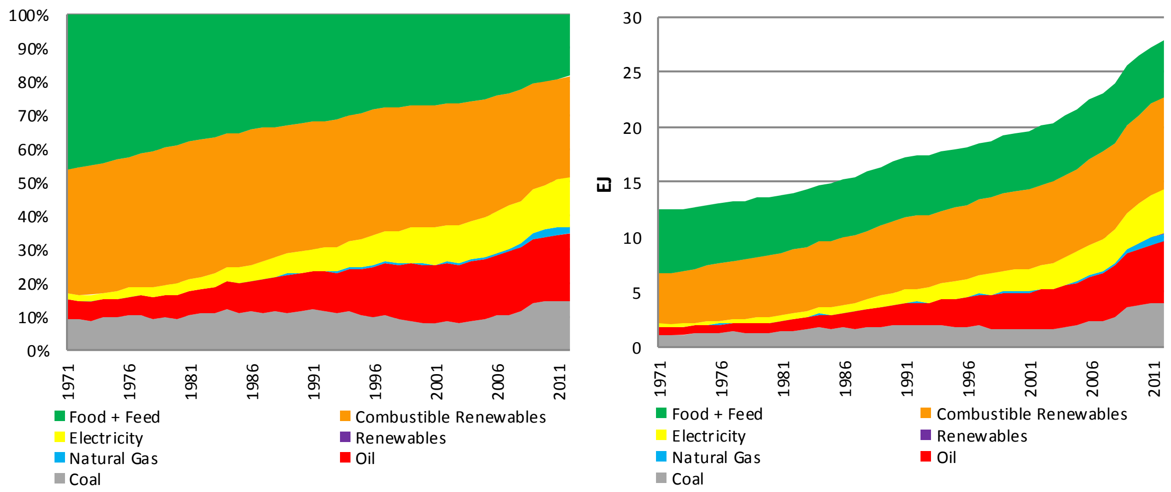


Figure 2: Total primary exergy supply in a) Shares of total and b) Absolute numbers in Exajoules (EJ); India 1971–2012

Own calculations based on IEA (2015)

Aggregate primary exergy rose from 13 EJ at the starting point of the analysis to a total of 41 EJ in 2012, a more than three-fold increase. As Figure 2a) and b) illustrate, combustible renewables (firewood, etc.) together with food & feed biomass for human and animal manual labour were the most dominant sources of primary exergy in India at the beginning of the observed period. In 1971, together they accounted for around 80% of the total exergy input. During the 41 years studied, a gradual shift away from primary biofuels to fossil fuels can be observed. Coal has become by far the most dominant fossil energy carrier in India. Its share has increased significantly during the whole analysed timeframe, from slightly above 10% (or more than 1.6 EJ) in 1971 to 37% (or 16 EJ) in 2012, except for two short phases of decline and stagnation at the end of the 1970ies and again at the end of the 20th century. A large share of total primary coal input (from 23% in 1971 to 71% in 2012) has been used for electricity generation (see also 4.2). Heavy industries like the iron & steel sector also have a high demand for coal, as will be explained in detail in section 4.3.7. The share of oil in total primary exergy (6% in 1971, 14% in 2012) has been stagnating since 1998 while the share of natural gas grew from 0.1% at the beginning of the observed period to a maximum of 5% in 2010. Since then, its share has been declining to 4% in 2012. At the end of the 1980ies, primary exergy provided by natural gas exceeded primary exergy provided by renewables and nuclear power (at that time around 1% of the total primary exergy supply, or 0.20 EJ). The Indian government undertook several efforts to increase power output from nuclear plants and renewables (Tata Energy Research Institute, 2006). In 2007 plans were presented to achieve energy independence (“self-sufficiency”) by increasingly using domestic alternative sources of energy such as thorium, hydrocarbon, and renewables (Ahn and Graczyk, 2012). Despite growing shares and absolute numbers in total primary exergy, renewables still play a minor role compared to fossil, and traditional fuels (biomass, e.g. firewood). Renewables share in the total primary exergy input grew from 0.6% in 1971 to slightly above 1% in 2012 while the share of nuclear energy rose from 0.1% to 0.8%, respectively.



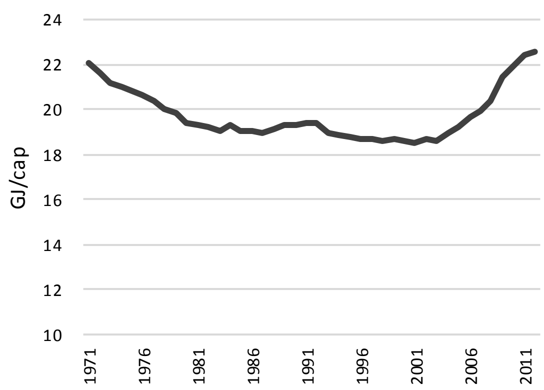
a) b)

Figure 3: Final exergy consumption by source of energy. a) Shares of total. b) Absolute numbers in Exajoules (EJ); India 1971–2012

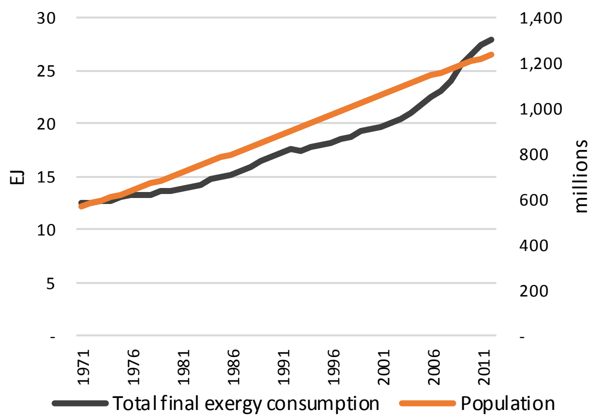
Own calculations based on IEA (2015)

Figure 3a) and b) show final exergy consumption in India in shares of total and absolute values, after transformation processes like electricity production, crude oil refining etc. took place. Therefore, final exergy inputs for the Indian economic sectors are obviously smaller in quantity than initial primary values presented in Figure 2b). Especially in the last decade of the analysed timeframe, a huge amount of primary exergy has been used within the transformation & energy sector. This share rose from 5% in 1971 to 32% in 2012. As already mentioned, this is especially true for coal, of which the largest part of primary exergy is used for electricity production (23% in 1971, 71% in 2012). Therefore, although primary exergy values of coal have been constantly increasing, its share in final exergy has been more or less constant at

10% throughout the whole period. As a result absolute numbers for final electricity increased 18-fold since 1971 (from 0.24 EJ to above 4 EJ in 2012), as shown in Figure 3b). The growing demand for electricity is driven by household electrification efforts, enforced by the government since the 1970ies (Das and Paul, 2013), the increasing substitution of biofuels by electricity (especially for lighting), and rising affluence levels resulting in, among many other aspects, a growing demand for electrical appliances, most notably in urban households (Hubacek et al., 2007; Pachauri and Jiang, 2008).



4)



5)

Figure 4: Per-capita final exergy consumption. Absolute Numbers in Gigajoules (GJ); India 1971-2012.

Figure 5: Population and total final exergy consumption. Absolute numbers, Population in millions (primary axis); Exergy in Exajoules (EJ) (secondary axis); India 1971-2012.

Own calculations based on IEA (2015). Population data derived from FAO (2015b)

Final per-capita exergy consumption, as shown in Figure 4 declined from almost 22 GJ/cap in 1971 to around 19 GJ/cap in 1983, remained at this level until 1992, decreased again to slightly above 18 GJ/cap in 2001 and levelled of thereafter (to above 22 GJ/cap in 2012). This trajectory can be explained by two main reasons: First, it reflects the overall decline of feed input for working animals during the whole period, and the decline of food for manual workers until 1995, which together accounted for 46% of total per-capita final exergy consumption in 1971 (and still 18% in 2012). Second, total final exergy inputs grew at a lower rate than population (which increased almost linear during the observed period, as depicted in Figure 5). This is attributable to the economic situation in India at that time: After independence the country, following the example of the Soviet Union, adopted many elements of socialist economies, e.g.: centralised 5-year planning, rigorous state regulations etc. This lead to various economic problems during the 1970ies and early 1980ies: An inefficient agricultural sector faced higher than ever before population growth. Due to the state ownership of most sectors, private firms were confronted with high taxes and regulations. Industrial export goods were increasingly less successful on the international markets. Reforms, aiming to turn India into a modern, self-reliant economy, reduce poverty, increase privatisation, foreign direct investment, and stimulate economic growth were proposed by the Rajiv Gandhi administration in the mid 1980ies but it took until the early 1990ies before these reforms were finally applied. The Indian financial crisis of 1991/1992 was a strong incentive for the new administration under Narasimha Rao to take immediate action. Large-scale deregulation, privatisation and liberalisation took place, which lead to steep economic growth since around the year 2000 (Ahn and Graczyk, 2012; Bronger and Wamser, 2005).

4.2 Transformation & Energy Sector Own Use

4.2.1 Transformation Sector

The transformation sector covers all '[t]*ransformation processes* (…) *of primary forms of energy to secondary and further transformation (e.g. coking coal to coke, crude oil to oil products, and fuel oil to electricity)'* (IEA, 2004, p. 12). The transformation sector demands continuously growing quantities of various sources of energy, especially of fossil origin. While in 1971 the sum of all exergy inputs (of all energy carriers) into the transformation sector were as high as 2 EJ, in 2012 they had already increased to 26 EJ. This corresponds to approximately 16% of all primary exergy inputs in 1971, rising to 58% in 2012.

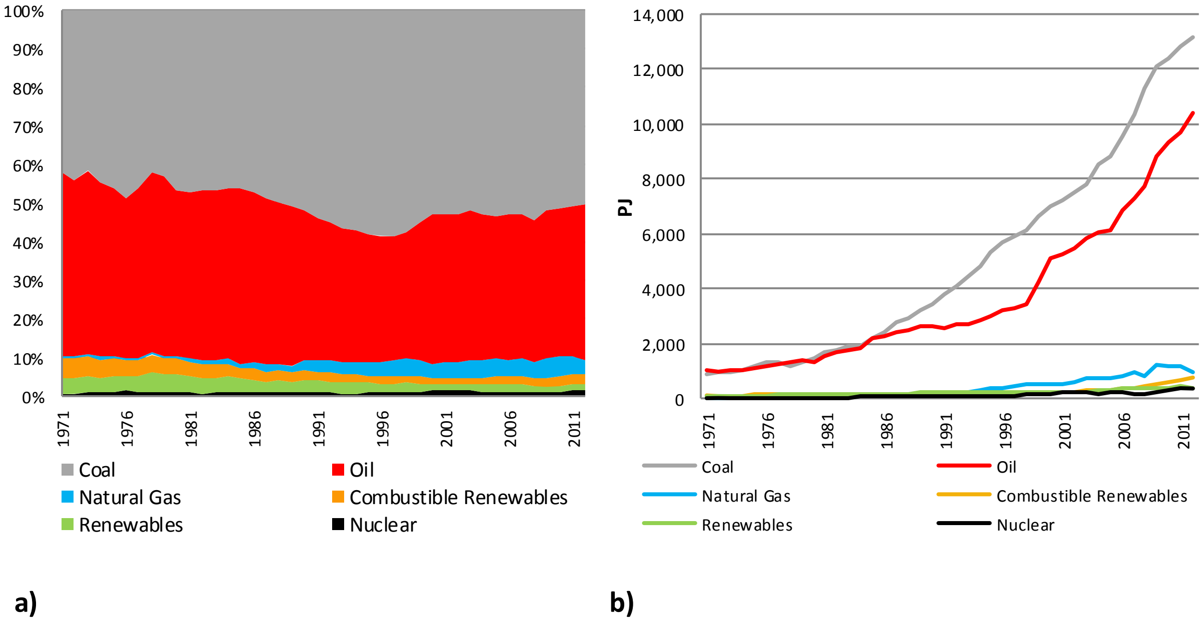


Figure 6: Exergy input for transformation per source of energy. a) Shares of total. b) Absolute numbers in Exajoules (EJ); India 1971–2012

Own calculations based on IEA (2015)

Overall, the dependence on fossil fuels is very high within the sector, as can be seen in Figure 6a) and b). Throughout the whole period, between 80-90% of all inputs for transformation processes stemmed from oil, coal and natural gas. At the beginning of the studied period, with 48% of all exergy inputs to the transformation sector, oil was the most dominant energy carrier in this sector but has been overtaken by coal in 1974 (Figure 6a). As visible in Figure 6b, from 1971 until 1987 absolute inputs of coal and oil remained roughly at the same level (from 897 and 990 PJ, respectively to 2,500 PJ). From this year onwards, coal emerged as the dominant input fuel to the transformation sector both in absolute and relative numbers. Figure 6a) shows that the share of oil, on the other hand, decreased until around 1995, increased again afterwards but stayed at a lower level than coal ever since (around 40%). Both the share and absolute values of natural gas inputs to the transformation sector have increased during the observed period from 1% (10 PJ) in 1971 to 4% (970 PJ) in 2012. The share of combustible renewables has decreased from 5% in 1971 to 2% in 2009, rose again by 1% during the next year, and remained like this until 2012. In absolute terms, the quantity of combustible renewables used in the transformation sector has constantly risen from 110 PJ at the beginning of the studied timeframe to 760 PJ in 2012, an almost 7-fold increase. A similar trajectory can be observed for other renewables (hydro, wind, solar photovoltaic), of which inputs in absolute terms increased constantly, from initially 90 PJ to 400 PJ in 2012. On the other hand, their share in total exergy input into the transformation sector declined by half, from 4% to 2% during the studied period. The share of Nuclear power stayed at 1% from 1971-2012, which represents an increase in absolute numbers from 10 to 360 PJ.

As stated above, solid fuels and other energy carriers are used for various transformation processes within the transformation sector. Kinetic energy from hydro power and wind plants, as well as hot steam from nuclear power plants, and solar-photovoltaic panels are used exclusively for electricity generation. Coal, oil, natural gas, and in recent years, combustible renewables (since 1999 primary solid biofuels, since 2003 municipal waste, and since 2007 bio-gas) serve as fuels for electricity production in thermal power plants (IEA, 2015). Additionally, varying fractions of coal, oil, and primary solid biofuels are used for several transformation process apart from electricity production:

4.2.2 Transformation Processes

The largest share of crude oil in India (varying shares between 89%-97% in the years studied) is transformed inside oil refineries into secondary petroleum products such as liquefied petroleum gas (LPG), naphta, gasoline, jet fuel, bitumen, refinery gas etc. (IEA, 2004). Besides electricity production, coal is used in several transformation processes: In coke ovens, coking coal is turned into coke oven coke, and bituminous coal is transformed into gas works gas. These two products are used in blast furnaces to produce blast furnace gas. In BKB[10] (Brown coal briquettes) plants, lignite is used to gain brown coal briquettes (IEA, 2004). While these transformation processes (coke oven coke, blast furnace gas, brown coal briquettes production) used 32%, 24%, and 1% of the total coal exergy input into the transformation sector in 1971, these shares had declined to 7%, 5%, and 0.2% respectively in 2012. From 1971-1999, the only combustible renewables used in the transformation sector were primary solid biofuels, of which 100% were turned into charcoal in charcoal production plants.

4.2.3 Electricity Production

Demand for electricity has increased substantially during the observed period. Final electricity consumption had increased from 240 PJ (or 0.2 EJ) in 1971 to over 4,000 PJ (or 4 EJ) in 2012 (see Figure 3b). A large amount of the country's electric power generation is based on fossil fuels (82% in 1971, 91% in 2012), especially on coal (and to a lesser degree on oil, natural gas, renewables, nuclear, and combustible renewable biofuels). Figure 7 shows total electricity production by shares of these energy carriers. The shares of coal, natural gas, and combustible renewables used for electricity production have increased against the shares of other renewables and oil, while the share of nuclear remained relatively unchanged. Coal has been the dominant energy source for electricity production since the 1970ies, both in absolute numbers and shares: Its share in total exergy input for electric power generation grew from over 65% (370 PJ) in 1971 to 81% (almost 12,000 PJ) in 2012 (Figure 7). The shares of exergy inputs from renewables, and oil for electricity production have decreased from 1971-2012 (16% to 3%, and 13% to 3% respectively).

[10] The origins for the abbreviation "BKB" for brown coal briquettes plants stems from the German term "**B**raun**k**ohle**b**riquettes".

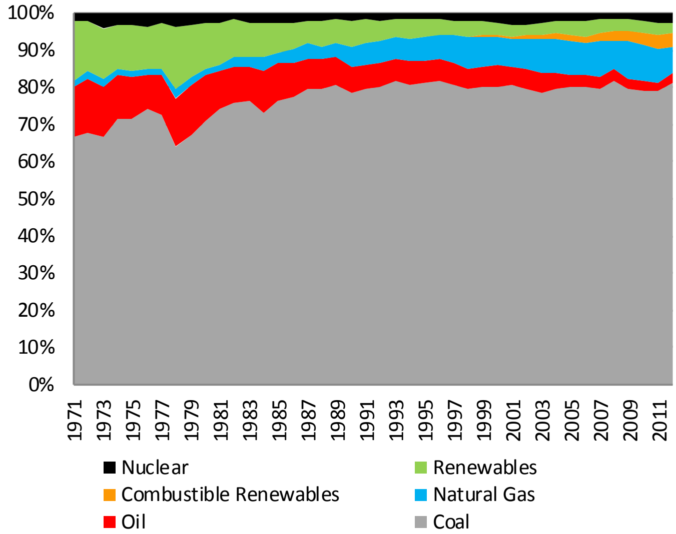


Figure 7: Shares of exergy inputs by source of energy in total electricity production. India 1971-2012

Own calculations based on IEA (2015)

However, in absolute terms, exergy inputs from renewables for electricity production have grown more than 4-fold, from 90 PJ in 1971, to 400 PJ in 2012, and 5-fold in the case of oil, from 70 PJ to 360 PJ, respectively. Compared to 11,480 PJ of coal used for electric power generation, this is relatively low. While the contribution of nuclear power, as mentioned above, stayed almost constant at around 3%, in absolute terms it increased from 10 PJ to 360 PJ during the years studied. The share of natural gas has increased from 2% in 1971 to 10% in 2010, and decreased to 7% in 2012. Combustible renewables' share in total electricity production has increased from 1% in 2000 to 4% at the end of the observed timeframe.

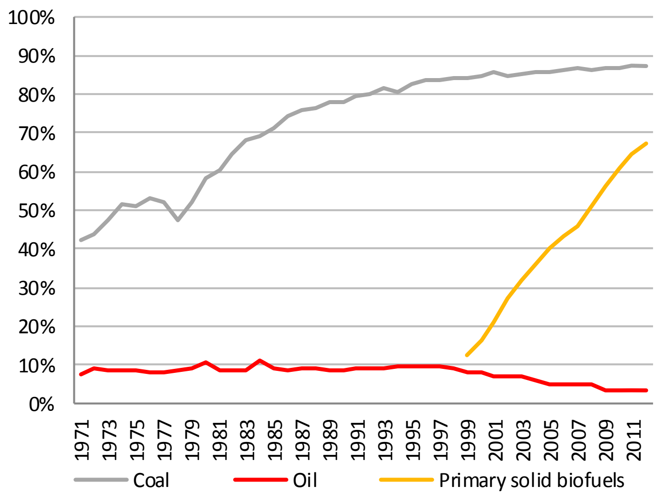


Figure 8: Solid and liquid fuels, shares for electricity production in total use in the transformation sector. India 1971-2012

Own calculations based on IEA (2015)

Figure 8 shows the shares of solid and liquid fuels used for electricity production against other uses inside the transformation sector, as described in section 4.2.2. Renewables, nuclear, and natural gas are excluded from Figure 8 because they are exclusively used for electricity production within the transformation sector. As mentioned before, the main share of total coal inputs to the transformation sector is used as fuel for electricity production in thermal power plants (1971: 42%, 2012: 87%). From the mid 1980ies until 2010, this share almost stabilised due to the increased use of natural gas and combustible biofuels for electricity generation. The share of oil, after stagnating around 10% from 1971 until 1996 has decreased constantly ever since, to 3% in 2012. Combustible renewables, as mentioned before, are used for electricity production at an increasing rate: The share of primary solid biofuels (e.g. wood chips, and pelleted wood fuel) used for electricity production has accelerated substantially from 12% in 1999 to 73% in 2012 (The remaining share is used in charcoal production). Other combustible renewables (biogas and municipal wastes, as defined in section 4.3.2) are used exclusively for electric power generation in the transformation sector.

4.2.4 Energy Sector

Energy sector's own use represents the amount of exergy consumed within electricity, heat and charcoal production plants. This sector '*covers the amount of fuels used by the energy producing industries (e.g. for heating, lighting and operation of all equipment used in the extraction process, for traction and for distribution). It includes energy consumed by energy industries for heating, pumping, traction and lighting purposes*' (IEA, 2016, p. 12). The energy sector is powered by inputs from coal, oil and electricity. Altogether, its exergy consumption rose from 0.09 EJ in 1971 to over 7 EJ in 2012, which amounts to an 85-fold increase. Exergy use within the energy sector is allocated to final consumption.

4.3 Sources of Exergy & Fields of Application

4.3.1 Food & Feed

Food for humans and feed for draught animals represent the exergy input ("fuel") for muscle work (for estimation methods see chapter 3.2.1). For this thesis I assumed human manual labour to take place mainly in the industrial and agricultural sector. As mentioned earlier, (traditional) agriculture still plays an important role in India. Although numbers of working animals have been declining throughout the whole period, and employment of human manual workers has shifted towards services and industry, agriculture in 2012 was still the biggest sector of employment. A large part of the agricultural work is still done by draught animals and, to a lesser degree, by human manual labour (Ramaswamy, 1998; Vaidyanathan, 1986).

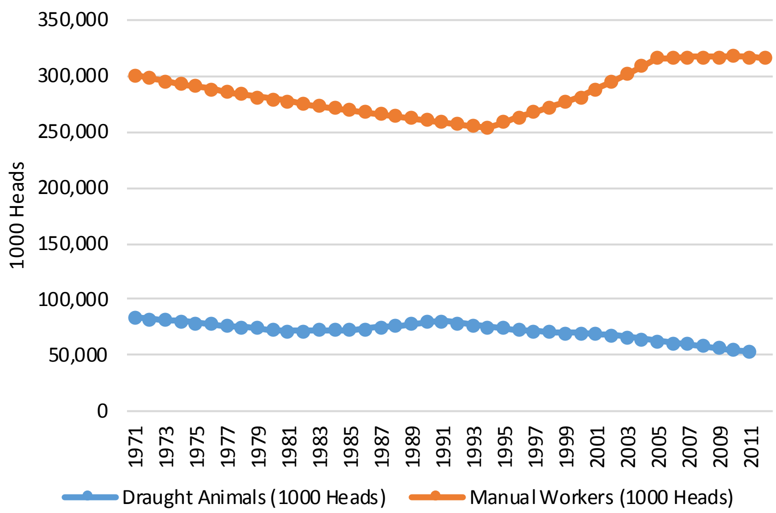


Figure 9: Total manual worker and draught animal population. Absolute numbers in 1000 heads; Both sexes; India 1971–2012

Own calculations based on The World Bank (2016); Krishi (2003, 2005, 2014); Phaniraja and Panchasara (2009); Singh (1999)

Figure 9 shows the constantly declining number of working animals in India, reaching a total of around 50 million animals in 2012, opposed to 84 million animals in 1971, a decline of 37%. On the other hand, after a long phase of downturn, "total manual labour population" (comprising of manual workers in industry and agriculture, both sexes) has increased from 254 million workers in 1994 to 316 million in 2005, but has stagnated in the following years. The upwards trend in total manual labour population (Figure 9) until 2005 can be explained by an increase of employment in the industrial sector. The stagnation in total manual workers after this year stems from a decrease in total employment in agriculture, while the number of industry workers still increased (The World Bank, 2016). In the 41 years studied, food & feed have become far less important as sources of exergy in India, as shown in Figure 2a). The aggregate food & feed share in the total primary exergy input dropped from 44% in 1971 to 12% in 2012.

4.3.2 Combustible renewables

According to the IEA (2015), combustible renewables used in India are primary solid biofuels, biogasoline, biodiesel, biogases, and municipal waste. Primary solid biofuels defined by the International Energy Agency (IEA, 2016, p. 34) are '*any plant matter used directly as fuel or converted into other forms before combustion. This covers a multitude of woody materials* *generated by industrial process or provided directly by forestry and agriculture (firewood, wood chips, bark, sawdust, shavings, chips, sulphite lyes also known as black liquor, animal materials/wastes and other solid biofuels).*'

Biogasoline includes '*bioethanol (ethanol produced from biomass and/or the biodegradable fraction of waste), biomethanol (methanol produced from biomass and/or the biodegradable fraction of waste), bioETBE (ethyl-tertio-butyl-ether produced on the basis of bioethanol*' (IEA, 2016, p. 35).

Biodiesels '*compris*[e] *of biodiesel (a methyl-ester produced from vegeta-ble or animal oil, of diesel quality), biodimethylether (dimethylether produced from biomass), Fischer Tropsch (Fischer Tropsch produced from biomass), cold pressed bio-oil (oil produced from oil seed through mechanical processing only) and all other liquid biofuels which are added to, blended with or used straight as transport diesel'* (IEA, 2016, p. 35).

Biogas is '[a] *gas composed principally of methane and carbon dioxide produced by anaerobic digestion of biomass, comprising: Landfill gas, formed by the digestion of landfilled wastes. Sewage sludge gas, produced from the anaerobic fermentation of sewage sludge. Other biogas, such as biogas produced from the anaerobic fermentation of animal slurries and of wastes in abattoirs, breweries and other agro-food industries*' (IEA, 2004, p. 185).

Municipal waste comprises of '*solid waste (*[non-renewable and] *renewable): Waste produced by households, industry, hospitals and the tertiary sector which contains* [non-]*biodegradable* [and biodegradable materials] *that are incinerated at specific installations'* (IEA, 2004, p. 191).

Combustible renewables represented 36% of the total aggregate primary exergy input in 1971 and still contributed to around 20% in 2012. According to the IEA (2015), from 1971 until 2000, the year when biogasoline entered the Indian energy mix, primary solid biofuels where the only combustible renewables in India. In 2003 municipal waste appeared for the first time in the energy statistics. Biogases followed in 2007, and biodiesels in 2009. Non-commercial primary solid biofuels made up over 99% of the total combustible renewables in India during the observed period. Primary biofuels such as firewood or dung-cake have traditionally served as the primary source for cooking in India, and continue to do so for a large number of households up until today, especially in rural regions (Tata Energy Research Institute, 2006). Thus, the main end-use of this fuel type in the commercial & public, residential, and to a lesser degree, also in the non-specified industry sector, is the provision of low temperature heat 1

(LTH1, up to 100°C) (Das and Paul, 2013; IEA, 2015). Together these sectors are responsible for 97% of LTH1 end-uses, of which on average 70% occur in the residential sector.

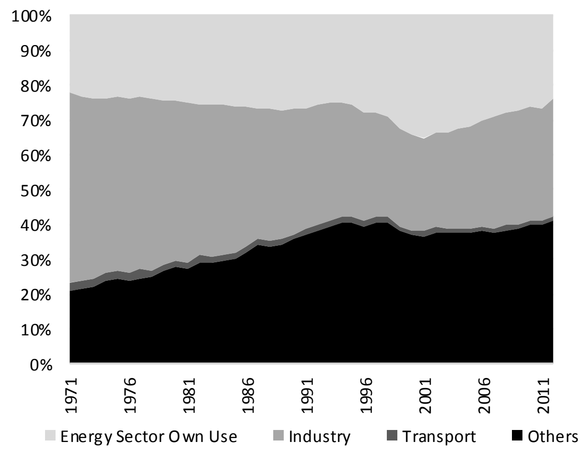
Biogasolines and biodiesels are used exclusively in the transport sector for mechanical drive at small amounts (around 0.2% of the total final exergy input into mechanical drive). Biogasoline was introduced in India in 2000, and biodiesel in 2005, when the first state started to use a commercial biodiesel fuelled bus-service according to the Tata Energy Research Institute (2006). However, numbers for biodiesel do not appear in the IEA statistics before 2009. Biogases and municipal wastes are used in the transformation sector exclusively for electricity generation (as elaborated in section 4.2.3).

As mentioned before, primary solid biofuels (foremost firewood) still hold a relevant proportion of the total Indian primary exergy mix, although a shift to fossil fuels can be observed (Figure 2). Biomass consumption in absolute terms is expected to stabilise within the next decade, according to model projections made by de la Rue du Can et al. (2009). For household energy consumption (mainly cooking purposes), Pachauri and Jiang (2008) found a shift mainly to LPG (from 1% of all rural households in 1987 to 12% in 2005, and from 20% of all urban households to 61% in 2005). Nevertheless, primary biofuels will probably remain to be the primary source of exergy for millions of people, especially in rural areas (Daioglou et al., 2012; de la Rue du Can et al., 2009). Consumption of fuelwood in rural households even increased slightly from 86% of all households in 1983 to 88% in 2005. At the same time, the number of rural households using dung cake as biofuel declined from 53% in 1983 to 46% in 2005 (Pachauri and Jiang, 2008).

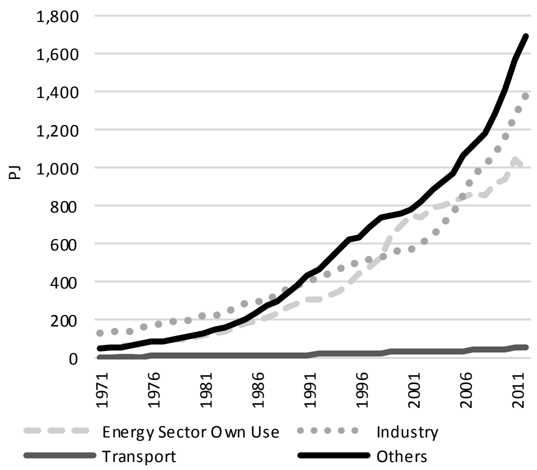
4.3.3 Electricity

Electricity's share in the total Indian final energy mix rose significantly throughout the observed period (see Figure 3), from initially 2% to over 10% in recent years, and is expected to become one of India's most important sources of energy in the future (de la Rue du Can et al., 2009). Despite its increasing importance, electricity is still not available to all Indian citizens. In post-colonial India (after 1947), preference was given to the electrification of industry instead of households. Attempts to provide citizens access to electricity, especially in rural regions, were delayed until the 1970ies, when household electrification programs slowly started to gather pace (van de Walle et al., 2013). While in the 1990ies the overall electrification rate (the percentage of people with access to electricity in relation to the total population) was only as high as 50%, 10 years later it had reached 62% and increased significantly until 2012, to almost 80% (The World Bank, 2016).

Electricity is used in all economic sectors of India. Figure 10 presents a) the shares and b) absolute numbers of final electricity inputs into these sectors. The share of the industry in total electricity consumption has declined from over 50% in 1971 to its lowest share of 27% around 2000, and rose marginally afterwards to 33% in 2012 (Figure 10a). In absolute terms, it has risen constantly throughout the observed period, and since around 2001 at a higher rate than before (from 130 PJ in 1971 to over 1,380 PJ in 2012; Figure 10b). The share of "energy sector own use" reveals an opposite trend, starting at around 20% in 1971, extending until 2000 (where it reached its highest share of 35%) and declining thereafter. In 2012, the energy sector's share in total final electricity consumption was 24% (or 994 PJ). In absolute terms, electricity consumption of this sector in the period 1998-2006 (529 PJ to 747 PJ) was higher than the Industrial sector's (526 PJ to 567 PJ).



a)



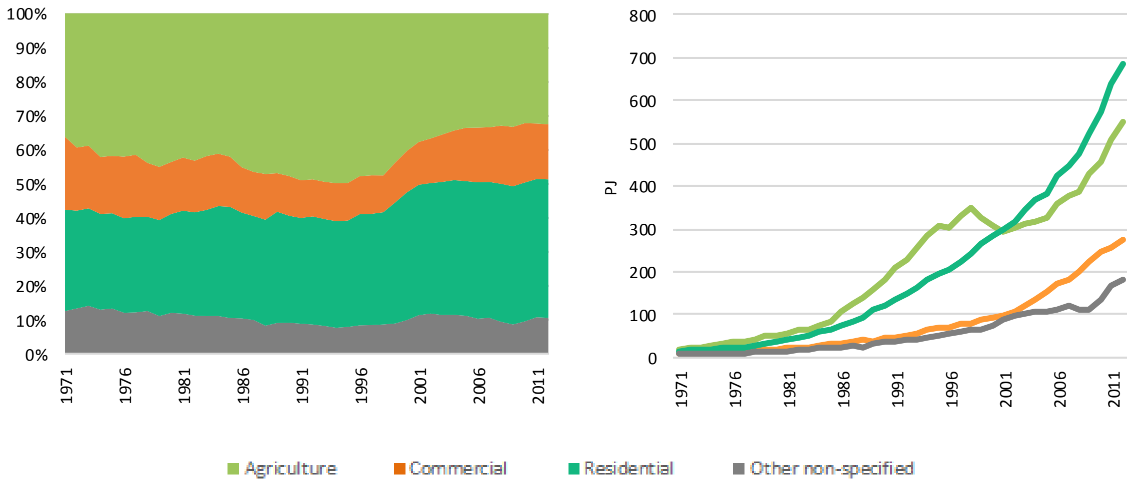
b)

Figure 10: Sector-wise exergy inputs of final electricity. a) Shares of total. b) Absolute numbers in Petajoules (PJ); India 1971 - 2012.

Own calculations based on IEA (2015)

Total electricity input into the transport sector remained at an almost constant share of around 1-2% throughout the whole period. Inputs into "other sectors", subsuming agricultural, commercial & public, and residential sectors, as defined by the IEA (2015), rose significantly throughout the observed period. The share of "other sectors" in total electricity consumption (Figure 10a) has increased constantly until 1995 when it reached almost 40% of overall electricity inputs. This share declined by 3% until around 2000 and grew again to 38% in 2012. These sectors overtook Industry in absolute numbers in 1991 (Figure 10b) and have emerged as the biggest electricity consumer ever since, reaching 1,691 PJ (compared to 1,380 PJ industrial electricity consumption) in 2012. In order to better understand which of the subsectors subsumed under the "other sectors" category emerged as the main electricity consumers, and due to the manifold end-uses of electricity within "other sectors", a more granular breakdown for the end-use mapping for each sub-sector has been carried out.

As can be seen in Figure 11a) and b), the agricultural as well as the residential sector emerged as the main electricity consumers within "other sectors", accounting for 551 and 687 PJ of total electricity consumption in these sectors in 2012, respectively. The agricultural sector's share in total "other sectors" electricity consumption (visible in Figure 11a) has, after a phase of constant growth, declined from 48% around 1998 to 32% in 2011, while residential sector's share has risen from 33% to 41% during the same period.



a) **b)**

Figure 11: Sub-sector electricity consumption detail of "other sectors". a) Shares of total. b) Absolute numbers in Petajoules (PJ); India 1971 – 2012

Own calculations based on IEA (2015)

In absolute terms, electricity inputs into agricultural from 1998 until 2001 declined sharply, while residential electricity consumption in absolute terms rose constantly throughout the whole timeframe (from around 15 PJ in 1971, 687 PJ in 2012, visible in Figure 11b). The following section presents the utilisation of electricity and corresponding shares within each "other sectors" subsector. The mapping is based on the methodology for China by Brockway et al. (2015) with in-country data adopted from Nadel et al. (1991) and the Tata Energy Research Institute (2006).

Electricity in the agricultural sector is almost exclusively used to operate irrigation pumps, other uses are negligible, according to Nadel et al. (1991). Therefore in this study, agricultural electricity use is assumed to stem 100% from irrigation. For the industrial sector data were available for only one year (1991). Estimates for the evolution of the shares of industrial end-uses where not available, hence, I assumed the rates to stay constant for the years remaining. The biggest part (75%) of electricity in the industrial sector is used to operate static motors. Other uses are lighting (9%), process heat (8%) and other electric appliances – electronic devices for telecommunication, computers etc. (8%) (Nadel et al., 1991). Electric trains (mechanical drive) were identified to be the sole power consumers (100%) in the transport sector (Tata Energy Research Institute, 2006). In the commercial and public sector, electricity is used for lighting, heating, refrigeration & air-conditioning (combined in one category due to the absence of available data for each), and other electric appliances as well (Nadel et al., 1991). Of the total exergy consumption in this sector, these end-use categories hold 60%, 32%, and 8%, respectively. For this study, similar to the industrial sector, percentages were assumed to remain constant throughout the 41 years observed.

De la Rue du Can et al., (2009) and Van Ruijven et al., (2011) expect the residential sector to become the biggest electricity consumer in the whole country in the future. Additionally, residential electricity use is a proxy for an ongoing transition in energy use patterns towards that of industrial countries (de la Rue du Can et al., 2009; Pachauri and Jiang, 2008). Thus, end-uses occurring in this sector are of particular interest. Importance of electricity has increased significantly within households over the last decades and it already replaces other commercial fuels in some parts, e.g. kerosene for lighting (Pachauri and Jiang, 2008), a trend which may possibly continue. According to Nadel et al. (1991), and Boegle et al. (2010) lighting, refrigeration, cooling/heating (including services from space heaters, fans, desert coolers, and similar), air conditioning, and other uses (computers, telecommunications, TVs, stereos etc.) are the primary domestic Indian electricity end-uses. For this thesis, to model the saturation of different electric household appliances over time, I have estimated time-depended electricity consumption shares for each of the above mentioned device category. These estimations are based on a multitude of studies focusing on Indian domestic energy consumption. Some papers offer detailed insights into household appliances energy consumption and/or appliance ownership (de la Rue du Can et al., 2009; Parikh and Parikh, 2016; Nadel et al., 1991; Boegle et al., 2010). Unfortunately, empiric data (based on household surveys) were only available for the years 1970, 1991 (Nadel et al., 1991) and 2008 (Boegle et al., 2010). Hence, for the remaining years, the evolution of the respective electricity consumption of household appliances has been interpolated in this study.

According to Pachauri and Jiang (2008), lighting is the primary electric utilisation when access to electricity is first provided. De la Rue du Can et al. (2009) found a certain hierarchical pattern of appliance ownership which they link, among other aspects, to electrification and household income levels: Electric appliance ownership seems to increase significantly with rising electrification and income. Spanning over households with varying earnings, apart from using electricity for lighting, “basic” appliances such as simple cooling (e.g. fans), and entertainment devices (e.g. TVs) are bought. Air-conditioners and water heaters are regarded as luxury goods, which only the households with higher income levels can afford, while refrigerators, in terms of ownership, seem to be placed in the middle between the above mentioned groups. However, their numbers are increasing slowly among all income groups. Van Ruijven et al. (2011) found similar results. Other equipment, e.g. washing machines, are also considered as higher income goods but have been neglected in this thesis due to their minor contribution to overall electricity consumption (Boegle et al., 2010). These factors all influence the composition of device related electric exergy consumption, a proxy for appliance saturation among households, depicted in Figure 12.

Especially from 1971 until the early 1990ies, major changes in the breakdown of electricity consumption of household appliances occurred: While at the starting point of the analysis electricity had been used foremost for lighting (over 90%), in the following decades the increasing saturation of different cooling and heating devices, as well as “other appliances” lead to a diversification of domestic electricity consuming equipment, and therefore of end-uses.

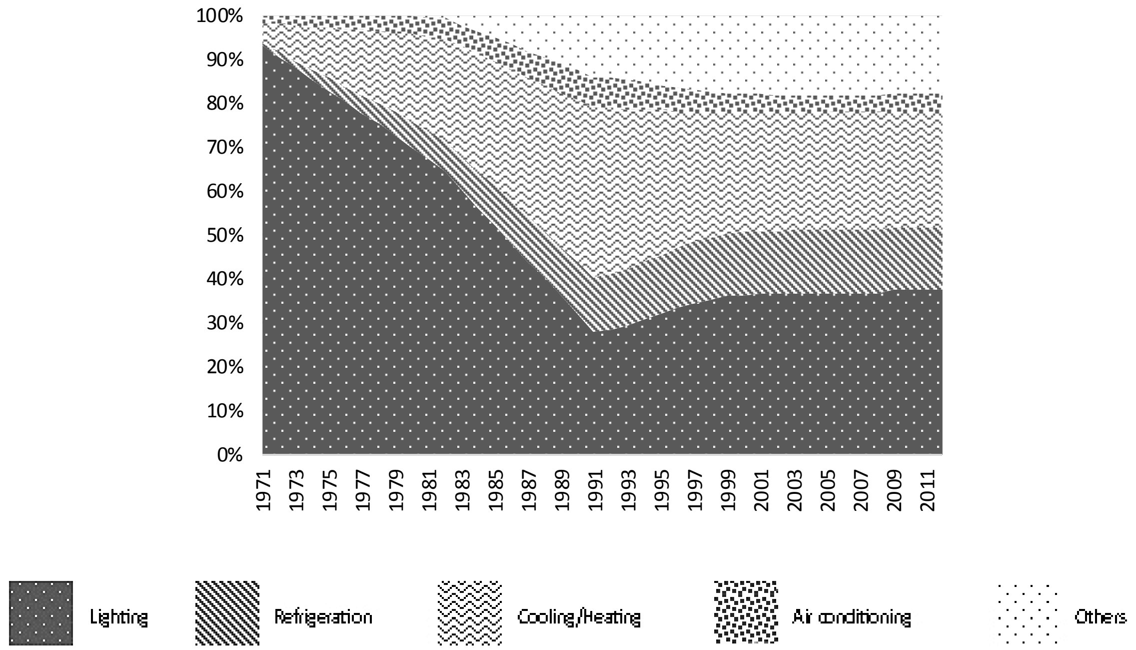


Figure 12: Final electricity consumption of household appliances by categories, shares of total. Rural and Urban households; India 1971–2012

Own calculations based on Boegle et al. (2010); IEA (2015); Nadel et al. (1991); Parikh and Parikh (2016)

Cooling and heating devices' share in total electricity consumption peaked around 1990 (40%) but declined afterwards to around 30% in 2000 (Figure 12). This can be explained by the emergence of "other appliances" (from 1% in 1982 to 18% in 1999) and the increasing share of refrigerators' consumption (from 1% in 1972 to 14% from 1996 onwards). The share of electricity used for lighting purposes reached its lowest share around 1990 (28%) but has increased again afterwards, to 38% in 2012. I argue here that this trend may be linked to the rising household electrification rate because according to Pachauri and Jiang (2008), the first electricity end-use once households are electrified is lighting. Interestingly, the share of "other devices" consumption has stabilised around 1999 and stayed around close to 20% until the end of the timeframe. Overall, growth in the residential sector's electricity consumption is not only attributable to increasing household electrification but also to the introduction of a wide range of different electronic devices. Concerning useful work and aggregate electricity efficiency, this is an important observation, as will be elaborated in section 4.5.4.

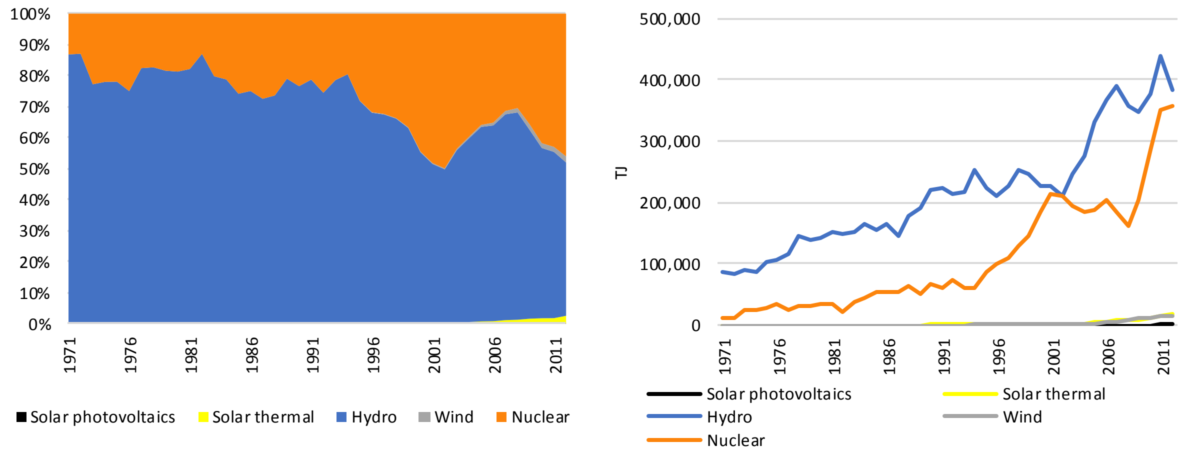
4.3.4 Renewables & Nuclear Power

In the 1970ies, realising the potential and importance of alternative sources of energy, the Indian Government put increased attention to the development and promotion of renewable energies (Tata Energy Research Institute, 2006). Although potential for renewables in India is high and contribution to overall exergy input rose from 0.09 EJ in 1971 to 0.36 EJ in 2012, this represents only 1% of the total exergy mix. Exergy from nuclear power reactors represents only 0.86% of the total exergy mix in 2012, or 0.36 EJ. High acquisition costs of the new technologies, as well as finding investors who were put off due to possible financial risk, were major obstacles for development and usage of renewable energies in the 1980ies. Therefore, in 1987 the Indian Renewable Energy Development Agency LTD (IREDA, a public enterprise) has been founded to help financing renewables (Tata Energy Research Institute, 2006).

As described in section 4.1 (and indicated by Figure 2), the share of “alternative” sources of energy in the total primary exergy is still low but has increased steadily until 2000, and at an accelerating rate ever since. Absolute exergy inputs of renewable energy in the total primary exergy mix increased at a compound annual growth rate of 4% during the 41 years observed (IEA, 2015). Sources of renewable energy in India currently in use are solar thermal, solar photovoltaic, hydro, and wind. Tidal and wave, as well as geothermal power generation are at different stages of development (Tata Energy Research Institute, 2006).

According to the Tata Energy Research Institute (2006), estimated potential reserves of power generation from renewables in 2014 in India were on the order of approximately 147,000 MW (Megawatt), against an already installed capacity[11] (in that same year) of over 72,000 MW, composed of approximately 40,000 MW from hydro, 21,000 MW from wind, 3,800 MW from small hydro power plants, and 2,600 MW from solar power. The remaining 4,600 MW stemmed from combustible renewables, which have been accounted for separately in section 4.3.2.

[11] The installed capacity is the maximum amount of electricity a given plant or device can supply under ideal conditions (IEA, 2004).



a) **b)**

Figure 13: Sources of renewable energy & nuclear power generation. a) Shares of total. b) Absolute numbers in Terajoules (TJ); India 1971-2012

Own calculations based on IEA (2015)

Figure 13a) and b) show that hydropower is the predominant source of renewable energy in India, followed by solar thermal, wind, and solar photovoltaic. After hydropower, nuclear energy is the second largest non-fossil contributor to electricity production. Its share has more than tripled during the observed period, from 13% to 46%. Figure 13b) shows that in 2012, electricity output from nuclear plants in absolute numbers (358,657 TJ) had almost reached that of hydro power (385,099 TJ). Taking into account that the Indian Government is enforcing its nuclear program (additional reactors are in various states of construction), this trend is likely to continue (Central Statistics Office, 2015; Srinivasan and Gopi Rethinaraj, 2013; Tata Energy Research Institute, 2006). The significant decline of nuclear electricity production between 2000 and 2008 is a result of a severe shortage in uranium fuel during that time, due to restrictions from the Nuclear Supplier's Group (NSG) (Curtis, 2007). The next section presents further insights into history, development and end-use of each source of renewable energy, as well as nuclear power in India.

4.3.4.1. Solar photovoltaic & Solar thermal

Solar photovoltaic technology development programmes in India were initialised in the 1980ies. This technology is used solely to generate electricity. Its typical fields of application are provision of rural local energy services (e.g. small portable lights, household energy), decentralised, mostly semi-commercial energy supply, grid-connected power supplies (on rooftops of public buildings as backup for peak loads, and as support for small rural grid systems) (Tata Energy Research Institute, 2006, p. 177 f). Solar photovoltaic cells also provide power for '*telecom*[munication]*, railway network,* [as well as for the] *oil and gas sector'* (ibid., p.165). Additionally, they are used in the energy sector, and for other (unspecified) applications. Solar thermal energy is mainly used for heating water, in salt gradient solar ponds (devices that store and use solar heat to create other forms of energy at very low (~ 5%) efficiency), solar cooking (especially in the domestic sector), as well as to provide industrial process heat of 100-250°C, used for food processing, dairy, textiles, etc. (Tata Energy Research Institute, 2006).

4.3.4.2. Wind

India started using wind turbines for commercial power generation in 1983/84. Since 1986 exergy produced by wind plants has increased by a compound annual growth rate of over 540%, rising from 1.62 TJ in 1987 to more than 15,000 TJ in 2012. There is great potential for generating electricity from wind in the country. Gross wind power had been estimated to be around 45,000 MW in 2004, with a realisable technical potential (depending on the reliability and availability of the electric grid) of 13,400 MW (Tata Energy Research Institute, 2006). In 2012, installed capacity of wind power has reached more than 17,300 MW (Central Statistics Office, 2013), exceeding the technical realisable potential estimated back in 2004.

4.3.4.3. Hydro power

Hydro power accounted for over 80% of total electricity generation from non-fossil energy sources in 1971, decreasing to over 50% in 2012 (see Figure 13a). India's installed hydro power potential to-date lies around 40,000 MW (Central Statistics Office, 2015). Due to the growing demand for electricity, increased attention is paid to hydro power by the Indian Government (Tata Energy Research Institute, 2006). From 2001 onwards, power generation from hydro-power plants in absolute numbers levelled off (visible in Figure 13b). By 2012, their electricity output (385,099 TJ) was more than 4 times the amount of 1971 (85,787 TJ) and 1.6 times the output at the beginning of the 21st century (227,894 TJ). This increase in electricity generation from hydro power was enabled through the successful implementation of various governmental programs which led to the development and expansion of small hydro power systems (run-of-river plants) (Tata Energy Research Institute, 2006). Although hydropower is generally regarded as "clean" energy, negative environmental effects, e.g. deforestation, destruction of animal habitats, or species extinction (Pandit and Grumbine, 2012), as well as social impacts, e.g. forced resettlements (Cernea, 1997) do often go hand in hand with the construction of hydro-plants.

4.3.4.4. Nuclear Power

India's first commercial nuclear reactor commenced electricity production in 1969 (Energy and Resources Institute New Delhi, 2009). Since then, 14 additional nuclear power plants have been built (Central Statistics Office, 2015). The share of nuclear power in total electricity generation remained relatively constant around 2% throughout the studied time frame. This translates as 4,780 MW (Megawatt) of electricity generated by nuclear power plants in 2012 (Central Statistics Office, 2013). India plans to enlarge its nuclear capacity to a total of 60,000 MW by 2030 (Srinivasan and Gopi Rethinaraj, 2013). The Fukushima-catastrophe in 2011 inflamed debates about safety risks of nuclear energy and led to a series of public protests against the enforcement of nuclear power generation in India, which temporarily delayed the expansion programs. Nevertheless, the movement had soon been forced by the officials to disband, favouring the nuclear energy development program over public concerns (Srinivasan and Gopi Rethinaraj, 2013).

4.3.5 Natural Gas

Natural gas use in India dates back to as early as 1866, when the first deposits were discovered, but it took until after independence from the United Kingdom in 1947 for the Indian gas industry to develop: Prior to 1947, the British Assam Oil Company and the Attock Oil Company were the only companies in the country producing oil and gas (Corbeau, 2010). Natural gas consumption in India started to increase in the 1970ies with the discovery of offshore gas fields and pipeline constructions. In the light of liberalisation and economic reforms in the 1990ies, endogenous drilling was further stimulated, leading to a significant growth of domestic production and demand for natural gas in the decade to follow (Corbeau, 2010). In 2012 domestic production was almost twice as high as in 1995 but still contributed only 5% to the total primary exergy input (IEA, 2015). India does not export natural gas but started importing gas in 2003 at a capacity of around 12 PJ. Until 2012, imports have risen significantly to a total of 652 PJ, or 34% of the Indian total primary natural gas supply. Natural gas is used to generate electricity, in the fertiliser industry, and as direct fuel for heating (Tata Energy Research Institute, 2006). It has been introduced to the transport sector at the end of the 1990ies (IEA, 2015), where CNG (compressed natural gas) is used as fuel to power a variety of gas driven vehicles (ibid.). Natural gas in the industry sector is used to provide process heat at medium and high temperature. In the agricultural sector, and, since the mid 1970ies also in the residential sector, the demand for gas has been growing constantly, where it is used for low temperature heat purposes such as room heating, and cooking, respectively (Brockway et al., 2015; IEA, 2015; Pachauri and Jiang, 2008). Even though domestic exergy consumption is still dominated by primary solid biofuels (as explained in 4.3.2), de la Rue du Can et al. (2009) stated that households tend to climb up an “energy ladder” when incomes rise. As a consequence, consumption of “modern”, more efficient but also more expensive sources of energy (kerosene and coal, later LPG, natural gas, and finally electricity) for cooking, and to some extent, for heating increases (Corbeau, 2010; Dzioubinski and Chipman, 1999). In India, this transition has already begun in recent years, as a growing fraction of urban households is replacing biomass with natural gas (Pachauri and Jiang, 2008). During almost 40 years, natural gas consumption in the domestic sector has increased over 500 times (IEA, 2015). According to Corbeau (2010), this trend is very likely to continue - Meeting the increased demand for gas will be a critical future challenge for the country. Another problem for the gas market is an appropriate pricing policy, since there exist state-owned as well as private gas companies, of which prices for gas supply differ widely. A common policy regulatory framework and sufficient infrastructure for distribution are yet to be established (ibid.).

4.3.6 Oil

The history of oil production in India dates back to the 19th century when the first oil well was discovered in the village of Digboi, Assam (Oil India Limited, 2016). After independence, the country strived to develop its own, autonomous petroleum industry, free from the influence of Western countries. As a consequence, the two most important oil companies of the nation, the Indian Oil Corporation and the Oil and Natural Gas Commission were established in 1956. During the 1970ies, the oil sector was nationalised but due to slow progress in development and exploration of reserves, re-liberalised again in the 1990ies (Ahn and Graczyk, 2012).

Applications of petroleum and derived products are widespread across all economic sectors in India. End-uses range from direct heat (at high and medium temperatures in the industrial, and low temperatures in the agricultural, and commercial & public sector), fuel use for mechanical drive in various engines in the transport sector (and again, to some extent, in the industrial, and agricultural sectors), to lighting (and to a small degree cooking) purposes in the residential, and commercial & public sector, and of course, electricity generation in the power sector.

Since the 1970ies the demand for oil in the country has increased significantly. The share in total primary exergy supply rose from 7% in 1971 to 18% in 2012. Total crude oil input into the transformation sector increased significantly from 990 PJ in 1971 to almost 10,400 PJ in 2012, while its share for electricity generation decreased from a maximum of 11% in 1980 and 1984 to 3% in 2012. Oil is the only fossil fuel of which inputs to electric power generation declined substantially in recent years, while the inputs for refining of crude oil into derived fuel products have increased, as elaborated in section 4.2 (and visible in Figure 6).

4.3.7 Coal

Coal has emerged as the most important source of exergy for the Indian economy. Over the last 40 years, the share of coal in the country's exergy mix almost tripled. In 2011, overall coal-inputs reached a total of 15.5 EJ, or 37% of the total primary exergy supply, outnumbering total biomass input (combustible renewables & food and feed). The greatest part (around 77%) of the total primary coal supply in 2012 was still met by domestic production. Nevertheless, this share has been constantly declining, while imports increased dramatically since India started importing coal at the end of the 1970ies from Australia and Canada (IEA, 2001). The main consumers today, visible in Figure 14, are the transformation and industry sector, with the transformation sector consuming over 70% of total primary coal, where it is used mainly for electricity production, and to a lesser degree for several other transformation processes, as described in section 4.2.2.

The sector-wise breakdown of coal consumption (Figure 14) reveals several important findings: The drastic increase of coal inputs into the transformation sector reflects the growing demand for electricity (see also section 4.3.3) while industrial coal consumption has been declining from over 30% in 1971 to 16% in the early 2000s and started to rise again soon after, reaching 23% in 2012.

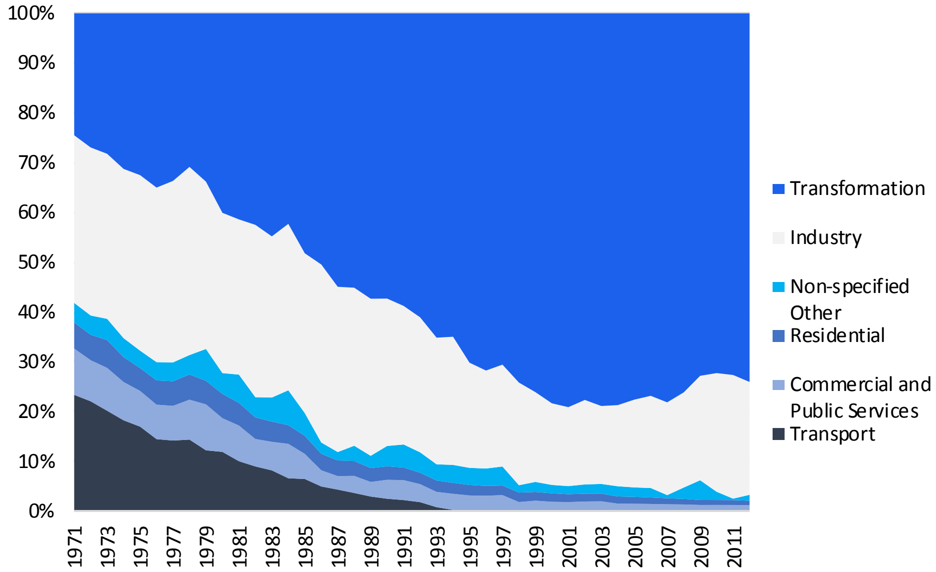


Figure 14: Sector-wise coal exergy inputs, shares of total. India 1971–2012

Own calculations based on IEA (2015)

This increase reflects the growth in crude steel production, which ascended steeply since 2006, as can be seen in Figure 15. Today Iron & Steel production is one of the biggest industry branches in India. The country ranked 4th in world crude steel production in 2011 (Hyvonen and Langcake, 2012). The raw material requirement for steel making comprises of iron ore, coking coal, non-coking coal, met (metallurgical) coke, and PCI (pulverised coal injection) (Krishan et al., 2013). There are several methods of iron and steel making and different types of furnaces are in use: Besides Open Hearth/Basic Oxygen Furnaces (BOF), which are fuelled by coal, oil, and gas, a growing number of Electric Arc Furnaces (EAF) have been established in the country since the 1960ies and steel production outputs from EAFs have increased constantly ever since (Economics Committee, World Steel Association, 2012; Ramachandran, 1984). Nevertheless, coal (as raw material and as fuel) remains to be the predominant resource used in the iron & steel industry (IEA, 2015; OECD et al., 2002). Compared to international standards, the quality of Indian coal is rather poor – it has high ash and low sulphur content. Because of this reason, high quality coal needs to be imported in order to fulfil the requirements of the steel industry (Choudhury and Bhaktavatsalam, 1997; Coal Directory of India, 2013). Although according to the OECD et al. (2002), India's coal reserves rank 3rd worldwide after USA and China, and are rich in good quality iron ore, coking coal is not available in sufficient quality and quantity to meet the requirements of steel making. Hence, the country has become increasingly depended on imports (Hyvonen and Langcake, 2012).

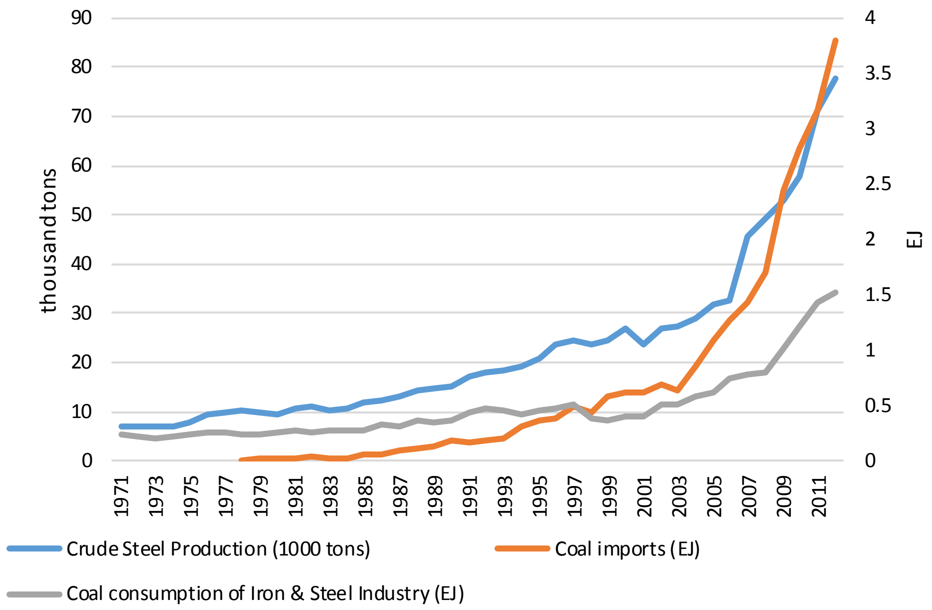


Figure 15: Crude steel production, coal consumption of the iron & steel industry, and coal imports. Absolute numbers, Crude steel production in 1000 tons (primary axis); Coal consumption and imports in Exajoules (EJ) (secondary axis); India 1971–2012

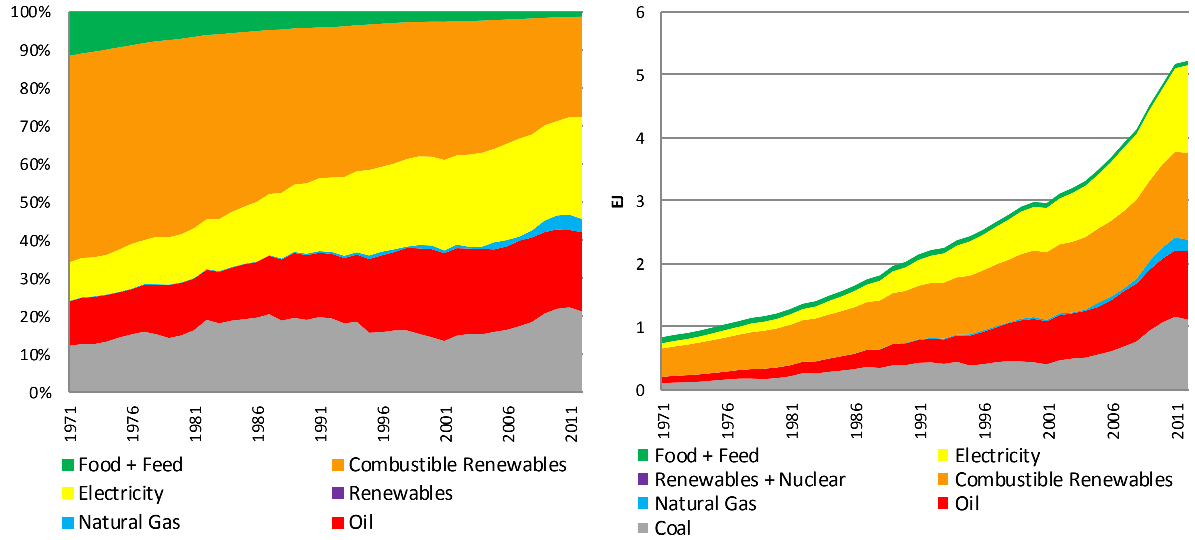
Own calculations based on Committee on Statistics (1978, 1980, 1981, 1982, 1983, 1984, 1985, 1986, 1987, 1988, 1989, 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2004a, 2004b, 2005, 2006, 2007, 2009); Economics Committee, World Steel Association (2012); IEA (2015); Worldsteel Committee on economic Statistics (2009, 2010a, 2010b, 2011)

In the transport sector, change of technology and associated input fuels can be observed: In 1971 coal-powered trains still accounted for more than 20% of the total coal demand. In the following years, steam locomotives where replaced by diesel and electricity driven trains (Ministry of Railways, 2015). Hence, coal consumption in this sector went to zero in 1998.

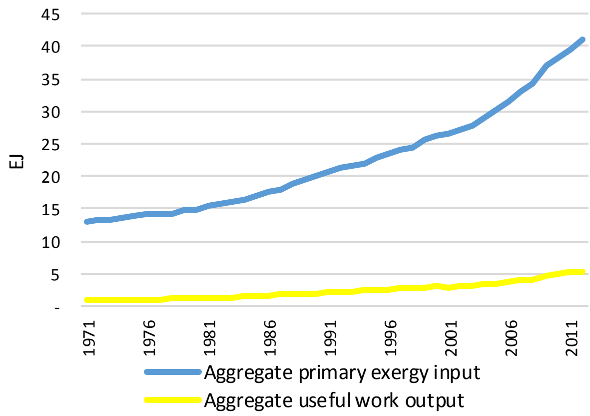
Direct low temperature heat purposes such as water heating and cooking are the main end-uses of coal in the commercial and public, as well as in the residential sector. Consumption has been constantly declining in these sectors. As mentioned before, this is a result of the substitution of coal with cleaner and more efficient fuels (4.3.2) (Pachauri and Jiang, 2008).

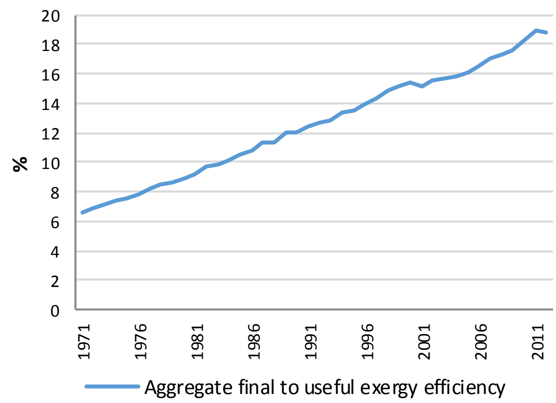
4.4 Useful work - Overview

Useful work represents the portion of exergy which delivers energy-services to end-users. Aggregated supply of useful work rose from 0.8 EJ in 1971 to above 5 EJ in 2012, which represents a more than 6 fold increase.



16 a) **b)**





17) **18)**

Figure 16: Overall useful work by source of energy. a) Shares of total b) Absolute numbers in Exajoules (EJ); India 1971–2012

Figure 17: Aggregate final exergy consumption and aggregate useful work, absolute numbers in Exajoules (EJ); India 1971–2012

Figure 18: Total aggregate primary-to-useful, and final-to-useful efficiency. India 1971–2012

Own calculations based on IEA (2015)

Figure 16a) and b) illustrate the Indian useful work supply by sources of energy in relative and absolute values. Comparing the initial primary exergy input (Figure 2) with useful work supply, the most obvious observations are: 1) Overall useful work figures are much smaller than the overall exergy input 2) the composition of useful work by sources of energy is substantially different as compared to the input side. This implies that large differences in exergy conversion efficiencies of technologies across sectors and sources of energy occur. The results support the hypothesis that the Indian society is replacing biomass with fossil fuels and electricity to fulfil its energy services.

While coal is the dominant resource in terms of exergy input, its contribution to useful work output is much smaller. This confirms several findings: A high amount of coal is not directly used for any end-use service but enters the transformation sector, mainly for electricity generation. The increase of useful work from coal from 2001 onwards may be linked to enhanced heat efficiency inclined by technological improvements and rising imports of good quality coal (see also section 4.3.7). Oil share in the useful work mix increased until around the year 2000 where it reached a peak and declined afterwards. Electricity's share followed a similar evolution path. Food & feed decline throughout the observed period, from 10% at the starting point to around 1% in 2012. Useful work from combustible renewables, which accounted for around 60% of total in the 1970ies shrunk to under 30% at the end of the studied timeframe. The share of solar thermal, which is the only renewable energy type providing useful work in the form of direct heat (besides electricity generation) in total useful work is less than 0.005%.

Aggregate primary-to-useful exergy efficiency (or simply exergy efficiency) is a measure to describe how efficiently energy is used throughout the whole economic system, from inputs of primary exergy to the point of useful work (Brockway et al., 2015). Vice versa it is also an indicator for the degradation of energy. In this thesis, (primary) exergy efficiency is used to compare India to China, and some fully industrialised countries (Section 5).

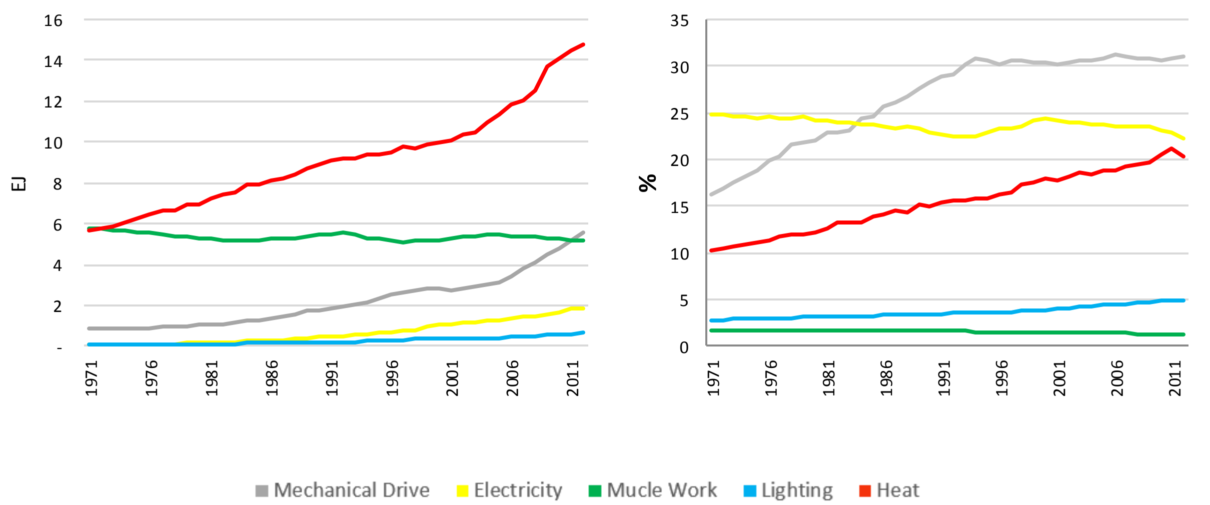
Aggregate final-to-useful efficiency is a simple but effective indicator, describing overall technological efficiency evolution across all sectors, as well as the potential for efficiency improvement and a value for energy degradation from final exergy to useful work (Serrenho, 2013). It is obtained by dividing aggregate useful work output by aggregate final exergy input. In the 41 years studied, aggregate final-to-useful exergy efficiency shows a constant upwards trend, rising from 6% to almost 18% (Figure 18).

From 1971 to 2012, aggregate useful work, in comparison to aggregate primary exergy (Figure 17) increased by an annual compound growth rate of 5%, while the latter increased at a rate of 3%. However, in the last third of the analysed years, aggregate primary exergy input increased at a faster growth rate than before (4%), while aggregate useful work grew unchanged at 5% (Figure 17).

As visible in Figure 18, aggregate final-to-useful efficiency, after relatively stagnating at the end of the 1990ies and a short phase of increase between 2004 and 2010, began to decline.

Although there have been some technological improvements in different sectors (e.g. iron & steel, ammonia), increasing aggregate final-to-useful efficiency as well as ascending useful work might, similar to the findings of Brockway et al. (2015) for China, not only stem from major efficiency improvements or adoption of modern technology. Increased use of relatively high efficient energy carriers, foremost higher quality coal, natural gas, and electricity instead of e.g. primary biofuels and muscle work, might also have a significant effect on aggregate final-to-useful efficiency. Additionally, a structural shift to higher energy efficient but resource demanding industries (e.g. iron & steel) results in an increase in overall useful work and thus higher aggregate efficiency. This trend can be further explained by examining the individual end-use categories.

4.5 End-Use Categories



19) **20)**

Figure 19: Final exergy input by end-use category, absolute numbers in Exajoules (EJ); India 1971–2012

Figure 20: Aggregate final-to-useful efficiencies by end-use category. India 1971–2012

Own calculations based on IEA (2015)

Figure 19 provides an overview of final exergy inputs by end-use categories. Direct heat emerged as the most important end-use, consuming most of the Indian exergy from 1972 onwards (close to 6 EJ in 1971, almost 15 in 2012). Mechanical drive overtook muscle work as the second most important exergy consumer in 2010 and consumed 5.52 EJ, or 20% of total final exergy inputs in 2012. Increasing electrification and therefore increased end-use of "direct" electricity is reflected in a more than 20-fold increase in final electricity throughout the whole period (1971: 0.07 EJ; 2012: 1.83 EJ). Food and feed inputs for muscle work remained relatively stable between 5 and 6 EJ. They still accounted for 18% of overall exergy inputs in 2012 and will most probably continue to do so, simply because of the basic metabolic needs of humans and animals. On the other hand, the (economic) contribution of muscle work to overall useful work (roughly 1%) is nowadays almost irrelevant (see also Figure 16a). Exergy input in absolute numbers for lighting end-use also increased throughout the whole period (from initially 0.08 EJ to 0.65 EJ), although its contribution to total useful work remained at a constant share of around 1%.

Final-to-useful efficiencies for each end-use category are shown in Figure 20. Heat efficiency increased constantly form 10% in 1971 to over 25% in 2012, with the most pronounced efficiency gains observable from 2007 onwards. Significant improvements were also found for mechanical drive. Its efficiency doubled from over 16% at the beginning of the timeframe until 1994, when it reached around 25%. Thereafter no more significant efficiency improvements can be observed. Another interesting result is electricity final-to-useful efficiency, which declined until the mid 1990ies (from almost 25% to 22%), improved by 2% until around 2000 and declined ever since, reaching again 22% in 2012. Lighting efficiency improved marginally from around 3% to around 5% from 1971-2012, while muscle work descended slightly throughout the whole period, from 1.6% to 1.3%.

In the following sub sections these trends will be elaborated in detail, insights into the structure and dynamics of each end-use category will be given, and underlying drivers of change, as well as information about efficiency improvements and implications for overall Indian aggregate efficiency will be explored.

4.5.1 Heat

Heat end-uses, as mentioned earlier, are divided into 5 subcategories: High temperature heat (HTH; 550°C and above), medium temperature heat 1 (MTH1; 250 up to 550°C), medium temperature heat 2 (MTH2; 100 up to 250°C), low temperature heat 1 (LTH1; 100°C), and low temperature heat 2 (LTH2; 20°C). Low temperature heat 1 use stems almost completely from household cooking. Ammonia production, and iron & steel industries are considered to be good representatives for medium temperature heat 1, and high temperature heat uses respectively, according to Serrenho (2013). Processes requiring mixed heat end-uses of 50% MTH1 and 50% HTH occur in the non-metallic minerals and non-ferrous metals sectors.

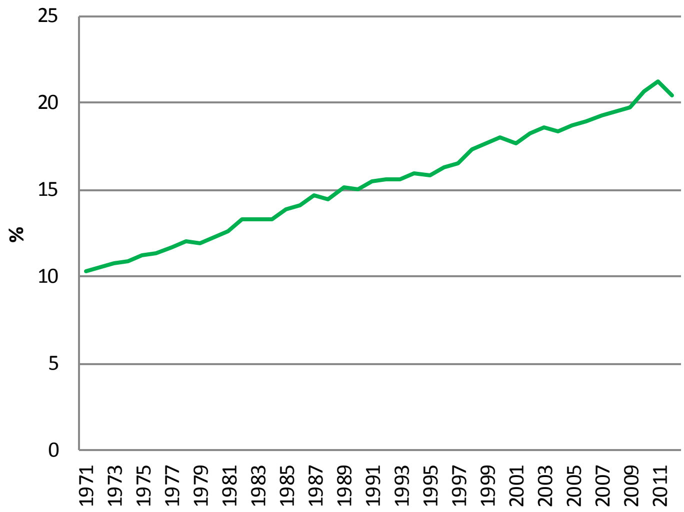


Figure 21: Aggregate heat final-to-useful efficiency. India 1971–2012

Own calculations based on Energy and Resources Institute New Delhi (2009); IEA (2015); Price et al. (1999); Schumacher and Sathaye (1998); Sudhakara Reddy and Kumar Ray (2011); Tata Energy Research Institute (2006)

Aggregate heat final-to-useful efficiency more than doubled during the observed period, visible in Figure 21. The detailed sub-category breakdown, as can be seen in Table 5 (and Appendix 8.2.1), reveals that most of the sub-categories' individual final-to-useful efficiencies increased from 1971 to 2012. High temperature heat and medium temperature heat show the most pronounced improvements. A shift to more energy efficient technologies such as electric arc furnaces (Committee on Statistics, 1978; Price et al., 1999; Schumacher and Sathaye, 1998; Worldsteel Committee on economic Statistics, 2009) contributed to constant efficiency improvement in the iron & steel industry from 1971-2003. High temperature heat efficiency had accelerated from 15% in 1971 to almost 40% in 2003 but decreased again to 25% in 2012, due to an increased use of less efficient coal based furnaces. In combination with the accelerated steel production, this development led to a slight decrease in aggregate heat efficiency from 21% in 2011 to 19% in 2012, visible in Figure 21. In the ammonia industry, a proxy for MTH1, technological improvements led to an almost doubling of 2nd law efficiency (from 26% to 50%; see Table 5) throughout the observed period (Institute for Industrial Productivity, 2013; K. Schumacher and Sathaye, 1999). In the residential sector, traditional cooking stoves were to some extent replaced with modern cookers (Tata Energy Research Institute, 2006), and commercial energy carriers were introduced (see also section 4.3.2), resulting in low temperature heat 1 gains in exergy efficiency from 10% to 17% during the observed period (Table 5). Medium temperature heat 2 (250°C) efficiency, represented by the paper & pulp industry, as well as low temperature heat 2 (20°C) (space heating) efficiencies remained almost unchanged during the studied period.

Table 5: Final-to-useful efficiencies for heat sub-categories. India 1971 & 2012

Own calculations based on Brockway et al. (2015); IEA (2015)

Heat sub-category	1971	2012
HTH (>550°C)	15%	25%
MTH1 (550°C)	26%	50%
MTH2 (250°C)	6%	6%
LTH1 (100°C)	10%	17%
LTH2 (20°C)	4%	6%

Nevertheless, technological change is not the only reason for aggregate heat efficiency improvements: Figure 22 shows that the vast majority of useful work from heat (over 80%) lay in the LTH1 range in 1971, followed by high temperature heat (around 10%). In the following 41 years, a major transition in the distribution of heat end-uses occurred, mainly to medium temperature heat 1, high temperature heat, and 50% high/ 50% medium temperature heat end-uses.

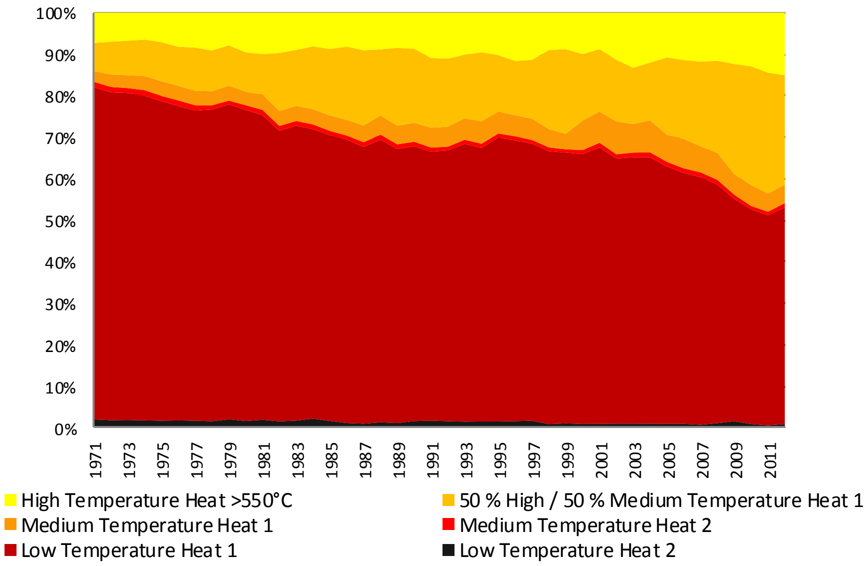


Figure 22: Total useful-work from heat, sub end-use categories, shares of total. India 1971–2012

Own calculations based on IEA (2015)

The share of low temperature heat 1 in overall heat end-uses had declined from over 80% in 1971 to around 50% in 2012. By the same year HTH, and especially mixed high and medium temperature heat end-uses had increased to 15% and 26% of total, respectively. The gradual shift from low efficiency LTH1 to more efficient high- and medium temperature end-uses is also a reason for the upswing of aggregate heat exergy efficiency (Figure 21). This transition, which can be observed throughout the whole period, and especially from 2005-2012 (Figure 22), translates foremost as an intensification of heavy industries such as the iron & steel sector, and the petrochemical industry (specifically, of fertiliser production). The increase of the fractions of high temperature heat, and high/medium mixed end-uses during the last 7 years of the studied period can be directly linked to accelerated steel production, visible in Figure 15, and increased ammonia production quantities (830,000 tons in 1971, over 12,200,000 tons in 2012) (The Fertiliser Association of India, 2017).

4.5.2 Mechanical Drive

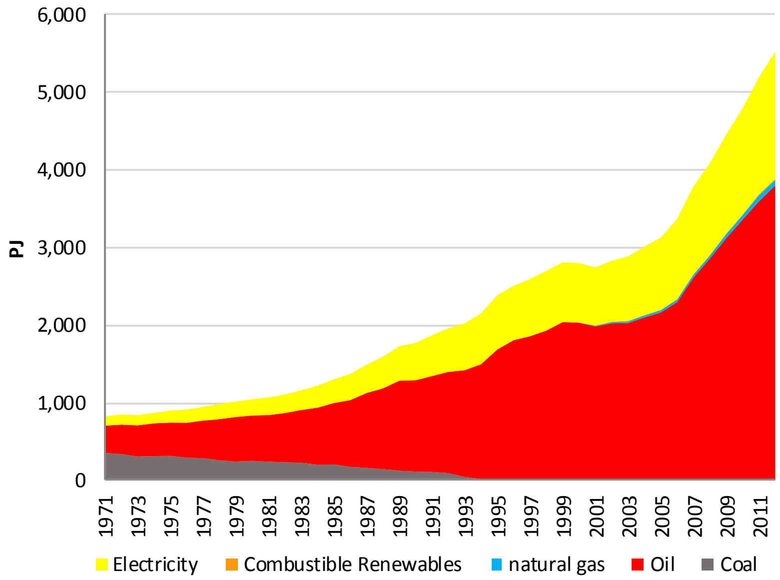


Figure 23: Final exergy inputs for mechanical drive by source of energy. Absolute numbers in Petajoules (PJ); India 1971–2012

Own calculations based on IEA (2015)

Figure 23 unveils the heavy dependence of mechanical drive end-uses on inputs of oil (69% of all inputs in 2012) and electricity (30%, respectively). While coal inputs (for steam powered locomotives) disappeared in the middle of the 1990ies, oil inputs to mechanical drive increased 10-fold, from 353 PJ in 1971 to a total of 3,800 PJ in 2012. This enormous increase can be explained by the remarkable rise of motorised vehicle ownership in the country, which according to Figure 24 rose from 1.9 million in 1971 to 159.5 million in 2012.

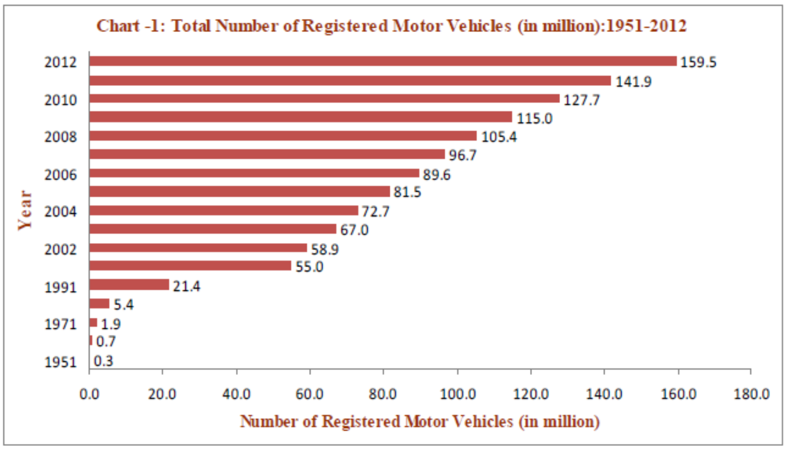
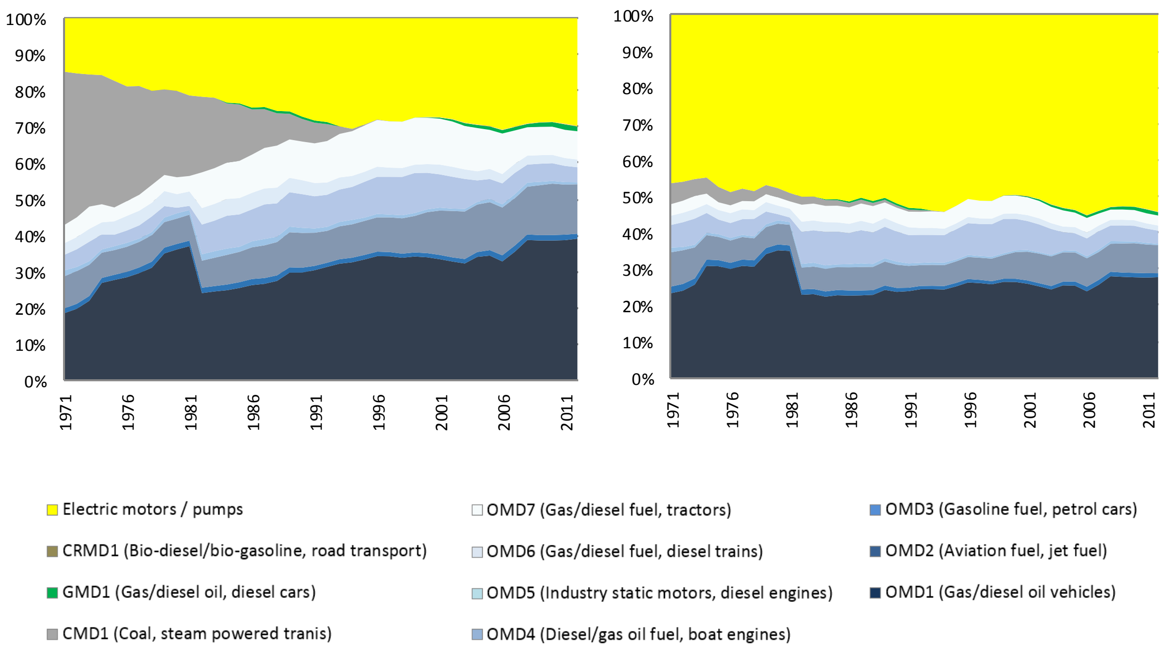


Figure 24: Total number of registered motor vehicles. (In millions); India 1951–2012

(Transport Research Wing, 2013, p. V)

Final exergy inputs for mechanical drive, as presented in Figure 25a), at the beginning of the observed period consisted of about 40% coal (CMD1), 14% electricity, and oil-based fuels (the remaining share) (OMD1-OMD7). The evolution of this structure changed to significantly higher inputs of oil and electricity-based mechanical drive end-uses, for the reasons mentioned above. The useful-work structure of mechanical drive, on the other hand, is dominated by industrial static electric motors (Figure 25b). This indicates that electricity-based devices are more efficient than devices/vehicles based on solid and liquid fuels.



a) b)

Figure 25: Mechanical drive by end-use sub-category, shares of total. a) Exergy input. b) Useful work. India 1971–2012

Own calculations based on Brockway et al. (2015); IEA (2015)

Interestingly, the noticeable spikes around 1980/81 in Figure 25 show that exergy input for, as well as useful work from sub-category "other mechanical drive 1" (OMD1), which represents fuel use for gas/diesel oil vehicles (Brockway et al., 2015), has significantly decreased in just two years, while overall exergy inputs from oil to mechanical drive (Figure 23) do not reflect any of these dynamics at all. The time of occurrence of these spikes (around 1979/1980) indicates that the rapid decline in OMD1 could be related to the second global oil-price shocks, which hit the Indian economy at that time (Bhatia, 1974; Panikar, 1991) and led to significant declines in oil imports, according to (Reddy, 1981). This is also reflected in the IEA (2015) import statistics of diesel oils.

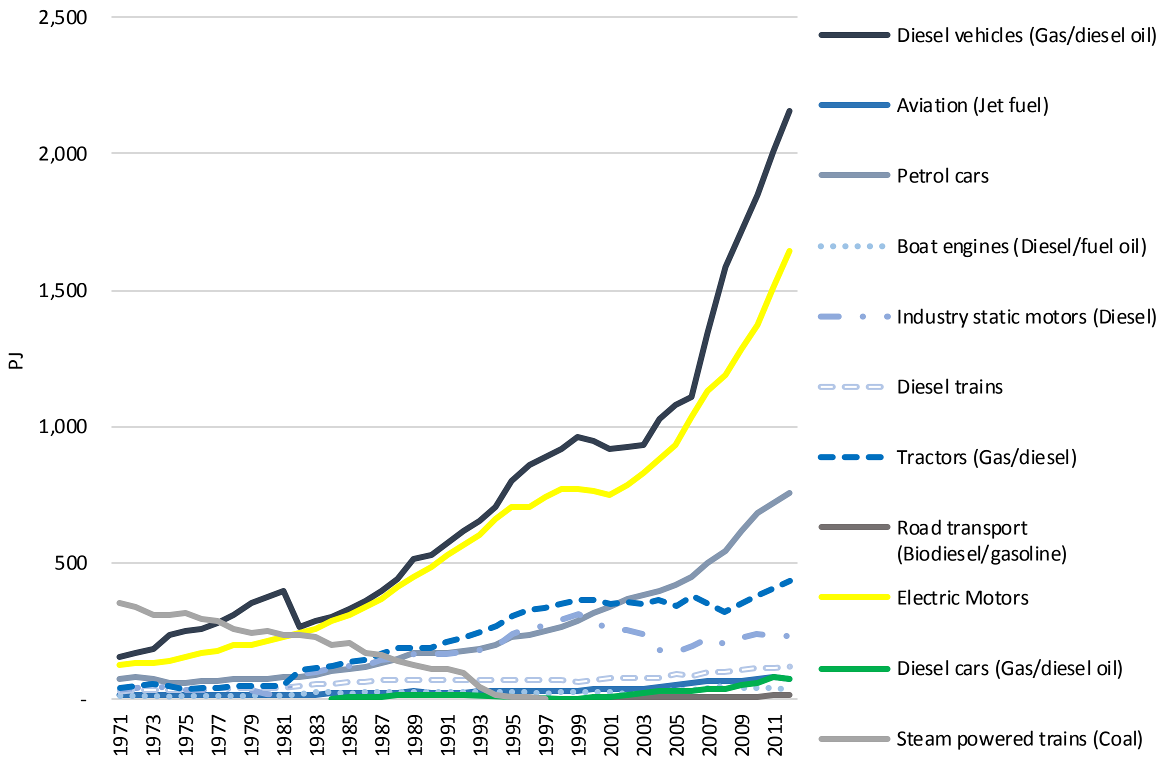


Figure 26: Final exergy inputs for mechanical drive sub-categories, absolute numbers in Petajoules (PJ); India 1971–2012

Own calculations based on Brockway et al. (2015); IEA (2015)

The exergy inputs into each individual sub-category, shown in Figure 26, reveal that the above mentioned decline of inputs to diesel vehicles correlates with increasing inputs for gas/diesel tractors and industrial static diesel motors. While the first increased steadily since the rapid fall around 1980 (when it dropped to 284 PJ), and at an accelerated rate since 2005/2006, the latter two increased until the end of the 20th century (to 360 PJ and 282 PJ, respectively). From 1999 on, exergy inputs for tractors (gas/diesel) more or less stabilised until 2007, declined slightly until 2008 and increased afterwards to almost 430 PJ, while inputs for industrial static diesel motors declined to 171 PJ in 2005 and slightly increased again afterwards. Unsurprisingly, exergy inputs to petrol cars (together with inputs for diesel vehicles), due to the growing number of registered vehicles, have grown significantly and at higher rates at the end of the observed period (to 754 PJ in 2012). Exergy inputs for electric static motors (& agricultural pumps) grew constantly during the studied years (1971: 121 PJ; 2012: 1,642 PJ), except a short phase of minimal decline from 1998-2001, while inputs to the rest of the sub-categories remained relatively unchanged.

Table 6: Final-to-useful efficiencies for mechanical drive sub-categories. India 1971, 1990, 2012

Own calculations based on Brockway et al. (2015); IEA (2015)

	1971	1990	2012
Diesel vehicles (gas/diesel)	20%	23%	22%
Aviation (jet fuel)	23%	23%	25%
Petrol cars	17%	19%	18%
Boat engines (diesel/fuel oil)	13%	17%	21%
Industry static motors (diesel)	23%	25%	27%
Diesel trains	13%	17%	21%
Tractors (gas/diesel)	10%	11%	11%
Steam powered trains (coal)	2%	3%	-
Diesel cars (gas/diesel oil)	-	23%	22%
Road transport (biodiesel/gasoline)	-	-	20%
Electric motors / pumps	51%	54%	57%

Following a constant uptake from 1971 until around 1993, mechanical drive aggregate final-to-useful efficiency, as shown in Figure 27, hasn't changed a lot since this turning point. The increase from above 15% to 30% in 1993 can be explained by the fact that the number of inefficient steam trains had constantly declined up to that point, before completely disappearing in 1997. Representing different groups of input fuels and end-use technologies, individual final-to-useful efficiencies for each sub-category of mechanical drive (

Table 6) have changed only marginally, except for diesel trains and boat engines, which rose from 13% to 21%. The efficiencies of diesel and petrol cars have even slightly decreased.

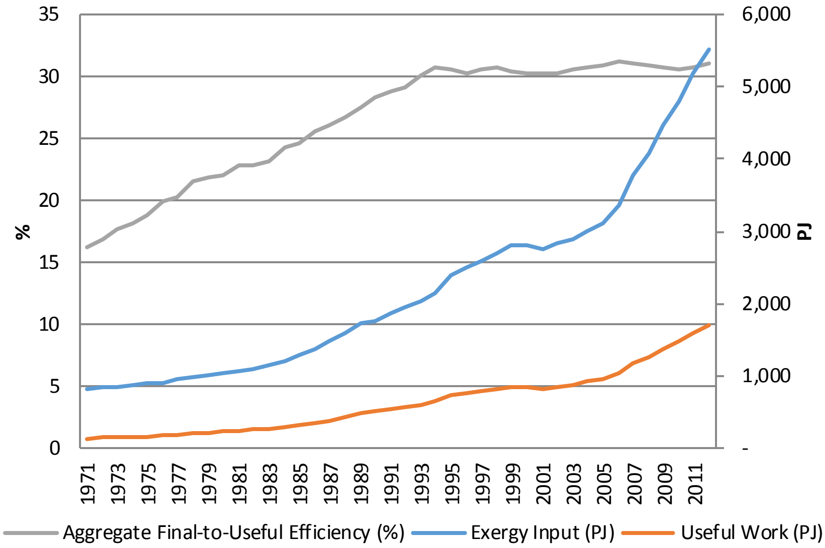


Figure 27: Aggregate final-to-useful efficiency, exergy input, and useful work of mechanical drive. Final-to-useful efficiency percentage (primary axis); Exergy input and useful work in absolute numbers in Petajoules (PJ) (secondary axis); India 1971–2012

Own calculations based on Brockway et al. (2015); IEA (2015)

In fact, Figure 27 supports this finding by revealing that both mechanical drive useful work and exergy input have grown similarly (6% average annual growth rate vs 5% respectively). Hence, it is reasonable to conclude that the observed increase in aggregate mechanical drive final-to-useful efficiency from 1971–1993 is not only the result of technological efficiency improvements but rather a combination of the declining use (and ultimately, disappearance) of inefficient steam trains as well as a shift to (or increased use of) (industrial) electric static motors, which operate at high - but across time relatively unchanged - 2nd law efficiencies.

4.5.3 Lighting

According to Pachauri and Jiang (2008), nowadays the greatest part of Indian households rely on electric power for lighting: The authors found that this end-use represents the first use of electricity once it is available to households (see also section 4.3.3) - In the 1970ies, if a household was electrified, almost all (90%) of residential electricity was used for lighting. However, the primary energy source for illumination in the past, due to the lack of access to electricity in most houses had been kerosene, which provided for 60% of all lighting services in 1971 (Ekholm et al., 2010). Growing electrification lead to a decline of this share in the following years. Nevertheless, in 2012, still around 20% of lighting was supplied by kerosene, especially in rural areas, as elaborated in chapter 3.2.1 (Nadel et al., 1991). Aggregate final-to-useful efficiency of all lighting end-uses was 3% in 1971 and rose to almost 5% in 2012. This is a consequence of accelerated electric light usage due to increasing household electrification.

4.5.4 Electricity

In this chapter, "direct" electricity end-uses other than light, mechanical drive or industrial process heat are analysed, as explained in section 3.2.1.4 (Serrenho, 2013). To maintain consistency, electricity used for lighting, mechanical drive, and heat end-uses have been included in the respective end-use category sections (4.5.3, 4.5.2, and 4.5.1). Overall electricity inputs to all economic sectors (and therefore to all end-uses) have already been presented in section 4.3.3. "Direct" end-use services include electric power used for operating appliances providing space heating (e.g. radiators) & cooling (e.g. fans), refrigeration, as well as electronic devices like computers, TVs, communication equipment etc.

Because of the diversity of these end-use devices in different sectors, and the variation in their respective 2nd law efficiencies, in accordance with Brockway et al. (2015) I conducted a detailed breakdown of these "direct" electricity end-uses for India. In order to gain individual useful work figures for each appliance category, the following end-use sub-categories[12], based on the availability of individual 2nd law efficiencies[13] and in-country data from household surveys (as explained in 4.3.3) were derived:

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[12] Some of the appliances included in this section actually do provide heating purposes, e.g. space heaters, although electric process heat is subsumed under heat (4.5.1). There are several reasons for categorisation: First, (Brockway et al., 2015) give individual 2nd law efficiencies for this type of appliance (heating/cooling equipment), enabling the author to account for the technological characteristics of these devices. Therefore, they can be differentiated from technology and processes subsumed under low temperature heat 1 (e.g. traditional cooking stoves) or high temperature heat (e.g. Electric arc steel furnaces). Second, in the light of the already high and (forecasted growing) importance (Daioglou et al., 2012) of energy consumption in the residential sector (see also section 4.3.3), a disaggregation at the highest possible level of detail for this sector seemed reasonable, especially in order to identify drivers for change of end-use and aggregate efficiency development trends.

[13] Opposed to the end-use decomposition made in industry, and public & commercial sector, residential air conditioning, and cooling/heating are considered two different sub categories due to the availability of independent 2nd law efficiency values for each.

Table 7: "Direct" electricity end-uses, sector-wise sub categories. India 1971-2012

Based on data by Brockway et al. (2015); de la Rue du Can et al. (2009); Parikh and Parikh (2016); Nadel et al. (1991); Boegle et al. (2010)

Energy Sector	Industry	Commercial & Public	Residential
Energy sector own use	Other electronic appliances (communication, computers etc.)	Heating & air-conditioning, refrigeration	Heating/Cooling (e.g. fans, radiators)
		Other electronic appliances (communication, computers etc.)	Air-conditioners
			Refrigerators
			Other electronic appliances (water heaters, computers, telecommunication equipment, entertainment devices such as TVs, Stereos etc.)

Aggregate electricity final-to-useful efficiency, visible in Figure 28, was subject to several fluctuations during the 41 years studied and declined altogether from close to 25% to around 22% in 2012. Aggregate exergy input for "direct" electricity end-uses, on the other side, has increased at a dramatically higher rate than aggregate useful work, resulting in declining aggregate final-to-useful efficiency.

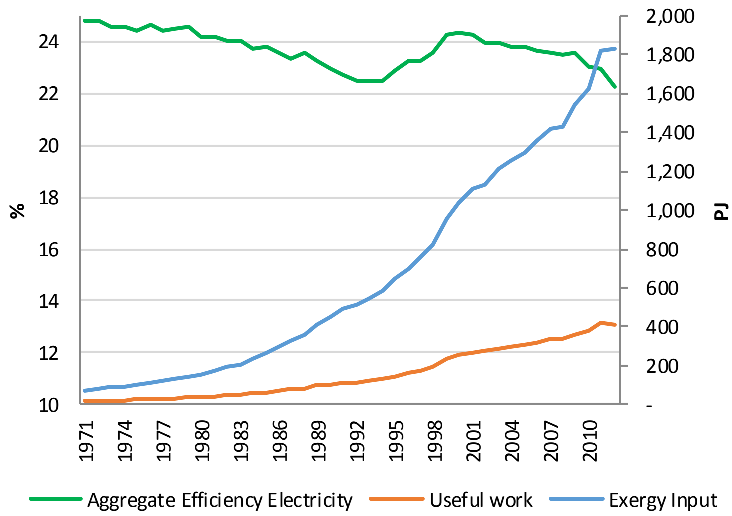


Figure 28: Aggregate electricity final-to-useful efficiency, exergy input and useful work. Final-to-useful efficiency, percentage (primary axis); Exergy input and useful work, absolute numbers in Petajoules (PJ) (secondary axis); India 1971–2012

Own calculations based on Brockway et al. (2015); IEA (2015)

According to Williams et al. (2008), this effect occurs when efficiency improvements are cancelled out by increasing use of low efficiency technology. This so-called '*efficiency dilution*' (ibid., p. 4968) has already been found in other exergy and useful work analysis for Japan (ibid.), and the US (Brockway et al., 2014a).

In the Japanese case, two different types of this phenomenon have been identified. The first has been found in electric power generation, where high efficient technologies (hydro) are substituted by less efficient ones (e.g. thermal fossil fuel plants) because they cannot, in terms of quantity, satisfy the growing demand in electricity (given that hydro reserves have been fully explored in Japan). The second type has been observed in the transport sector, where automobile and truck efficiencies diluted overall transport efficiency gains which were achieved through improvements of trains. Although both types of vehicles initially started with comparable efficiency values, the provision of more flexible mobility lead to greater use of automobiles instead of trains, resulting in overall lower efficiency (Williams et al., 2008). For the US, similar results have been found by Brockway et al. (2014a). The authors state that '*structural shifts to less efficient electricity uses (e.g., air conditioning) occur faster than task-level efficiencies rise for each electricity end use type*' (ibid. p. 9876). The above described decline in aggregate efficiency (Figure 28) implies that the same effect might occur in India.

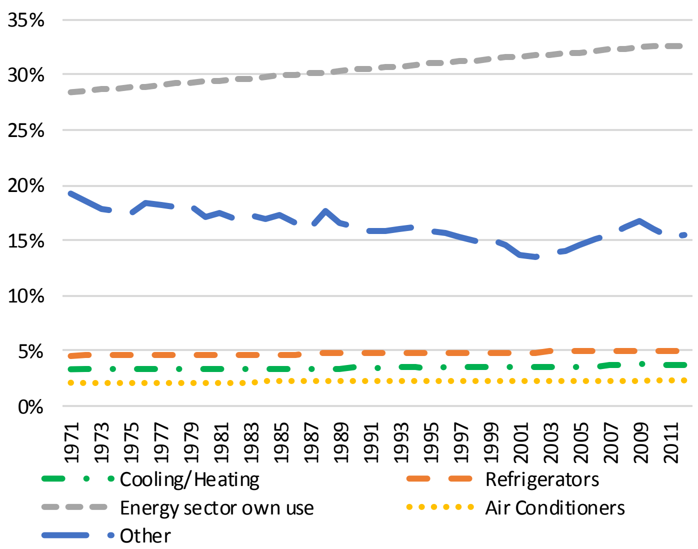
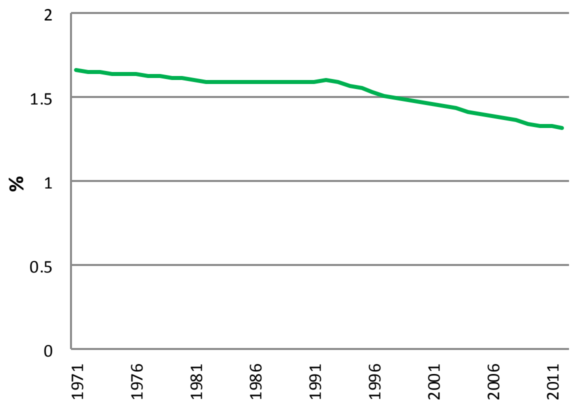


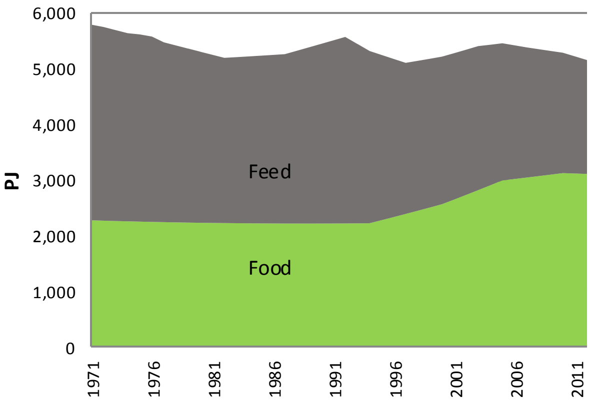
Figure 29: Final-to-useful efficiency of electricity end-use subcategories, all sectors. India 1971–2012

Own calculations based on Boegle et al. (2010); Brockway et al. (2015); IEA (2015); Parikh and Parikh (2016)

An explanation can be found in the decomposition of electricity final-to-useful efficiencies of all end-use subcategories (as defined in Table 7). Individual device efficiencies (summed across all sectors) are shown in Figure 29. Energy sector own use is the only final-to-useful efficiency where an increase occurred, from 28% in 1971 to 33% in 2012. While refrigerators, heating & cooling devices, and air conditioner efficiencies have barely changed (5%, 3%, 2%, respectively), “other” sub-category efficiency declined from 19% at the beginning of the observed period to 15% at its end. The detailed breakdown of end-use device saturation in the residential sector, as presented in Figure 12, indicates that an efficiency dilution effect is indeed taking place in India. “Other” appliances have emerged as the biggest electricity consumer within the residential sector. The increasing number of these low-efficiency devices lowers aggregate electricity final-to-useful efficiency (Figure 27). However, it must be noted that this finding has no significant effect on overall final-to-useful efficiency (opposed to Japan). Nevertheless, it is an important indication for future household electricity consumption in India, because increasing electrification and device saturation, as expected by de la Rue du Can et al. (2009) may lead to a greater diluting effect.

4.5.5 Muscle Work





30) **31)**

Figure 30: Aggregate final-to-useful efficiency muscle work. India 1971–2012

Figure 31: Food and feed exergy input for muscle work, absolute numbers in Petajoules (PJ); India 1971–2012

Own calculations based on Anne Pearson (1989); Bakari et al. (1999); Bhusan et al. (2005); Brockway et al. (2014b); FAO (2015a; 2015b); Henriques and Lunds universitet (2011); Khanna et al. (2004); Phaniraja and Panchasara (2009); Smil (1994); Wiener et al. (2003); Wirsenius (2000)

Muscle work aggregate final-to-useful efficiency, as shown in Figure 30, constantly declined over the analysed period. Muscle work efficiency is obviously limited to biological boundaries. According to Smil (1994), muscles are capable of turning no more than a total of 20-25% of input food/feed into kinetic energy. Hence, the maximum of useful muscle work is limited by the natural physiological boundaries of humans and animals and cannot be increased by technological efficiency improvements. The downward trend of final-to-useful efficiency as well as of feed exergy input (Figure 31) are direct results of the declining number of draught animals (see also 4.3.1.), which are twice as exergy efficient as human workers are. Due to increasing employment in the industrial sector, a more pronounced growth of food intake for manual workers can be observed for the years 1994–2008. From 2009 onwards, food input began to decline again.

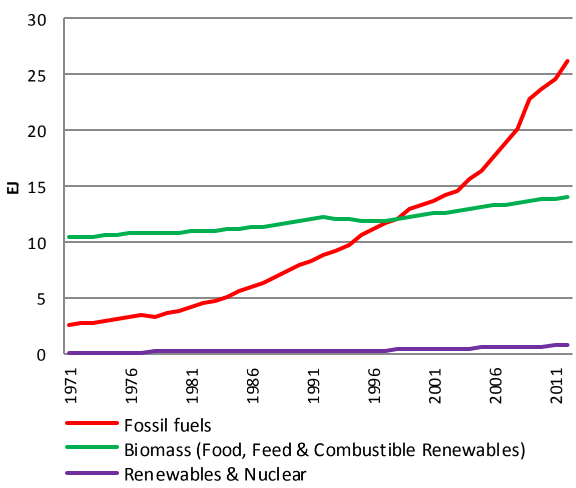
5 Discussion

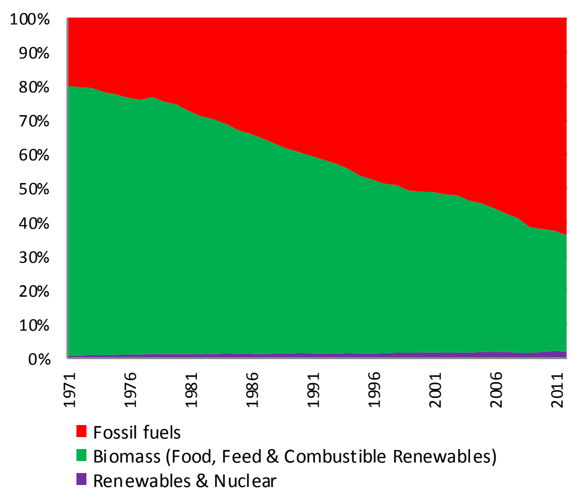
The findings of the exergy analysis of India reveal typical signs for a sociometabolic transition (as elaborated in sections 2.2 and 2.3) towards an industrial regime: Foremost noteworthy is the substitution of biomass by fossil fuels, and the increasing usage of these energy sources across a multitude of sectors. The composition of the Indian primary exergy mix (as shown in Figure 32 and Figure 2) has changed dramatically during the observed period. In 2012, the distribution of the main sources of primary exergy was almost the opposite of what it was in 1971. In just 41 years, biomass inputs (combustibles renewables and food & feed) have decreased by half while fossil fuels, especially coal, gained pronounced relevance. On the aggregate level these results are similar to that of long-term studies focusing on historic transitions of nowadays post-industrial countries like Austria, Japan, US, or UK (Krausmann et al., 2008b, 2008a; Krausmann and Haberl, 2007; Warr et al., 2010). However, on a more detailed level, this analysis identified several important characteristics for the Indian case.

As explained in 2.2 and 2.3, different aspects of various sociometabolic regimes may coexist within one socioeconomic system. This is the case in India: Aspects of agricultural regimes (subsistence farming dependent on manual labour inputs) as well as typical elements of industrial regimes (extended use of fossil fuels in the agricultural system; energy intensive heavy industries, large urban centres) can be found. Although India is still in the process of intensively building up material stocks as a consequence of urbanisation (Singh et al., 2012), employment is already increasingly shifting to the service sector (see also section 4.3.1). This is usually a feature of fully industrialised countries (Warr et al., 2010). On the other hand, despite the rapid industrialisation, and growth of the service sector, a large agricultural sector remains to be the biggest employer in the country. Opposed to rural households, which still depend mostly on traditional fuels such as firewood, urban households use increasing quantities of modern energy sources such as LPG, and electricity, as already discussed in chapter 4.3.2. Indian sociometabolic rates, represented by per-capita primary exergy consumption in 1971 where only as high as 23 GJ/cap, rising to 33 GJ/cap until 2012. These are substantially lower rates compared to that of industrial societies such as the USA, the EU, Japan or South Korea, (150-400 GJ/cap and year) and even lower than the typical 40–70 GJ/cap and year for historical European agricultural societies, according to Krausmann et al. (2008), and Schandl et al. (2009).

5.1 Fossil fuels in India

In the 41 years observed, the relevance of fossil fuels in India increased significantly. The share of fossil energy sources in the total primary exergy mix in 1971 was 20%, rising significantly to 64% in 2012 Figure 32b). Altogether, aggregate primary fossil exergy inputs in absolute numbers had increased 10 times from 1971–2012, from 2.6 EJ to 26 EJ, as shown in Figure 32a). The evolution of aggregate primary fossil exergy inputs can roughly be divided into three phases: 1) relatively slow growth from 1971 until the oil price shocks around 1980 at an average annual growth rate of around 4%, 2) slightly accelerated growth from 1980 until 2003 (around 6%) 3) a steep increase in fossil fuel consumption in just 9 years (7% average annual growth rate from 2003–2012).





a) **b)**

Figure 32: Aggregate primary exergy input by fossil fuels, biomass (food, feed, combustible renewables), renewables, nuclear (electricity). a) Absolute numbers in Exajoules (EJ); b) Shares of total; India 1971-2012

India: own calculations based on IEA (2015); China: (Brockway et al., 2015)

Several drivers for the increase of India's fossil fuel demand have been identified in this analysis: Direct heat and mechanical drive are the most (fossil) resource demanding end-use categories. In 1971, 56% of total final fossil exergy were used to provide heat. This share had risen to 61% in 2012. Although a large fraction of heat end-uses stem from firewood and dung-cake-based, low temperature cooking purposes in the residential sector (80% of all heat end-uses in 1971, below 50% in 2012), high and medium temperature heat uses in (fossil) resource intensive industries like iron & steel, and ammonia production have grown substantially (from around 20% in 1971 to around 50% in 2012). More or less constantly throughout the observed period, around 38% of aggregate final fossil exergy were used for mechanical drive. Increasing private mobility has led to a surge in mechanical drive end-uses, which emerged as the second biggest end-use category after direct heat. In 2012, 70% of all mechanical drive end-uses were based on oil-derived fuels. Another important driver for Indian fossil fuel demand is electricity generation, which consumes large quantities of coal. Although electricity end-uses accounted for only 2% of the total Indian useful work supply in 1971, this share had grown to 8% in 2012. Hence, as the majority of energy end-uses in the country are based on fossil fuels, the economy has become increasingly dependent on coal and oil, of which large quantities have to be imported. In 2012 imports accounted for 26% of the total primary exergy supply of coal, and 90% of the total primary exergy supply of oil.

Figure 32a) and b) show that alternative sources of energy still play only a minor role in the Indian exergy mix, although, as discussed in section 4.1, the Indian government plans to substantially enlarge power outputs by renewables to around 40% of the total energy supply until 2040 (International Energy Agency, 2015). Electricity generated by renewables during the observed period has increased in absolute terms (from 85 to 385 PJ) but its share in the total primary exergy mix has not exceeded 2%. Electric power production by nuclear plants was of a similar order. Interestingly, the decomposition of exergy inputs into the transformation sector (section 4.2.3) revealed that a rapidly growing amount of combustible renewables (wood chips and pellets) is being used to generate electricity.

Fischer-Kowalski and Hausknost, (2014), Fischer-Kowalski and Schaffartzik, (2015) and Schaffartzik and Fischer-Kowalski, (2017) recently argued that the share of fossil fuels in primary energy use is a much better (and easier to be quantified) indicator for the onset of a transition towards industrialisation than the introduction and use of certain (fossil fuel based) technologies. According to Fischer-Kowalski and Hausknost, (2014) the share of fossil fuels in primary exergy consumption in mature industrial economies on average lies between 70-80%. India's share of 64% in 2012 was very close to that. Since 1971 (20%), it has more than tripled (Figure 32b). Obviously, according to the composition of the exergy input (Figure 2 and Figure 3) and useful work supply (Figure 16) in India, the transition had already started years before the starting point of this analysis: As stated by Fischer-Kowalski and Schaffartzik, (2015), transition towards industrialisation were triggered by revolutionary events. In the case of India these are the independence movements from the end of the 19th century until 1947 (ibid.).

5.2 Country Comparison

5.2.1 GDP and Fossil Exergy Consumption

The share of fossil fuels in primary exergy consumption in China from 1971-2010 grew at a similar rate as in India but on average 15% higher (37-77%). Schaffartzik and Fischer-Kowalski (2017) related Indian and Chinese economic growth, represented by their gross domestic products (GDP, in 1990 Geary-Khamis dollars, or international dollars), to the countries' respective fossil energy consumption (in EJ) from 1950-2005. Based on this comparison, I also analysed the relation of fossil fuels and GDP in India and China from 1971-2010, but from an exergy perspective, as show in Figure 33. In China fossil exergy consumption from 2002 onwards levelled off, while Indian fossil exergy consumption from the same year on showed much weaker growth (as explained in detail in section 4.1). In the 1970ies, GDP was roughly at the same level in both countries.

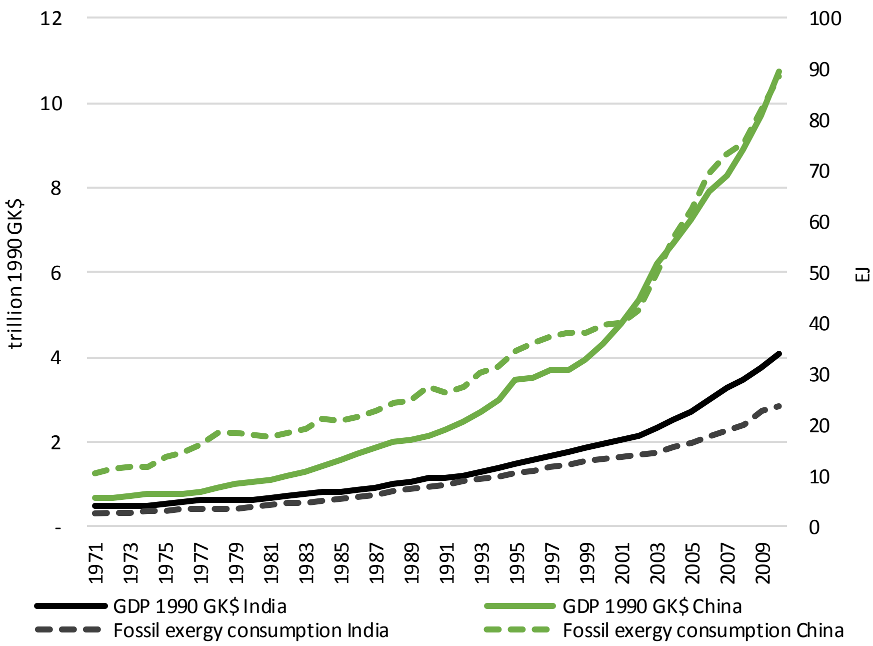


Figure 33: Primary fossil exergy use and GDP in China and India, absolute numbers. GDP in trillion 1990 GK$ (primary axis); Fossil exergy in Exajoules (EJ) (secondary axis); India 1971–2012; China 1971-2010

India: own calculations based on IEA (2015); China: (Brockway et al., 2015). GDP-Data: (The Maddison Project, 2013)

Chinese GDP values took off at the end of the 1990ies/beginning of the 2000s, similar to fossil fuel consumption in the country. From 2002-2010, GDP in China has been growing at an average annual growth rate of 9% while fossil exergy consumption grew at a rate of 10%. However, in India during the same period, GDP has been growing slightly stronger than fossil exergy consumption (8% and 7%, respectively).The accelerated economic growth in China from around 2002 onwards seems to go hand in hand with increased consumption of fossil exergy. The gains in Indian GDP, on the other hand, could be attributed to another factor: Its fast growing service sector, which in 2008 has emerged as the second biggest employer in the country, already had a share of over 50% in total GDP in the same year (Eichengreen and Gupta, 2011; Schaffartzik and Fischer-Kowalski, 2017).

5.2.2 Useful Work supply & End-Use Categories

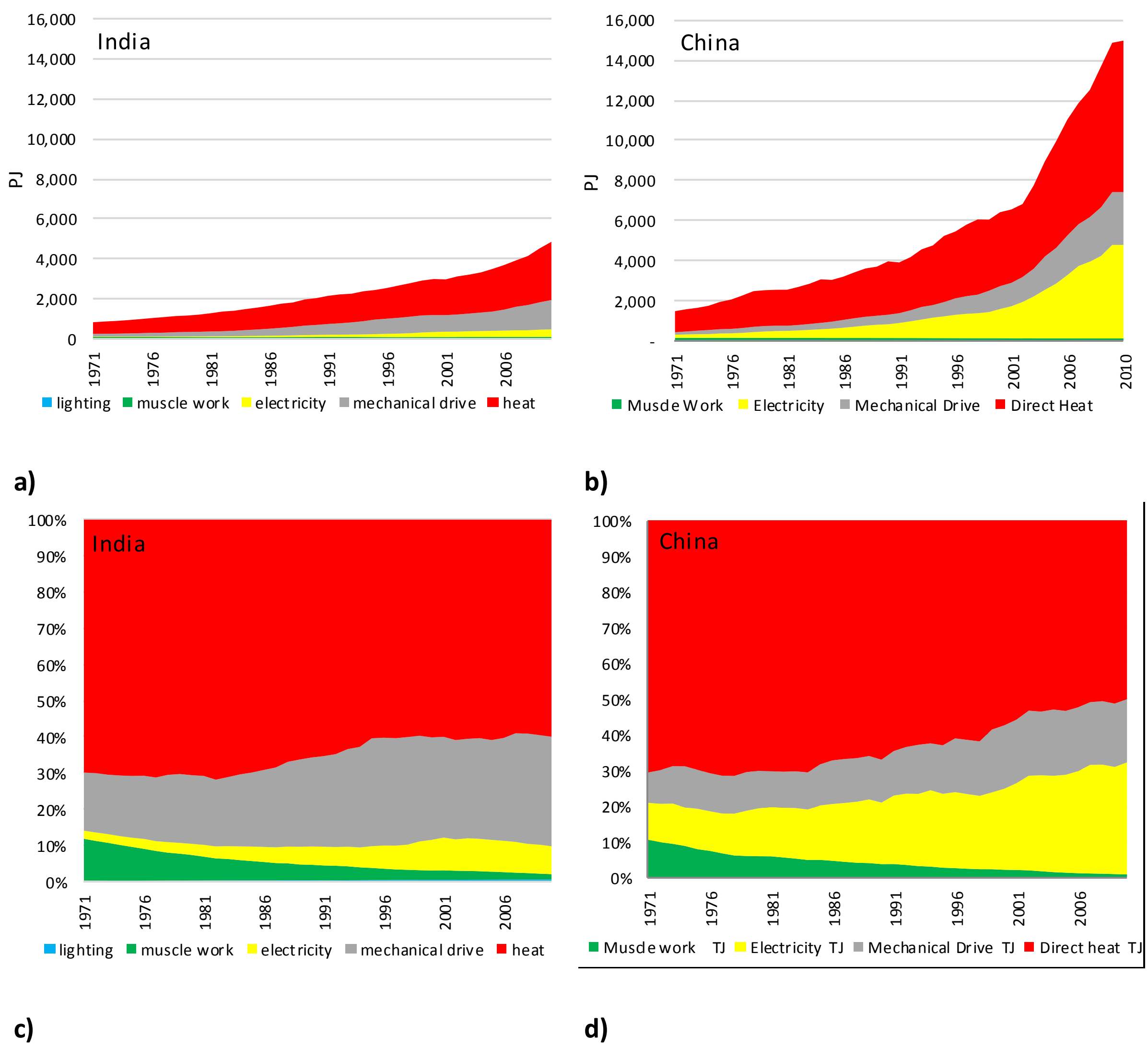


Figure 34: Useful work supply by end-use category, country comparison. a) India 1971-2010; b) China 1971-2010, absolute numbers in Petajoules (PJ). c) India 1971-2010; d) China 1971-2010, shares of total.

India: own calculations based on IEA (2015); China: (Brockway et al., 2015).

Aggregate Indian useful work supply increased from around 800 PJ in 1971 to 5,200 PJ in 2012, opposed to an increase of total primary exergy input from 13,000 PJ to 41,000 PJ during this timeframe. In other words, in 1971, only 6% of total primary exergy inputs where available as useful work for end-users, while 94% where degraded, and ultimately lost for productive use along the energy conversion chain (from primary to final to useful). By 2012, this share had decreased to 87%. China's useful work supply started at 1,400 PJ in 1971 and grew to 15,000 PJ in 2010, a 10-fold increase and almost 3 times that of India. This corresponds to a decrease in the ratio of exergy wasted from 95% to 87% in China from 1971-2012. Decrease in the amount of exergy wasted indicate that significant improvements in aggregate efficiency have taken place while at the same time there still is a large potential for improvement.

Despite the fundamental difference in absolute values, Figure 34b), several similarities, but also deviations between the Indian and the Chinese useful work supply in relative terms have been found: Throughout the whole period, the largest, but in total declining share of Indian (70-58%) and Chinese useful work (71-50%) stems from direct heat, as visible in Figure 34c) and d), followed by mechanical drive in India and electricity in China. It must be noted though, that the share of heat in India's total useful work has been stagnating form around 1995 until 2010, despite growing in absolute values, as can be seen in Figure 34c). This stems from a massive decrease (from over 80% to around 55%) of the share of low temperature heat in India from 1971-2012. The share of heat in total useful work in China (Figure 34d) has decreased during the whole timeframe (from 70% to 50%), while absolute numbers increased from 1,000 PJ to 7,500 PJ (Figure 34b).

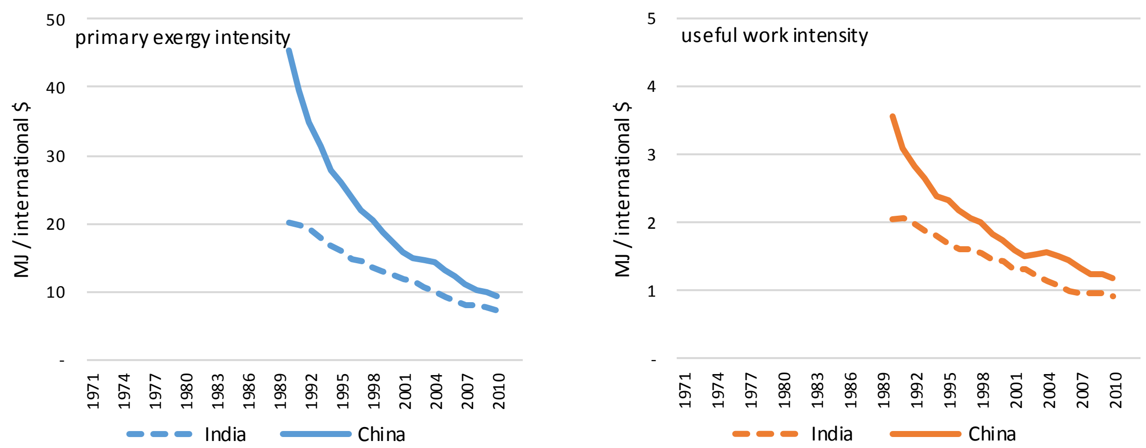
The composition of China's heat sub-categories is quite different from India. The major share (80%) of Indian heat end-uses in 1970 stemmed from low-efficient low temperature heat for cooking purposes (100°C). Although this share has declined to around 55% in 2012 and a shift to more efficient high and medium temperature heat has occurred, aggregate direct heat final-to-useful efficiency was influenced negatively by the high amount of low temperature heat (as explained in 4.5.1). Nevertheless, aggregate heat final-to-useful efficiency doubled from 10% in 1971 to over 20% in 2012. China's direct heat useful work structure is fundamentally different: It consists mainly of high and medium temperature heat (which together accounted for almost 60% of useful work in 1971, rising to almost 80% in 2012) with only a very small share stemming from low temperature heat (100°C). Opposed to India, where the share of space heating purposes is negligible, in China this end-use is a considerable part of total heat end-uses (close to 40% in 1971, around 20% in 2012). The shares of electricity end-uses are substantially different, in China accounting for more than 10% in 1971, growing to almost 30% in 2012, while the respective values for India are 2% to 8%. The reason for this difference is a methodological discrepancy:

In the China study conducted by Brockway et al. (2015), the electricity powered shares of mechanical drive, high temperature heat, and lighting are all subsumed under the electricity end-use category, while for this thesis, electricity category is defined as useful work supplied only by electric devices, in analogy to Serrenho (2013) (as explained in sections 3.2.1 and 4.5.4). This explains the high fraction of mechanical drive in the total useful work structure of India, because a large part of this category (in 2012 over 50%) stems from highly efficient industrial static electric motors and agricultural irrigation pumps. The substantially larger amount of useful work and the higher aggregate final-to-useful efficiency of mechanical drive in India is also attributable to this methodological difference. Mechanical drive is the second biggest end-use category in India, increasing from 16% in 1971 to 33% in 2012.

Nevertheless, the development paths of the useful work structure in the two countries are in large parts similar: Both China and India are dominated by direct heat, although its share declined in both countries throughout the observed period. Heat useful work structures in both countries reflect the shift from low to higher exergy efficient (medium and high temperature heat) end-uses or, in other words, the advanced but still ongoing transition from agriculture to manufacture and production-focused industries. Muscle work shares had substantially declined in both nations down to 10% in 1971. Mechanical drive and electricity, on the other hand, had rapidly gained importance in the 41 years studied in China as well as in India. These are clear indicators for industrialisation, as similar patterns occurred in most industrialised nations, e.g. during the second half of the 20th century in Japan and Austria or in the 18th and 19th century in UK (Warr et al., 2010). The useful work structure of nowadays fully industrialised countries like the EU-15 or the US, on the opposite, show stagnating or even declining shares of high and medium temperature heat useful work (Serrenho, 2013), a typical aspect of mature service economies (Brockway et al., 2015). By 2012 this development had not started in China nor in India (where the shares of high and medium temperature heat uses still increase), but might already lie ahead in the near future (for China maybe sooner).

The higher amount of useful work for electricity and mechanical drive in China both in shares and absolute numbers suggests that the country might be further ahead in the transition from agrarian to industrialised economy than India. This hypothesis is supported by the fact that the share of fossil fuels in primary exergy consumption in China in 2010 was already as high as in typical industrial countries (37% in 1971, 77% in 2010; India: 20% and 64%, respectively). Additionally, China's urban population (% of total population living in urban areas) had increased significantly: In the 1970ies, with 17%, it was behind India's (19%) but quickly overtook it in the early 1990ies. In 2012, urban population accounted for more than half (52%) of the total Chinese population. On the contrary, 31% of the total Indian population lived in urban areas in the same year (The World Bank, 2016).

5.2.3 Exergy and Useful Work Intensities



a) **b)**

Figure 35: Trends in primary exergy and useful work intensity in China and India. a) Primary exergy intensity. b) Useful work intensity. Absolute numbers in Megajoules (MJ)/2011 international $. India, China 1990-2010.

Exergy and useful work: India: own calculations based on IEA (2015); China: (Brockway et al., 2015). GDP: (The World Bank, 2016).

Figure 35a) and b) show trends in primary exergy inputs and useful work outputs per units of GDP (displayed in current (2011) international $). These measures of intensity are commonly used to display the relative decoupling of energy (exergy) use and economic growth (Serrenho, 2013). Both indicators in both countries show a constant declining trend throughout the whole period, reflecting a relative decoupling of economic growth from exergy use and useful work supply. Reductions in primary exergy intensity of 80% (from 45 to 9 MJ per unit of GDP; 1990-2010) and of 66% in useful work intensity (more than 3 to 1 MJ in the same period) occurred in China, while in India improvements were smaller: 64% in primary exergy intensity (20 to 7 MJ) and 55% (2 to 0.9 MJ) in useful work intensity. This means that China used 16% less primary exergy and 9% less useful work than India to produce the same amount of GDP.

5.2.4 Carbon Dioxide Emissions

Figure 36 shows total CO_2 emissions from China and India during the observed period, while Figure 37 depicts exergy and useful work/CO_2 intensities (CO_2 emissions per unit of exergy used and useful work supplied). A large fraction of global CO_2 emissions can be related to increased fossil fuel use. Therefore, measures of CO_2 emissions can be used as a proxy for the environmental burden caused by economic activities (Haberl, 2001b). Not very surprisingly, trajectories of the emissions of India and China (Figure 36) are in accordance with that of fossil exergy inputs (Figure 33). Chinese total emissions levelled off around 2002, while Indian emissions show much slower growth.

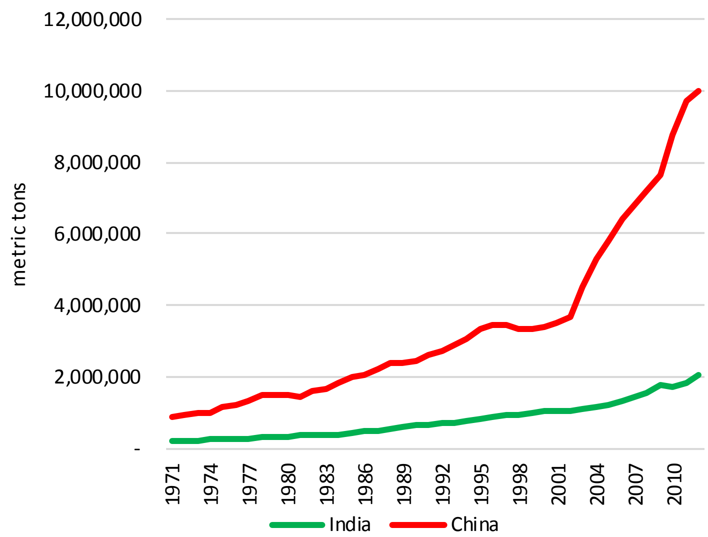
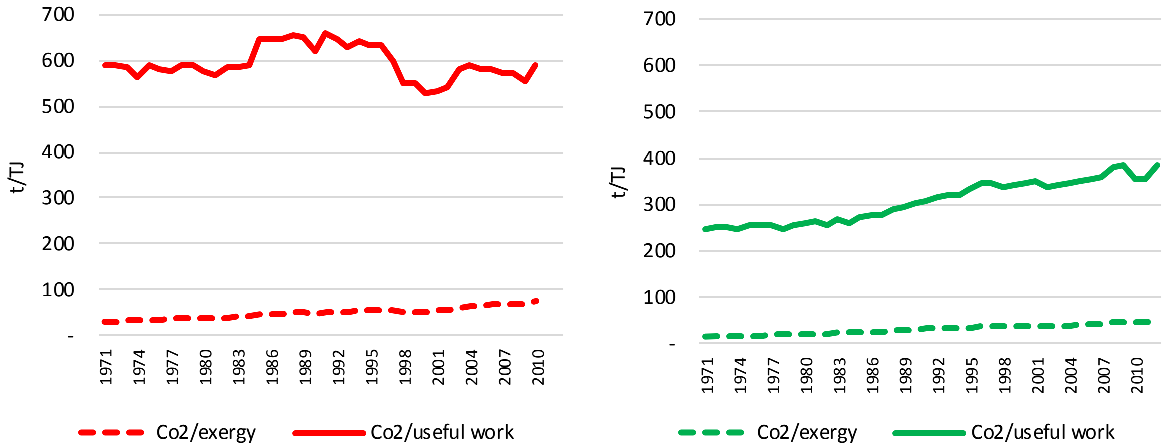


Figure 36: Carbon dioxide (CO_2) emissions by China and India. China 1971-2010. India 1971-2012. CO_2 emissions in absolute numbers in metric tons (t).

(The World Bank, 2016)

As can be seen in Figure 37a) and b), CO_2 emissions per exergy input show a similar trajectory in both countries, increasing by 3% in India from 1971-2012 and by 2% in China from 1971-2010. Figure 37a) reveals that CO_2 emissions per unit of useful work in China stayed at a more or less constant level of between 560-590 t/TJ from 1971 until the mid 1980ies, when it increased in just one year from 591 to 646 t/TJ. This might be an effect of the global oil price shocks. In the mid 1990ies, CO_2 emissions per unit of useful work again started to decline and reached a minimum of around 530 t/TJ in 2000. From 2002 onwards rates increased again but returned in 2012 to the exact same level of 1971. However, as can be seen in Figure 37b), the trajectory in India was different.



a) **b)**

Figure 37: Exergy inputs and useful work outputs in relation to carbon dioxide (CO_2) emissions. a) China 1971-2010. b) India 1971-2010. Absolute numbers, Exergy and useful work in Terajoules (TJ); CO_2 emissions in metric tons (t).

India: own calculations of exergy and useful work based on IEA (2015); China: (Brockway et al., 2015). CO_2 emissions derived from (The World Bank, 2016)

In Comparison to China, the country emitted, in total, less than half the amount of CO_2 per unit of useful work in 1971 (248 t/TJ) but numbers increased constantly during the observed period, to 386 t/TJ in 2012. China managed to maintain a more or less constant level of CO_2 emissions per unit of useful work during the 41 years studied. Indian values constantly increased, meaning that Indian utilisation of more environmentally harmful resources to produce useful work also increased, although absolute numbers are stubstantially lower than in China.

5.2.5 Aggregate Exergy Efficiency and Per-capita Consumption

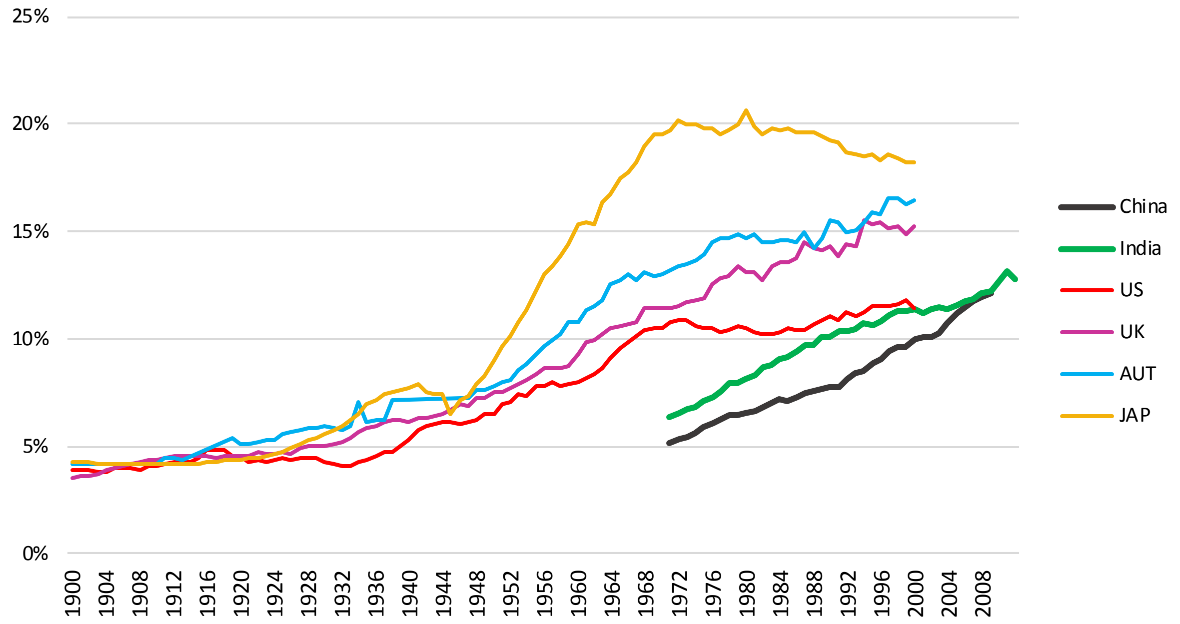


Figure 38: Aggregate exergy efficiency of India, China, US, UK, Austria, and Japan. (Disruptions in Austria and Japan 1938-1945 due to data quality during World Wars)

India 1971-2012: own calculations based on IEA (2015); China 1971-2010: (Brockway et al., 2015); US, UK, Austria, Japan 1900-2000: (Warr et al., 2010)

Figure 38 depicts aggregate exergy efficiencies of India, China, and four industrialised countries, namely the United States, the United Kingdom, Austria, and Japan. According to a study conducted by Nakićenović et al. (1996), exergy efficiency values of developing countries in 1990 were around 10%, which is exactly what was estimated in the thesis at hand. The comparisons of Indian values with China and the industrialised countries in terms of aggregate (primary-to-useful) exergy efficiency (Figure 38) and per-capita primary exergy consumption (Figure 39) reveals several important findings: Trajectories of both Indian and Chinese exergy efficiencies are quite similar, with Indian values lying on average 2% above Chinese from 1971-2010. The evolution of aggregate efficiency in the two countries are very similar to what they were 30 years earlier in the US, UK, and Austria. Both India and China show significant improvements in overall exergy efficiency: India's efficiency (6% in 1971 to 13% in 2012), as well as China's (from 5% in 1971 to 12% until 2010) more than doubled. In 2000, at the end-point of the available time series for the Industrial countries, India had already reached an aggregate exergy efficiency of 11%, the same value as the US, while China was still at 10%. US aggregate efficiency had stayed at 11% since around 2000, due to the diluting effect of low-efficiency devices (e.g. air-conditioning) (Brockway et al., 2015). Despite their low per capita consumption rates, India (in 2005) and China (in 2004) both overtook the stable aggregate exergy efficiency of the USA.

Nevertheless, this result may not be interpreted as a quantum leap in terms of technological improvement: As Brockway et al. (2015) elaborated in their exergy & useful work analysis of China, '*technological leapfrogging*' (ibid., p. 896), which means that China didn't have the problem of low-efficient capital stocks (like industrialised countries) while adopting high efficient technologies very quickly, is not the reason for this gain in efficiency. Although Chinese high temperature heat and mechanical drive efficiencies had significantly improved during the observed timeframe, they were still below US values. Rather, the Chinese production-focused industries used large amounts of high temperature heat processes, opposed to the US consumer-orientated service economy. This indicates that '*structural differences make a significant contribution to China's increasing efficiency'* (ibid., p. 896).

The end-use category analysis (chapter 4.5) revealed that this is also partly true for India: Although there have been significant improvements in high- and medium temperature heat 2nd law efficiencies, the majority of Indian sub-category efficiencies are, on average, as well below that of industrialised countries like the US or UK (apart from a view exceptions) (Serrenho, 2013). The majority of useful work gains stemmed from a structural shift to more efficient end-uses like high and medium temperature heat or electric mechanical drive. Vice versa, there is less contribution of relatively inefficient end-uses e.g. low temperature heat, and steam-powered trains. Nevertheless, the analysis revealed that the improvement in aggregate efficiency in India is the result of both technological innovations and the structural shift in end-uses.

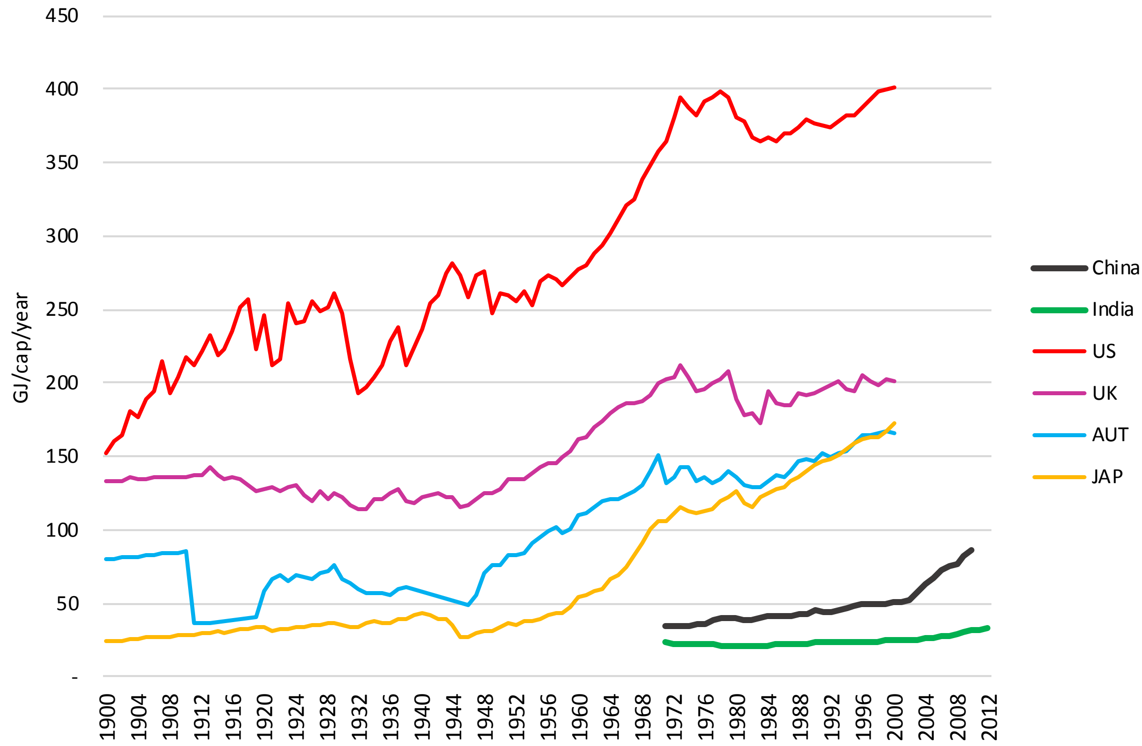


Figure 39: Per-capita primary exergy consumption in India, China, US, UK, Austria, and Japan, absolute numbers in Gigajoules per year (GJ/cap/year). (Disruptions in Austria between 1910-1918, and Austria and Japan between 1939-1945 due to data quality during World Wars)

India 1971-2012: own calculations based on IEA (2015); China 1971-2010: (Brockway et al., 2015); US, UK, Austria, Japan 1900-2000: (Warr et al., 2010)

In terms of per-capita primary exergy consumption, on the contrary, both nations' values (especially China's) are more comparable to Japan's development during the 20th century. India ranked lowest of all 6 countries in 1971 with 23 GJ/cap and experienced only moderate growth throughout the observed period (2010: 31 GJ/cap). China, besides also having far lower per capita consumption levels than industrialised countries (1971: 34 GJ/cap), experienced rapid growth from around 2002 until 2010, when consumption rates where already as high as 86 GJ/cap. This is an interesting implication regarding the distinction of different sociometabolic regimes: while aggregate exergy efficiencies of India and China reached the same level as the USA - a fully industrialised economy - in the early 2000s (Figure 38), their per-capita consumptions stayed closer to that of typical, historical agrarian regimes (Figure 39) – see also section 2.2.

Among the 6 countries in comparison, aggregate exergy efficiency values of 12% occurred independent of time and per-capita consumption, as can be seen in Table 8.

Table 8: Per capita primary exergy consumption and point in time at 12% aggregate primary-to-useful exergy efficiency in India, China, US, UK, Austria, and Japan; absolute Numbers in Gigajoules per person and year (GJ/cap/year).

India 1971-2012: own calculations based on IEA (2015); China 1971-2010: (Brockway et al., 2015); US, UK, Austria, Japan 1900-2000: (Warr et al., 2010)

Country	GJ/cap/year	Reached 12% aggregate primary-to-useful efficiency in
India	27	2005
China	75	2007
US	392	1997
UK	204	1972
Austria	115	1962
Japan	40	1955

As listed in Table 8, the evolution of primary-to-useful exergy efficiency is independent from time and per-capita exergy consumption. Japan had already reached 12% exergy efficiency in 1955, at only 40 GJ per-capita exergy consumption, which puts it in between India and China, only around 50 years earlier. All three Asian countries have (and had) relatively high population densities (The World Bank, 2016) and low per-capita exergy consumption rates in the year they had reached 12% aggregate efficiency. This might indicate that population density is an important factor influencing aggregate exergy efficiency, probably more important than primary per-capita exergy consumption. However, elaborating this hypothesis would require additional research. The transition from agricultural to industrial regime in all three Asian countries started when population density was already high (Schandl et al., 2009), opposed to the now industrialised nations, where increased population growth was influenced by the emergence of industrial agriculture. The low population density of the USA (compared to China, India and Japan) results in larger transport distances, which, among other aspects, are contributors to their higher per-capita consumption rates and lower aggregate efficiency (due to fuel consuming and inefficient automobiles) (Warr et al., 2010).

Table 9: Timespan for aggregate efficiency increase from 6% to 12%, India, China, US, UK, Austria, Japan.

India 1971-2012: own calculations based on IEA (2015); China 1971-2010: (Brockway et al., 2015); US, UK, Austria, Japan 1900-2000: (Warr et al., 2010)

Country	Years	Timespan
India	34	1971-2005
China	33	1974-2007
US	56	1941-1997
UK	38	1934-1972
Austria	37	1925-1962
Japan	25	1930-1955

Both India and China seem to experience a similar sociometabolic transition pattern as the industrialised countries have in the past. In 41 years, both countries were transformed from mostly biomass based economies with big agricultural sectors to large scale fossil fuel consumers with aggregate exergy efficiencies similar to that of Western industrial nations. Surprisingly, except for Japan and the USA, the timespan to increase aggregate exergy efficiency from 6% to 12% (as did India in the observed period from 1971-2012) was more or less the same in all countries, as shown in Table 9 - on average 38 years. The USA needed much more time for this efficiency increase – 56 years. Only Japan with 25 years surpassed China (33 years) and India (34 years). Both nations have experienced steep economic growth since they have opened up and liberalised their economies. This could indicate that globalisation and related effects e.g. technology and knowledge transfers, foreign direct investment etc. had influenced, and still do influence the development paths of the two rapidly growing economies. However, examining this topic would require further research.

6 Conclusions

This work contributes to research about energy use and energy transitions in emerging economies and fills a gap by conducting a first time exergy and useful work analysis of India. The main results described above suggest that by and large, the transition in India is following in the footprints of the nowadays western industrialised countries, although there are some key differences: Although their shares in the primary exergy mix are relatively small, alternative sources of energy like nuclear, and renewables were already part of the primary exergy mix at earlier stages of the energy transition in India than in industrialised countries. Besides comparable aggregate efficiency rates, per-capita consumption in the country is considerably lower than in developed countries, and lower than in China. This is a result of an inefficient economic system and high population growth in the past, as well as discrepancies in regional energy availability, especially between urban and rural areas. In India, traditional sources of energy like dung cake or firewood still play an important role while the electrification rate of households is below that of industrialised economies.

Although primary exergy inputs of renewables in India in absolute numbers have increased, shares in the total exergy mix are still quite low. On the opposite, the iron & steel, and petrochemical industries, a strong growth of the transport sector, as well as high demand for electricity have pushed the demand for fossil exergy. As a matter of fact, fossil fuels' share in primary per-capita exergy consumption has increased substantially, but is still lower than in China. While China's growth in GDP seems to be strongly connected to accelerated fossil fuels use, this seems to be not true for India: GDP is growing at an increasing rate, although a significant take-off phase in fossil fuel consumption is still absent. This phase might eventually lie ahead in the near future.

Combustible biomass still plays a significant role in the total primary exergy mix of India, especially in rural regions. A large number of people (still) depend on traditional fuels like firewood as their main source of residential energy. This is an important implication for sustainable development: Concerning its future energy demand, India is caught in a dilemma. Energy use is a prerequisite for human development, hence the country needs to provide access to energy to all of its citizens. To achieve this goal, India's exergy inputs and useful work outputs will need to increase substantially. To keep up with the strong demand for energy, the Indian government is planning to enlarge its renewable and nuclear capacity, but will foremost need much more fossil fuels, especially coal, for electricity generation. This will, without a doubt, increase pressure on the environment and contradict development towards sustainability. At the same time, India needs to provide for energy sources which are less hazardous to its citizens' health, more efficient, and less environmental damaging, especially in rural households. On the other hand, the saturation of low-efficiency electric appliances in (foremost) urban households might eventually lead to efficiency dilution in the long run, as can be observed in industrial countries like the US and Japan. Indian CO_2 intensities of exergy and useful work have already increased during the observed period and will probably continue to do so.

Without a doubt, the two growing Asian giants India and China will play crucial roles in the global community in the 21st century. Whether India will follow China's example and that of the industrialised nations or take a different, more sustainable development path can only be speculated. Even if countries in transition, like India and China, would achieve a more sustainable development, fulfilling the goals agreed upon at international climate conferences in the last decades will only be feasible if the industrialised countries can manage to substantially reduce their material and energy use.

The exergy and useful work framework proved to be a strong analysis tool for understanding the interconnections between energy degradation, technological innovation and energy end-use in this thesis. While Indian aggregate exergy efficiency had risen impressively, the decomposition of the exergy and useful work structure revealed that structural shifts in energy carriers as well as in useful work categories are at least as important as technical efficiency improvements. The use of exergy, applicable as a single measure across the whole societal energy throughput, solves several consistency problems of "conventional" energy flow analyses e.g. accounting for losses at the final-use stage, measuring energy both quantitatively and qualitatively; the need to use different thermodynamic potentials at the useful stage; the problem of accounting for primary energy from renewables, etc.

Although the strong sides of the method are its consistency, easy applicability, and compatibility with international energy balances, several points for improvement have been identified: Robustness of the analysis strongly depends on data availability and quality. This is especially a problem when studying emerging economies. For this thesis, a lot of second-law efficiencies had to be adopted from other studies. In the case of residential electricity use, consistent timelines were only available from 1990 onwards. Prior years had to be interpolated where data for single years were available. Finding enough studies on residential energy end-use, and calculating all country specific 2^{nd} efficiencies for India was beyond the scope of this study. In order to fully understand the underlying dynamics of the whole societal energy use system from macro to micro scale, as well as the drivers for efficiency improvements, much more additional data would have been needed. Therefore, in order to improve the quality of in-country data and to provide a more consistent picture of the current state of the Indian sociometabolic transition, subsequent research would be needed.

In my opinion, there are several challenges for the exergy and useful work community: Increasing the prominence of this approach outside the scientific field as well as making it and its advantages easier understandable. Scientist of other disciplines, and especially the general public would profit from this effort. Promoting the implementation of exergy and useful work analysis into policy frameworks would help starting new research projects, foster development, and enable improving research tools and their applicability.

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8 Appendix

8.1 Final-to-useful mapping

The mapping of final exergy to end-use categories in this study is based on Serrenho's (2013) allocation for IEA (2015) energy balance data. Where possible, end-uses have been adapted for India using in-country data (see reference list below). When no country-specifics were available, I used data from the Chinese exergy study conducted by Brockway et al. (2015). Where neither of the sources provided accurate data, I used Serrenho's (2013) original end-use mapping.

Colour code for sources of energy and derived commodities:

Coal commodities	Oil commodities	Natural gas	Electricity	Combustible Renewables	Other Renewables

Sub-category/Task-Level Abbreviations of End-Use Categories:

Direct heat	**Reference for task-level subdivison**
HTH = High Temperature Heat (>550°C)	(Krishan et al., 2013)
MTH1 = Medium Temperature Heat 1 (250-550°C)	(Energy and Resources Institute New Delhi, 2009)
50 HTH/50 MTH1 = 50% High Temperature Heat (>550°C) / 50% Medium Temperature Heat 1 (250-550°C)	(Brockway et al., 2015)
MTH2 = Medium Temperature Heat 2 (100-250°C)	(K. Schumacher and Sathaye, 1999)
LTH1 = Low Temperature Heat 1 (20-100°C)	(Tata Energy Research Institute, 2006)
LTH2 = Low Temperature Heat 2 (20°C)	(Tata Energy Research Institute, 2006)

Mechanical drive	**Reference for task-level subdivision**
OMD1 = Mechanical Drive (Gas/diesel oil vehicles)	(Brockway et al., 2015)
OMD2 = Mechanical Drive (Aviation fuel, jet fuel)	(Brockway et al., 2015)
OMD3 = Mechanical Drive (Gasoline fuel - Petrol cars)	(Brockway et al., 2015)

OMD4 = Mechanical Drive (Diesel/gas oil fuel – Boat engines)	(Brockway et al., 2015)
OMD5 = Mechanical Drive (Industrial static diesel motors)	(Brockway et al., 2015)
OMD6 = Mechanical Drive (gas/diesel fuel – diesel trains)	(Brockway et al., 2015)
OMD7 = Mechanical Drive (gas/diesel fuel – tractors)	(Brockway et al., 2015)
CRMD1 = Mechanical Drive (biodiesel/bio-gasoline (road transport)	(Brockway et al., 2015)
GMD1 = Mechanical Drive (gas/diesel oil cars)	(Brockway et al., 2015)
CMD1 = Mechanical Drive (steam powered trains)	(Brockway et al., 2015)
El-MD = Mechanical Drive (electricity powered trains)	(Brockway et al., 2015)
El-MD2 = Mechanical Drive (electric static motors & irrigation pumps)	(Nadel et al., 1991)

Electricity	**Reference for task-level subdivision**
El-own = Energy sector electricity own use (unspecified)	(Brockway et al., 2015)
El-other = Electricity appliances (air-conditioners, refrigerators, fans, water-cookers) + other electronic devices (TVs, computers, telecommunication, stereos)	(Alam et al., 1998; Jain et al., 2014; Wolter, 1996; McNeil et al., 2008; McNeil and Letschert, 2008)

Lighting	**Reference for task-level subdivison**
Coal/Oil Light = Kerosene and other lights	(Bhattacharyya, 2006)
El-lighting = Electric lamps	(Pachauri and Jiang, 2008)

References for Sources of Energy and Derived Commodities End-use Mapping:

(1) (Serrenho, 2013)
(2) (Brockway et al., 2015)
(3) (Ministry of Petroleum and Natural Gas, 2015)
(4) (Bhattacharyya, 2006)
(5) (The International Institute for and Sustainable Development, 2014)
(6) (Nadel et al., 1991)
(7) (Krishan et al., 2013)
(8) (Energy and Resources Institute, 2014)
(9) (Tata Energy Research Institute, 2006)

Energy Sector Own Use				
Flow	**Energy Commodity**	**Reference**	**End-Use Category**	**Sub-Category/ Task-Level**
Coal Mines				
	Hard coal (if no detail)	2	Heat	MTH2
	Other bituminous coal	2		MTH2
	Coking coal	2		MTH2
	Electricity	2	Electricity	El-own
Blast Furnaces				
	Coke oven gas	2	Heat	HTH
Coke ovens				
	Coke oven gas	2	Heat	HTH
	Electricity	2	Electricity	El-own
BKB/Briquettes Plants				
	Lignite	1	Heat	MTH2
	Brown coal (if no detail)	1		MTH2
Gas Works				
	Other bituminous coal	2	Heat	HTH
	Gas works gas	2		HTH
	Electricity	2	Electricity	El-own
Own Use in Electricity, CHP and Heat Plants				
	Electricity	2	Electricity	El-own
Oil Refineries				
	Crude Oil	2	Heat	MTH2
	Refinery feedstocks	2		MTH2
	Refinery gas	2		MTH2
	Liquefied petroleum gases (LPG)	2		MTH2
	Naphtha	2		MTH2
	Lubricants	2		MTH2
	Bitumen	2		MTH2
	Paraffin waxes	2		MTH2
	Petroleum coke	2		MTH2
	Other oil products	2		MTH2
	Other kerosene	2		MTH2
	Kerosene type jet fuel excl. biofuels	2		MTH2
	Fuel oil	2		MTH2
	Gas/diesel oil excl. biofuels	2		MTH2
	Motor gasoline excl. biofuels	2		MTH2
	Electricity	2	Electricity	El-own

Final Consumption - Industry				
Flow	**Energy Commodity**	**Reference**	**End-Use Category**	**Sub-Category/ Task-Level**
Iron and Steel				
	Hard coal (if no detail)	7	Heat	HTH
	Lignite	7		HTH
	Other bituminous coal	7		HTH
	Coking coal	7		HTH
	Gas works gas	7		HTH
	Coke oven Coke	7		HTH
	Blast furnace gas	7		HTH
	Coke oven gas	7		HTH
	Liquefied petroleum gases (LPG)	2		HTH
	Naphtha	1		HTH
	Fuel oil	2		HTH
	Gas/diesel oil excl. biofuels	2	Mechanical Drive	OMD5
Chemical and Petrochemical				
	Hard coal (if no detail)	9	Heat	MTH1
	Lignite	9		MTH1
	Brown coal (if no detail)	9		MTH1
	Other bituminous coal	9		MTH1
	Coking coal	9		MTH1
	Liquefied petroleum gases (LPG)	9		MTH1
	Naphtha	9		MTH1
	Fuel oil	9		MTH1
	Gas/diesel oil excl. biofuels	2	Mechanical Drive	OMD5
Non-Ferrous Metals				
	Lignite	2	Heat	50HTH/50MTH1
	Other bituminous coal	2		50HTH/50MTH1
	Fuel oil	2		50HTH/50MTH1
	Gas/diesel oil excl. biofuels	2	Mechanical Drive	OMD5
Non-Metallic Minerals				
	Hard coal (if no detail)	2	Heat	50HTH/50MTH1
	Lignite	2		50HTH/50MTH1
	Other bituminous coal	2		50HTH/50MTH1
	Coking coal	2		50HTH/50MTH1
	Petroleum coke	1		MTH2
	Fuel oil	2		50HTH/50MTH1
	Gas/diesel oil excl. biofuels	2	Mechanical Drive	OMD5
Machinery				
	Liquefied petroleum gases (LPG)	2	Heat	50HTH/50MTH1
	Fuel oil	2		50HTH/50MTH1
	Gas/diesel oil excl. biofuels	2	Mechanical Drive	OMD5

Flow	Energy Commodity	Reference	End-Use Category	Sub-Category/ Task-Level
Mining and Quarrying				
	Liquefied petroleum gases (LPG)	2	Mechanical Drive	OMD5
	Fuel oil	2	Heat	50HTH/50MTH1
	Gas/diesel oil excl. biofuels	2	Mechanical Drive	OMD5
Food and Tobacco				
	Fuel oil	9	Heat	MTH2
	Gas/diesel oil excl. biofuels	9		MTH2
Paper, Pulp and Printing				
	Hard coal (if no detail)	2	Heat	MTH2
	Lignite	2		MTH2
	Other bituminous coal	2		MTH2
	Coking coal	2		MTH2
Construction				
	Gas/diesel oil excl. biofuels	2	Mechanical Drive	OMD5
Textile and Leather				
	Hard coal (if no detail)	9	Heat	MTH2
	Lignite	9		MTH2
	Other bituminous coal	9		MTH2
	Liquefied petroleum gases (LPG)	9		MTH2
	Fuel oil	9		MTH2
	Gas/diesel oil excl. biofuels	2	Mechanical Drive	OMD5
Non-specified Industry				
	Hard coal (if no detail)	2	Heat	50HTH/50MTH1
	Lignite	2		50HTH/50MTH1
	Other bituminous coal	2		50HTH/50MTH1
	Coking coal	2		50HTH/50MTH1
	Electricity	2	Mechanical Drive	El-MD2
	Electricity	6	Lighting	El-lighting
	Electricity	6	Heat	HTH-el
	Liquefied petroleum gases (LPG)	2		OMD5
	Naphtha	2	Heat	50HTH/50MTH1
	Fuel oil	2		50HTH/50MTH1
	Gas/diesel oil excl. biofuels	2	Mechanical Drive	OMD5
	Natural Gas	2	Heat	50HTH/50MTH1
	Primary solid biofuels	2		LTH1
	Solar Thermal	9		MTH2

Final Consumption - Transport				
Flow	**Energy Commodity**	**Reference**	**End-Use Category**	**Sub-Category/ Task-Level**
Road				
	Liquefied petroleum gases (LPG)	9	Mechanical Drive	GMD1
	Fuel oil	2		OMD1
	Gas/diesel oil excl. biofuels	2		OMD1
	Motor gasoline excl. biofuels	2		OMD3
	Natural Gas	2		GMD1
	Biogasoline	2		CRMD1
	Biodiesels	2		CRMD1
Rail				
	Hard coal (if no detail)	2		CMD1
	Other bituminous coal	2		CMD1
	Electricity	2		El-MD
	Fuel oil	2		OMD6
	Gas/diesel oil excl. biofuels	2		OMD6
Domestic Navigation				
	Fuel oil	2		OMD4
	Gas/diesel oil excl. biofuels	2		OMD4
Domestic Aviation				
	Kerosene type jet fuel excl. biofuels	2		OMD2

Final Consumption - Other Sectors				
Flow	**Energy Commodity**	**Reference**	**End-Use Category**	**Sub-Category/ Task-Level**
Agriculture & Forestry				
	Electricity	6	Mechanical Drive	El-MD2
	Fuel oil	9		OMD7
	Gas/diesel oil excl. biofuels	9		OMD7
	Natural Gas	2	Heat	LTH2
Commercial and Public Services				
	Hard coal (if no detail)	2	Heat	LTH2
	Other bituminous coal	2		LTH2
	Electricity	6	Electricity	El-other
	Electricity	6	Lighting	El-lighting
	Liquefied petroleum gases (LPG)	2	Heat	LTH1
	Other kerosene	2		LTH1
	Primary solid biofuels	2		LTH1
	Solar Thermal	9		LTH1
Residential				
	Hard coal (if no detail)	2	Heat	LTH2
	Other bituminous coal	2		LTH2
	Coking coal	9		LTH1
	BKB	2		LTH2
	Electricity	6	Electricity	El-other
	Electricity	6	Lighting	El-lighting
	Liquefied petroleum gases (LPG)	5	Heat	LTH1
	Other kerosene	3	Lighting	Coal/Oil-Light
	Natural Gas	9	Heat	LTH1
	Primary solid biofuels	4		LTH1
	Solar Thermal	9		LTH1
Non-specified Other				
	Hard coal (if no detail)	2	Heat	LTH2
	Other bituminous coal	2		LTH2
	Electricity	2	Electricity	El-other
	Liquefied petroleum gases (LPG)	1	Mechanical Drive	OMD5
	Other Kerosene	2	Heat	LTH2
	Fuel oil	1		MTH2
	Solar Thermal	9		LTH1

8.2 Second Law Efficiencies

For 4 different heat end-use task-levels (HTH, MTH1, MTH2, LTH1), I have estimated 2nd law efficiencies following Brockway et al. (2014) and Brockway et al., (2015). Deriving new 2nd law efficiency estimates for all Indian end-uses would have gone beyond the scale of this thesis. Additionally, data on the actual end-use device/process level were rarely available. Therefore, for this study the remaining 2nd law efficiencies have been obtained from the China exergy study conducted by Brockway et al., (2015). However, investigating end-use data and estimating 2nd law efficiencies for India would strengthen the robustness of this thesis' results.

8.2.1 Second Law Efficiencies Estimation

8.2.1.1. High Temperature Heat (HTH)

For iron & steel, which is the main sector where temperatures of 550 °C and above occur, calculations are based on the procedure described in detail by Brockway et al. (2014a, pp. 6–10), supplemented with in-country data. In principal, there are three different types of plants used in Iron & Steel Production: Basic Oxygen Furnace, Open Hearth Furnace (BOF/OHF) and Electric Arc/Electric Induction Furnace (EAF). While the first two feed on coal, oil and gas commodities, the latter is driven by, as the name already indicates, electricity (Schumacher and Sathaye, 1998; IEA, 2015; Krishan et al., 2013).

In a first step, I calculated individual energy efficiencies for each manufacturing process as minimum-to-actual energy requirement per tonne of crude steel ratios. For this study, data for production by process were obtained from yearly reports of Committee on Statistics, (1980). Values for theoretical minimum energy requirement are adopted from Fruehan et al. (2000) for BOF/OHF and EAF at 8,6 and 1,3 GJ/tes, respectively, while for actual energy consumption, various data sources have been used (Price et al., 1999; Sudhakara Reddy and Kumar Ray, 2011; IEA, 2015; Committee on Statistics, 1980; Energy and Resources Institute New Delhi, 2009). Missing values have been interpolated. Finally, Carnot temperature ratio is added to equation 5, producing second law efficiencies for the High Temperature Heat end use category.

$$\epsilon = \eta * (1 - \frac{T_0}{T_2})$$

ϵ ... *exergy efficiency*

η ... *device / process energy efficiency*

T_0 ... *average annual outdoor temperature*

T_2 ... *desired process heat*

Equation 5: Exergy efficiency calculation

Based on Brockway et al. (2014b)

I obtained average annual outdoor temperature statistics from the Climatic Research Unit (CRU) of University of East Anglia (UEA) (2016). Desired process heat lies above 550°C, according to Krishan et al. (2013).

8.2.1.2. Medium Temperature Heat 1 (MTH1)

Temperatures between 250–550°C occur mainly in the petrochemical sector. Because of its extent and economic importance ammonia fertilizer production acts as a proxy for the medium temperature heat task level. I obtained minimum energy requirement values for the production of 1 ton of ammonia from Rafiqul et al. (2005). The Bureau of Mines (1972), and K. Schumacher and Sathaye (1999) provide data on the actual energy requirement of Indian ammonia production, while production data in tons was acquired by The Fertiliser Association of India (2017). The calculation procedure was the same as for high temperature heat (Equation 5) except for the different energy efficiency and lower process heat (hot reservoir). In absence of precise data for the actual temperature of Indian ammonia production processes, the average temperature of the whole range - 400°C (Saygın et al., 2009) - was chosen for this analysis.

8.2.1.3. Medium Temperature Heat 2 (MTH2)

This category corresponds to industries using temperatures between 100-250°C. Examples are paper & pulp production, food processing, dairy, textile industry etc. (as elaborated in chapter 3.2.1.1). However, due to the absence of efficiency data for each processes, and the importance of this industry branch, in this study paper & pulp has been chosen as a representative for this subcategory. I have obtained best practice data of energy consumption in the paper & pulp industry from Worrell et al. (2008). Katja Schumacher and Sathaye (1999) provide specific data for Indian paper mills. Paper production data in tons for the estimation have been acquired from the Central Pulp & Paper Research Institute (2006); the FAO (2015); Sudhakara Reddy and Kumar Ray, (2011) and Trudeau et al. (2011). I used Equation 5 with adopted values for energy efficiency and process temperature (hot reservoir) for estimating the 2nd law efficiency.

8.2.1.4. Low Temperature Heat 1 (LTH1)

This end-use sub category is represented by household cooking, using temperatures of up to 100°C. The majority of Indian households (as explained in sections 4.3.2) use traditional cooking stoves and biofuels such as firewood or dung cake. Brockway et al. (2015) give average energy efficiency values for combustion of firewood, as well as for traditional cooking stoves. By adopting these values and multiplying them by Carnot ratio, I estimated LTH1 2nd law efficiencies.

8.2.1 Adopted Second Law Efficiencies

On the following pages, time-dependent second law efficiencies used in this thesis to calculate useful work figures are presented. Tables include both own estimated efficiency values for High (HTH), Medium 1 (MTH1), Medium 2 (MTH2), and Low Temperature Heat 1 (LTH1), as elaborated in the previous section, as well as the remaining efficiencies which have been obtained from Brockway et al. (2015).

End- Use Categories/Task-levels	Abbrevations	Ref.	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980
Heat – High Temp. Heat (>550ºC)	HTH	own	14%	16%	17%	16%	17%	19%	20%	24%	21%	25%
Heat – Medium Temp. Heat1 (550°C-250ºC)	MTH1	own	26%	26%	26%	27%	27%	28%	28%	29%	29%	29%
Heat – Medium Temp. Heat2 (250ºC)	MTH2	own	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%
Heat – Low Temp. Heat1 (100ºC)	LTH1	own	10%	10%	10%	10%	10%	10%	11%	11%	11%	11%
Heat – Low Temp. Heat2 (20ºC)	LTH2	2	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%
Heat - Industrial process Heat (Electricity)	HTH-el	2	27%	27%	27%	27%	27%	27%	27%	28%	28%	28%
Mechanical Drive - Gas/diesel oil (assume diesel vehicles)	OMD1	2	20%	21%	21%	21%	21%	21%	21%	21%	21%	21%
Mechanical Drive - Domestic Aviation fuel, jet fuel	OMD2	2	23%	23%	23%	23%	22%	22%	22%	23%	23%	23%
Mechanical Drive - Gasoline fuel (Petrol cars)	OMD3	2	17%	17%	17%	18%	18%	18%	18%	18%	18%	18%
Mechanical Drive - Diesel/gas oil fuel (Boat engines)	OMD4	2	13%	13%	13%	13%	13%	13%	14%	14%	14%	14%
Mechanical Drive - Industry static motors (diesel engines)	OMD5	2	23%	24%	24%	24%	24%	24%	24%	24%	24%	24%
Mechanical Drive - Gas/diesel fuel (diesel trains)	OMD6	2	13%	13%	13%	13%	13%	13%	14%	14%	14%	14%
Mechanical Drive - Gas/diesel fuel (tractors)	OMD7	2	10%	10%	10%	10%	10%	11%	11%	11%	11%	11%
Mechanical Drive - bio-diesel / bio-gasoline (road transport)	CRMD1	2	19%	19%	19%	19%	19%	19%	19%	20%	20%	20%
Mechanical Drive - bio-diesel (diesel trains)	CRMD2	2	13%	13%	13%	13%	13%	13%	14%	14%	14%	14%
Mechanical Drive - Gas/diesel oil (assume diesel cars)	GMD1	2	20%	21%	21%	21%	21%	21%	21%	21%	21%	21%
Mechanical Drive - Gas fired engines (for pipeline transport)	GMD2	2	23%	21%	21%	21%	21%	22%	22%	22%	22%	22%
Mechanical Drive - Coal (steam powered trains)	CMD1	2	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Mechanical Drive - Coal (steam powered boats)	CMD2	2	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Mechanical Drive - Industry static motors/pumps (electricity)	El-MD2	2	53%	53%	53%	53%	53%	53%	54%	54%	54%	54%
Mechanical Drive - Electric trains	El-MD	2	13%	13%	13%	13%	13%	13%	14%	14%	14%	14%
Electricity - Energy sector own use	El-own	2	28%	29%	29%	29%	29%	29%	29%	29%	29%	29%
Electricity - Industry - others	El-other-ind	2	31%	31%	31%	31%	32%	32%	32%	32%	32%	33%
Electricity - Commercial & public - heating & air-conditioning	El-heat/cool-comm	2	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%
Electricity - Commercial & public - others	El-other-comm	2	18%	18%	18%	18%	18%	18%	18%	18%	18%	18%
Electricity - Residential - Fans & radiators	El-cool/heat-resid	2	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%
Electricity - Residential - Refrigerators	El-refrige-resid	2	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Electricity - Residential - Air-conditioners	El-aircon-resid	2	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Electricity - Residential - others	El-other-resid	2	15%	15%	15%	15%	15%	15%	15%	15%	15%	15%
Lighting - Electric	El-light	2	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%
Lighting - Coal & Oil	Coal/Oil-Light	2	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%

End- Use Categories/Task-levels	Abbrevations	Ref.	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
Heat – High Temp. Heat (>550ºC)	HTH	own	27%	29%	27%	25%	29%	23%	29%	25%	26%	25%
Heat – Medium Temp. Heat1 (550°C-250ºC)	MTH1	own	30%	30%	31%	31%	32%	32%	33%	35%	37%	37%
Heat – Medium Temp. Heat2 (250ºC)	MTH2	own	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%
Heat – Low Temp. Heat1 (100ºC)	LTH1	own	11%	11%	12%	12%	12%	12%	12%	12%	13%	13%
Heat – Low Temp. Heat2 (20ºC)	LTH2	2	4%	4%	4%	4%	4%	4%	4%	4%	4%	5%
Heat - Industrial process Heat (Electricity)	HTH-el	2	28%	28%	28%	28%	28%	28%	28%	28%	28%	28%
Mechanical Drive - Gas/diesel oil (assume diesel vehicles)	OMD1	2	22%	22%	22%	22%	22%	22%	22%	22%	22%	23%
Mechanical Drive - Domestic Aviation fuel, jet fuel	OMD2	2	23%	22%	22%	22%	22%	22%	22%	22%	23%	23%
Mechanical Drive - Gasoline fuel (Petrol cars)	OMD3	2	18%	18%	18%	18%	18%	19%	19%	19%	19%	19%
Mechanical Drive - Diesel/gas oil fuel (Boat engines)	OMD4	2	14%	14%	14%	14%	14%	14%	15%	15%	16%	17%
Mechanical Drive - Industry static motors (diesel engines)	OMD5	2	24%	24%	25%	25%	25%	25%	25%	25%	25%	25%
Mechanical Drive - Gas/diesel fuel (diesel trains)	OMD6	2	14%	14%	14%	14%	14%	14%	15%	15%	16%	17%
Mechanical Drive - Gas/diesel fuel (tractors)	OMD7	2	11%	11%	11%	11%	11%	11%	11%	11%	11%	11%
Mechanical Drive - bio-diesel / bio-gasoline (road transport)	CRMD1	2	20%	20%	20%	20%	20%	20%	20%	21%	21%	21%
Mechanical Drive - bio-diesel (diesel trains)	CRMD2	2	14%	14%	14%	14%	14%	14%	15%	15%	16%	17%
Mechanical Drive - Gas/diesel oil (assume diesel cars)	GMD1	2	22%	22%	22%	22%	22%	22%	22%	22%	22%	23%
Mechanical Drive - Gas fired engines (for pipeline transport)	GMD2	2	22%	22%	22%	22%	22%	22%	22%	23%	23%	23%
Mechanical Drive - Coal (steam powered trains)	CMD1	2	2%	2%	2%	2%	2%	2%	3%	3%	3%	3%
Mechanical Drive - Coal (steam powered boats)	CMD2	2	2%	2%	2%	2%	2%	2%	3%	3%	3%	3%
Mechanical Drive - Industry static motors/pumps (electricity)	El-MD2	2	54%	54%	54%	55%	55%	55%	55%	55%	55%	55%
Mechanical Drive - Electric trains	El-MD	2	14%	14%	14%	14%	14%	14%	15%	15%	16%	17%
Electricity - Energy sector own use	El-own	2	29%	30%	30%	30%	30%	30%	30%	30%	30%	30%
Electricity - Industry - others	El-other-ind	2	33%	33%	33%	33%	33%	34%	34%	34%	34%	34%
Electricity - Commercial & public - heating & air-conditioning	El-heat/cool-comm	2	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%
Electricity - Commercial & public - others	El-other-comm	2	19%	19%	19%	19%	19%	19%	19%	19%	19%	19%
Electricity - Residential - Fans & radiators	El-cool/heat-resid	2	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%
Electricity - Residential - Refrigerators	El-refrige-resid	2	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Electricity - Residential - Air-conditioners	El-aircon-resid	2	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Electricity - Residential - others	El-other-resid	2	15%	15%	15%	16%	16%	16%	16%	16%	16%	16%
Lighting - Electric	El-light	2	3%	3%	3%	4%	4%	4%	4%	4%	4%	4%
Lighting - Coal & Oil	Coal/Oil-Light	2	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%

End- Use Categories/Task-levels	Abbrevations	Ref.	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
Heat – High Temp. Heat (>550ºC)	HTH	own	27%	29%	27%	25%	29%	23%	29%	25%	26%	25%
Heat – Medium Temp. Heat1 (550°C-250ºC)	MTH1	own	30%	30%	31%	31%	32%	32%	33%	35%	37%	37%
Heat – Medium Temp. Heat2 (250ºC)	MTH2	own	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%
Heat – Low Temp. Heat1 (100ºC)	LTH1	own	11%	11%	12%	12%	12%	12%	12%	12%	13%	13%
Heat – Low Temp. Heat2 (20ºC)	LTH2	2	4%	4%	4%	4%	4%	4%	4%	4%	4%	5%
Heat - Industrial process Heat (Electricity)	HTH-el	2	28%	28%	28%	28%	28%	28%	28%	28%	28%	28%
Mechanical Drive - Gas/diesel oil (assume diesel vehicles)	OMD1	2	22%	22%	22%	22%	22%	22%	22%	22%	22%	23%
Mechanical Drive - Domestic Aviation fuel, jet fuel	OMD2	2	23%	22%	22%	22%	22%	22%	22%	22%	23%	23%
Mechanical Drive - Gasoline fuel (Petrol cars)	OMD3	2	18%	18%	18%	18%	18%	19%	19%	19%	19%	19%
Mechanical Drive - Diesel/gas oil fuel (Boat engines)	OMD4	2	14%	14%	14%	14%	14%	14%	15%	15%	16%	17%
Mechanical Drive - Industry static motors (diesel engines)	OMD5	2	24%	24%	25%	25%	25%	25%	25%	25%	25%	25%
Mechanical Drive - Gas/diesel fuel (diesel trains)	OMD6	2	14%	14%	14%	14%	14%	14%	15%	15%	16%	17%
Mechanical Drive - Gas/diesel fuel (tractors)	OMD7	2	11%	11%	11%	11%	11%	11%	11%	11%	11%	11%
Mechanical Drive - bio-diesel / bio-gasoline (road transport)	CRMD1	2	20%	20%	20%	20%	20%	20%	20%	21%	21%	21%
Mechanical Drive - bio-diesel (diesel trains)	CRMD2	2	14%	14%	14%	14%	14%	14%	15%	15%	16%	17%
Mechanical Drive - Gas/diesel oil (assume diesel cars)	GMD1	2	22%	22%	22%	22%	22%	22%	22%	22%	22%	23%
Mechanical Drive - Gas fired engines (for pipeline transport)	GMD2	2	22%	22%	22%	22%	22%	22%	22%	23%	23%	23%
Mechanical Drive - Coal (steam powered trains)	CMD1	2	2%	2%	2%	2%	2%	2%	3%	3%	3%	3%
Mechanical Drive - Coal (steam powered boats)	CMD2	2	2%	2%	2%	2%	2%	2%	3%	3%	3%	3%
Mechanical Drive - Industry static motors/pumps (electricity)	El-MD2	2	54%	54%	54%	55%	55%	55%	55%	55%	55%	55%
Mechanical Drive - Electric trains	El-MD	2	14%	14%	14%	14%	14%	14%	15%	15%	16%	17%
Electricity - Energy sector own use	El-own	2	29%	30%	30%	30%	30%	30%	30%	30%	30%	30%
Electricity - Industry - others	El-other-ind	2	33%	33%	33%	33%	33%	34%	34%	34%	34%	34%
Electricity - Commercial & public - heating & air-conditioning	El-heat/cool-comm	2	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%
Electricity - Commercial & public - others	El-other-comm	2	19%	19%	19%	19%	19%	19%	19%	19%	19%	19%
Electricity - Residential - Fans & radiators	El-cool/heat-resid	2	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%
Electricity - Residential - Refrigerators	El-refrige-resid	2	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Electricity - Residential - Air-conditioners	El-aircon-resid	2	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Electricity - Residential - others	El-other-resid	2	15%	15%	15%	16%	16%	16%	16%	16%	16%	16%
Lighting - Electric	El-light	2	3%	3%	3%	4%	4%	4%	4%	4%	4%	4%
Lighting - Coal & Oil	Coal/Oil-Light	2	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%

End- Use Categories/Task-levels	Abbrevations	Ref.	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Heat – High Temp. Heat (>550ºC)	HTH	own	28%	27%	26%	26%	26%	30%	29%	31%	33%	34%
Heat – Medium Temp. Heat1 (550°C-250ºC)	MTH1	own	38%	38%	38%	38%	40%	40%	40%	43%	43%	45%
Heat – Medium Temp. Heat2 (250ºC)	MTH2	own	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%
Heat – Low Temp. Heat1 (100ºC)	LTH1	own	13%	13%	13%	14%	14%	14%	14%	14%	15%	15%
Heat – Low Temp. Heat2 (20ºC)	LTH2	2	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Heat - Industrial process Heat (Electricity)	HTH-el	2	28%	28%	28%	29%	29%	29%	29%	29%	29%	29%
Mechanical Drive - Gas/diesel oil (assume diesel vehicles)	OMD1	2	23%	23%	23%	23%	23%	23%	23%	23%	23%	24%
Mechanical Drive - Domestic Aviation fuel, jet fuel	OMD2	2	23%	23%	23%	23%	23%	23%	24%	24%	23%	23%
Mechanical Drive - Gasoline fuel (Petrol cars)	OMD3	2	19%	19%	19%	19%	19%	19%	19%	20%	20%	20%
Mechanical Drive - Diesel/gas oil fuel (Boat engines)	OMD4	2	17%	16%	17%	18%	18%	19%	19%	19%	19%	19%
Mechanical Drive - Industry static motors (diesel engines)	OMD5	2	25%	25%	25%	26%	26%	26%	26%	26%	26%	26%
Mechanical Drive - Gas/diesel fuel (diesel trains)	OMD6	2	17%	16%	17%	18%	18%	19%	19%	19%	19%	19%
Mechanical Drive - Gas/diesel fuel (tractors)	OMD7	2	11%	11%	11%	11%	12%	12%	12%	12%	12%	12%
Mechanical Drive - bio-diesel / bio-gasoline (road transport)	CRMD1	2	21%	21%	21%	21%	21%	21%	21%	21%	22%	22%
Mechanical Drive - bio-diesel (diesel trains)	CRMD2	2	17%	16%	17%	18%	18%	19%	19%	19%	19%	19%
Mechanical Drive - Gas/diesel oil (assume diesel cars)	GMD1	2	23%	23%	23%	23%	23%	23%	23%	23%	23%	24%
Mechanical Drive - Gas fired engines (for pipeline transport)	GMD2	2	23%	23%	23%	23%	23%	23%	23%	23%	23%	23%
Mechanical Drive - Coal (steam powered trains)	CMD1	2	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%
Mechanical Drive - Coal (steam powered boats)	CMD2	2	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%
Mechanical Drive - Industry static motors/pumps (electricity)	El-MD2	2	55%	56%	56%	56%	56%	56%	56%	56%	56%	57%
Mechanical Drive - Electric trains	El-MD	2	17%	16%	17%	18%	18%	19%	19%	19%	19%	19%
Electricity - Energy sector own use	El-own	2	31%	31%	31%	31%	31%	31%	31%	31%	31%	32%
Electricity - Industry - others	El-other-ind	2	35%	35%	35%	35%	35%	36%	36%	36%	36%	36%
Electricity - Commercial & public - heating & air-conditioning	El-heat/cool-comm	2	3%	3%	4%	3%	3%	4%	4%	3%	4%	3%
Electricity - Commercial & public - others	El-other-comm	2	19%	19%	19%	19%	19%	19%	19%	19%	19%	19%
Electricity - Residential - Fans & radiators	El-cool/heat-resid	2	3%	3%	4%	3%	3%	4%	4%	3%	4%	3%
Electricity - Residential - Refrigerators	El-refrige-resid	2	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Electricity - Residential - Air-conditioners	El-aircon-resid	2	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Electricity - Residential - others	El-other-resid	2	16%	16%	16%	16%	16%	16%	16%	16%	16%	16%
Lighting - Electric	El-light	2	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%
Lighting - Coal & Oil	Coal/Oil-Light	2	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%

End- Use Categories/Task-levels	Abbrevations	Ref.	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Heat – High Temp. Heat (>550ºC)	HTH	own	30%	33%	39%	32%	29%	27%	28%	28%	26%	25%
Heat – Medium Temp. Heat1 (550°C-250ºC)	MTH1	own	45%	46%	46%	48%	48%	48%	49%	48%	49%	49%
Heat – Medium Temp. Heat2 (250ºC)	MTH2	own	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%
Heat – Low Temp. Heat1 (100ºC)	LTH1	own	15%	15%	15%	15%	16%	16%	16%	16%	16%	16%
Heat – Low Temp. Heat2 (20ºC)	LTH2	2	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Heat - Industrial process Heat (Electricity)	HTH-el	2	29%	29%	29%	29%	29%	29%	29%	29%	29%	29%
Mechanical Drive - Gas/diesel oil (assume diesel vehicles	OMD1	2	23%	23%	23%	23%	23%	23%	22%	22%	22%	22%
Mechanical Drive - Domestic Aviation fuel, jet fuel	OMD2	2	24%	23%	24%	23%	23%	24%	24%	25%	25%	25%
Mechanical Drive - Gasoline fuel (Petrol cars)	OMD3	2	19%	19%	19%	19%	19%	18%	18%	18%	18%	18%
Mechanical Drive - Diesel/gas oil fuel (Boat engines)	OMD4	2	18%	19%	18%	19%	19%	19%	19%	20%	20%	21%
Mechanical Drive - Industry static motors (diesel engines)	OMD5	2	26%	26%	26%	26%	27%	27%	27%	27%	27%	27%
Mechanical Drive - Gas/diesel fuel (diesel trains)	OMD6	2	18%	19%	18%	19%	19%	19%	19%	20%	20%	21%
Mechanical Drive - Gas/diesel fuel (tractors)	OMD7	2	12%	12%	12%	11%	11%	11%	11%	11%	11%	11%
Mechanical Drive - bio-diesel / bio-gasoline (road transport)	CRMD1	2	21%	21%	21%	21%	21%	21%	20%	20%	20%	20%
Mechanical Drive - bio-diesel (diesel trains)	CRMD2	2	18%	19%	18%	19%	19%	19%	19%	20%	20%	21%
Mechanical Drive - Gas/diesel oil (assume diesel cars)	GMD1	2	23%	23%	23%	23%	23%	23%	22%	22%	22%	22%
Mechanical Drive - Gas fired engines (for pipeline transport)	GMD2	2	24%	24%	24%	24%	24%	24%	24%	24%	24%	24%
Mechanical Drive - Coal (steam powered trains)	CMD1	2	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%
Mechanical Drive - Coal (steam powered boats)	CMD2	2	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%
Mechanical Drive - Industry static motors/pumps (electricity)	El-MD2	2	57%	57%	57%	57%	57%	57%	57%	58%	58%	58%
Mechanical Drive - Electric trains	El-MD	2	18%	19%	18%	19%	19%	19%	19%	20%	20%	21%
Electricity - Energy sector own use	El-own	2	32%	32%	32%	32%	32%	32%	32%	32%	32%	33%
Electricity - Industry - others	El-other-ind	2	36%	37%	37%	37%	37%	37%	38%	38%	38%	38%
Electricity - Commercial & public - heating & air-conditioning	El-heat/cool-comm	2	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%
Electricity - Commercial & public - others	El-other-comm	2	19%	19%	19%	19%	19%	19%	19%	19%	19%	19%
Electricity - Residential - Fans & radiators	El-cool/heat-resid	2	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%
Electricity - Residential - Refrigerators	El-refrige-resid	2	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Electricity - Residential - Air-conditioners	El-aircon-resid	2	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Electricity - Residential - others	El-other-resid	2	16%	16%	16%	16%	16%	16%	17%	17%	17%	17%
Lighting - Electric	El-light	2	4%	4%	5%	5%	5%	5%	5%	5%	5%	5%
Lighting - Coal & Oil	Coal/Oil-Light	2	3%	3%	3%	3%	3%	4%	4%	4%	4%	4%

End- Use Categories/Task-levels	Abbrevations	Ref.	2011	2012
Heat – High Temp. Heat (>550ºC)	HTH	own	26%	24%
Heat – Medium Temp. Heat1 (550°C-250ºC)	MTH1	own	50%	50%
Heat – Medium Temp. Heat2 (250ºC)	MTH2	own	6%	6%
Heat – Low Temp. Heat1 (100ºC)	LTH1	own	17%	17%
Heat – Low Temp. Heat2 (20ºC)	LTH2	2	5%	6%
Heat - Industrial process Heat (Electricity)	HTH-el	2	29%	29%
Mechanical Drive - Gas/diesel oil (assume diesel vehicles	OMD1	2	22%	22%
Mechanical Drive - Domestic Aviation fuel, jet fuel	OMD2	2	25%	25%
Mechanical Drive - Gasoline fuel (Petrol cars)	OMD3	2	18%	18%
Mechanical Drive - Diesel/gas oil fuel (Boat engines)	OMD4	2	21%	21%
Mechanical Drive - Industry static motors (diesel engines)	OMD5	2	27%	27%
Mechanical Drive - Gas/diesel fuel (diesel trains)	OMD6	2	21%	21%
Mechanical Drive - Gas/diesel fuel (tractors)	OMD7	2	11%	11%
Mechanical Drive - bio-diesel / bio-gasoline (road transport)	CRMD1	2	20%	20%
Mechanical Drive - bio-diesel (diesel trains)	CRMD2	2	21%	21%
Mechanical Drive - Gas/diesel oil (assume diesel cars)	GMD1	2	22%	22%
Mechanical Drive - Gas fired engines (for pipeline transport)	GMD2	2	24%	24%
Mechanical Drive - Coal (steam powered trains)	CMD1	2	3%	3%
Mechanical Drive - Coal (steam powered boats)	CMD2	2	3%	3%
Mechanical Drive - Industry static motors/pumps (electricity)	El-MD2	2	58%	58%
Mechanical Drive - Electric trains	El-MD	2	21%	21%
Electricity - Energy sector own use	El-own	2	33%	33%
Electricity - Industry - others	El-other-ind	2	38%	38%
Electricity - Commercial & public - heating & air-conditioning	El-heat/cool-comm	2	4%	4%
Electricity - Commercial & public - others	El-other-comm	2	19%	19%
Electricity - Residential - Fans & radiators	El-cool/heat-resid	2	4%	4%
Electricity - Residential - Refrigerators	El-refrige-resid	2	5%	5%
Electricity - Residential - Air-conditioners	El-aircon-resid	2	2%	2%
Electricity - Residential - others	El-other-resid	2	17%	17%
Lighting - Electric	El-light	2	5%	5%
Lighting - Coal & Oil	Coal/Oil-Light	2	4%	4%

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