



LUND UNIVERSITY

Coal, commerce and communism

Empirical studies on energy history in the Czech Republic

Nielsen, Hana

2017

Document Version:

Publisher's PDF, also known as Version of record

[Link to publication](#)

Citation for published version (APA):

Nielsen, H. (2017). *Coal, commerce and communism: Empirical studies on energy history in the Czech Republic*. [Doctoral Thesis (compilation), Department of Economic History]. Lund University (Media-Tryck).

Total number of authors:

1

General rights

Unless other specific re-use rights are stated the following general rights apply:

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

Read more about Creative commons licenses: <https://creativecommons.org/licenses/>

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

Coal, commerce and communism

Empirical studies on energy history in the
Czech Republic

Hana Nielsen

LUND STUDIES IN ECONOMIC HISTORY 79



LUND
UNIVERSITY

Coal, commerce and communism

Empirical studies on energy history in the
Czech Republic

Hana Nielsen



LUND
UNIVERSITY

DOCTORAL DISSERTATION

by due permission of the School of Economics and Management,
Lund University, Sweden.

To be defended at EC3:210. Date 2017-03-24 and time 13.15.

Faculty opponent
Professor Herman de Jong

Organization LUND UNIVERSITY	Document name DOCTORAL DISSERTATION	
	Date of issue 2017-03-24	
	Sponsoring organization	
Author(s) Hana Nielsen		
Title and subtitle: Coal, commerce and communism: Empirical studies on energy history in the Czech Republic		
<p>Abstract</p> <p>This thesis employs an international comparative perspective to empirically analyse the Czech energy transition between 1830 and 2010. It addresses the utilization of energy in shaping modern economic growth through structural and technological change and the implications of those changes on specialization and foreign trade. New historical data is collected and utilized to investigate the impact of changing institutional settings on energy and economic growth. Through its six papers, the thesis examines how the Czech Republic underwent substantial economic transformation, driven largely by the availability of domestic coal. Coal was important for the location of industries and led to the formation of new industrial clusters and complementary industries. This brought about the region's first industrialization and gave rise to far-reaching consequences for the country's development. In the period leading up to Second World War, energy intensity and energy-intensive patterns of trade bore a striking resemblance to the coal-rich West. Post-war institutional turmoil and the seizure of power by the Communist Party led to rapid structural change and forced Czechoslovakia off its energy transition path. The temporary increase in the country's energy intensity during this central-planning period was, however, far less of a systematic failure. As such, this thesis challenges the general perception of inefficiencies related to a system of central-planning, and for the first time provides quantitative evidence on the East-West divide.</p>		
Key words: industrialization, coal, modern economic growth, central planning, iron and steel, energy efficiency		
Classification system and/or index terms (if any)		
Supplementary bibliographical information		Language
ISSN and key title: 1400-4860		ISBN 978-91-87793-30-1
Recipient's notes	Number of pages:	Price
	Security classification	

I, the undersigned, being the copyright owner of the abstract of the above-mentioned dissertation, hereby grant to all reference sources permission to publish and disseminate the abstract of the above-mentioned dissertation.

Signature



Date: 2017-02-16

Coal, commerce and communism

Empirical studies on energy history in the
Czech Republic

Hana Nielsen



LUND
UNIVERSITY

© Hana Nielsen 2017

School of Economics and Management
Department of Economic History

ISBN 978-91-87793-30-1

ISSN 1400-4860

Printed in Sweden by Media-Tryck, Lund University
Lund 2017



Table of contents

Acknowledgments	7
List of papers	9
Introduction	11
Overview	11
Motivation	13
The Czech Republic as a case study	14
Research questions	16
Limitations	17
Studying energy history and its wider implications	18
Outline of the introduction chapter	20
Theory and previous research	21
Historical context	21
Past quantitative long-run energy history studies	25
Previous research and overview of major topics and theories	27
Data and methods	49
Data	49
Methods	52
Results	60
Contribution	60
Abstracts of the included papers	61
Paper I.	62
Paper II.	63
Paper III.	63
Paper IV.	64
Paper V.	64
Paper VI.	65
Discussion and conclusion	66
References	70

Acknowledgments

This thesis is not only a result of my four years of work; it has involved the work of many others. Importantly, my two supervisors and academic heroes Astrid Kander and Kerstin Enflo were outstanding mentors, always ready to give feedback on my work and always ready with plenty of encouragement. I would also like to thank my two discussants from my final seminar, Ellen Hillbom and Aleh Cherp for their valuable feedback; and Martin and Patrick for their work as the directors of the PhD programme. Thanks go also to Kristin, Tina, Anneli and Birgit for their support throughout the years.

My PhD studies were enabled by generous financial support from the Department of Economic History, the School of Economics and Management, the Institute of Economic Research and Swedish Research Council. I also participated at two 3-months research visits at IIASA in Vienna and the University of Cambridge generously financed through Formas and Handelsbanken respectively.

During my PhD studies I not only gained some valuable experience, I also met some remarkable people. A big thank you goes to Paul Warde for his continuous support and friendship.

Also I feel that a simple thank you is not even enough to express my gratitude to all my colleagues. You really meant a lot to me and made me feel welcome and joyful, be it in the office, at conferences or on the top of Mt.Fuji. Thank you also to Thor, my officemate, for his company throughout the years, his sense of humor and for being able to share the ironies of academic life together.

A big thank you to both my Czech and Danish families for always being so loving, caring and enthusiastic. To “babi”, my mum, who would jet to Sweden whenever needed to take care of the boys. I cannot even describe how grateful I am for all you did for me.

This dissertation would have never happened if it was not for you, Skat. It was you who got me hooked on doing a PhD in the first place, and it was you

who supported me the most throughout. Thanks for being such a supporting, understanding and loving husband, and for all your enthusiasm and curiosity about my research.

And last, thank you, Jakob, Matthias and Nikolai. You were just babies when I started this journey and I feel it was our journey together. You have grown up so much now and have become the most amazing and the sweetest kids one could ever wish for. Thank you for reminding me every single day what really matters in life – Star Wars and Lego.

List of papers

- I Nielsen, Hana (2016). Coal and sugar: the black and white gold of the Czech industrial revolution (1841 – 1863). *Under review*.
- II Nielsen, Hana & Warde, Paul & Kander, Astrid (2016). East versus West: Energy Intensity in Coal-Rich Europe 1830-2000. *Under review*.
- III Kander, Astrid & Warde, Paul & Henriques, Sofia & Nielsen, Hana & Kulionis, Viktoras & Hagen, Sven (2016). International trade and energy intensity in Europe, 1870-1935. *Under review*.
- IV Nielsen, Hana (2016). The rise in energy consumption in Czechoslovakia and the role of foreign trade in a long-run perspective (1920-1998): The “Machine shop” hypothesis. *Under review*.
- V Nielsen, Hana (2017). Productive efficiency in the iron and steel sector under state planning: The case of China and former Czechoslovakia in a comparative perspective. *Applied Energy*, 185:1732-1743.
- VI Nielsen, Hana (2016). Technology and scale changes: The steel industry of Czechoslovakia in a comparative perspective. *Under review*.

Introduction

Overview

In the early nineteenth century, the Czech Republic¹ was largely an agriculture-based country with some small-scale proto-industries, located in the very middle of the European continent and under the dominance of the Austro-Hungarian Empire. By the beginning of the First World War, the Czech Republic had become the most developed part of the region and the most important trading partner of the whole monarchy, with 70 per cent of the total production destined for exports (Cisar and Pokorny, 1922). Much of this growth, as I argue throughout my papers, was driven by the domestic coal resources and the expansion of the energy-intensive industries that formed the backbone of the Czech economy and shaped its economic structures, which persist until the present day. Indeed, it was in the age of steam that the Czech Republic transformed into one of the fastest growing and most successful countries in Europe. The global rise of protectionism after the First World War and the turmoil of the post-Second World War institutional settings had some negative implications for the economic growth of the newly established Czechoslovakia but led to increased specialization in energy-intensive sectors and dramatic expansion of the domestic coal mining output. From an energy perspective, the Czech Republic thus represents a truly fascinating case study.

There are three underlying themes in this dissertation – institutions, energy and technology – and it is my major argument that the interplay between these underlying causes formed the foundations and mechanisms of modern economic growth. The political/institutional aspects of energy use have often

¹ The issue of changing country borders will be discussed in more detail in the historical context section, but, for clarity, between 1830 and 1913 the dissertation covers the Czech lands, between 1918 and 1993 it refers to Czechoslovakia and post-1990 it refers to the Czech and Slovak Republics. For more detail concerning the geographical scope of this thesis, see Figure 7.

been researched in connection with security or economic efficiency. It is to this area that this dissertation aims to contribute. This is because, from an energy point of view, the institutional factor can be channelled not only through the economic performance but also through other mechanisms, such as efficient environmental protection, foreign trade regime or specialization. It is in the interaction between these factors, which is the focus of this dissertation.

This dissertation consists of an introductory chapter and six individual papers. The major purpose of the introductory section is to provide an overview of the theories and topics concerning the use of energy and economic growth and to relate them to the Czech case and its specific historical context. Using quantitative historical data, each paper seeks to test empirically different theoretical proposition(s), which are discussed in the introductory chapter. The time scope of this dissertation commences at the very early stages of the first Industrial Revolution in 1830 and stretches all the way until the last decades of the twentieth century. Paper 1 assesses the importance of coal and proximity to coal mines for the industrialization of the Czech Republic and shows how coal-intensive industries were located close to existing coal mines. The paper further discusses the role of energy-intensive industries not only in the Czech transition to modern energy but also in the Czech economic development. Paper 2 analyses the respective energy transitions in the Czech Republic in comparison with England and Germany. A similar pattern of developments in energy intensity is identified, though with divergence after the Second World War in both Czechoslovakia and East Germany. The paper puts forward a number of explanations for this development, such as inefficiency of the electricity transformation system and structural changes in the economy. Papers 3 and 4 focus on the role of foreign trade and its impact on the domestic energy consumption as well as the energy intensity curve. Using a panel of European countries, Paper 3 reassesses the existence of the environmental Kuznets curve during the first globalization wave by taking into account foreign trade. In Paper 4 I extend the calculations of energy embodied in trade to test whether the sudden increase in Czechoslovak energy intensity could be explained by the country's specific trade regime. In absolute terms Czechoslovakia was a large exporter of energy embodied in manufactured goods, though in relative terms the share of embodied energy in exports in the domestic energy consumption did not change substantially throughout the twentieth century. The last two papers, Papers 5 and 6, examine the developments in the iron and steel sector in Czechoslovakia, paying special attention to the energy efficiency issues

and scaling patterns under the system of central planning. In spite of the general belief that a non-market-based system is detrimental to productive efficiency, both papers show that Czechoslovakia managed to achieve satisfactory productivity increases, primarily driven by policies, adjustments to the existing technology, unit and industry scaling and efficiency policies and targets.

Motivation

From an energy perspective, industrialization and the onset of modern economic growth were accompanied by unprecedented changes in the quantity and quality of energy resources. In the past as much as nowadays, any transformation and material production has always involved the consumption of energy. In the pre-modern world, the availability of energy was largely confined to the human ability to capture solar energy through plant photosynthesis (Kander et al., 2013; Wrigley, 2016). In all the productive sectors, the access to energy came predominantly from the consumption of fodder and feed, which was transformed into muscular power by animals and humans (Debeir, Deleage & Hemery, 1991). Obviously, this set a ceiling on the amount of energy that could be transformed and utilized in the economy – the availability of organic energy sources was largely restricted by the size of the land and its ability to grow trees for heat or agricultural goods to be consumed to provide the precious motive power. Although land could barely be expanded and its supply is often considered as fixed, mankind has tried for centuries to fight the static nature of pre-modern society through a range of productivity-enhancing methods, new crops and other improvements that would secure even greater volumes of output given the existing fixed material inputs (Boserup, 1965; Wrigley, 2016). The discovery of coal and its later utilization to generate mechanical energy was path-breaking in the economic development of England and other European countries (Landes, 1969). The regime change from an organic economy to a mineral-based energy economy was not only accompanied by unprecedented rates of economic growth but also enabled the rise of new industries for which organic material inputs were no longer relevant, such as machine building, chemicals, glass or metals (Wrigley, 1988). Nevertheless, coal did not necessarily replace the existing energy sources; it rather augmented them (Berners-Lee & Clark, 2013), as did other fossil fuels. In addition, this

transition from an organic economy to an economy based on mineral wealth, which occurred in such a short time span, brought substantial changes to the economic as well as the societal aspects of the global development (Wrigley, 2016). Technology, as we have experienced over the past two centuries, has not only been the major driver of productivity increases but has also called for an economy-wide transition towards a mineral-based society and our enormous consumption of the majority of resources. As the world has come to grasp the reality of the consequences of our mineral-based economy, technology, contrary to its image as a contributor to environmental degradation, now has the chance to demonstrate its enormous potential to provide the solution to pollution.

Therefore, it is important to think in the long run, not only with respect to the past development trajectories of the Western world but mainly to take full advantage of the lessons learned, because one thing is clear and unavoidable: the rise of newly industrial countries will pose a challenge to our climate and energy resources. Past historical studies on this change in the energy regime can thus provide an enriching and enlightening interpretation of many events that marked our modern society. In other words, ‘the history of energy is the secret history of industrialization’ (Sieferle, cited by Wrigley, 2016).

The Czech Republic as a case study

The geographical scope of this manuscript is largely confined to areas of the Czech Republic, though most papers are written from a *comparative perspective* to place the developments against those recorded in Western countries.

The Czech Republic underwent a transition to a modern economic growth regime in a different way from some of the early industrializers in the West. As this dissertation illustrates, the Czech Republic can be portrayed as a country that successfully developed on agricultural-based industries, with coal playing a major role in fuelling this rise. The expansion of food processing was another major driver of the rapid fossil fuel transition, the fastest on the European continent. The newly established food sector became the largest consumer of coal, accounting for the largest share of steam engines and well over 60 per cent of the industrial value added by 1885 (Rudolph, 1976). Although the food-processing sector mainly offered complementary seasonal work to agricultural labourers and did not result in vast migration flows to the agricultural areas (also given the very high level

of mechanization and productivity), it had a profound impact on minimizing the regional disparity between urban and rural centres during the first Industrial Revolution. The food sector accounted for increasing numbers of the industrial labour force and had some long-lasting implications for the upcoming engineering branch (which in turn created a stimulus for the shift of iron and steel production from Upper Austria to the Czech lands).

Furthermore, the focus of this dissertation is on a country that has experienced various systems of economic planning, it has the potential to enlarge our understanding of the role of institutions not only in economic development but also in terms of energy use and technology adoption. The Czech Republic has also some rich experience of being part of a larger economic entity, either as the crownlands of the Austro-Hungarian Empire or in the Comecon trading block of post-war Eastern Europe, sharing some distinct trade regimes. In fact, the country has existed as a sovereign state for only short spans of time: first during the interwar period, 1918–1939, as Czechoslovakia and then after 1989 as Czechoslovakia (and since 1993 as the Czech Republic). On one hand being part of a larger entity potentially allows for increased access to specific markets and specialization, while on the other hand the changes in the institutional settings can alter the behaviour and incentives of the individual actors. This can, in turn, exert a substantial impact on the process of industrialization and structural change in the Czech Republic, be it a success or failure.

The Czech Republic, although a relatively newly established sovereign country with little over 20 years of existence, has been present in the central European history for centuries. However, with a few exceptions (Broadberry & Klein, 2011; Cvrcek, 2013; Cvrcek & Zajicek, 2013; Klein & Ogilvie, 2015), the current leading research in economic history largely ignores this region of Central Europe. Its transitory position within the European economic history is very enriching and is an example of a country, contrary to some of the most successful industrializers, that combines elements of industrial leadership as well as backwardness. Past energy and economic history studies are mostly confined to England or the USA.² This dissertation seeks, for the first time, to explore the role of energy and economic growth in a central European country in the long run. Mainly through a compilation of

² Though the geographical scope in recent decades has also spread to other countries, which were more peripheral during the Industrial Revolution, such as Sweden (Kander, 2002), the Netherlands (Gales et al., 2007; Hölsgens, 2016), Italy (Malanima, 2006; Malanima, 2016), Austria (Krausmann & Haberl, 2002) and Portugal (Henriques, 2011)

quantitative empirical studies, the dissertation addresses several ongoing debates in the field of economic history, including the role of *natural resource endowments*, *institutional changes*, *energy intensity*³ and *foreign trade*.

Research questions

Overall, this dissertation aims, from a comparative perspective, to analyse the energy transition process of the Czech Republic. The dissertation addresses three major areas of research.

First (1), **what was the role of energy in driving the Czech industrialization?** Here the dissertation studies the role of energy, and importantly access to modern energy carriers, in facilitating the industrialization of the Czech Republic. Within this research scope, attention is also given to new technology adoption and productivity changes in connection with the transition to a fossil-fuelled economy. By drawing on studies on other coal-rich countries, this part of the dissertation also addresses the existence of the environmental Kuznets curve⁴.

Second (2), **what is the possible impact of past institutional changes on the energy and growth nexus and productive efficiency?** Given the dissertation's geographical focus on the Czech Republic, the impact of different systems of economic planning (market economy and planned economy) on energy use, energy efficiency and productivity is researched. Attention is devoted to the role of structural change in the Czech economy and its relationship with the energy intensity and energy efficiency of the country as well at the level of one individual sector – iron and steel production. Technology adoption is furthermore studied against the background of the changes in the trade regimes imposed by the different

³ Energy intensity here refers to the amount of energy consumed per one unit of monetary output. An energy intensity of a country thus refers to the amount of all primary energy consumed within the country relative to its GDP (measured in constant prices). Similarly, energy intensity of a manufacturing sector refers to the energy consumed within the sector divided by the output of the sector (usually measured in terms of value added).

⁴ Based on Goldenberg and Reddy (1990) that proposed that energy intensity will increase at low levels of income per capita as countries industrialize and then, after attaining a certain level of per capita income, energy intensity will start to decrease.

institutional arrangements as well as within the frameworks of the technology adoption field.

Last (3), **what was the role of foreign trade in driving the upward trend in energy intensity?** Given the importance and magnitude of foreign trade during the first globalization and after the Second World War, the dissertation seeks to quantify the role of foreign trade over time and its relevance to current climate change research.

Overall, with the exception of Paper 1, all the papers present the Czech case against other countries, usually other Western European countries. Table 1 provides an overview of the papers and which major research question these address.

Table 1 Overview of research questions and papers

Paper	Research question	Status (as of 16th February 2017)
(I) Coal and sugar: the black and white gold of the Czech industrial revolution (1841 – 1863)	RQ 1)	R&R at Journal of Economic History
(II) East versus West: Energy Intensity in Coal-Rich Europe 1830-2000	RQ 1 & 2)	Under review at Journal of Comparative Economics
(III) International trade and energy intensity in Europe, 1870-1935	RQ 3)	R&R at Ecological Economics
(IV) The rise in energy consumption in Czechoslovakia and the role of foreign trade in a long-run perspective (1920-1998)	RQ 2 & 3)	R&R at Ecological Economics
(V) Productive efficiency in the iron and steel sector under state planning: The case of China and former Czechoslovakia in a comparative perspective	RQ 2)	Published in Applied Energy (2017)
(VI) Technology and scale changes: The steel industry of Czechoslovakia in a comparative perspective	RQ 1 & 2)	R&R at Economic History of Developing Regions

Limitations

The papers within this dissertation are written from a comparative perspective to place the developments in relation to those recorded in Western countries. The choice of countries for the comparative purposes was primarily conditioned on the availability of historical data and the study could therefore only be conducted against other Western countries. Arguably, it would also be of significant value to make a comparison with other regions, in Asia or the former Soviet Republics for example, but the lack of long-run historical data on energy presents a major barrier. In addition, although the comparative perspective may aid our understanding of the topic in question, one has to bear in mind that it might also challenge the interpretation of the

results. This is also why in some instances the Czech Republic can be portrayed in the same period as a successful example of a country with increasing agricultural productivity and rapid industrialization and as a backward economy (with respect to the rest of Western Europe) (Gerschenkron, 1962).

It also has to be stressed that the focus of the dissertation is on the role of energy in technological and structural change and economic growth, and it deals only marginally with the negative externalities, such as pollution. Clearly, the increased deployment of energy, especially fossil fuels, is tightly linked to environmental degradation and pollution, and these negative externalities were profound in the Czech context. The major scope, however, is the role of energy as a driver or agent of economic development.

Equally, less attention is paid to the positive impact of a central-planning system on personal energy consumption, as the focus is mainly on the manufacturing sectors. However, it is worth mentioning that, from an environmental perspective, a central-planning system was beneficial for Czechoslovakia, leading to low personal consumption levels, low car ownership rates, centralized accommodation blocks and low levels of waste (Ürge-Vorsatz, Miladinova & Paizs, 2006).

Studying energy history and its wider implications

Although the utilization of mineral-based fuels has been growing exponentially over the last 200 years, the first studies of negative externalities date back only a couple of decades. Recently, mainly in the past two decades, the urgency of global climate change has become far more acute, calling for global action as the research in the field intensified.

To understand fully the basic principles of a mineral-based energy economy, however, the past energy transition and the role of energy in economic growth require further research attention. The move away from a biomass-shaped economy to a mineral economy, as we have witnessed over the past 200 years in the developed world, fundamentally transformed the established economic structures, created new materials and needs and raised the productivity levels to unprecedented heights. Many studies have been devoted to the role of various factors of production in the productivity growth since the first Industrial Revolution, some in greater depth than others, but in general the role of energy has been neglected.

The growing material and energy consumption associated with low-income countries adopting Western patterns of consumption are commonly discussed as potential threats to the meeting of global emission targets. There is a risk that the world's energy needs will continue to grow in the future to a magnitude never previously experienced by planet Earth. Ever since Malthus himself, researchers have been concerned with the prospects of humanity in a world of finite resources (Meadows et al., 1972) and the carrying capacity of the Earth (Ehrlich, 1968; Ehrlich & Ehrlich, 1990). At the same time, the often invisible threat (at least for most of the developed world) of global warming has been slowly spreading across the globe, though it has largely been ignored by the majority of its leaders. The tragedy of the atmospheric commons (Hardin, 1968), the facts that global change affects us all and every benefit will necessarily be spread over more than seven billion people, prevents many countries from being the first really to act (Berners-Lee & Clark, 2013). Therefore, given the fact that climate change is largely a result of our energy use, energy history studies can provide some useful insights. Here, two major strands of research have surfaced to help to make the transition as smooth and sustainable as possible without limiting the development possibilities of most of the world and without reaching the resource limits of the mineral-based energy economy.

First, there are studies on past energy intensity trends, with specific attention directed towards the energy efficiency of the manufacturing sector, which has historically shown the highest levels of energy consumption. Energy efficiency and improvements have become buzzwords in the political arena, as increasing energy efficiency allows continuous economic growth while at the same maintaining or even reducing the absolute levels of energy consumption and global CO₂ emissions (Biroi & Keppler, 2000)⁵.

The second strand of research focuses on the other major mechanism of economic growth – extensive economic growth – and ventures into the ability of mankind to capture and transform large amounts of solar energy, thus expanding the access to additional factors of production. Indeed, the total

⁵ Within the terminology of economic history, this relates to the research on intensive economic growth and thus an increase in the GDP per capita derived from a productivity increase. Past studies on how various economies, regions or productive sectors achieved intensive economic growth are thus crucial to our full understanding of how developing countries could continue to grow without sacrificing the global environment.

quantity of energy that the Earth receives is enormous and far exceeds our growing energy needs⁶.

It has also become clear that a sustainable transition does not only involve the transition to a fossil fuel-free society but is also largely embedded in other areas, such as technological, social, institutional and economic change (Geels, 2011; Grübler, 2012). This is because our current system is based on technical solutions that are deeply entrenched in the way in which our society and institutions work. New technological innovations have thus a far more complex impact and do not only ‘involve changes in technology, but also changes in user practices, regulation, industrial networks or infrastructure’ (Geels, 2002). Although this dissertation focuses on technological transitions and their impact on energy consumption, it also, at the same time, highlights the profound complexity of larger systems, both at the national level and as part of the global world.

Outline of the introduction chapter

Following the motivation and research question, the next section starts by introducing the historical context. The case of the Czech Republic is discussed specifically with a brief description of the economic history of the country, the country’s energy transition and the existing research in the field of quantitative energy history studies. The major purpose of this section is to situate the Czech developments in a wider historical, and international, context.

Next, the theory part provides an overview of the major theoretical concepts that have been formed in the field of energy and economic growth, all of which are in essence related to the papers included in this dissertation. Here, most of the attention is devoted to the development of the theories and how

⁶ In this respect the transition towards additional flows of sustainable energy is central to meeting the global emission targets. In contrast to this is the currently dominant energy system utilizing the existing stocks of fossil energy. The exploitation of these stocks will continue in the future, but the extent and pace of this exploitation require revision. This is mainly due to the large amount of negative externalities associated with the material throughput in a mineral economy as well as the finite nature of fossil fuel reserves (Daly, 1977; Georgescu-Roegen, 1971).

the academic literature has addressed these issues, but references are also made to the papers and their contribution to the debates.

The data and method section provides more details of the type of data sources that formed the basis of this dissertation and introduces some of the major methods employed in the individual papers.

The results section highlights the major contribution of this dissertation and provides an extended abstract of the individual papers. The results of each paper and how they relate to each other are then presented in the final section, titled Discussion, along with concluding remarks.

Theory and previous research

Historical context

A 'crash course' in Czech economic history

The Czech lands have experienced a series of institutional changes during their history. The early seventeenth-century Czech lands were characterized by relative religious and political freedom. Although predominantly Roman Catholic, the region stood out among its neighbouring countries with a growing and relatively numerous Protestant population. After the death of the emperor Matthias in 1619, his cousin and successor Ferdinand – a counter-reformist and devoted Catholic – threatened to confiscate the property of the Protestants. The tensions escalated in the White Mountain Battle in 1620, during which the Bohemian army lost to the army of the Holy Roman Empire, Spanish and Catholic league. The '30-year' war that followed the battle finally ended in 1648, when the Czech lands became part of the Habsburg Empire. As a consequence, land was seized and around five-sixths of the nobility went into exile. The total Czech population of roughly 3 million was decimated to around 800,000. To ensure the continuation of the agricultural production, which was essential to the economy, the serfs who worked the soil of these farms 'were bound to the land under such stringent conditions that it is debatable whether their fate in remaining was any better than that of their exiled social superiors' (Wright, 1966: p.12). And while in the Western parts of Europe, serfs had been gaining ever greater liberties, the situation in the Czech lands was the opposite, often referred to as the 'second serfdom' or 'manorialism' (Klein and Ogilvie, 2015; Ogilvie, 2007).

The abolition of serfdom in 1781, which in theory enabled the serfs to move freely, was thus an important milestone in the transition from serfdom. However, in practice most serfs remained bound to the land as a result of their hereditary subjection of labour services and paid dues in money and kind for the access to part of the lord's estate. This was first abolished in the revolutionary year of 1848, which transferred the right of the land directly to the peasants. The landlords consequently received a substitute for their loss of earnings whereby one-third of the land's value had to be paid by the peasant, one-third was paid by the monarchy and the remaining third was omitted, as the lords' costs associated with managing the estates suddenly fell apart.

However, the institutional changes of the nineteenth century were very slow, gradual and initiated by the Monarch ('the revolution from above'). This explains the slow process, which took around 90 years to complete the abolishment of serfdom, as reforms were proposed gradually to meet the least resistance from the rent seekers as possible (Khawaja and Khan, 2009). This gradual approach to institutional change is, according to North (1990), just a natural element of institutions, which are simply a reflection of the beliefs of the society, and these are difficult to change with one stroke. Moreover, the fact that the Czech lands represented a heterogeneous society with a relatively strong German minority (and so did the Empire to an even larger extent) resulted in slower convergence of the common beliefs and perceptions of the society and delayed the process of institutional reform. Nowadays, most historians agree that the language, cultural and religious heterogeneity of the Empire was the major contributor to its dissolution after the First World War (Cvrcek, 2013; Schulze and Wolf, 2012).

Historically, Czechoslovakia, or the Czech lands (when referring to the pre-First World War period as part of the Austro-Hungarian Empire), was one of the most developed parts of Eastern Europe, despite still being on the periphery and catching up with its Western counterparts (Cvrcek, 2013). According to Gerschenkron's theory of economic backwardness, the development of Austria-Hungary at the beginning of the 1800s lagged behind that of its Western counterparts, such as France or Germany (Gerschenkron, 1962). Although delayed, the relatively rapid industrialization, especially in the second half of the 19th century, laid the ground for the industrial structures of the country. By 1913 Czechoslovakia had become the most industrialized part of the Austro-Hungarian Empire, supplying much of the material needs of the monarchy. It has been estimated

that only around 30 per cent of the final Czechoslovak production in this period was consumed domestically (Cisar & Pokorny, 1922). In fact, it is believed that, before the Second World War, ‘most of the products known on the world’s market as Austrian came from the territory comprising the new Republic’ (Cisar and Pokorny, 1922). Following the First World War and the disintegration of the Austro-Hungarian Empire, Czechoslovakia lost virtually all of its export markets, which were fundamental to the development of its industries. It was also during the interwar period that the country started to fall behind the technological advances of Western Europe, especially in terms of electrical engineering and transportation equipment (Berend, 2001). However, although the share of domestic exports, particularly those of consumer goods (textiles, leather goods, glass and porcelain) declined after the First World War, the Czechoslovak economy attracted foreign investment and increased its gross domestic product by 40 per cent between 1913 and 1929 (Berend, 2001). In fact, in terms of economic growth, Czechoslovakia performed best among all the Central and Eastern European countries (Teichova, 2013).

Immediately after the Second World War, over 60 per cent of the exports were destined for Western markets (Germany, the USA and Sweden in particular). When the Communist Party won the country’s first democratic elections in 1946, Czechoslovakia was the second country (after the USSR) to introduce a model of central planning. The 2-year plan of the Czechoslovak Government was to a significant extent based on the country’s trading balance, and its primary focus was on reconstructing the country’s economy and increasing the living standards of the population while at the same time keeping some elements of market mechanisms. The Czechoslovak economy recovered in these 2 years and was set on a socialist path of growth with some market mechanisms. It was the full seizure of power by the Communists in 1948 that radically shifted the direction of development. The first 5-year plan was heavily influenced by Soviet officials, and Czechoslovakia, as the most industrialized country of the newly established Comecon, became the machine shop of Eastern Europe while at the same time subordinating its own needs to meet ‘the demands of industrialization of the other Comecon states’ (Teichova, 2013). The pattern of trade changed significantly: while in 1947 the Soviet Union accounted for 5 per cent of trade (with the rest of Eastern Europe accounting for a further 7 per cent), by 1953 the share of exports to the Soviet Union had increased to over 32 per cent. The year 1948 is therefore often seen as the turning point in Czechoslovak development and the beginning of the industrial

intensification, which was more or less sustained for the next 40 years. As a result of the 5-year plan of 1948, production became realigned, for example armament and ammunition production quadrupling in 1950–1952 (with the majority for exports).

Czech energy transitions

The origins of the research on past energy transitions date back to the decades after the Second World War. At this time of expanding industrial production and infrastructure building, studies of past energy use were often used for future forecasts and models. This was largely driven by the growing concern not for the environment itself but for the finite supply of natural resources. Numerous papers and books devoted solely to energy history emerged after 1960 (Jorgenson, 1984; Schurr, 1972; Schurr & Netschert, 1960), largely produced by energy analysts. Recently, the field has experienced a resurgence and a stronger presence within economic history (Kander, 2002; Kuskova, Gingrich & Krausmann, 2008; Malanima, 2016; Smil, 1994; Smil, 2003).

Within the Czech context, the importance of coal, as the papers within this dissertation discuss, was significant and had some profound and long-lasting effects not only on the adoption of technology but largely also on the industrial structure of the country and its overall energy intensity (Figure 1).

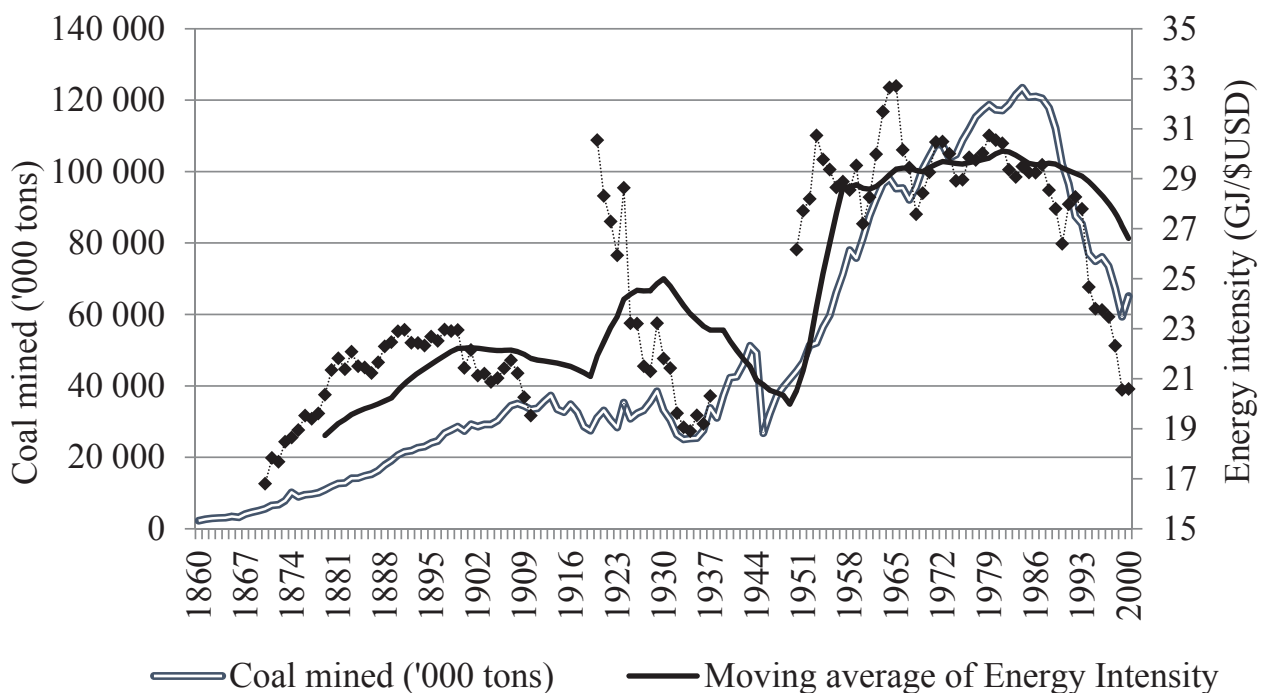


Figure 1 Coal mining and energy intensity in the Czech Republic (Czechoslovakia)

Moreover, the actual transition to coal was fast when compared with other countries (Figure 2). It took roughly 50 years for coal to increase its share from 5 per cent to 50 per cent in Germany, while in the Czech Republic this transition took only around 35 years. In fact, compared with other countries for which data are available, the Czech Republic had the fastest transition to coal. In Sweden, for example, traditional energy carriers accounted for more than 50 per cent of the domestic energy consumption until the late 1920s, while in Italy and Spain the transition to fossil fuels occurred first before the Second World War.

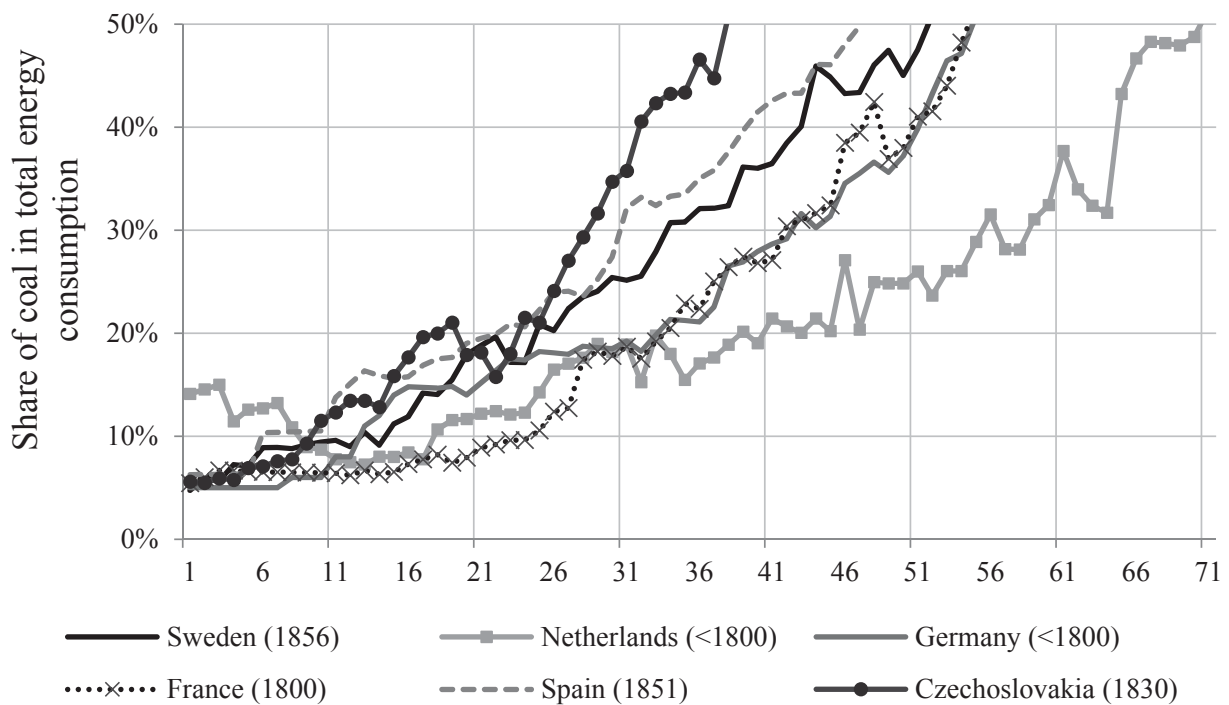


Figure 2 Number of years in which coal increased its share in the national energy consumption from 5 to 50 per cent

Note. The number in brackets for each country refers to the year when coal reached a 5 per cent share. England is omitted, since the share of coal was already 92 per cent in 1800.

Past quantitative long-run energy history studies

The origins of the research on energy history date back to 1960 (Schurr & Netschert, 1960) with a resurgence in the 1990s (Ayres, Ayres & Warr, 2003; Fouquet & Pearson, 1998; Kander, 2002; Smil, 1994). This growing research field of energy history has, over the past decades, led to the formation of several research groups, taking various levels of aggregation, such as economic sectors, cities and villages, countries or entire continents.

Importantly, each group also has various definitions of energy, which thus sometimes make it difficult to compare the findings of their studies.

This dissertation adopts an approach to energy accounting based on the methodologies of the Long-term Energy Growth (LEG) network. The LEG network consists of a number of researchers progressively publishing long-run accounts of energy consumption in Sweden (Kander, 2002), the Netherlands (Gales et al., 2007; Hölsgens, 2016), Italy (Malanima, 2006; Malanima, 2016), Spain (Bartoletto & Rubio, 2008), Norway (Lindmark, 2007), England (Warde, 2007) and Portugal (Henriques, 2009). Contrary to other studies, both traditional (such as food and feed for draft animals) and modern (usually fossil fuels) energy carriers are included in the analysis. In the past it has been shown that including traditional energy carriers is important and substantially changes the energy intensity curve for some countries. In calculating traditional energy carriers, this paper uses a method identical to that of Kander and Warde (2009). Using the same methodological approach is indeed very important for the comparative nature of the papers. The data, which are also published by Kander, Malanima and Warde (2013), are available for downloading on the website of the Center for History and Economics at Harvard University.

The Vienna Group of Social Ecology (Universitat Klagenfurt) studies predominantly biophysical flows from the long-run perspective. Its methodological scope differs somewhat from that of the LEG network and focuses greatly on the interactions of the society with its environment, the ecological footprint or land use changes. The group produces time series of energetic metabolism at the level of individual regions or countries, such as Austria (Krausmann & Haberl, 2002), the Czech Republic (Kuskova, Gingrich & Krausmann, 2008), Japan (Warr et al., 2010) and most recently the USSR (Krausmann et al., 2016). With certain relevance to the Czech Republic, the group also publishes accounts of agricultural social metabolism (Greslova et al., 2015; Krausmann, 2004).

The last major research group within the field of long-run energy transitions studies energy use in terms of ‘useful work’. Here, the argument is that measuring the energy actually used within the economy gives a far better result than measuring the energy employed. The methodology is thus again different and takes into account the final energy use (contrary to the primary energy measured by the LEG network), its use in useful work categories (such as heat, light or mechanical power) and the actual efficiency in converting this energy into useful work (and thus the provision of the much-

needed energy service). The pioneering work in this field is by Ayres and Ward, initially for the USA (Ayres, Ayres & Warr, 2003; Ayres & Warr, 2009; Warr et al., 2010), but others also try to adopt a similar approach in other countries (Warr et al., 2010). In a recent publication, the IIASA research institute provides global long-run data (1900–2014) on energy and exergy use, even with some sectoral disaggregation (De Stercke, 2014). The data are available for downloading free of charge on the institute’s website.

Previous research and overview of major topics and theories

The overarching theme of this dissertation is the use of energy in the context of the Czech Republic with a particular focus on the role of energy resources, technology and changing institutional settings in the economic development of the country. Clearly this is a wide topic with a multitude of potential areas to study. The overall theoretical scope and major topics of this dissertation are outlined in Figure 3. The aim of this illustration is to visualize the links between each major concept discussed in this dissertation. In the subsequent chapters of this section, more attention will be devoted to each topic and they will be related to each other as well as to the findings of the individual papers.

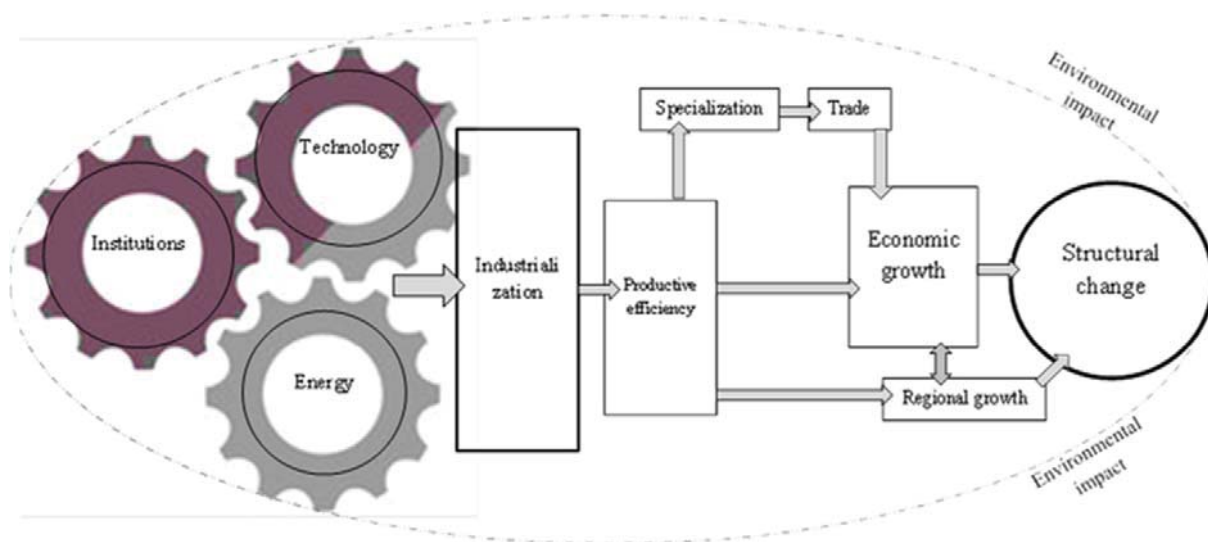


Figure 3 An overview of the major theoretical concepts discussed

This dissertation views technology, energy and institutions as largely interrelated mechanisms of the industrialization process. The role of institutions and different political systems, in particular, is indeed an all-

encompassing theme throughout. Most authors agree that institutions, the humanly devised social and political rules of economic interaction, are crucial to economic development and can provide some enriching explanations for why countries with similar factor endowments and technologies often perform so differently (Acemoglu et al., 2004; North, 1990; Ogilvie, 2007). I also argue that institutions have both a direct and an indirect impact on the nation's energy deployment. The impact can be channelled indirectly through the structural change in the economy (for example with a structural change towards an energy-intensive industrialization path) or directly through poorly designed incentives that do not encourage efficiency gains. Last, the impact of institutional settings can also be channelled indirectly through the degree of technology adoption. While other factors of production, such as labour and human capital, are also important, these are not discussed extensively within this dissertation.⁷ The utilization of energy, and primarily of modern energy sources (such as coal and oil), has historically been linked to major technological advancements, which brought forward unprecedented rates of per capita growth in Western Europe (Allen, 2009; Kander, Malanima & Warde, 2013; Wrigley, 2010). The different deployment of technology and energy in various institutional settings leads to various levels of productivity of a nation overall as well as at the level of individual productive sectors. While some sectors manage to increase their productivity substantially, others lag behind. Meanwhile, the overall supply of produced goods increases and leads to economic growth. This in turn shapes the structure of the economy directly (through structural as well as technological change) and indirectly through the role that the economy plays internationally (mainly through increased specialization and global trade). Technological differences and the availability of domestic resources do not only create those predispositions for the onset of modern economic growth; the two combined also largely determine the regime and composition of trade (Estevadeordal, 1997; O'Rourke & Williamson, 1999). Countries tend to export goods or commodities in which they possess a certain comparative advantage compared with the rest of the world (Laursen, 2015). Furthermore, as argued by Heckscher-Ohlin, this comparative advantage often lies in the production of goods that can be characterized by

⁷ For a working paper on the historical developments of energy and labor productivity and especially the changes in the energy/labor ratio across Europe and the USA, the reader is advised to read the working paper by Nielsen et al. (2016) titled *The Productivity Race in Industry (1870–1935): Empirical Evidence on the Role of Energy in Labor Productivity Growth*.

the extensive use of resources that are abundant in those countries (Crafts, 1985). However, economic growth in an economy does not only imply changes to the volumes of economic activities. The process of modern economic growth is equally reflected in the unequal regional development. The increased use of coal, for example, occurred in the mining sector, where coal-driven steam engines were used to pump water. Thus, coal-rich areas had a certain lead in the utilization of coal, which shortly also spread to other productive sectors of the economy (Allen, 2009). In the end the sum of the internal domestic forces, global trade and regional growth equal the absolute national economic growth. But even though the rates of growth in our production capacity increased substantially, the most significant were the structural changes induced by the modern economic growth regimes. Long-term growth does not only equal growth in the quantities of production volumes (Schön, 2010). Importantly, long-term growth is most characteristic for the shifts in the qualities of production, the ongoing changes in the production output and our consumption patterns.

Industrialization and modern economic growth from the long-run perspective

Modern economic growth refers to a period in which the per capita GDP grows at a sustained and long-run pace. Until recently, there has been a consensus that before 1800 there was virtually no upward trend in most societies (Clark and Jacks, 2007; Maddison, 2007), a pattern that was however followed by rapid and sustained growth in per capita incomes. This would mean that a modern economic growth is only a phenomenon of the past two centuries, barely a tiny fraction of the existence of the human mankind. This stagnant view of pre-industrial Europe has been recently challenged by new long-run estimates on national accounts which identify period of growth (Fouquet and Broadberry, 2015), largely building upon the legacies of Maddison's pioneering work (Maddison, 2007; Bolt and Van Zanden, 2013). What the new estimates show is that, relative per capita growth has been characteristic for many European countries in pre-industrial times, sometimes even lasting for decades (Fouquet and Broadberry, 2015). Interestingly, while there is little doubt about England being the cradle of European industrialization, countries such as Italy, Holland or Sweden experienced spells of economic growth long before 1800 (Malanima, 2011; Schön and Krantz, 2012; van Zanden and van Leeuwen, 2012). It is also therefore that the well-established economic history theories have been challenged recently by describing the Industrial Revolution much more as a gradual process of economic change rather than a new regime with rapid /

revolutionary take-off (Broadberry et al., 2008). And it was those spells of economic growth in pre-industrial times which laid foundation for the future modern economic growth by creating new urban middle class with changing material needs, an image of aspiration for the rest of the society (De Vries, 1994; McCloskey, 2016). Indeed, the Industrial Revolution is no longer seen as an abrupt, revolutionary event but rather as a process of consecutive changes throughout the middle ages (Allen, 2006). Nevertheless in spite of these limitations, for most of the developed world, the very beginning of modern economic growth remains placed sometime in the middle of the nineteenth century, yet it is here that the question arises of why some economists still focus on developments dating back only a couple of years or decades.

While economic growth has existed since the beginning of humankind, widespread modern economic growth first came together with the age of industrialization (Acemoglu, 2009). It is also the age of industrialization which does not only relate to the onset of the modern economic growth regime but also the beginning of the differential economic growth across countries and continents. The magnitude of this differential development has puzzled economists for as long as modern economic growth has dominated the world. However, understanding why some countries succeed while others continually fall behind is beyond the mechanics of traditional economic models (Acemoglu, 2009). How can two locations that share a similar cultural background and climate develop so differently?

Much research has been devoted to the factor endowments and their cross-country differences (the accumulation of physical capital and human capital or technology adoption) in the search for the causes of modern economic growth and to understand why some countries grow more rapidly than others. While studies of these factors of production, which Acemoglu refers to as proximate causes of growth, contribute to our understanding of long-run economic growth, they fail to explain the fundamentals of why societies make such technology or accumulation choices.

Structural change and economic growth

The onset of the modern economic growth regime is commonly characterized by rapid changes in the structure of the national output as well as employment (Kuznets, 1973, 1966). According to Kuznets, in the past technological change was the major source of shifts in productive structures: structural change from an agriculture-based society to an industrial one. This

structural shift from agriculture was largely driven by the increases in human productivity (Schön, 2010) which was induced by innovation and technological change leading to more efficient resource utilisation. Technological change brought forward new industrial branches, which in turn led to changes in the country's distribution of national output and productive sources, such as labour. It has become common to associate those changes in the occupational structure – from agriculture to industry and services – with modern economic growth (Klein and Ogilvie, 2015; Schön, 2010). Structural changes in the distribution of labour are often believed to be preceded by improvements in agricultural productivity. This is because changes in agricultural productivity were important for the pre-industrial society, as they created an agricultural surplus for the future industrial workers; some even argue that agricultural productivity was an absolute prerequisite for industrialization (Kuznets, 1966).

The improvements in agricultural productivity freed labour for the upcoming industrial branches and initiated massive shifts in the distribution of national output, labour and urbanization rates (Schön, 2010). Not only in terms of employment shares, these structural changes were equally accompanied by changes in the distribution of other production resources – capital as well as energy. It was also within this period of the first Industrial Revolution that many of the structural changes were sustained through substantial increases in the deployment of energy. The fast expansion of the industrial sector as well as the establishment of major infrastructure networks, such as railways or steam-operated machinery, required large volumes of energy, much of which was fuelled by the previously unutilized fossil fuels.

Environmental Kuznets curve

It is with deepening industrialization that economic growth thus becomes, in the light of environmental pressures, an undesirable outcome. If economic growth is accompanied by a proportional increase in energy consumption, our future economic opportunities may be endangered by an inelastic supply or associated drawbacks. If, on the other hand, economic development can be decoupled from economic growth, a more optimistic picture emerges, particularly taking into account the rapid economic growth of the rest of the 'global south'.

The most widely accepted perspective on this relationship is the concept of the environmental Kuznets curve (EKC) (Panayotou, 1997). According to the concept of the environmental Kuznets curve, as countries industrialize and

consequently increase their production of industrial goods and intensify the establishment of major infrastructures, they cause an upward slope of the EKC. Analogically, the downward slope of the EKC is then a result of industrialized countries having established major infrastructures while increasingly importing industrial goods instead of producing them domestically (Suri and Chapman, 1998) but also through structural and technological change (Henriques & Kander, 2010; Kander, Malanima & Warde, 2013). Much of the research within the field is driven by the search for the ultimate causes of falling energy intensity in the developed world (though one has to remember that declining energy intensity refers to changes in relative measures of energy use and does not translate into environmental relief). The field of ecological economics has gained a surfeit of decomposition studies aiming to identify individual drivers of energy intensity (Henriques & Kander, 2010; Zhang 2003; Zhao, Ma & Hong, 2010). The search is motivated by two simultaneous intentions. First, the academic and political arena became aware of the negative externalities of energy use and the measures that could aid in avoiding or at least limiting those externalities. Second, the rise of new emerging economies, in particular that of China, accelerated the urgency of this matter.

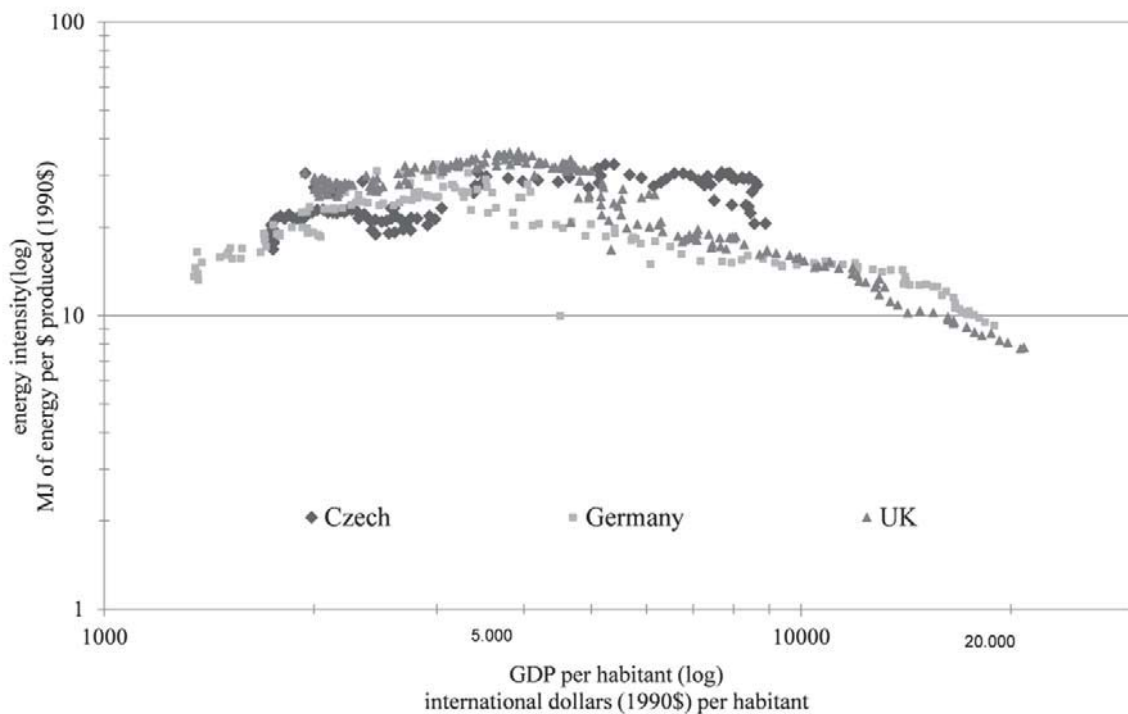


Figure 4 The environmental Kuznets curve in coal-rich Europe (energy intensity versus income per capita)

Source: own data and (Kander et al., 2013)

The concept of the EKC, however, is commonly criticized, as it has become evident that many countries do not exhibit this pattern of falling energy intensities, particularly when traditional energy carriers are included, by taking a long-run perspective (Gales et al., 2007) or if accounting for foreign trade and outsourcing (Antweiler, 1996; Chen, Pan & Xie, 2008; Ghertner & Fripp, 2007; Kander et al., 2015; Sato, 2012). In the case of the Czech Republic and two other coal-rich countries (Germany and the UK), however, a clear pattern of the EKC is identified, though with some deviation from the trend in post-Second World War Czechoslovakia (Figure 4).

Energy and modern economic growth

Energy and its role in modern economic growth have proven to be one of the concepts largely overlooked by modern-day economists, mainly as a result of them not fully understanding the importance of adopting a long-run view. For some reason this was largely supported by the relatively small share of energy in the total production costs, as we have experienced over the past decades. However, adopting a long-run approach, a period of more than a century, paints a substantially different picture of energy's role in modern economic growth.

Recent research finds that energy played a crucial role in stipulating economic growth (Ayres & Warr, 2009; Kander & Stern, 2014; Stern & Kander, 2012). Consequently, if we are to agree that it was modern economic growth that brought our society to its current level of development, we need to acknowledge that this was achieved on the back of the increased deployment of additional mineral-based energy services. Without those services that the new modern energy fuels embodied, the economy would be likely to have continued to grow at a pace consistent with that achieved for centuries, growth that could never be defined as modern economic growth (Ayres & Warr, 2003; Ayres & Warr, 2009). Nevertheless, most studies on the energy–growth nexus adopt a rather limited time period, and the results remain inconclusive (Ozturk, 2010; Stern & Enflo, 2013).

Several studies attempt to estimate the role of energy in economic growth (Stern & Kander, 2012; later studies in an extended form Kander & Stern, 2014). Adopting a long-run perspective of 200 years, Stern and Kander (2012) find that when 'energy services are abundant the economy exhibits the behaviour of modern economic growth'. On the other hand, when energy is scarce, the economy turns into a steady-state economy with limited output growth (Stern & Kander, 2012). In a pre-modern economy, or an economy

that could equally be termed an organic economy, the energy services available in the form of organic resources are clearly limited and constrained given the fixed amount of land available. Even within an organic economy, the productivity and output can increase; however, the rate of growth cannot be paralleled with those increases achieved when additional energy services are deployed. Following the regime change from an organic to a mineral-based economy, energy availability increased substantially (primarily coal), as did the actual energy quality. Indeed, research shows that it was energy that was the major driver of growth until 1950 in Sweden (Kander & Stern, 2014). A simulation exercise in the same paper (Kander & Stern, 2014) demonstrates that, if there were no increases in the availability of energy, there would be almost no economic growth.

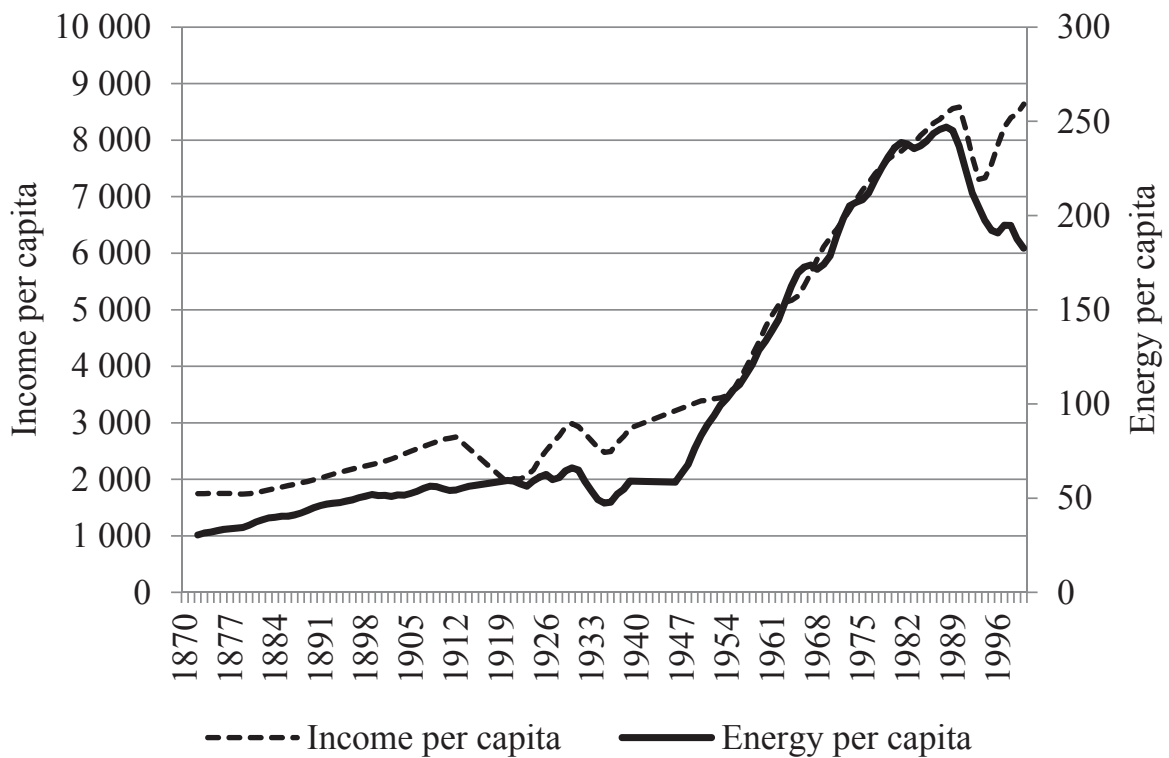


Figure 5 Income per capita and energy per capita in the Czech Republic since 1870 (three-year moving averages)

Source: own data and (Bolt and Van Zanden, 2013)

Figure 5 parallels the developments in the relative levels of energy and income (in per capita terms). Until 1990, as Figure 5 shows, both the income and the energy curve show a strikingly similar pattern of development. The industrialization processes that emerged during the nineteenth century were to a large extent fuelled by similar increases in the use of energy. First, after

1990 a form of decoupling can be seen in the figure, which is a couple of decades later than a similar trend started to appear in the West.

Not only was the economic growth particularly correlated with the increased energy use until 1990, the relative levels of both incomes and energy differed substantially from those of other European countries. Table 2 provides a comparison of the development in GDP/capita and energy/capita across Europe. In 1870 England had by far the highest levels of income and energy per capita, while the Czech lands followed a similar development to Germany. After 1870, however, the rate of growth on both accounts started to lag behind those of Germany, and, by the beginning of the First World War, the Czech lands had per capita energy consumption that was 40 per cent lower. This trend was largely reversed after the Second World War with the per capita consumption of energy growing rapidly while the income levels lagged increasingly behind those of Western Europe.

Table 2 Czech GDP and energy consumption from a comparative perspective

Source: own data and (Kander et al., 2013)

	GDP per capita					Energy per capita (GJ)				
	1870	1910	1950	1970	1990	1870	1914	1950	1970	1990
Czech	1 757	2 766	3 429	6 428	8 464	30	54	90	188	223
Sweden	1 092	2 206	5 959	12 372	17 630	28	55	77	175	166
Netherlands	2 648	3 559	5 996	11 961	17 262	36	54	62	139	163
England	3 657	4 906	7 090	11 000	16 281	118	138	135	168	157
Germany	1 768	3 260	3 881	10 839	15 929	33	91	89	160	166
France	1 956	3 091	5 270	11 668	18 093	29	53	68	123	122
Italy	1 589	2 472	3 639	9 784	16 262	17	22	24	89	107
Spain	1 218	1 889	2 196	6 329	12 131	19	24	27	56	86
Portugal	997	1 164	1 998	5 267	10 892	19	22	24	39	73

The role of energy and technology

The inseparability of energy from technology that led to the Industrial Revolution is indeed obvious. Steam engines were first deployed in coal mining, pumping water from over-flooded mines, but the use of the mechanical power provided by steam engines soon spread to other productive branches, in which the productivity rates increased substantially (Kander, Malanima & Warde, 2013). Initially the use of steam technology was largely confined to mining and the textile sector, the staple goods of British industrialization, but quickly found uses in other existing as well as newly

developing manufacturing sectors as well. Coal and steam also enabled the rise of new urban agglomerations, creating new demands for iron and other related goods to service the necessary infrastructure of large water and energy systems (Landes, 1969).

This complementarity between energy and new technology was critical to the actual start of modern economic growth. Nevertheless, the adoption of steam engines per se in an economy was not likely to spur these impressive rates of growth, which were merely a result of an often-lengthy preceding process of technology adoption and diffusion, conditioned on the structural changes in the overall economy. Here again, research shows that taking a long-run perspective can provide our understanding of the role of technology and energy technology in particular with some valuable lessons (Grübler 1998; Grübler & Wilson, 2013). The evidence on energy technologies, coal-related technologies such as steam engines or coal-fired power stations, not only shows a lengthy process of adoption, followed by unit and system upscaling, but also highlights the probability of technological lock-in and pervasiveness and the overall lengthy transitions not only of technologies but also of energy systems (Grübler, 2012).

As the Czech Republic has sometimes been referred to as a periphery in terms of economic development (Gerschenkron, 1962) or new steel technology adoption (Nielsen, 2017; Tarr, 1985; ZumBrunnen & Osleeb, 1986), a framework of technology diffusion also needs to be discussed from a geographical point of view. This framework has been used historically to understand the cross-country differences in technology diffusion, in which frontier economies are usually the first movers of new technology adoption, only to be followed later by more peripheral countries (Acemoglu, 2009).

The road to industrialization and geographies of development

Generally, it is assumed that the adoption of new technology and the consequent upscaling, the lengthy process for all technologies before reaching maturity, differs across countries. This is mainly due to the fact that certain countries are front-runners in developing new technologies. However, as this is a learning process with many experimental small-scale units of various designs, the initial adoption stage is particularly prolonged in first-mover countries (Wilson, 2012). Analogically, once technology is developed and makes its way into the existing system on a large scale, other countries can adopt the technology and are often not required to undergo the same lengthy period of testing and development. Historically, countries like Britain

and the USA have been the core of new technology adoption (the frontier), while the Czech lands are often referred to as peripheral, and the adoption of new technology there would be merely a consequence of the technology's acceptance and widespread use in the core. Obviously, this would allow latecomers to skip the lengthy testing stage and reap the fruits of technology development elsewhere. Outside the field of technology adoption, the similar concept of leapfrogging is also used in ecological economics to explain the differential levels of energy intensity curves between the core countries and the latecomers (Goldenberg & Reddy, 1990), though it is often challenged by empirical studies.

When it comes to new technology adoption, however, and in particular the adoption of coal-related technology, the process is far more complex. This is mainly because the scaling-up of energy technologies (albeit developed in other countries) usually requires fundamental changes to the existing systems of the economy. The adoption of steam technology, for example, depended largely on the new infrastructure development to provide the newly established and constantly expanding industries with a stable supply of coal (Nuvolari, Verspagen & Tunzelmann, 2011). Similarly, electricity adoption in manufacturing did not only require the formation of a reliable national grid; it fundamentally changed the organization and layout of the producing plants, the structure of which was conditioned on the previously installed steam engines as the centre of mechanical power (Devine, 1983).

Although we can observe cross-country differences in technology adoption and economic development, an immense amount of disparities are apparent even within one country's borders (Bairoch & Levy-Leboyer, 1981). In the economic history and economic geography literature, there is a whole body of research devoted to the study of location choice and why some regions are left behind while others manage to race ahead when it comes to economic development (Crafts & Wolf, 2014; Roses, 2003; Wolf, 2007 just to name a few). There are two major theories that are often addressed in the existing research, though complementarity of the two approaches can hardly be ruled out.

The 'first nature' of location refers mainly to resource endowments (such as climate, soil quality or coal) and the degree to which those conditions are prerequisites for industrial development. What is most characteristic of the 'first nature' of location is its destiny or something that can hardly be adapted or changed. As Pollard argues, coal was king during the Industrial Revolution and 'the map of the British industrial revolution, it is well known, is simply

the map of coalfields' (Pollard, 1981). Other papers on coal and urban growth (Fernihough & O'Rourke, 2014) or the location of the German industries (Gutberlet, 2014) are prime examples of the impact of 'first-nature' geographies. In the Czech lands (Paper 1), the coal scarcity/endowment also resulted in an unequal distribution of economic centres during the industrialization. As Paper 1 shows, industries with a large share of steam in their production did tend to locate in proximity to coal mines to secure a consistent supply of this strategic energy source. Although the relatively fast development of the railway networks later created 'cheap' transportation options, it did not manage to erase fully the regional disparities in economic development, and some regions remained geographically locked in (Karnikova, 1960).

The other theory, the 'second nature' relates more to access to markets or other man-made geography, as opposed to the 'natural geography' under the first nature. Here, the second nature is characterized more by endogeneity over the foreseeable future (not destiny as with the first nature), and a large focus is devoted to the concentration of certain economic activities as a result of agglomeration effects. The concentration of firms and workers in areas with high levels of economic activity allows for lower transport and transaction costs and places available labourers in close proximity to potential employers. The existence of railways, which is commonly related to agglomeration effects, is found to have an important impact on the local economic development (Atack et al., 2010; Berger & Enflo, 2014; Donaldson & Hornbeck, 2016; Hornung, 2015). At the same time, the marginal effect of other 'acquired' conditions, such as access to railway or market potential, increased over the course of the first Industrial Revolution. This is largely in line with the growing body of historical literature from other countries, which similarly finds second-nature aspects of industrial location to be more pronounced as countries' industrialization progressed (Crafts & Mulatu, 2005; Crafts & Wolf, 2014; Klein & Crafts, 2011; Missiaia, 2016; Roses, 2003; Wolf, 2007).

However, the effect of geography on new technology adoption can be studied from multiple angles. First, geography in itself can affect the institutional settings, which in return can provide protection to innovators and support their drive to invest time in innovating further (Mokyr, 1990; Mokyr, 2009; North, 1990). Second, geography can also have a profound impact on the costs of factors of production, which in turn can affect the type of innovation required to economize on what is abundant in a country. Allen, among others,

provides rich quantitative evidence regarding why Britain, for example, opted for so much labour-saving technology while other countries with cheaper labour had weak economic incentives to adopt similar technologies (Allen, 2012; Allen, 2014; Habakkuk, 1967).

'The technical innovations and their lasting impact' (Smil, 2005)

The adoption of modern fuels in production processes did not only provide the necessary fuel to reach output levels that had never been experienced before. More importantly, coal and later other fossil fuels laid the foundations for the invention of new materials and processes (Landes, 1969). Smil provides a detailed analysis of the actual magnitude of the impact that those technologies had and still have to the present day (Smil, 2005; Smil, 2006; Smil, 2016). Imagine steel, for example. While iron and steel production was invented thousands of years ago, its enormous fuel demand did not allow for steel production to scale up and become one of the most important commodities of the nineteenth and twentieth centuries until innovations allowed coal to replace (wood-based) charcoal. Until the mid-nineteenth century, the whole iron and steel industry was dominated by puddling practices in small artisan shops; the process innovations introduced by Henry Bessemer in 1856 and Pierre-Emil Martin and Sir William Siemens (the 'Siemens–Martin' or the 'open hearth') ten years later transformed the whole sector by a process that was entirely based on coal and coke. The diffusion of these two new innovative production processes led to the mass production of steel from about 1 million tons worldwide in 1870 to over 100 million tons in 1920 (Grübler, 1998). Steel and the industrial processes associated with steel-making have become a 'hallmark of the late 19th century' (Smil, 2005), fundamentally transformed the modern world in the past century and are continuing to do so today (Smil, 2016). Steel has not only become an indispensable material in the construction of railways, machinery and reinforced building structure; it has also created new markets and demands, for example in the electrical industry or the future oil and gas industry. Other sectors in which the achievements have been at least as spectacular are the chemical sector, metallurgy and electric power, which again remain largely grounded on the mineral-based energy economy of the modern world.

However, although the world demand for materials such as steel is expected only to increase in the future, impressive achievements have been reached in the energy efficiency of the actual production processes, providing a more positive outlook for the generations to come. Between 1900 and 2010, the energy use per ton of steel dropped by 80 per cent. These impressive

advancements in energy efficiency were brought forward mainly as a result of the quest for ‘lower cost and higher productivity’ (Smil, 2014a), a trend achieved not only as a result of technological change but also due to the increasing sizes and capacities of steel furnaces, as Papers 5 and 6 also discuss within the Czech context.

As technology advanced progressively through various parts of the world, the degree to which it enhanced savings with respect to various factors of production differed substantially across manufacturing.

Productivity growth and efficiency improvements

From an energy perspective, two major technological inventions had a profound impact on the overall productivity growth, albeit with efficiency improvements at different levels. It was the use of steam, with its consequent mechanization of manufacturing, and the electricity network. What the two technologies have in common is their sole dependence on coal, at least within the Czech context. Coal-fuelled steam engines served as an energy converter supplying unprecedented amounts of energy for the newly developed mechanized industries, which were increasingly concentrated in large-scale units (Landes, 1969). The increased use of steam technology and mechanization (and thus capital deepening of various productive sectors) is generally considered to be the major driver of increased labour productivity in nineteenth-century Western Europe, together with improvements in human capital, organization of production and scale increases. Relative market and plant size are seen as drivers of productivity as these innately lead to increased demand but also through agglomeration effects and other external efficiencies (De Jong, 2003).

Britain, at the beginning of the first industrialization, had the largest incentive to introduce modern labour-saving technology and to overcome the constantly growing labour costs (Allen, 2009). It is shown that, during the eighteenth century, the country was unique in having ‘particularly high wages and low energy prices’ (Allen, 2009). This complemented well the newly introduced technologies, which enabled a certain degree of labour saving while consuming relatively cheap and abundant energy, a setting that was profitable in a country like Britain but unlikely to be reproduced in other countries with different relative factor prices (Allen, 2009). The Industrial Revolution would only spread to Europe when improvements in the efficiency of steam engines occurred, by reducing the energy costs and increasing the incentive for low-wage countries to mechanize (Allen, 2009).

In less developed countries, such as India or Egypt, without domestic coal reserves and highly dependent on firewood energy, this development pattern could not have been reproduced. With the abundance of cheap labour, the relative costs of labour to energy did not lead to the adoption of modern technology (Allen, 2014). Consequently, labour productivity differences at the sectoral level are also attributed to the differential use of energy and capital, and exploring the differences in cross-country labour productivity has been a topic of many heated debates in economic history (Allen, 2012; Broadberry & Fremdling, 1990; Broadberry & Irwin, 2006; Veenstra & De Jong, 2015). At the same time, while differences in labour productivity are commonly linked to the deployment of energy capital, they are rarely related to each other.

Equally, the deployment of electricity in manufacturing, the other most influential energy-related innovation of the past century, had some tremendous impacts on the developments in labour productivity, which indeed some authors have tried to assess and quantify. In Sweden, for example, the increasing share of electricity in the manufacturing sector is found to be a strong driver of both labour productivity (Schon, 2000) and energy productivity (Enflo, Kander & Schön, 2009).

The role of steam engines and electrification in driving productivity gains differed and proceeded at different rates in various countries (De Jong, 2003). During the First Industrial Revolution, the move from water to steam power posed little change on the organization of manufacturing plants while at the same time replacing some of their workers. Labour productivity increased by around 60 per cent between 1880 and 1900 (Grübler, 1998). Steam engines thus provided some significant breakthroughs in both energy use and labour productivity, but due to their nature – static, immobile and heavy – steam engines also represented certain limitations. The introduction of electricity as the driver of mechanical power in manufacturing dates back to 1884 in the USA, but the first productivity gains could first be observed during the 1920s, a time when electric motors supplied over 50 per cent of all mechanical power in manufacturing (Devine, 1983). The reason for this relatively long lag in productivity gains can be explained by the technological nature of electric drives. In fact, in the early stages of electrification, electric motors were simply used to replace centralized steam engines with an identical power distribution system, and each machine had to be connected to the centralized electric motor (Grübler, 1998). The overall efficiency of an electric motor utilized in the same manner as a steam engine remained

unchanged. To increase the efficiency of the newly implemented electric motors, it was necessary to change the organization and layout of producing plants fundamentally. Only in this sense could the decentralized electric motor now be used to power each machine individually and thus materialize flexibility. In turn, the organizational changes and the full deployment of electric motors had a tremendous impact on labour, energy and capital productivity growth. In the US labour productivity in manufacturing is believed to have increased by a factor of 100 only in the decade 1920–1930 (Devine, 1983). Both Schurr and Jorgenson further argue that the role of electrification was in fact critical in the period after 1920, supported by the improvements in thermal efficiency of the conversion of fuels into electricity as well as the widespread use and flexibility of electricity in the manufacturing processes (Jorgenson, 1984; Schurr, 1972; Schurr, 1990). In Sweden in 1900–1990, for example, electricity was found to be largely ‘complementary to new technology and skills’, having a profound impact on the overall productivity (Schon, 2000). In the Czech lands, on the other hand, the relatively highly developed engineering sector in the 1920s was hindered by the lacking electrification (Purs, 1978).

Nevertheless, there are also potential downsides of increased electrification, especially when this large-scale technological shift is not administered under optimal conversion efficiency, as Paper 2 shows. While Czechoslovakia and Eastern Europe generally lacked installed electricity capacity and per capita production was relatively low until the Second World War, the post-war socialist planning accelerated this process of nationwide electrification substantially (Etemad & Luciani, 1991; Hughes, 1983). This has often been seen as a step forward and by some praised as one of the major benefits of the planned economy (Allen, 2005), though the low level of thermal efficiency of the conversion of fuels into electricity had some detrimental and long-lasting implications for the energy intensity of the planned economies and their natural environment. The increased electrification of industrial production carried the inefficiencies from the electricity sector to the final produce. As Paper 2 shows, the low level of efficiency in the electricity transformation sector in Czechoslovakia was indeed a phenomenon that first emerged after the Second World War. Paradoxically, in the period 1890–1939, Czechoslovakia was ranked among the producers with the highest level of efficiency in terms of the average efficiency of its thermal power stations (Etemad & Luciani, 1991). A question thus arises regarding the extent to which the imposed institutional changes affected the productivity levels and the rate of growth of industrial development.

Institutions and political aspects of industrial development

In the existing literature, much research is devoted to the role of institutions in economic development (Acemoglu, 2009), although the reverse causality of economic change in shaping and changing the institutional settings of various countries receives less attention (Wilson, 2016). As a result, institutions often tend to be explained by their consequences rather than as causes of development (Persson, 2010). In China, for example, efficient institutions are found to be crucial in harnessing the benefits of economic development rather than kick-starting them (Wilson, 2016). This is much in line with other countries, where studies find that changing the incentives for economic actors can give rise to long-run economic growth and stimulate institutional changes (Acemoglu, 2009). A poorly designed economic structure that does not clearly define property rights may have a negative impact on the accumulation of capital and human capital as well as technological progress (Acemoglu, 2009). Even external actors trying to enter countries with poor institutional settings and poorly defined property rights might be discouraged, which in turn prevents the more productive firms from entering (Acemoglu, 2009).

The shift from a market-based economic system to the Soviet-style system of central planning is much debated, not only within the economic history literature. Given the fact that this institutional change was sudden and largely imposed from above, some authors refer to this period in Eastern European economic history as an economic experiment (Rosenberg, 1992).

Even though originating from the writings of Marx and Engels (1888), the Soviet-style socialist planning that swept across the whole of Eastern Europe during the twentieth century was embraced as an anti-capitalist system of economic planning rather than socialism (Rosenberg, 1992). Originally, as Marx himself acknowledged, the system of capitalism was fundamental for rapid economic growth and the substantial increase in human productivity. This was because a capitalist system provided the right incentives to innovate and invest and thus to increase productivity (Rosenberg, 1992). Indeed, it was necessary for every country to pass through intensive stages of capitalist development on its road to socialism. Marx's theories, written in the nineteenth century, were far more concerned with the future of those societies in the industrial capitalist countries and less so with their relevance to transforming a peasant society of the twentieth century into an industrialized nation (Campbell, 1960). Instead, the system of Soviet-style economy imposed in Eastern Europe was more of a totalitarian system with a great

focus on rapid industrialization and economic growth than a system reflecting on the fundamentals of socialism (Campbell, 1960; Rostow, 1990).

Nevertheless, this sudden institutional shift, which took place in Czechoslovakia between 1948 and 1989, provides a great opportunity to study various aspects of energy use under two diverse systems of economic planning. As the dissertation shows, this 40-year natural experiment penetrates various aspects of technology adoption as well as energy efficiency. The major hypothesis behind this encompassing concept is that the style of the economic system may have had a profound impact on the adoption of new technology, efficiency and productivity and in general on the consumption of energy and the pattern of energy transition. The insecurity of property rights and barriers to entry for external actors are likely to have prevented 'activities by the more productive firms' and led to productive inefficiencies (Acemoglu, 2009). Imperfect information is also found to be linked to resource misallocation and consequently lower productivity and output (David, Hopenhayn & Venkateswaran, 2016), and findings from behavioural science show risk aversion and cautiousness among managers in planned economies, often with respect to new technology adoption (Allen, 2012; Arens, Worrell & Eichhammer, 2016; Kogut & Zander, 2000; Poznanski, 1986). After all, managers are still humans.

Simply plotting a curve of energy intensity for Czechoslovakia across time provides excellent motivation for the research on the political aspects of energy use. As the following figure shows (Figure 6), from a comparative perspective, the curve for the Czechoslovak energy intensity diverged substantially from the trend observed in other European countries after the Second World War.

According to the existing theories, central planning is associated with multiple inefficiencies, which in turn affect the levels of energy consumed and the actual energy transition. The impact of central planning is analysed from an economic perspective, with studies surrounding differential developments in the overall productivity (Fare et al., 1994; Land, Lovell & Thore, 1994) or the productivity of factors of production between the East and the West (Broadberry & Klein, 2011; Vonyo & Klein, 2016).

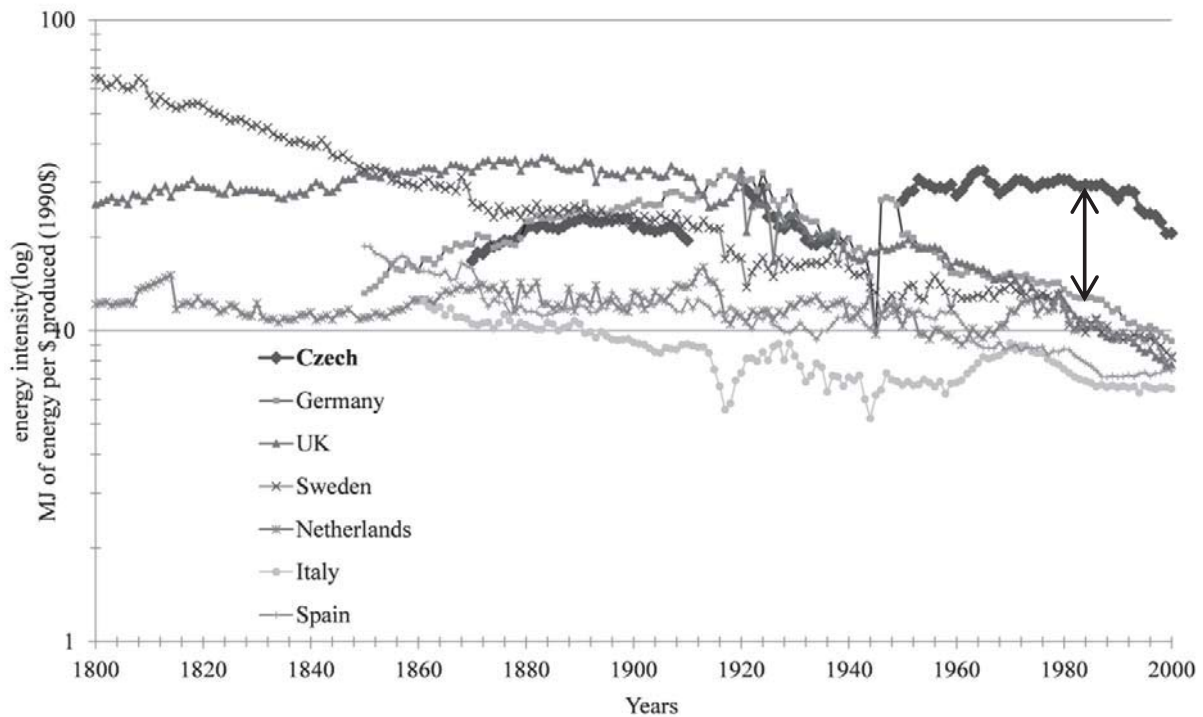


Figure 6 Energy intensity across Europe 1800–2000
 Source: own data and (Kander et al., 2013)

Contrary to popular belief, research shows that a system of central planning can indeed be growth enhancing, particularly for countries at an early stage of development (Allen, 2005) or for industries characterized by mass production (Broadberry & Klein, 2011). Establishing non-existent infrastructures obviously requires the large-scale production of iron and steel or cement, and it is here that underdeveloped countries can benefit the most from a system of central planning. The consensus, however, remains that a non-democratic system is inferior to economic development (Acemoglu & Robinson, 2006; Easterly, 2002), technology adoption and transfer (Acemoglu & Zilibotti, 2001; Bairoch & Levy-Leboyer, 1981; Hilding, 1992) or even our environment (Acemoglu, Aghion & Hemous, 2015; Lindmark, 2004).

Generally, it is assumed that the energy and material waste of the centrally planned economy thus originated from the productive inefficiencies. It is unlikely that energy and materials were wasted in a manner such as overconsumption of surplus energy or materials (e.g. by having production machines running overnight). ‘Inefficient use of inputs is not just excessive use’ (Land, Lovell & Thore, 1994), as many would assume. Surprisingly, both state socialism and capitalism draw on the same heritage of Western economic thinking, and socialist economists accept the postulate of the ‘economic man’ to minimize the producer costs. With respect to energy

(particularly electricity and fossil fuel use), the waste of central planning is identified in areas such as the following: energy embodied in final products that had to be scrapped due to their low quality (a scrap rate of up to 30 per cent of the total production) or later modified to meet certain quality standards (again up to 30 per cent of the total production); energy embodied in the components used for the production of these scrapped products; technologically obsolete production processes; and unoptimized production processes. Importantly, as Paper 2 shows, the inefficiencies in energy use were not systematic across the whole economy but only present in a handful of sectors. Moreover, some sectors, such as steel and pig iron, even managed to increase their energy efficiency under the planned economy to reach the efficiency frontier of the West by the 1980s, despite the technological lag in modern steel production (Paper 5).

Barriers to new technology adoption are also commonly discussed in relation to institutional settings (Comin & Hobijn, 2004; Oster, 1982). More productive firms may not have access to the respective markets or might be deterred from entering certain markets in the absence of clear property rights. Uncertainty also operates differently under various systems of economic planning. Since many major technological inventions introduce uncertainty concerning future gains and given the fact that these technology decisions are usually made with a long horizon in mind, any distortion in the future profits or tax revenues might deter actors from adopting new technology (Acemoglu, 2009). Take a new steel production technology for example. Clearly the introduction of this new technology might in theory seem attractive from an economic point of view, though the possibility of uncertainty, the large dependence of the economy on this one particular sector and the importance of future plan fulfilment might cause delays in the fundamental decision to adopt the new technology and scrap the existing ones.

However, the political factor can also be channelled through other areas, not only through economic performance. In Czechoslovakia, from an energy point of view, the impact of the system of central planning proved most palpable with respect to environmental protection and trade specialization. Overall, the environmental legislation in communist Czechoslovakia was lagging behind its Western counterparts, which indeed resulted in some of the most severe environmental damage in history. The first directives to limit pollution appeared in the 1980s and stemmed from the growing public discontent. The black triangle that formed around the border areas of Czechoslovakia, Poland and East Germany was one of the most polluted

areas in the world, an area that even now carries signs of environmental damage despite intense CO₂ emission cuts since 1991 (Locatelli, 1993; Ürge-Vorsatz, Miladinova & Paizs, 2006).

Foreign trade

Institutions are without a doubt a deep determinant of economic growth (Bloch & Tang, 2004). Institutions are often believed to be shaped by geography and in turn, based on geography, have an impact on the country's trade. This is because trade, from a historical perspective, is seen as a direct result of the country's resource endowments, technological differences and transport possibilities (Ogilvie, 2007). Resource endowments are found to explain fairly well the past trade pattern of many industrialized countries, as was the case for Britain in 1910–1935 or the USA in 1879–1940 (O'Rourke & Williamson, 1999). The gravity model is often applied when explaining the volume and composition of trade. According to the model, the trade regime between two countries is determined by the demand conditions in the destination country, the supply conditions in the country of origin (and here usually the resource endowments), the distance and other trade-enhancing or -restricting legislation (Nilsson, 1999).

The emergence of foreign trade can be dated back as far as the first civilizations, but the magnitude of openness, level of protectionism and structure of trade have varied considerably in the past millennium (Findlay & O'Rourke, 2007). The transport revolution of the Industrial Revolution led to a dramatic decline in transport costs throughout the nineteenth century, which in turn led to growth in global trade and, to some degree, price convergence (O'Rourke & Williamson, 1999). Taking trade into account when analysing modern economic growth is vital to gain a better understanding of the specific mechanisms (Acemoglu, 2009). This is because most countries do not operate in isolation and usually (exceptions do exist, though) interact with the rest of the world (Acemoglu, 2009).

Openness to trade is found to be beneficial for economic growth not only by allowing countries to specialize in their comparative advantage but also to stimulate technology transfer and scale economies (Bloch and Tang, 2004; De Jong, 2003). This is also why small countries, such as the Czech Republic, in theory are even more dependent on foreign trade as one of the drivers of economic growth (Kuznets, 1966). Without foreign trade, in small countries the domestic markets and resources are too limited to allow for increased specialization and scale as the size of the market is determined by

the country's population size (De Jong, 2003). In the Netherlands during the 1930s, for example, heavily protected small domestic market together with limited export opportunities, had a negative effect on the industrial labour productivity (De Jong, 2003). The empirical evidence shows that trade liberalization leads to increased productivity, though the level varies across industries (Alcalá & Ciccone, 2004; Caliendo & Rossi-Hansberg, 2012).

At the early stages of the British Industrial Revolution, cotton goods accounted for a little over 1 per cent of the British exports, but by the early 1800s the share had increased to well over 40 per cent of the total exports (Findlay & O'Rourke, 2007). The growing demand for textile goods in other parts of the world led to increased mechanization, factory production and a 'vertical' division of labour. Britain, over the course of the Industrial Revolution, developed into a country that primarily imported intermediate inputs while exporting manufactured goods. It is thus believed that the great success of the technological innovations of the Industrial Revolution would not have materialized to such an extent or would not have been sustained for this crucially prolonged period of time if it was not for trade openness (Findlay & O'Rourke, 2007).

The openness to trade allowed the moving and provision of the necessary factors of production (be they coal, labour, natural resources or capital) with the help of growing consumption and new technological innovations. With respect to the new technology adoption, trade openness is often linked to technology transfers, though the effect is shown to be inconsistent in past studies. Openness to trade does indeed enable technology transfer; however, the eventual success of the actual technology adoption in the receiving country is largely dependent on its domestic resources, available human capital and importantly institutional settings (Levcik & Skolka, 1984; Poznanski, 1984; Wan, Baylis & Mulder, 2015).

At the same time, there are numerous drawbacks related to increased openness to trade. The British comparative advantage in the highly mechanized production of cotton goods, for example, is discussed in connection with the demise of the traditional labour-intensive cotton production in India and its consequent deindustrialization as a result of the influx of cheap British goods (Findlay & O'Rourke, 2007). Another aspect related to openness to trade is the concept of unequal exchange and our exploitation of the less developed parts of the world, the North–South divide. This concept, introduced by the Marxists, originally built on the exploitation of cheap labour but has become a much-discussed theme in ecological

economics recently. In today's terminology one can also talk about outsourcing or displacement, a process whereby one country relocates parts of its production to countries with lower wages and/or environmental protection levels (Lindmark, 2004). It is this utilization of the production differentials among countries, a common consequence of increased trade openness, which some argue have had negative consequences for certain parts of the world and contributed to the formation of the North–South divide.

Data and methods

Data

This dissertation utilizes a wealth of data, ranging from primary (censuses, official statistics and government reports) to secondary sources. Most of the sources used for this dissertation consist of original data that have by now been made available online, some of which I also digitized, at venues such as the Österreichische Nationalbibliothek, Das Deutsche Digitale Zeitschriftenarchiv, Cornell University Library, Hathi Trust Book Collections and GoogleBooks. Pre-1918 data and statistical yearbooks are to a large extent written in German, while data after 1918 are predominantly available in the Czech language.

Clearly the immediate criticism would stem from the reliability of data published during the central-planning period due to misreporting or overestimation/underestimation. To avoid some of those issues, official Czechoslovak data are often compared with UN estimations and other non-governmental estimates. Although the use of manipulated data cannot be ruled out in this dissertation, great care and critique are taken when analysing and interpreting the official figures. As with any other statistical resources, there is a possibility of potential error, and an indication is given of possible data reliability issues. Table 3 summarizes the major resources used within this dissertation for each paper, including both primary and secondary sources.

Table 3 Major statistical data sources

Note. Relative data reliability (/+ low reliability, /++ good reliability, /+++ highly reliable)

Paper 1	Cvrcek, T. <i>Database of Steam Engines and Horsepower of Austria–Hungary</i> (unpublished source)/++ GIS files by Rumpler, H. & Seger, M. (n.d.) <i>Historical GIS Datafiles</i> . Censusmosaic/+++ IIASA & FAO (n.d.) <i>GAEZ Suitability and Potential Yield Database</i> /++
Paper 2	Kuskova, Gingrich & Krausmann (2008) <i>Energy Consumption Database</i> /++ Kander, Malanima & Warde (2013) <i>Power to the People Energy Database</i> /+++ Official energy statistics (Federalni Statisticky Urad, multiple editions; Statni Urad Statisticky, multiple editions; United Nations, multiple editions)/+
Paper 3 Paper 4	Industrial census (archival sources): 1841 (Schnabel, 1848)/+, 1934/1935 (Ceskoslovensky urad statisticky, 1936)/++ Official statistical yearbooks after 1950 (available online after 1990)/++ Industry-specific reports: iron and steel sector (Balling, 1849; Hain, 1853; Von Hingenau, 1865)/+, chemical sector (Rosner, 2004) /++, mining sector (Hwaletz, 2001)/++, sugar industry (Walkhoff, 1866)/+, beer industry, including malting (Noback, 1871)/+, cottons (Kertesz, 1915)/+ Foreign trade sources: 1841 stats (Schnabel, 1848)/+ and AH trade stats (Von Schwarzer, 1846)/+, 1841 & 1865 stats (Hain, 1853; Hwaletz, 2001; Vereine der Österreichischen Industriellen, 1866), 1870 stats (K.K. Statistischen Central Commission, 1872; Österreichische Statistik, 1884, 1874)/++, 1860–1916 stats (K.K. Statistischen Central Commission, 1881)/+, 1907 statistics (Österreichische Statistik, 1912), 1913 statistics (Cisar & Pokorny, 1922)/+, statistics from 1920 onwards (Statni Urad Statisticky, multiple editions, as well as Federalni Statisticky Urad, multiple editions)/+, post-1993 statistics (Cesky Statisticky Urad, multiple editions)/++
Paper 5	Steel statistical sources: UNIDO, multiple editions/++. <i>Industrial Statistics Yearbook</i> ; United Nations, multiple editions/+; Iron and steel scrap statistics; World Steel Association, multiple editions, <i>Steel Statistical Yearbook</i> /++ Energy statistical sources: IEA (2014) <i>Extended World Energy Balances 1960–2013</i> .
Paper 6	International Iron and Steel Institute, multiple editions. <i>A Handbook of World Steel Statistics</i> /++ Mitchell, B. R. (2008a) <i>International Historical Statistics: Europe, 1750–2005</i> /++ Mitchell, B. R. (2008b) <i>International Historical Statistics: Africa, Asia and Oceania, 1750–2005</i> /++ Center for Industry Studies (2003) <i>Steel Plant Database</i> . University of Pittsburgh/++ Steel plant data of Czechoslovakia: personal correspondence with the Czech Steel Association/+++

Changing borders throughout history

Historical border changes in any long-run studies clearly represent a great challenge. The Czech Republic in its current form has existed for little more than 20 years, and historically it has belonged to a larger entity. Figure 7 shows a timeline of the past 170 years and illustrates how the country in focus has changed its name, borders and blocks of influence. Unless otherwise specified in the individual papers, the geographical coverage refers to three major periods of the Czech past:

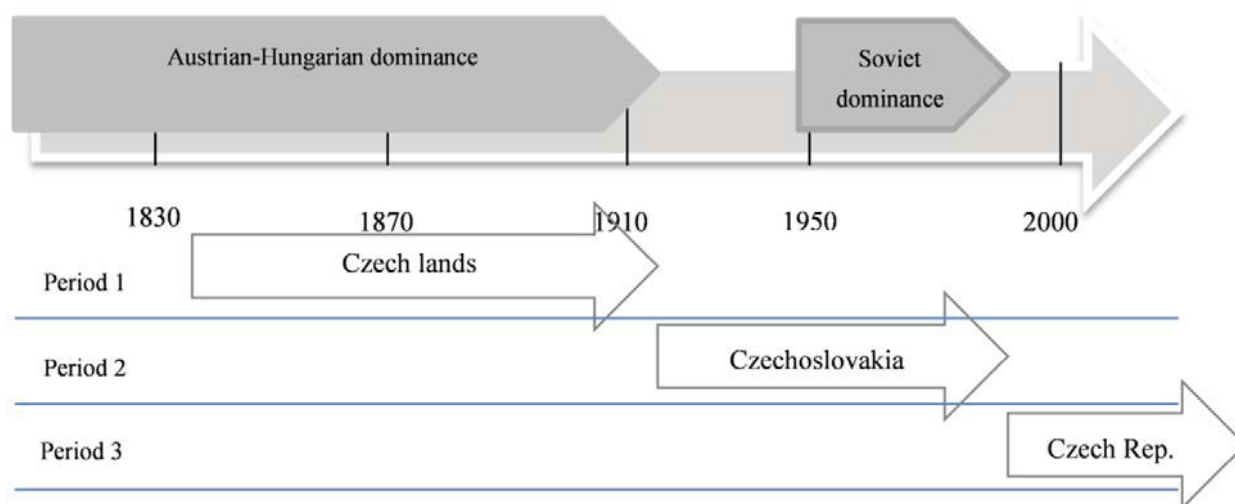


Figure 7 Changing borders, names and institutional settings

- 1) Pre-1918 (Period 1): the Czech lands, which are an area on a par with the current borders of the Czech Republic, consisting of three major regions: Bohemia, Moravia and Silesia. Historically, the Czech lands were part of a much larger entity, the Austro-Hungarian Empire, until the end of the First World War. Slovakia, which was part of the Kingdom of Hungary, is therefore not included in the pre-1918 data.
- 2) 1918–1993 (Period 2): Czechoslovakia, which largely resembles the present territory of the Czech and Slovak Republics. After the Second World War, Czechoslovakia lost a small part of its territory in the east – the Sub-Carpathian Rus, though the major changes were in the population totals. Although many European countries recorded a population decline as a consequence of the war, in the case of the Czech Republic, there were a further 3 million inhabitants of German origin who were forcibly displaced in 1945 and 1946, only to appear in the German population statistics. This needs to be taken into consideration when studying per capita changes of various measures, as this large population displacement may introduce short-term fluctuations into the data.
- 3) Post-1993 (Period 3): Czechoslovakia as an aggregate of the newly formed Czech and Slovak Republic. Although this time period is part of the analysis in some of the papers, there is less focus on the developments of energy consumption and intensity in this particular period. The major reason is the fact that the transition period, from a planned to a market economy, is quite extensively researched, given the ease and availability of data. Although some references will be

made to this specific period, the reader is also referred to other empirical studies with an energy focus that have already been published (Carlin, Schaffer & Seabright, 2013; Cornilie & Fankhauser 2004; Meyers, Salay & Schipper, 1994; Salay, 1999; Üрге-Vorsatz, Miladinova & Paizs, 2006).

Figure 8 places the individual papers of this dissertation against the timeline of 1830–2000, which is the major time scope. Paper 2 undoubtedly provides the longest time perspective, though the disruptions of border and population changes as well as two world wars need to be accounted for in the interpretation of possible short-term fluctuations.

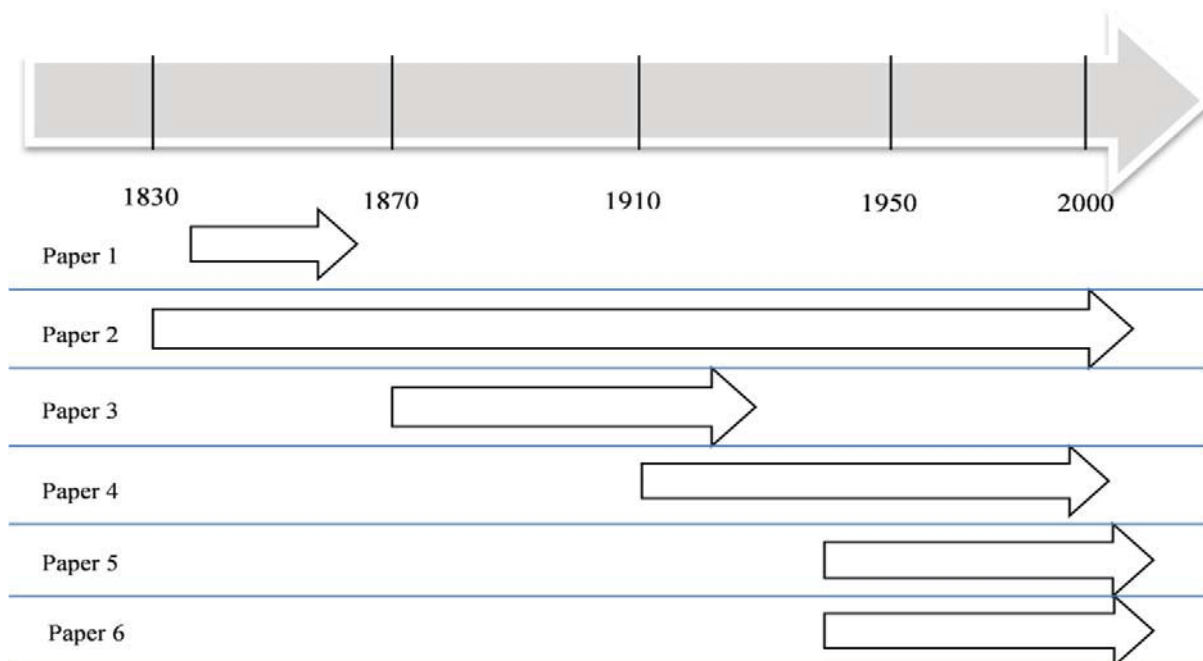


Figure 8 The timeline of the papers included in this dissertation

Methods

The major aim of this section is to explain the major methods that were employed within this dissertation. Overall, all the papers are largely based on a combination of various quantitative methods. The use of quantitative methods for each paper was chosen carefully to suit the actual research question and theoretical considerations of the paper. In general the dissertation utilizes to a large extent long-run time series data, which enable

the observation of the process of change and long-run development. The dissertation starts with econometric tools and moves progressively to other economic analytical tools, such as efficiency analysis and decomposition techniques.

Count data models and spatial regression

The analysis in Paper 1 is largely based on a combination of econometric tools. The major part of the results is derived using the Poisson regression model. For the robustness checks, two alternative econometric models are also adopted, though some of them are presented only in the Appendix section of the paper. First, to analyse the importance of proximity to coal and the adoption of steam, multivariate OLS regression is used. Second, due to the nature of the data and the possibility of some spatial mechanisms influencing the overall analysis, spatial regression models are also used as an alternative to the main Poisson regression. This is one of the possible drawbacks when using spatial data, because there is a risk that there might be some clustering/spillover effects in the data or another mechanism that is geographically determined, and traditional OLS or Poisson regression could suffer from omitted variable bias.

The major purpose of the Poisson model is to account for the likelihood of a potential steam engine owner locating this technology in a place that can be characterized by a number of geographical variables. It is then assumed that the expected number of steam engines (or the actual number of horsepower) I in county j , $E(n_j)$ is independently Poisson distributed with a region-specific mean as:

$$E(n_j) = e^{x_j\beta}$$

The estimation of the vector of coefficients β , as shown in the equation above, is performed using the maximum likelihood model and interpreted as the elasticity of the expected number of installed steam engines in county j as a result of the change in the locational characteristic of county j . As much of the economic geography literature concentrates on the magnitude of the impact of ‘first’ (natural) predispositions and ‘second’ nature (acquired) conditions, the locational characteristics of different natures and from different data sources were combined. Furthermore, the paper explored the interactions of both natural and acquired conditions, and the predicted number of steam engines/installed horsepower was explored. The Poisson distribution is good for models that are best suited to applications in which the data adopt non-negative integer values (Reilly, 1996).

Obviously, in analysing such a complex and multidimensional phenomenon as the adoption of coal-using technology, there is a risk of not capturing so many multiple relationships in one model. Nevertheless, great care was taken when trying to capture as many locational variables as possible from a variety of data sources. Furthermore, alternative approaches, such as OLS and spatial models, were used to correct for possible unobserved mechanisms. All the models in the paper led to the same conclusions and implications.

Frontier analysis and data envelopment analysis

Measuring efficiency was initially conducted in managerial science to assess the efficiency of multiple decision-making units (DMUs), such as stores; however, it has since become widespread, especially in industrial efficiency studies as well as energy studies. There are various methods of assessing efficiency and frontier analyses: stochastic frontier analysis (SFA) and data envelopment analysis (DEA) are some of the most common. Although the two methods are very similar in their nature and aim primarily to identify the technological frontier, there are also some significant differences that need to be taken into consideration.

Contrary to SFA, DEA is a non-parametric approach that is less restricted, and there is no danger that a wrong functional form will be imposed on our data (Daraio & Simar, 2007). DEA makes its own assumptions about the production technology, thus requiring less information on the production structure, for example. The data necessary for DEA are then only input and output measures.

The fundamental assumption behind the DEA approach is that, if one country is able to produce volume y with input x , then the other countries should be able to achieve the same if they are to operate efficiently. The efficiency of a country is measured as the relative distance to the frontier. Importantly, DEA allows for models with variable returns to scale (VRS), which are particularly relevant to the case of the iron and steel sector (Mitra Debnath & Sebastian, 2014). In models with variable returns to scale, the change in the output is not proportional to the change in the input, as is the case of constant returns to scale (CRS). Here, clearly the scale of an industry of one country (but also the relative scale of the individual plants) may have an impact on the efficiency of a sector (for example through economies of scale). In the CRS model, 1 unit of coke in the production process would result in 1 additional unit of pig iron produced, taking no notice of the actual size of the sector or plant in the respective country. On the other hand, the CRS model has some

disadvantages, particularly for DMUs located at the ends of the spectrum (the smallest- and largest-scale observations). This needs to be taken into consideration when interpreting the results, and it is sometimes recommendable to compare the two DEA measures using constant as well as variable returns to scale (as shown in Paper 5).

Decomposition techniques

Decomposition methods form part of the methodology captured in Paper 2. The first decomposition used in Paper 2 is the Commoner–Ehrlich identity, which is a frequently used identity for decomposing the environmental impact into its main components:

$$I = P \times A \times T \quad (1)$$

where I refers to the environmental impact of a group or nation, P is the population size, A is the per capita affluence (measured by proxies such as income per capita) and T is a residual and an indicator of the relative environmental impact. Translated into an energy context, the Commoner–Ehrlich formula becomes the following identity, where E stands for the total energy consumption and Y for the GDP (A in (1)), while the T -factor is the energy intensity (E/Y):

$$E = P * \frac{Y}{P} * \frac{E}{Y} \quad (2)$$

Written as annual growth rates instead, this is the same as:

$$e = p + y + e_y \quad (3)$$

where e , p , y and e_y are the annual rates of increase in the total energy consumption, population, per capita GDP and energy intensity. In our identity (3), whenever $p+y$ exceeds e_y , the consequence is an increase in the total energy consumption e .

For the second part of the decomposition analysis, Paper 2 also utilizes a widely accepted decomposition method pioneered by Ang (Ang, 2005; Ang and Zhang, 2000). Here, the interpretation is similar to that of the Commoner–Ehrlich identity, though the decomposition focuses only on the decomposition of the energy/electricity intensity, which is a relative measure, as opposed to the total energy consumption, which is an absolute measure of environmental impact. Consequently, decomposing a relative measure

disregards the absolute scales of the changes. On the other hand, as Paper 2 shows, it enables researchers to distinguish between structural and technological change and is thus better suited to disaggregated data.

In energy studies decomposition approaches have become one of the most common methods for identifying the drivers of changing energy intensity or energy consumption, the results of which have also often been used for policy recommendations (and have become mainstream for institutions such as the IEA or UNIDO) (Ang, 2005). Their flexibility of use and the ease of various adapted decomposition formulas make the method particularly suitable for largely disaggregated data sets as well as cross-country comparisons. Decomposition methods are also very useful for addressing the theories of the environmental Kuznets curve or determining why some countries have increasing energy intensities while others have reached their peak and the energy intensity has been declining for decades. It is also decomposition techniques that show that the reason why developed countries have been on a path of declining energy intensity is largely attributable to the technological processes rather than structural change from industry dominance to a service-based economy (Henriques & Kander, 2010).

Process analysis

Papers 3 and 4 are the most data-intensive papers, largely as a result of the methodology used for the analysis. Contrary to most recent studies on the impact of foreign trade and the phenomenon of environmental dumping, which commonly deploy EIO methods (the environmental input–output approach) at various levels of aggregation, the approach within the papers is based on process analysis, sometimes referred to as the material balance approach (Bullard, Penner & Pilati, 1978; Wiedmann, 2009). The major advantage of this approach is that it enables us to calculate the energy embodied in foreign trade in a time period of virtually non-existent input–output tables (Bullard, Penner & Pilati, 1978; Sato, 2014).

The use of input–output tables (and the later versions that also included the flows of energy and emissions) has become the dominant method for assessing the environmental footprint of a country from a consumption perspective. Thus, contrary to production-based accounting, the environmental impact of a country is based entirely on the actual consumption of final goods by the country's population and not only on the overall production of the economy. This is not only an often-debated topic in ecological economics but has even become a heated topic in global climate

negotiations. Although nationwide I-O tables were a cornerstone of the central-planning system, with its detailed resource allocation consequences, the use of I-O tables prior to the 1950s was virtually non-existent. Even so, the environmentally extended I-O date back to the 1990s, which is indeed a rather recent period for an economic historian. Therefore, to overcome the issue of data availability, a bottom-up approach is used in both Paper 3 and Paper 4. The reason why this approach is referred to as the bottom-up approach is the fact that it follows all manufactured products and their movement throughout the economy from the very bottom. Based on this approach, trade flows expressed in physical volumes are multiplied by a respective product energy intensity factor. By adopting this method, each traded product is assigned a specific energy requirement to account for both direct and indirect energy as each step in the production is considered, though it is not always additive.

Obviously, given the scope of foreign trade and particularly the growing complexities of traded goods, this is a very data-demanding process, not only in collecting the trade data at a largely disaggregated level and measured in physical outputs but mainly in calculating the actual energy needs to produce those products – an indicator that obviously changes constantly and sometimes at levels with substantial cross-country differences.

Putting aside the high data requirements for the process analysis, there are some other major shortcomings that needed to be taken into consideration when interpreting the final results. First, as a result of the growing complexities of the Czechoslovak foreign trade, a category termed ‘others’ has to be included. At the beginning of the period of study, the category of ‘others’ was far less significant and accounted for around 10 per cent of the total of physical quantities traded. After the Second World War, however, the share of this group increased due to the growing complexity of the product composition of the global trade. Second, the major assumption that is implemented in this study is the assumption of the same energy intensity factors for both exports and imports. Only Czech energy intensity data are thus used. For the purposes of accuracy, a sensitivity analysis is run for the year 1925, in which for all imports the intensity factors are calculated based on the British census of production and thus using the British energy intensity coefficients. The results of this analysis show the energy embodied in imports to Czechoslovakia (under the assumption that all of them were produced in England) to be lower by 1.8 per cent.

Logistic fit

Paper 6 studies technological growth and substitution in one particular manufacturing sector. For this purpose the S-shaped logistic curve of technology diffusion is adopted as the main method of analysis. It is important to keep in mind that the logistic curve within this study serves rather illustrative purposes regarding the pattern of technology change in the steel industry and does not provide explanations for why it evolved differently in various parts of the world. On the other hand, applying the logistic curve to the available time series data is advantageous, particularly in the case of incomplete series, which is the case of the data from the steel sector (particularly the unit size data are scarce).

In technology adoption studies, the logistic fit curve is widely used not only to analyse the adoption of new technology but also to understand the cross-country dispersion. For a country the logistic fit curve is believed to capture the slow and lengthy process of the early stages, as the new technology penetrates the established structures. Once the new technology has been adopted by some of the front-runners and it has been fine-tuned and cleared of its start-up faults, this is followed by relatively rapid growth of nationwide adoption. The speed of this sudden increase in the market share is then largely determined by the slope of the logistic curve. Last, once a technology reaches a certain level of maturity, the search for a new substitute has already started, but the existing technology remains the dominant one in the market until the new upcoming technology has passed through its initial lengthy period of trial and error. At that point the market shares between the existing and the new technology begin to shift again.

The logistic fit curve approach is then applied to both measures of technology diffusion in terms of the overall market size but also at the level of individual units. The equation of the logistic curve is as follows (Grübler, 1998):

$$y = \frac{K}{1 + e^{-b(t-t_0)}}$$

where K denotes asymptote (saturation in tons of steel), t_0 denotes the infection point at $K/2$ (maximum growth), b is the diffusion rate (steepness of the curve) and Δt refers to the diffusion time (the number of years over which y grows from 10 per cent to 90 per cent of K); the diffusion rate can be rewritten as:

$$\Delta t = \frac{1}{b} \text{Log}81 = \frac{1}{b} 4.39444915 \dots$$

Both the diffusion time (Δt) and the saturation level (K) are important parameters, as these denote the speed of diffusion and the extent of diffusion, respectively, allowing cross-country comparisons (Wilson, 2009). Often, in various studies of new technology adoption, those parameters are compared with each other, particularly in cross-country studies. For the purposes of Paper 6, the logistic fit curve is used for two major reasons. First, it enables the study of the diffusion of various steel-producing technologies in the context of a centrally planned economy and the determination of why certain technology adoption was delayed. As in the original study by Griliches (1957), the visualization of the adoption patterns of various technologies support the argument about the profitability of various technologies in a planned economy. Second, using the logistic fit curve for the individual unit size (here the actual size of installed furnaces) allows the observation not only of the cross-country pattern in scaling up (which is indeed crucial for technology adoption and wide-ranging diffusion) but also of the actual average size of the installed units as well as the capacities of the new additions.

Even though the logistic fit curve has become a mainstream economic tool in technology planning and forecasting, the method is also characterized by several drawbacks. Importantly, past studies of technology diffusion find that many technologies do not necessarily fit the logistic curve, especially when the intensive margin is taken into consideration (Comin, Hobijin & Rovito, 2006). In addition, the dispersion of a technology across various countries differs far more than the dispersion of the countries' wealth. There are many other aspects related to why the sole use of the logistic fit curve may be problematic, especially when the approach is used for forecasting purposes. It is therefore important to highlight that only historical data are used for Paper 6 and that the logistic fit curve serves greatly as a visualization tool. Furthermore, the goodness of fit of each model is always calculated and reported in each table.

Results

Contribution

Understanding the mechanisms and consequences of energy transition in different countries represents a potential source to learn from in ‘the much needed energy transition towards sustainability’ (Grübler, 2012; Kander, Malanima & Warde, 2013). In the wake of global warming, not only do developing countries need to make their own energy transitions towards more sustainable paths; they also have to make the most economic use out of their energy consumption. That means having low levels of energy intensity (energy/GDP) or high levels of energy efficiency (GDP/energy).

There are several contributions of this dissertation that can be categorized either in terms of new data or in terms of theory development. Overall, this dissertation provides newly collected long-run historical data on various aspects of energy use and the use of empirical methods. Among others, these include estimates of animal power and firewood since 1830, sectoral energy consumption data since 1863 and the energy intensities of well over 20 products since 1841 (with annual data from 1955) until 1995. Bearing that in mind, there are three major theoretical contributions that need to be highlighted here.

First, the geographical scope is unique and provides a long-term analysis of energy transition in a country that has not been researched before. At the same time, the comparative nature of all the papers enables the reader to place the results in the context of other existing literature. The natural experiment of the imposed system of central planning and its impact on energy use provides a unique research setting, and there are some interpretations that can be relevant for the policy makers of today. Contrary to the general belief, the system of central planning is not found to be systematically detrimental to the energy efficiency of Czechoslovakia, though a handful of sectors exhibit comparatively worse efficiency levels.

The second major contribution is the energy perspective given in all the papers and energy’s role in stimulating economic development, specialization and trade regime. Not only can energy be considered as an important factor of production but its geographical availability can also shape the location of industrial activities as well as the nature of the country’s foreign trade. In the Czech lands, the availability of domestic fossil fuels led to a structural change

towards energy-intensive industrialization, a legacy that is palpable in the economic structures until nowadays. The high dependence on domestic coal supplies of the major industrial branches led to the creation of industrial clusters and specialization in energy-intensive production and exports thereof.

Last contribution is the fact that this dissertation offers a long-run perspective stretching over a period of nearly 180 years. The papers within the dissertation illustrate how studies of extended time periods aid in understanding some of the recent economic developments and events. Indeed, most world events are a result of long-lasting trends and processes and cannot be understood fully when analysed in isolated time periods. It is the major aim of the dissertation to bring the Czech case within a wider global historical context.

Abstracts of the included papers

Figure 9 places each individual paper within the theories discussed in the section. Overall Papers 1 and 2 have a wider conceptual framework, while the remaining papers contribute to a more narrowly defined field with a specific focus on two issues – foreign trade, and the productive efficiency of the iron and steel sector. Altogether three aspects – institutions, technology and energy – are encompassed in each paper. It is also these three concepts that provide a narrative for all the papers, and their impact on various outcome variables is tested within the papers.

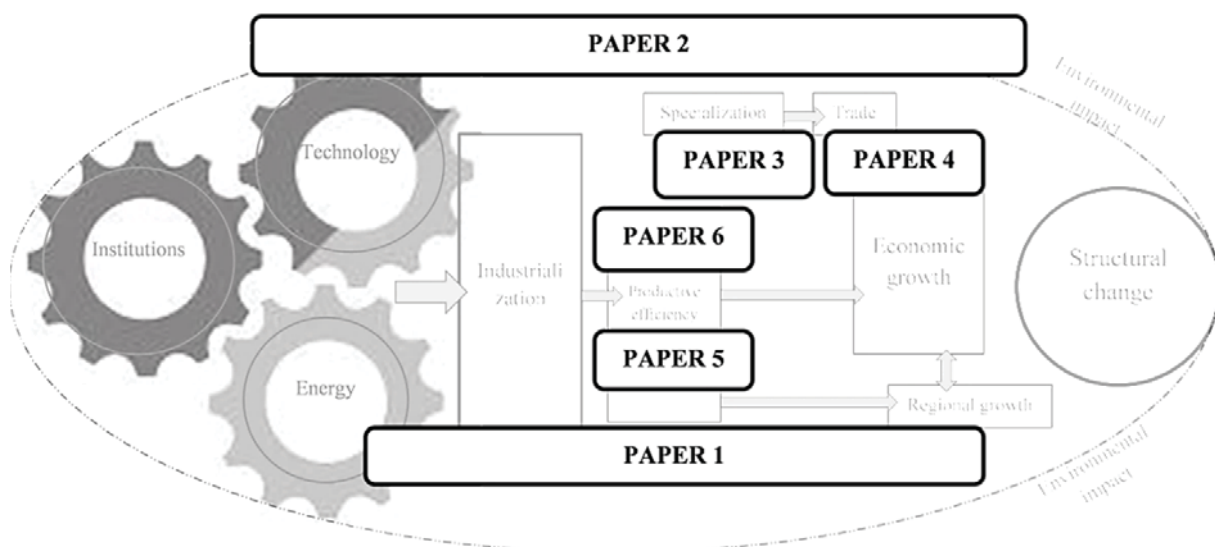


Figure 9 An overview of the major theoretical concepts discussed with individual papers positioned

Paper 1 discusses the interplay between the availability of domestic energy resources for the industrialization process, economic development and regional divergence in economic growth and industrial clustering.

Paper 2 provides the longest time scope of all the papers and therefore covers the complete transition from pre-industrial society to a modern economy from an energy perspective. Clearly, some aspects have become far more important in understanding the developments, such as energy intensity (which is the inverse of productivity) and the environmental Kuznets curve, and the individual drivers of the changing patterns of energy intensity curves, most importantly the structural and technological change.

Papers 3 and 4 focus to a large extent on the role of foreign trade and its impact on the energy intensity curve. While Paper 3 is a comparative paper including a total of 7 European countries between 1870 and 1935, Paper 4 focuses entirely on Czechoslovakia after 1920. Besides the role of trade in the energy intensity curve, specialization is discussed, as both papers find some evidence on the persistence in the pattern of trade.

Last two papers, Papers 5 and 6, discuss one particular productive sector – the iron and steel sector – within the paradigm of new technology adoption, productive efficiency and institutional settings. As the papers show in the case of Czechoslovakia, the iron and steel sector is an example of an industrial sector that became fundamental to the Czech energy transition. And despite an obvious technological lag in terms of new technology adoption, Czechoslovakia benefited immensely from economies of scale and learning by doing which in turn brought forward substantial improvements in the energy efficiency of the sector.

Paper I Coal and sugar: The black and white gold of the Czech industrial revolution (1841–1863)

The paper assesses the importance of coal for the industrial development in the Czech lands. The technological advancements in the use of steam were related not only in substance to coal but also geographically to proximity to a coal mine. As this paper tests, the importance of a relatively short distance to a coal mine remained highly significant for the location of new industries throughout the period of study. The availability of domestic coal and the rise of energy-intensive industries consequently led to one of the fastest fossil fuel transitions in the European history and brought about the economic development of the Czech lands. It was, indeed between 1841 and 1863, that

coal and sugar became increasingly intertwined and laid foundations for the key development block of the Czech Industrial Revolution. It was those two commodities – coal and sugar – that led to the absolute dominance of the Czech lands relative to other parts of the monarchy by the turn of the century.

R&R at the Journal of Economic History

Paper II East versus West: Energy transition and energy intensity in coal-rich Europe 1830–2000

Abstract Low energy intensity is important to meet future emission targets and make the most economic use of our energy resources. We present a stylized graph of the energy intensities in four typical European sets of countries: North, South, East and West, 1800-2000. The coal-rich West and East differ from the coal-poor South and North, in that their pattern is an inverted U-curve, while both North and South have consistently declining energy intensities, i. e. improving their economic use of energy over time. Energy intensity peaks about 50 years earlier in the West than in the East, and is in both cases driven by specialization in heavy industrial goods. An additional reason for the inefficient energy use in the East (exemplified by Czechoslovakia and East Germany) is the planned economy. For the first time we have been able to demonstrate that the gap between the West and East actually started in the 1950s, and to single out the main driver behind the East European inefficiency. It is not general systematic wastefulness of energy or lack of innovativeness, but surprisingly for a planned economy, it is the inefficiency in the expanding electricity system that accounts for most of the effect. The negative impact of the planned economy on energy intensity was largest between 1950 and 1970.

Under review at Journal of Comparative Economics

Paper III International trade and energy intensity in Europe, 1870–1935

Abstract Previous research suggests there is an inverted U-shape curve for energy intensity in the long-run for Western Europe with a peak in the early 20th century. This paper tests the hypothesis that the increase of German and British energy intensity was an effect from the concentration of heavy industrial production to these countries, although the consumption of a significant share of these goods took place elsewhere. We use an entirely new

database that we have constructed (TEG: Trade, Energy, Growth) to test whether these countries exported more energy-demanding goods than they imported, thus providing other countries with means to industrialize and to consume cheap-energy demanding goods. The pronounced inverted U-curve in German energy intensity without trade adjustments entirely disappears when we account for energy embodied in the traded commodities. For Britain the shape of the curve is also flattened during the second half of the 19th century, before falling from WWI onwards. These consumption-based accounts are strongly influenced by the trade in metal goods and fuels, facilitating industrialization elsewhere.

R&R at Ecological Economics

Paper IV The rise in energy consumption in Czechoslovakia and the role of foreign trade from a long-run perspective (1920–1998): The ‘machine shop’ hypothesis

This paper examines the role of foreign trade in the consumption of energy in Czechoslovakia through a bottom-up approach accounting for energy embodied in manufactured goods. It provides a unique analysis of the annual changes in energy embodied in trade in a country characterized by changing political regimes. On the whole Czechoslovakia was a net exporter of energy throughout the twentieth century, with an average 12% share of net energy embodied in exports. The role of central planning is found to have a significant effect on the absolute levels of energy embodied in trade, which reached their peak in 1972, when Czechoslovakia had net exports of embodied energy of 19 GJ/capita, very much on a par with Sweden in 1970 or China in 2013. The increased product specialization with a shift towards heavy industrial goods also had a clear impact on the composition of the energy embodied in exports. This effect is not found in the energy embodied in imports. Despite this development, the energy intensity curve of Czechoslovakia does not change substantially when adjusted for foreign trade.

R&R at Ecological Economics

Paper V Productive efficiency in the iron and steel sector under state planning: The case of China and former Czechoslovakia from a comparative perspective

State ownership is often discussed as one of the major causes of poor industrial energy efficiency performance. This paper utilizes long-run historical data on the energy and material use in one specific industrial sector – iron and steel production – in countries with both a central-planning and a market-based system, with a particular focus on the former Czechoslovakia paralleled with the developments in China. The productive efficiency of the Czechoslovak iron and steel sector fluctuated below the energy efficiency frontier. Until the early 1970s, the country's iron sector was one of the least efficient ones in our sample. It was, however, during the decades of the 1970s and 1980s that efficiency measures were adopted and the energy efficiency of the Czechoslovak iron and steel sector increased significantly, despite a priori expectations, to reach the energy efficiency frontier. The empirical results for other planned economies show similar development, catching up with the market economies, particularly in the iron production sector during the 1980s. A pattern of efficiency convergence is identified. In China, despite its move toward a more market-oriented economy, the productive efficiency lagged behind as recently as 2000 (20–35 per cent below the efficiency frontier). The relatively late adoption of energy conservation programmes and the persistent government control of the sector in certain provinces slowed down the efficiency improvements. In the socialist economies of Eastern Europe, though, central planners were able to achieve satisfactory productivity increases, primarily driven by efficiency and saving policies and adjustments to the existing technology. It is likely that, as was the case of Eastern Europe, the adoption of vigorous energy policies with clearly defined targets accompanied by monitoring and supervision will have a tremendous impact on the energy intensity as well as the absolute energy use of the sector in China.

Published in Applied Energy (2017) and in a different form in Energy Procedia (2015), both peer reviewed

Paper VI Technology and scale changes: The steel industry of Czechoslovakia in a comparative perspective

This paper provides an in-depth analysis of the developments in the steel sector in Czechoslovakia compared to other major steel producing market-based countries. The primary method of analysis employed is the logistic-fit curve of technology diffusion, complemented with panel regression models. There are two major conclusions to be made: first, Czechoslovakia suffered from technological backwardness in the adoption of new steel technology. To

some degree, this was due to the detrimental nature of the system of central-planning on new technology adoption but also due to some specific characteristics of Eastern European markets, such as availability of scrap and individual plants vintage. Moreover, the focus on bigness which is often associated with the era of Soviet growth was evident not only at the industry level of the Czechoslovak steel sector, but also at the actual average size of the furnaces installed. Second, despite this technological backwardness, the large-scale units and the magnitude of steel production in Czechoslovakia can be linked to the improvements in relative energy efficiency - through economies of scale and learning by doing.

R&R at Economic History of Developing Regions

Discussion and conclusion

So what are the major conclusions to be made based on the papers included in this dissertation and in response to the three major research questions posed at the beginning of this chapter?

The Czech transition towards modern energy carriers, such as coal, was rapid and mimicked the pattern recorded in neighbouring Germany. Compared with other Western countries, the Czech transition to coal was one of the fastest, and coal increased its share of the domestic energy consumption from 5 per cent to 50 per cent within a period of around 30 years. The fast transition to coal itself is not as surprising, and, according to Smil (2014b), it is primarily small economies with resource endowments that are able to undergo relatively fast energy transitions, as is the case of latecomers and / or countries which can leapfrog. Nevertheless, it seems logical to look for the origins of this rather fast transition to coal in a search for the coal-using pioneers in an initially backward and organic-based economy. Here, as the first paper concludes, the proximity to coal was important for the location of some of the earliest Czech industries, particularly until the mid-nineteenth century, when access to railways was still limited. The initial stimulus for the transition to a mineral-based energy economy came with the introduction of steam engines in production around 1820, which really took off during the 1840s (Karnikova, 1958). The growing number of installed steam engines to produce mechanical power called for a substantial rise in the coal production, and, within only a couple of decades, the Czech lands' energy system was dominated by coal. It was during these two decades, between 1841 and 1863,

that new industrial structures, largely coal-based, emerged, which determined the future economic development of the Czech lands. After the 1860s, with the expansion of the railway network, other locational determinants became more important, particularly ‘acquired’ conditions such as market potential; however, the proximity to coal remained significant throughout the first Industrial Revolution.

The overall consequences of the expansion of steam technology and the development of the food-processing sector were more far-reaching than one would anticipate but also in line with the institutional changes in the region. Especially the significance of the sugar industry cannot be overlooked. First, this newly established sector accounted for well over 60 per cent of the industrial value added in 1885 (Rudolph, 1976). At the same time, the sector became the largest consumer of coal (almost 30 per cent of all black coal mined in the 1880s), was the first sector to promote the Czech middle class (as opposed to most industrial branches, which were dominated by Germans) and had long-lasting implications for the upcoming engineering branch as well as the beer industry. The engineering sector, which later became the core of the Czechoslovak industrial landscape (here the commonly used term ‘the machine shop’ of the East) was crucial in creating a stimulus for the shift of iron and steel production from Upper Austria to the Czech lands. Indeed, until 1870 the location of Austrian–Hungarian steel production was concentrated in Upper Austria (the source of iron ore), but the demand stimulus coming from the expanding Czech engineering sector shifted the production centre to the Czech lands after 1870.

The rapid industrialization, although somewhat delayed as some would argue, together with the fast transition to coal, resulted in increased consumption of modern energy carriers and led to a rise in the country’s energy intensity. As in Germany, the energy intensity curve kept rising well until 1913, when the events of the First World War and the following economic contraction put the energy intensity curve into a pattern of decline. This development, as experienced in Germany and the Czech Republic, would, if analysed in this time period, give an impression of an environmental Kuznets curve (an inverted U-shape), a pattern also characteristic of other coal-rich industrializing countries. Clearly this would be a great result, as it would confirm that there is a possibility for countries to reduce their environmental impact without limiting their economic growth. However, taking foreign trade into account shows a different pattern in energy intensity between 1870 and 1913. The revised view of the EKC suggests that considering foreign

trade gives rather flat or declining energy intensity, as was the case during industrialization for both the Czech lands and Germany. This provides evidence of the environmental burden that some European coal-rich countries experienced during industrialization to the benefit of later industrializers and less coal-rich countries. Britain, Germany and the Czech lands gave others the means to industrialize and develop and suffered from environmental degradation as a consequence. By 1913 around 70 per cent of the total Czechoslovak production was destined for exports, mainly within the borders of Austria–Hungary. Furthermore, as Paper 4 shows, this environmental degradation (part of it owing to the specialization in energy-intensive production and exports) stretched well into the 1980s.

Extending the analysis to the post-Second World War period shows a very different and diverging trend in the two countries. While in West Germany the energy intensity curve continued its downward slope, the energy intensity in Czechoslovakia and East Germany soared to reach its historical maximum by 1980. However, the result of an investigation into the actual causes of such high energy intensity increase is less obvious than anticipated. First, having been termed the ‘machine shop’ of the East, the actual magnitude of energy embodied in goods destined for exports was one of the most probable causes.

As the country was destined to become the ‘machine shop’ of the Eastern bloc, and with its lax environmental legislation, Czechoslovakia has been what ecological economists nowadays would coin as ‘pollution heaven’ (Antweiler, 1996; Copeland & Taylor, 2004; Grether & Mathys, 2013). Despite these expectations, the quantitative assessment presented in Papers 3 and 4 shows that Czechoslovakia was always historically a significant exporter of embodied energy as far back as 1870. Interestingly, it was during the period of economic growth in the 1920s that it recorded the largest relative shares of net embodied energy, topping 21 per cent of the total domestic energy consumption in 1928 (Paper 4). Earlier estimates place the share as high as 30 per cent of the domestic energy consumption in 1913 (Paper 3). To put this within the perspective of the most recent developments, in China it is estimated that around 30 per cent of domestically consumed energy is in goods destined for exports.

The impact of the economic system of central planning after the Second World War was clearly visible in the composition of the energy embodied in exports. Indeed, it was here that the two sectors (steel and machinery) accounted for over 48 per cent of the total energy embodied in exports in the

1970s. Czechoslovakia was a clear net energy exporter (and indeed still is well into the twenty-first century), with a share of net embodied energy at around 11 per cent of the domestic energy consumption.

Still, the bulk of the Czechoslovak energy was consumed within its borders, and the onset of the central-planning system was the major driver behind this high level of energy consumption. This increase was caused by a combination of three very specific factors: clear structural change towards heavy industry (pig iron, steel and chemicals), the growing electricity intensity of a few expanding heavy industries and an inefficient and energy-intensive electricity production sector. Historically, the introduction of electrical processes ‘provided the fundamental technological basis for producing particular metals and chemicals’ or even fully took over in the production of already-established processes, such as steel and glassmaking (Schurr, 1990). However, despite electricity’s wide-ranging impact on new processes and productivity growth, in Eastern Europe inefficiencies in the electricity transformation sector had some far-reaching consequences, particularly as coal-fired electricity production became the dominant energy source (Carlin, Schaffer & Seabright, 2013). In Czechoslovakia, for example, as Paper 2 shows, the growing electricity intensity of heavy industries and an inefficient and energy-intensive electricity production sector (high transformation and distribution losses compared with the West) led to overall Czechoslovak energy intensity levels that were incomparable to any other developed country. Initially this may not seem to be particularly surprising for a country in which the industrial structures were based on heavy industries; however, in combination with lacking environmental protection under the system of central planning, this high energy intensity and inefficiency of the electricity transformation sector quickly turned into a poisonous combination. The role of the political factor was most strongly palpable in the structural change of the economy and less so in the inefficient resource use and waste.

Although this may contradict one’s expectations about the inefficiencies of the central-planning system, one has to remember that keeping costs down was equally on the agenda of the planners as in the case of the West. This is also confirmed by the studies of the Czechoslovak steel industry itself, which showed some impressive improvements in energy intensity between 1973 and 1989. Interestingly, while operating with outdated technology, central planners were able to achieve satisfactory productivity increases, primarily driven by efficiency and saving, adjustments to the existing technology and

large-scale plants. Indeed, the focus on ‘bigness’ that is often referred to in relation to the Soviet industries (and often paralleled with the US) was also visible in the iron and steel sector, in which Czechoslovakia not only boasted one of the largest and most concentrated steel production but also possessed on average far larger steel plants and furnaces than those installed in the West. Clearly, scale was an important efficiency driver in such a bulk industry as iron and steel.

To conclude, this explorative study on energy transition processes in an Eastern European country identifies some similarities to other researched coal-rich countries in the West. The availability of domestic coal not only was important for the location of industries but also led to the formation of new industries as well as complementary industries, which brought about the first industrialization in the region and had some far-reaching consequences for the country’s development. The similarities to the West were striking, especially until the Second World War, after which a rapid structural change (this time ordered from above through administrative decisions) forced Czechoslovakia off its energy transition path. The temporary increase in the country’s energy intensity during the central-planning period, was, however, far less of a systematic failure than a very country-specific industrial structure and electricity transformation sector deviation.

References

- Acemoglu, D., 2009. *Introduction to modern economic growth*. Princeton University Press.
- Acemoglu, D., Aghion, P., Hemous, D., 2015. The Environment and Directed Technical Change in a North-South Model. *Oxford Rev. Econ. Policy* 30, 513–530.
- Acemoglu, D., Johnson, S., Robinson, J.A., 2004. *Institutions as the Fundamental Cause of Long-Run Growth* (No. 10481), NBER Working Paper.
- Acemoglu, D., Robinson, J.A., 2006. *Economic Origins of Dictatorship and Democracy*. Cambridge University Press.
- Acemoglu, D., Zilibotti, F., 2001. Productivity Differences. *Q. J. Econ.* 116, 563–606.
- Alcalá, F., Ciccone, A., 2004. Trade and Productivity. *Q. J. Econ.* 119, 613–646.
- Allen, R.C., 2014. American Exceptionalism as a Problem in Global History. *J. Econ. Hist.* 74, 309–350.

- Allen, R.C., 2012. Technology and the great divergence: Global economic development since 1820. *Explor. Econ. Hist.* 49, 1–16.
- Allen, R.C., 2009. *The British Industrial Revolution in Global Perspective*. Cambridge University Press.
- Allen, R.C., 2006. *The British Industrial Revolution in Global Perspective: How Commerce Created the Industrial Revolution and Modern Economic Growth*. Oxford.
- Allen, R.C., 2005. *Farm to Factory: A Reinterpretation of the Soviet Industrial Revolution*. Princeton University Press.
- Ang, B.W., 2005. The LMDI approach to decomposition analysis: a practical guide. *Energy Policy* 33, 867–871.
- Ang, B.W., Zhang, F., 2000. A Survey of Index Decomposition Analysis in Energy and Environmental Studies. *Energy* 25, 1149–76.
- Antweiler, W., 1996. The Pollution Terms of Trade. *Econ. Syst. Res.* 8, 361–366.
- Arens, M., Worrell, E., Eichhammer, W., 2016. Drivers and barriers to the diffusion of energy-efficient technologies—a plant-level analysis of the German steel industry. *Energy Effic.* 1–17.
- Attack, J., Bateman, F., Haines, M., Margo, R.A., 2010. Did railroads induce or follow economic growth?: Urbanization and population growth in the American Midwest, 1850-1860. *Soc. Sci. Hist.* 34, 171–197.
- Ayres, R.U., Ayres, L.W., Warr, B., 2003. Exergy, power and work in the US economy, 1900-1998. *Energy* 28, 219–273.
- Ayres, R.U., Warr, B., 2009. *The Economic Growth Engine: How Energy and Work Drive Material Prosperity*. Cheltenham: Edward Elgar.
- Ayres, R.U., Warr, B., 2003. Exergy, Power and Work in the US Economy, 1900-1998. *Energy* 28, 219–73.
- Bairoch, P., Levy-Leboyer, M., 1981. *Disparities in Economic Development since the Industrial Revolution*.
- Bartoletto, S., Rubio, M. d. M., 2008. Energy Transition and CO2 Emissions in Southern Europe: Italy and Spain (1861-2000). *Glob. Environ.* 1, 46–81.
- Berend, I.T., 2001. *Decades of Crisis: Central and Eastern Europe before World War II*. University of California Press.
- Berger, T., Enflo, K., 2014. Locomotives of Local Growth: The Short- and Long-Term Impact of Railroads in Sweden. *Lund Pap. Econ. Hist.*
- Berners-Lee, M., Clark, D., 2013. *The Burning Question: We can't burn half the world's oil, coal and gas. So how do we quit?*
- Birol, F., Keppler, J.H., 2000. Prices, technology development and the rebound effect. *Energy Policy* 28, 457–469.
- Bloch, H., Tang, S.H.K., 2004. Deep determinants of economic growth: institutions, geography and openness to trade. *Prog. Dev. Stud.* 4, 245–255.

- Bolt, J., Van Zanden, J.L., 2013. New Maddison Project Database [WWW Document].
- Boserup, E., 1965. *The Conditions of Agricultural Growth: The Economics of Agrarian Change under Population Pressure*. Chicago: Aldine.
- Broadberry, S., Fremdling, R., Solar, P.M., 2008. *European Industry, 1700-1870*.
- Broadberry, S., Klein, A., 2011. When and why did eastern European economies begin to fail? Lessons from a Czechoslovak/UK productivity comparison, 1921–1991. *Explor. Econ. Hist.* 48, 37–52.
- Broadberry, S.N., Fremdling, R., 1990. Comparative Productivity in British and German Industry 1907-1937. *Oxford Bull. Econ. Stat.* 52, 403–421.
- Broadberry, S.N., Irwin, D.A., 2006. Labor productivity in the United States and the United Kingdom during the nineteenth century. *Explor. Econ. Hist.* 43, 257–279.
- Bullard, C.W., Penner, P.S., Pilati, D.A., 1978. Net energy analysis. *Resour. Energy* 1, 267–313.
- Caliendo, L., Rossi-Hansberg, E., 2012. The Impact of Trade on Organization and Productivity*. *Q. J. Econ.* 127, 1393–1467.
- Campbell, R.W., 1960. *Soviet Economic Power: Its Organization, Growth and Challenge*. The Riverside Press, Cambridge (MA).
- Carlin, W., Schaffer, M., Seabright, P., 2013. Soviet power plus electrification: What is the long-run legacy of communism? *Explor. Econ. Hist.* 50, 116–147.
- Chen, Y., Pan, J., Xie, L., 2008. Energy Embodied in Goods of International Trade in China: Calculation and Policy Implications. *Econ. Res. J.*
- Cisar, J., Pokorny, F., 1922. *The Czechoslovak Republic*. T.Fisher Unwin; 1st Edition edition (1922).
- Clark, G., Jacks, D., 2007. Coal and the Industrial Revolution, 1700-1869. *Eur. Rev. Econ. Hist.* 11, 39–72.
- Comin, D.A., Hobijn, B., 2004. Cross-country Technological Adoption: Making the Theories Face the Facts. *J. Monet. Econ.* 39–83.
- Comin, D.A., Hobijn, B., Rovito, E., 2006. Five Facts You Need to Know About Technology Diffusion.
- Copeland, B.R., Taylor, M.S., 2004. Trade, Growth, and the Environment. *J. Econ. Lit.* 42, 7–71.
- Cornilie, J., Fankhauser, S., 2004. The energy intensity of transition countries. *Energy Econ.* 26, 283–295.
- Crafts, N., Mulatu, A., 2005. What explains the location of industry in Britain, 1871–1931? *J. Econ. Geogr.* 5, 499–518.
- Crafts, N., Wolf, N., 2014. The Location of the UK Cotton Textiles Industry in 1838: A Quantitative Analysis. *J. Econ. Hist.* 74, 1103–1139.

- Crafts, N.F.R., 1985. *British Economic Growth during the Industrial Revolution*. Clarendon Paperbacks.
- Cvrcek, T., 2013. Wages, Prices, and Living Standards in the Habsburg Empire, 1827–1910. *J. Econ. Hist.* 73, 1–37.
- Cvrcek, T., Zajicek, M., 2013. School, what is it good for? Useful Human Capital and the History of Public Education in Central Europe (No. 19690), NBER Working Paper.
- Daraio, C., Simar, L., 2007. *Advanced Rpbust and Nonparametric Methods in Efficiency Analysis: Methodology and Application*.
- David, J.M., Hopenhayn, H.A., Venkateswaran, V., 2016. Information, Misallocation, and Aggregate Productivity. *Q. J. Econ.* 131, 943–1005.
- De Jong, H., 2003. *Catching up twice: The nature of Dutch industrial growth during the 20th century in a comparative perspective*. Akademie Verlag GmbH, Berlin.
- De Stercke, S., 2014. *Dynamics of Energy Systems: A Useful Perspective*.
- De Vries, J., 1994. The Industrial Revolution and the Industrious Revolution. *J. Econ. Hist.* 54, 249–270.
- Debeir, J.-C., Deleage, J.-C., Hemery, D., 1991. In the Servitude of Power: Energy and Civilization through the Ages.
- Devine, W.D., 1983. From Shafts to Wires: Historical Perspective on Electrification. *J. Econ. Hist.* 43, 347.
- Donaldson, D., Hornbeck, R., 2016. Railroads and American Economic Growth: A “Market Access” Approach. *Q. J. Econ.* 131, 799–858.
- Easterly, W., 2002. *The Elusive Quest for Growth*. The MIT Press.
- Ehrlich, P., Ehrlich, A., 1990. *The Population Explosion*. London.
- Ehrlich, P.R., 1968. *The Population Bomb*.
- Enflo, K., Kander, A., Schön, L., 2009. Electrification and energy productivity. *Ecol. Econ.* 68, 2808–2817. doi:10.1016/j.ecolecon.2009.05.005
- Estevadeordal, A., 1997. Measuring protection in the early twentieth century. *Eur. Rev. Econ. Hist.* 1, 89–125.
- Etemad, B., Luciani, J., 1991. *World Energy Production 1800-1985*. Librairie DROZ.
- Fare, R., Grosskopf, S., Norris, M., Zhang, Z., 1994. Productivity Growth, Technical Progress, and Efficiency Change in Industrialized Countries. *Am. Econ. Rev.* 84, 66–83.
- Federalni Statisticky Urad, 1972. *Statisticka Rocenka Energetiky 1971*.
- Fernihough, A., O’Rourke, K., 2014. *Coal and the European Industrial Revolution*.
- Findlay, R., O’Rourke, K., 2007. *Power and Plenty: Trade, War, and the World Economy in the Second Millenium*. Princeton University Press.

- Fouquet, R., Broadberry, S., 2015. Seven Centuries of European Economic Growth and Decline. *J. Econ. Perspect.* 29, 227–244.
- Fouquet, R., Pearson, P.J.G., 1998. A thousand years of energy use in the United Kingdom. *Energy J.* 19, 1–41.
- Gales, B., Kander, A., Malanima, P., Rubio, M., 2007. North versus South: Energy transition and energy intensity in Europe over 200 years. *Eur. Rev. Econ. Hist.* 11, 219–253.
- Geels, F.W., 2011. The multi-level perspective on sustainability transitions: Responses to seven criticisms. *Environ. Innov. Soc. Transitions* 1, 24–40.
- Geels, F.W., 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Res. Policy* 31, 1257–1274.
- Gerschenkron, A., 1962. *Economic Backwardness in Historical Perspective*. Belknap Press of Harvard University.
- Ghertner, D.A., Fripp, M., 2007. Trading away damage: Quantifying environmental leakage through consumption-based, life-cycle analysis. *Ecol. Econ.* 63, 563–577.
- Goldenberg, J., Reddy, A.K.N., 1990. Energy for the Developing World. *Sci. Am.* 263, 111–18.
- Greslova, P., Gingrich, S., Krausmann, F., Chromy, P., Jancak, V., 2015. Social metabolism of Czech agriculture in the period 1830-2010. *AUC Geogr.* 50, 23–35.
- Grether, J.-M., Mathys, N.A., 2013. The pollution terms of trade and its five components. *J. Dev. Econ.* 100, 19–31.
- Griliches, Z., 1957. Hybrid Corn: An Exploration in the Economics of Technological Change. *Econometrica* 25, 501–522.
- Grübler, A., 2012. Energy transitions research: Insights and cautionary tales. *Energy Policy* 50, 8–16. doi:10.1016/j.enpol.2012.02.070
- Grübler, A., 1998. *Technology and Global Change*. Cambridge University Press.
- Grübler, A., Wilson, C., 2013. *Energy Technology Innovation*. Cambridge University Press.
- Gutberlet, T., 2014. Mechanization and the spatial distribution of industries in the German Empire, 1875 to 1907. *Econ. Hist. Rev.* 67, 463–491.
- Habakkuk, H.J., 1967. *American and British Technology in the Nineteenth Century*.
- Hardin, G., 1968. The Tragedy of the Commons. *Science* (80-.). 162, 1243 LP-1248.
- Henriques, S.T., 2011. *Energy transitions, Economic Growth and Structural Change: Portugal in a Long-run Comparative Perspective*. Lund University.
- Henriques, S.T., 2009. *Energy Consumption in Portugal: 1856-2006*. Consiglio Nazionale delle Ricerche, Naples.

- Henriques, S.T., Kander, A., 2010. The modest environmental relief resulting from the transition to a service economy. *Ecol. Econ.* 70, 271–282.
- Hilding, P., 1992. *Technology in a Controlled Economy: The Match Industry in India*.
- Hornung, E., 2015. Railroads and growth in Prussia. *J. Eur. Econ. Assoc.* 13, 699–736.
- Hughes, T.P., 1983. *Networks of Power: Electrification in Western Society, 1880-1930*. The Johns Hopkins University Press.
- Hölsgens, H.N.M., 2016. *Energy Transitions in the Netherlands: Sustainability Challenges in a Historical and Comparative Perspective Groningen*. University of Groningen.
- Jorgenson, D.W., 1984. The Role of Energy in Productivity Growth. *Am. Econ. Rev.* 74, 26–30.
- Kander, A., 2002. *Economic growth, energy consumption and CO2 emissions in Sweden 1800-2000*. Lund University.
- Kander, A., Jiborn, M., Moran, D.D., Wiedmann, T.O., 2015. National greenhouse-gas accounting for effective climate policy on international trade. *Nat. Clim. Chang.* 5, 431–435.
- Kander, A., Malanima, P., Warde, P., 2013. *Power to the People: Energy in Europe over the Last Five Centuries*. Princeton University Press.
- Kander, A., Stern, D.I., 2014. Economic growth and the transition from traditional to modern energy in Sweden. *Energy Econ.* 56–65.
- Kander, A., Warde, P., 2009. *Number, Size and Energy Consumption of Draught Animals in European Agriculture*.
- Karnikova, L., 1960. *Vyvoj uhelneho prumyslu v ceskych zemich do r. 1880*. Ceskoslovenska akademie ved.
- Karnikova, L., 1958. *Úloha uhlí v průmyslovém rozvoji Čech do poloviny 19. století*.
- Khawaja, M.I., Khan, S., 2009. Reforming Institutions: Where to Begin? *Pak. Dev. Rev.* 48, 241–267.
- Klein, A., Crafts, N., 2011. Making sense of the manufacturing belt: determinants of U.S. industrial location, 1880-1920. *J. Econ. Geogr.* 12, 775–807. doi:10.1093/jeg/lbr023
- Klein, A., Ogilvie, S., 2015. Occupational structure in the Czech lands under the second serfdom. *Econ. Hist. Rev.*
- Kogut, B., Zander, U., 2000. Did Socialism Fail to Innovate? A Natural Experiment of the Two Zeiss Companies. *Am. Sociol. Rev.* 65, 169–190.
- Krausmann, F., 2004. Milk, Manure, and Muscle Power. Livestock and the Transformation of Preindustrial Agriculture in Central Europe. *Hum. Ecol.* 32, 735–772.

- Krausmann, F., Gaugl, B., West, J., Schandl, H., 2016. The metabolic transition of a planned economy: Material flows in the USSR and the Russian Federation 1900 to 2010. *Ecol. Econ.* 124, 76–85.
- Krausmann, F., Haberl, H., 2002. The process of industrialization from the perspective of energetic metabolism: Socioeconomic energy flows in Austria 1830–1995. *Ecol. Econ.* 41, 177–201.
- Kuskova, P., Gingrich, S., Krausmann, F., 2008. Long term changes in social metabolism and land use in Czechoslovakia, 1830–2000: An energy transition under changing political regimes. *Ecol. Econ.* 68, 394–407.
- Kuznets, S., 1973. *Modern Economic Growth: Findings and Reflections*. *Am. Econ. Rev.* 63, 247–258.
- Kuznets, S., 1966. *Modern economic growth: Rate, structure, and spread*. Yale University Press.
- Land, K.C., Lovell, C.A.K., Thore, S., 1994. Productive Efficiency under Capitalism and State Socialism: An Empirical Inquiry Using Chance-Constrained Data Envelopment Analysis. *Technol. Forecast. Soc. Change* 139–152.
- Landes, D.S., 1969. *The Unbound Prometheus: Technological Change and Industrial Development in Western Europe from 1750 to the Present*.
- Laursen, K., 2015. Revealed comparative advantage and the alternatives as measures of international specialization. *Eurasian Bus. Rev.* 5, 99–115.
- Levcik, F., Skolka, J., 1984. *East-West Technology Transfer: Study of Czechoslovakia*. OECD.
- Lindmark, M., 2007. Estimates of Norwegian energy consumption 1835-2000.
- Lindmark, M., 2004. Patterns of historical CO2 intensity transitions among high and low-income countries. *Explor. Econ. Hist.* 41, 426–447.
- Locatelli, C., 1993. The energy heritage in Eastern and Central Europe: The search for a new model of development. *MOCT-MOST Econ. Policy Transitional Econ.* 3, 97–134.
- Maddison, A., 2007. *Contours of the World Economy 1-2030 AD: Essays in Macro-Economic History*. Oxford University Press, Oxford.
- Malanima, P., 2016. Energy consumption in England and Italy, 1560-1913. Two pathways toward energy transition. *Econ. Hist. Rev.* 69, 78–103.
- Malanima, P., 2011. The long decline of a leading economy: GDP in central and northern Italy, 1300–1913. *Eur. Rev. Econ. Hist.* 15, 169–219.
- Malanima, P., 2006. *Energy Consumption in Italy in the 19th and 20th Centuries: A Statistical Outline*. Consiglio Nazionale delle Ricerche, Naples.
- Marx, K., Engels, F., 1888. *The Communist Manifesto*.
- McCloskey, D., 2016. *Bourgeois Equality: How Ideas, Not Capital or Institutions, Enriched the World*. University of Chicago Press.

- Meadows, D.H., Meadows, D.L., Randers, J., Behrens, W.W., 1972. *The Limits to Growth*. 1972 Universe Books.
- Meyers, S., Salay, J., Schipper, L., 1994. Energy use in a transitional economy: The case of Poland. *Energy Policy* 22, 699–713.
- Missiaia, A., 2016. Where do we go from here? Market access and regional development in Italy (1871–1911). *Eur. Rev. Econ. Hist.* 20, 215–241.
- Mitra Debnath, R., Sebastian, V.J., 2014. Efficiency in the Indian iron and steel industry – an application of data envelopment analysis. *J. Adv. Manag. Res.* 11, 4–19. doi:10.1108/JAMR-01-2013-0005
- Mokyr, J., 2009. Intellectual Property Rights, the Industrial Revolution, and the Beginnings of Modern Economic Growth. *Am. Econ. Rev.* 99, 349–355.
- Mokyr, J., 1990. *The Lever of Riches: Technological Creativity and Economic Progress*. Oxford University Press, Oxford.
- Nielsen, H., 2017. Productive efficiency in the iron and steel sector under state planning: The case of China and former Czechoslovakia in a comparative perspective. *Appl. Energy* 185, 1732–1743.
- Nielsen, H., Henriques, S.T., Warde, P., Kander, A., 2016. Energy efficiency and the productivity race in industry (1870-1935).
- Nilsson, L., 1999. *Essays on North-South Trade*.
- North, D., 1990. *Institutions, Institutional Change and Economic Performance*. Cambridge University Press.
- Nuvolari, A., Verspagen, B., Tunzelmann, N. von, 2011. The early diffusion of the steam engine in Britain, 1700–1800: a reappraisal. *Cliometrica, J. Hist. Econ. Econom. Hist.* 5, 291–321.
- O’Rourke, K., Williamson, J.G., 1999. *Globalization and history*. The MIT Press.
- Ogilvie, S., 2007. “Whatever Is, Is Right”? Economic Institutions in Pre-Industrial Europe. *Econ. Hist. Rev.* 60, 649–684.
- Oster, S., 1982. The Diffusion of Innovation among Steel Firms: The Basic Oxygen Furnace. *Bell J. Econ.* 13, 45–56.
- Ozturk, I., 2010. A literature survey on energy–growth nexus. *Energy Policy* 38, 340–349.
- Panayotou, T., 1997. Demystifying the environmental Kuznets curve: turning a black box into a policy tool. *Environ. Dev. Econ.* 2, 465–484.
- Persson, K.G., 2010. *An Economic History of Europe: Knowledge, Institutions and Growth, 600 to the Present*.
- Pollard, S., 1981. *Peaceful Conquest: The Industrialization of Europe, 1760-1970*.
- Poznanski, K.Z., 1986. The Extinguishing Process: A case Study of Steel Technologies in the World Industry. *Technovation* 4, 297–316.
- Poznanski, K.Z., 1984. Technology Transfer: West-South Perspective. *World Polit.* 37, 134–152.

- Purs, J., 1978. *Hospodarske dejiny 2*.
- Reilly, B., 1996. Strike incidence and the business cycle in Ireland. *Appl. Econ.* 28, 765–771.
- Rosenberg, N., 1992. Economic Experiments. *Ind. Corp. Chang.* 1, 181–203.
- Roses, J., 2003. Why Isn't the Whole of Spain Industrialized? *New Economic Geography and Early Industrialization, 1797–1910*. *J. Econ. Hist.* 63, 995–1022.
- Rostow, W.W., 1990. *The stages of economic growth*, 3rd edition.
- Rudolph, R.L., 1976. *Banking and Industrialization in Austria-Hungary*.
- Salay, J., 1999. *Energy Use, Efficiency Gains and Emission Abatement in Transitional Industrialised Economies: Poland and the Baltic States*.
- Sato, M., 2014. Product level embodied carbon flows in bilateral trade. *Ecol. Econ.* 105, 106–117.
- Sato, M., 2012. *Carbon emissions and bilateral trade*. London School of Economics.
- Schon, L., 2000. Electricity, technological change and productivity in Swedish industry, 1890-1990. *Eur. Rev. Econ. Hist.* 4, 175–194.
- Schulze, M., Wolf, N., 2012. Economic nationalism and economic integration: the Austro-Hungarian Empire in the late nineteenth century. *Econ. Hist. Rev.* 65, 652–673.
- Schurr, S.H., 1990. *Electricity in the American Economy: Agent of Technological Progress*. Greenwood Publishing Group.
- Schurr, S.H., 1972. *Energy, Economic Growth and the Environment*. RFF Press.
- Schurr, S.H., Netschert, B.C., 1960. *Energy in the American economy, 1850-1975: an economic study of its history and prospects*, Volume 13. Johns Hopkins Press.
- Schön, L., 2010. *Sweden's Road to Modernity: an Economic History*.
- Schön, L., Krantz, O., 2012. *Swedish Historical National Accounts 1560 - 2010*, Lund Papers in Economic History.
- Smil, V., 2016. *Still the iron age: Iron and Steel in the Modern world*. Butterworth-Heinemann.
- Smil, V., 2014a. *Making the Modern World: Materials and Dematerialization*. Wiley.
- Smil, V., 2014b. The long slow rise of solar and wind. *Sci. Am.* 282, 52–57.
- Smil, V., 2006. *Transforming the Twentieth Century: Technical innovations and their consequence*. Oxford University Press.
- Smil, V., 2005. *Creating the Twentieth Century: Technical innovations of 1867-1914 and their lasting impact*. Oxford University Press.
- Smil, V., 2003. *Energy at the Crossroads. Global Perspectives and Uncertainties*. The MIT Press, Cambridge (MA).
- Smil, V., 1994. *Energy in World History*. Westview Press.

- Statni Urad Statisticky, 1960. *Statisticka rocenka Ceskoslovenske socialisticke republiky*.
- Stern, D.I., Enflo, K., 2013. Causality between energy and output in the long-run. *Energy Econ.* 39, 135–146.
- Stern, D.I., Kander, A., 2012. The Role of Energy in the Industrial Revolution and Modern Economic Growth. *Energy J.* 33, 125–152.
- Suri, V., Chapman, D., 1998. Economic growth, trade and energy: implications for the environmental Kuznets curve. *Ecol. Econ.* 25, 195–208.
- Tarr, D.G., 1985. The Efficient Diffusion of Steel Technology Across Nations 5, 541–560.
- Teichova, A., 2013. *The Czechoslovak Economy 1918-1980 (Routledge Revivals)*. Routledge.
- United Nations, 1980. *Annual Bulletin of General Energy Statistics for Europe*.
- van Zanden, J.L., van Leeuwen, B., 2012. Persistent but not consistent: The growth of national income in Holland 1347–1807. *Explor. Econ. Hist.* 49, 119–130.
- Veenstra, J., De Jong, H., 2015. A tale of two tails: Plant size variation and comparative labor productivity in U.S. and German manufacturing in the early 20th century.
- Vonyo, T., Klein, A., 2016. Why Did Socialism Fail? The Role of Factor Inputs Reconsidered. CAGE Online Work. Pap. Ser.
- Wan, J., Baylis, K., Mulder, P., 2015. Trade-facilitated technology spillovers in energy productivity convergence processes across EU countries. *Energy Econ.* 48, 253–264.
- Warde, P., 2007. *Energy consumption in England & Wales 1560-2000*. Consiglio Nazionale delle Ricerche, Naples.
- Warr, B., Ayres, R., Eisenmenger, N., Krausmann, F., Schandl, H., 2010. Energy use and economic development: A comparative analysis of useful work supply in Austria, Japan, the United Kingdom and the US during 100 years of economic growth. *Ecol. Econ.* 69, 1904–1917.
- Wiedmann, T., 2009. A first empirical comparison of energy Footprints embodied in trade — MRIO versus PLUM. *Ecol. Econ.* 68, 1975–1990.
- Wilson, C., 2012. Up-scaling, formative phases, and learning in the historical diffusion of energy technologies. *Energy Policy* 50, 81–94.
- Wilson, C., 2009. Meta-analysis of unit and industry level scaling dynamics in energy technologies and climate change mitigation scenarios.
- Wilson, R., 2016. *Essays in Empirical Institutional Analysis*.
- Wolf, N., 2007. Endowments vs. market potential: What explains the relocation of industry after the Polish reunification in 1918? *Explor. Econ. Hist.* 44, 22–42.
- Wright, W.E., 1966. *Serf, Seigneur, and Sovereign*.

- Wrigley, E.A., 2016. *The Path to Sustained Growth*. Cambridge University Press, Cambridge.
- Wrigley, E.A., 2010. *Energy and the English Industrial Revolution*. Cambridge University Press, Cambridge.
- Wrigley, E.A., 1988. *Continuity, Chance and Change*. Cambridge University Press, Cambridge.
- Ürge-Vorsatz, D., Miladinova, G., Paizs, L., 2006. Energy in transition: From the iron curtain to the European Union. *Energy Policy* 34, 2279–2297.
- Zhang, Z., 2003. Why did the energy intensity fall in China's industrial sector in the 1990s? The relative importance of structural change and intensity change. *Energy Econ.* 25, 625–638.
- Zhao, X., Ma, C., Hong, D., 2010. Why did China's energy intensity increase during 1998–2006: Decomposition and policy analysis. *Energy Policy* 38, 1379–1388.
- ZumBrunnen, C., Osleeb, J.P., 1986. *The Soviet Iron and Steel Industry*. Rowman & Allanheld, Publishers.