UNIVERSITY OF TARTU
Faculty of Social Sciences
School of Economics and Business Administration

Maria Orav

IMPACT OF TECHNOLOGY ON ECONOMIC DEVELOPMENT THROUGH ENERGY, TRANSPORT AND INFORMATION AND COMMUNICATION TECHNOLOGIES

Master's Thesis

Supervisor: Kadri Ukrainski (PhD)

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Kadri Ukrainski
(name of supervisor)

I have written this master's thesis independently. All viewpoints of other authors, literary sources and data from elsewhere used for writing this paper have been referenced.

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Abstract

The link between technology adoption and economic development is widely recognized, but too frequently overly broad generalisations are made. This thesis argues that most of technology adoption and, in turn, economic development, can be meaningfully estimated by three sectors: energy, transport and information and communication technologies (ICT). We estimate and specify the effect of these sectors on technology adoption and measure it through the proxy variables of energy, transport and ICT. The results indicate that a significant portion of economic development can be attributed to the efficient use of energy, transport and ICT. While the effects of insufficient energy production have lessened in recent years, the availability of efficient, high intensity power has become a major factor in determining growth. We argue that, while transport efficiency remains a crucial contributor to development, the most future growth potential stems from ICT and its applications.

Keywords: technology adoption, economic development, energy, transport, ICT

1 Introduction

The role of technology in economic growth is almost universally recognized (Metcalfe, 2010). However, the multifaceted nature of technology is frequently ignored or overlooked. While technology is one of the central drivers of economic development, there can be hidden pitfalls with its adoption, namely technological lock-ins and path dependency (Fouquet, 2016; Pierson, 2000). There are also key technological fields of application that are principal to growth – energy, transport and information and communication technologies (ICT) – and distinguishing these sectors helps to refine the role technology plays in economic development.

Growth economics literature recognises the role of technology, at the same time also highlighting the importance of institutional (Acemoglu, Robinson, 2012; Mokyr, 2002; Shin, 2018) and cultural factors (Tabellini, 2010) as well as the role of the state (Bardhan, 2016; Borcan et al., 2017; Doucouliagos, Ulubaşoğlu, 2008). Many treatments of the role of technology are one dimensional; treating it as a single variable in models for growth when, in fact, technological development is multidimensional (Schot, Kanger, 2018; Geels, 2002). Combinations of various technologies that co-exist in real time can work both for and against economic development. Existing technological paradigms can hamper progress and create lock-ins: situations in which states become stuck in sub-optimal paths for prolonged periods of time (Fouquet, 2016). Old and new technologies exist alongside each other and ultimately their combination and how they evolve determine development. A one-dimensional treatment of technology often leads to overly general recommendations for state intervention in technological development.

The main aim of this thesis is to estimate and specify the effect technology has on economic development. We aim to show that most of technological progress can be summarized by three technological sectors – energy, transport and ICT. To estimate the effect of technology on economic development, we treat technology adoption as endogenous. In order to do so, a plausible source of exogenous variation in technology indicators is needed. Perez (2010) identified five technological revolutions, starting with the Industrial Revolution and concluding with the current Age of Information and Telecommunications. Each revolution involved large surges of development that profoundly transformed society. These profound changes centred around upheavals in the fields of energy, transport and ICT. In this thesis, we link current differences in technology adoption to those three sectors and argue that they have the potential to indirectly account for a substantial portion of economic progress.

This thesis contributes to the literature by determining the role technology adoption plays in economic development. The impact of how well states have adopted technology through time is empirically measured through the proxy variables of the last technological revolutions (Perez, 2010) – energy, transport and ICT. We use the method of instrumental variables estimation, where the dependent variable is GDP per capita, a technology adoption index is treated as endogenous and energy efficiency regulation, efficiency of air transport services and fixed-broadband internet subscriptions are used as instruments. While the narrow sub-indicators that we use as instruments are likely not to have a sizeable direct impact on GDP per capita, the paper shows that they are a suitable measure of technology adoption. This paper demonstrates statistically significant effects between the energy, transport and ICT instruments and technology adoption and, in turn, between GDP per capita. Our results are robust to the addition of other instruments (electrification rate, quality of roads, internet users) and controls. The main data used in this research was taken from the World Bank (including the Global Competitiveness Report dataset) and Borcan et al (2017) and it was for 94 countries and mostly for the year 2017.

There is ample proof why energy, transport and ICT should be placed at the centre of the discussion revolving around technology adoption and economic development. Innovations in energy technologies have often been in the middle of wider technological surges, starting from water and steam power during the first Industrial Revolution to the more recent multiple source and flexible use electricity networks, enabling development (Perez, 2010). Even though the role of energy is likely to change at different stages of development, with it being a robust constraint at the early stages and less so later on, energy is essential to all production. Moreover, energy intensiveness is steadily increasing (Benthem, 2015), but there are crucial differences in the implications various technologies (renewable, fossil, nuclear etc) provide. Energy efficiency is the most appropriate measure of energy technology and advancements in it have been shown to trigger increases in total factor productivity. (Cantore et al., 2016)

Transport technology, as both a key carrier branch of the economy in addition to forming a notable portion of its infrastructure, has always been at the heart of larger technological progress (Perez, 2010). Transportation technology offers major market-widening effects, mobility and efficiency of resource distribution; all of which are crucial for establishing competitive markets. While being the “wheels” of any economic activity, it can also potentially be an important tool to combat poverty and inequality (Cigu et al., 2019). Efficiency of air travel was thought best to represent transport technology in the empirical part of this paper, as of the major means of transport – road, rail, air and water – it is usually the most advanced technologically.

The most recent technological surge has revolved around ICT and has completely redesigned modern societies and played a large role in globalisation (Perez, 2010). For example, the post-1995 surge in productivity[1] can be attributed to digital technology investment and usage (Goldfarb, Tucker, 2019). On the downside, ICT has also opened a "digital divide", as those being deprived of ICT services miss out on the momentous growth opportunities advanced countries enjoy. ICT services permit participation in the global market and projects to develop them provide much economic development potential, especially in poor areas. (Avgerou, 2003)

The key takeaway of the paper is that investments into the technologies of energy, transport and ICT have the potential to spur profound economic and societal development, but states should take care to keep the technological landscape flexible in order to promote innovation and further technological shifts. Of the three sectors, the most vulnerable to lock-ins is energy technology, because developing states tend to emulate the energy-intensive paths of developed countries. The lure of cheap energy, which is essential for economic development in the early phases, often leads to inefficient energy consumption, large social costs and debt in the long run. Our results suggest that the efficiency of transport services has been a highly influential determinant of technology adoption and economic development. However, ICT has had the biggest effect on technology adoption and it offers a crucial source of future growth potential.

The structure of the rest of this paper is as follows: section 2 reviews the literature related to technology, focusing on the role both technology and states play in economic development. Section 3 covers the inter-dependent development of technologies, with subsection 3.1 focusing on energy, subsection 3.2 on transport and subsection 3.3 on ICT. A detailed overview of the data and method used can be found in section 4. Section 5 presents the results and section 6 conducts an exercise to test the robustness of the findings. Finally, the conclusions are in section 7.

[1] Prior to the 1990s, the Solow productivity paradox persisted, where heavy investment into IT, specifically incorporating computers into daily use, did not appear to have any impact on productivity measures (Brynjolfsson, 1993; Goldfarb, Tucker, 2019).

2 Technology in Economic Development and the Role of the State

Technology is instrumental not only to economic growth, the creation of wealth and poverty alleviation, but also to wider societal issues such as globalisation, climate change, and the provision of health care and education (Faulkner et al., 2010). Technological progress is vital in order to understand growth and development, but as the link between productive factors and human satisfaction, it is also a primary part of the structure of economic life and any theory of coordination. It is widely accepted that improvements in productive efficiency have been closely tied to advances in the underlying technology. As a way of operating, technology relies heavily on the human dimensions of skill and knowledge. It comes in various forms, as information and knowledge, as skills and abilities and as human built structures. (Metcalfe, 2010)

Knowledge can move freely, so the benefits of new technologies have significant spill-overs to other areas. As it comes to regional economies, the degree to which technological spill-overs are appropriated locally can be more influential to economic development than the resources poured into local knowledge production or research and development might be. (Koo, 2005)

When it comes to economic growth models, Solow (1956, 1957) constructed a model in the neoclassical framework that attributed growth to capital, labour and technological progress and argued, that as capital and labour inputs eventually exhibit diminishing returns to scale, technological progress is the most important driving force of economic growth. Although a significant contribution to the field, Solow's theory has some crucial shortcomings. It treats technology as an external factor not determined in the growth process and assumes that technology adoption is costless and instantaneous, with technology nonrival and nonexcludable. These ideas have proven inconsistent with the empirical evidence of private firms' R&D spending increases for the past several decades, indicating that there has been an incentive to develop new technologies (Koo, 2005). New growth theory (Arrow, 1962; Lucas, 1988) provided an alternative approach. Arrow (1962) attributed the growth of labour productivity to workers' cumulative experience, often labelled as "learning by doing". Because this process is reactive to labour productivity and market incentives, technological progress becomes a part of the growth process. Arrow also assumed that knowledge was a pure public good, a conjecture that was modified by Romer (1990), who considered technology as partially excludable giving the incentive to invest in R&D. Consequently, technological change was no longer treated as exogenous. Schumpeter (1911, 1939) recognized that technological change and entrepreneurship are major drivers of economic growth, but he too considered technology as exogenous. However, his followers, the neo-Schumpetarians, consider novelties, of which technological innovation is the most notable form, to be the key driver of economies. (Hanusch, Pyka, 2007; Perez, 2010) Novelties often emerge in niches and are geared to solve the problems of existing technologies (Geels, 2002). Building on the ideas of Schumpeter, Aghion and Howitt (1992) also contributed to the endogenous growth literature, considering innovation as the driver of economic growth. Even though its popularity has dropped since the late 1980s and early 1990s, endogenous growth literature is still growing, but there is little consensus on the standard format of the model (Koo, 2005).

Technical change needs to be studied in the context of innovation, at the convergence of the economy, technology and the socio-institutional level (Perez, 2010). Despite variety in the consequences and sources of technical change, it is not a completely random process. There are consistencies in patterns which indicate the existence of technological paradigms and trajectories. Those patterns provide profitable and innovative investment opportunities and long-term growth in new markets along defined paths of development. (Freeman, 1988)

Existing technological paradigms may, however, also hamper further innovation and progress (Pierson, 2000). States play a key role in economic development and the support and incentives they offer for technology creation and adoption make up an essential part of its foundation. As states mature, their growth tends to dwindle and steady. There are a myriad of potential reasons for this. Technological transitions could be the key. As Geels (2002) pointed out, for stable economies, the networks of most industries within one technological regime become very rigid. This is also supported by Perez (2010), who believes that when the potential of one technology is exhausted and a new one begins to emerge, the embedded institutions and habits of the existing paradigm restrict innovation and function as a significant inertial barrier. Moreover, incorporating more efficient processes and tools, like IT solutions, into public institutions has been slow and is far from fully developed. Social and human resistance to change manifests itself as organisational inertia and, while it can be overcome by competition in the market economy, a lack of survival pressures in most public institutions has resulted in slow adoption.

Regimes do create innovations, but they are typically incremental. Radical innovations are generally generated in niches which are insulated and protected from the standard market selection in the regime. Profound technological advancements can initially have very low performance and be both extremely expensive and cumbersome. For example, many radically new inventions, such as the digital computer and radar, originated from military technology. The military technology niche provided a much better opportunity to develop than the normal market would have granted them. Ultimately, an inflexible landscape hinders technological transitions, stagnating growth. It is therefore imperative to recognize opportunities to cradle technological innovation and aid in its transition to the competitive market. Understanding the means to keep the technological landscape as flexible as possible could be the key element for continued competitive economic progress (Geels, 2002).

In addition, random chance or investment decisions can have long lasting effects on development. Economies can become stuck on socially sub-optimal paths since eventual outcomes often depend on the early history of particular technologies, often producing lock-ins. (Fouquet, 2016) Path dependency, as defined by Pierson (2000), is a self-reinforcing process in which each step along the path increases the probability of making further steps along the same path. This phenomenon can be triggered by a rigid technological landscape.

Kemp et al (2001) believed that there are three alternatives to intentionally construct a desirable path. The most basic method is brute force; planning a new system and overcoming the barriers that it faces by elimination. This method is frequently used for physical infrastructures and complex technical systems such as electricity grids. The second option is to provide economic or social incentives to direct the development path. Lastly, one can build on the ongoing dynamics of sociotechnical change and modulate it by applying pressure, for example with taxation. Dosi (1982) believed, that for new technologies to come to the forefront, much importance must be placed on institutions, which direct and support the accumulation of experience and knowledge. Institutions must create the right incentives to combat inertia. Another vital factor for supporting innovation is the existence of a large collection of risk-taking actors who are willing to try different technical and commercial solutions.

Kanger et al. (2020) distinguished six policy intervention points to support systems change. First, different niches should be stimulated. Examples of such measures include funding R&D, foresight exercises and relaxing the regulatory environment. The central aspect of this intervention is to sustain a variety of technologies. Second, niches should be accelerated so that emerging technologies can enter the market. Third, existing regimes should be destabilised so that niches can break through. Examples of destabilizing measures include the use of taxation to apply economic pressure. Fourth, the spill-over effects of regime destabilization should be addressed, meaning policy action should be directed at dis-embedding the system from its environment while alleviating and anticipating possible negative spill-overs. Measures in this fourth category include providing educational and financial support to manage skill mismatch and structural unemployment. The fifth policy intervention entails providing coordination for multi-regime interaction. As socio-technical systems are not simply created internally and result from the mutually reinforcing developments in multiple systems, this intervention entails breaking already existing links and forging new ones. Last, to change factors beyond specific systems and niches, the landscape should be tilted. This step includes participating in international negotiations to reach collectively binding agreements. One example of a successful intervention of this type was the phasing out of CFCs (chlorofluorocarbons, a chemical compound particularly harmful to the ozone layer).

3 Inter-dependent Development of Technology and Applications in Energy, Transport and ICT

The most momentous technological shifts are technological revolutions. Similar to how individual innovations are set in technology systems, the latter are interconnected in technological revolutions, which are a set of radical interrelated breakthroughs, creating interdependent technologies. Technological revolutions are distinguished from an arbitrary collection of technological systems by two factors. First, the systems which undergo a revolution have highly interconnected and interdependent markets and technologies. Second, and more importantly, revolutions have the capacity to transform the rest of the economy and society. Perez (2010) recognized five of such revolutions, which are summarized in Table 1.

Table 1. The five Technological Revolutions

Technological revolution	Year	Initiating technology	New/redefined technologies, industries or infrastructures
The Industrial Revolution	1771	Arkwright's mill	Mechanisation, canals and waterways, water power
Age of Steam and Railways	1829	Steam engine	Railways, great ports, depots, worldwide sailing, city gas, steam power, iron and coal mining, rolling stock production
Age of Steel, Electricity and Heavy Engineering	1875	Carnegie Bessemer steel plant	Steam engine for steel ships, worldwide shipping, electrical networks and equipment industry, transcontinental railways, national telephone
Age of Oil, the Automobile and Mass Production	1908	Ford Model-T	Mass-production (e.g. automobiles), cheap oil, internal combustion engine, networks of roads, ports, airports, worldwide analogue telecommunications
Age of Information and Telecommunications	1971	Intel microprocessor	Computers, software, telecommunication, multiple source, flexible use electricity networks, high-speed multi-modal physical transport links

Source: author, based on Perez (2010)

Each revolution consists of a large surge of development or great upheavals of the wealth-creating potential of the economy, producing, among other things, whole new supplementary or complementary technologies and infrastructures which provided major increases in the effectiveness and efficiency of most activities and industries. The fluctuations of growth and productivity increases, along with structural change, can be traced by identifiable technological change, which was dramatically shaped by the technological revolutions. Perez (2002) highlighted that there is a certain time lag for the spread of adopting new technologies, characterized by a large divergence in the growth rates of industries and countries.

The Industrial Revolution kick-started factory production and mechanization, creating new local networks and waterways. The Age of Steam and Railways rapidly expanded production, with power centres, railways and ports springing up. Using the improved steamships and transcontinental railways built with steel, the Age of Steel, Electricity and Heavy Engineering created a worldwide shipping industry. The electrical equipment industry was also redefined, electrical networks were created. The networks of roads, highways, ports and airports that we are familiar with today were largely built during the Age of Oil, the Automobile and Mass Production. In addition, the internal combustion engine was invented and notable improvements were made in energy intensity and worldwide analogue telecommunication. The most recent revolution, the Age of Information and Telecommunications, ushered in globalization through the development and wide use of computers, software, the Internet and digital telecommunication. It also introduced high-speed multi-modal physical transportation links by air, land and water.

If we consider the sectors where both the technologies that initiated the revolutions as well as where most of the accompanying momentous technological change occurred, it becomes clear that it is possible to distinguish central areas of technology adoption. The key sectors or fields of applications around which those five revolutions revolved were energy, transport and information and communications technology (ICT). As a result, we focus our analysis on them and aim to determine how they, through their impact on technology adoption, affect economic growth. We claim that they account for a substantial portion of economic development.

3.1 Energy

Energy and its infrastructure often has impactful repercussions on economic development. While growth cannot be explained in its entirety as a function of energy supply, energy is essential to all economic production. Energy scarcity imposes a robust constraint on economic growth. However, when it is readily available, marginal increases have greatly reduced effect. Empirical evidence is straightforward in indicating that energy availability plays an instrumental role in enabling growth. Nevertheless, technological progress, improved fuels and a larger availability of energy has greatly lessened energy's limiting effect on growth. (Stern 2010)

The impact of energy services is prone to change at different stages of economic development. Although access to affordable energy, provided by large scale projects and subsidies, is essential for economic development, it may inflict large social costs in the long run. Cheap energy options are likely to lock states into energy-intensive paths, making them vulnerable to energy price shocks. Those lock-ins frequently happen during industrialisation. If inadequately managed, an energy-intensive system that was once instrumental for rapid growth can, in the long run, lead to inefficient energy consumption and heavy debt.

Suboptimal energy-intensive paths lead to significant periods of inability to adjust fully to shocks and changes in market circumstances. (Fouquet 2016)

Benthem (2015) identified three key factors to energy intensiveness. More efficient technologies drive it down, while more export from developing economies and energy-intensive bundle consumption increases it. His study also found that energy-intensity has increased overall, meaning the first factor has been outweighed by the latter. This indicates that developing countries follow energy-intensive patterns and is presumably linked to various technological, institutional, infrastructural and behavioural lock-ins. For example, Fouquet (2016) highlighted that in nuclear power dominated France, where the electricity industry is interlinked with policy decisions and is highly concentrated, it is difficult to progress towards a more liberal and competitive market with potentially different energy systems, producing a major vulnerability and leading to an efficiency gap.

Various energy sources have different spill-overs on industrialisation and economic development. Developing countries today frequently base their energy policies on the existing industrial development paradigm of already industrialised nations. They construct heavy industrial clusters with high energy intensity in order to increase living standards and combat poverty. This usually entails using coal-based technologies, which in turn leads to extensive social costs such as health effects from ambient air pollution and the vast economic costs of global warming. Measures that account for the social costs of fossil fuel, such as carbon taxes, can improve long-term competitiveness and sustainable development. A crucial institutional challenge is to account for macroeconomic spillovers and structural change in environmental policy making. (Kalkuhl et al, 2019)

While some energy sources, like coal, predate recorded history, we can also find notable examples of niche development. The first experimental nuclear power apparatus was created in the University of Chicago in 1942, but it became a commercial power option in the 1950s only thanks to military interest in developing nuclear power (Krivit, Lehr, 2011). Despite this exception, the development of energy systems has generally been interlinked with the technological surges identified by Perez (2010), because of the importance of low cost energy inputs. Coal played a key part in the second and third technological revolutions, while we saw a shift to oil as the predominant source of energy in the fourth revolution (Kanger, Schot, 2019). As the dependence on fossil fuels accelerated, so did energy intensity. Swilling (2013) points to the fossil fuels industry use of their financial might to structurally block further transitions to understand why more sustainable energy sources have not become widespread in the face of growing ecological pressures. Different energy sources continue to co-exist alongside one another, so a general measure of a countries' energy technology can be gathered by assessing energy efficiency. Simple electrification rates or supply measures have lost their usefulness as indicators of energy technology. Because of this, we use energy efficiency regulation as an indicator of in the central model of this research. We expect this indicator to capture both the technological component as well as the institutional surrounding. This approach is supported by Cantore et al (2016), who argued that technological change through energy efficiency in manufacturing is a driver of growth. They found that energy efficiency triggered increases in total factor productivity, which can be used as an accurate proxy for technological change.

3.2 Transport

Transport is viewed as a key element of economic development because it possesses major market-widening effects as well as being integral for establishing competitive markets. Transport is essential for primary, secondary and tertiary production. The transport sector can be regarded as a tight combination of two activities: a construction and maintenance industry and a service industry. Efficiency improvements in transport services have spurred productivity growth by providing cheaper transport, with superior regularity and faster speeds (Ville, 1990).

Transport infrastructure is a significant economic growth factor. It provides mobility, efficiency and effectiveness in resource distribution. It can be classified as a productive public expenditure, as it accelerates access to services, increases market and labour mobility, improves social welfare and provides access to the exporting market. (Cigu et al, 2019) Transport infrastructure can spur changes in factor markets and firm location judgments which in turn create spatial clusters of economic actors and sectors and stimulate innovation, leading to a further reduction in costs. (Afraz et al, 2006)

Important advances of transport technology came not only through completely new technologies, but through organisational improvements such as timetable management and occupational specialisation. Development in the transport sector also prompted advancement in financial markets and created new forms of finance. Significant transport projects can also have a counter-cyclical influence on the economy since major, long-term projects are usually started in periods of prosperity but are completed during economic downturns during which they provide employment and create demand for supply firms. The betterment of transport also stimulated shifts in population movement; most notably towards suburban expansion. (Ville, 1990)

Transport infrastructure is also a noteworthy political instrument, implemented not only to spur economic growth, but to reduce inequality through public policies. Infrastructure developments usually require a sizable amount of capital and public expenditure, which places substantial pressure on public authorities to utilize resources efficiently. (Cigu et al, 2019) Great care should be taken in planning transportation systems, as they are one of the most impactful and long-lasting lock-ins, outlining the behaviour and geography of countries for centuries (Fouquet 2016). There is a real risk of socio-technical lock-in to a sub-standard transport system. The mobility and land use repercussions for rail and road projects have widely varying effects on population density, choice of transport mode and overall carbon impact in an urban region. Those far-reaching effects are frequently not taken into consideration in large-scale transportation infrastructure development plans. (Driscoll, 2014)

Technological change in transport has occurred much more gradually compared to most other areas. Initial unreliability of new technologies and conservatism were the main reasons for the slow diffusion of transport innovations. Variance in the relative competitiveness between different modes of transport in various markets lengthened the process considerably. For example, road transport was replaced by rail quicker over long hauls, where the terminal costs were less of a factor than on shorter distances. Shipping has much higher terminal costs than the two aforementioned, but of the three is the cheapest over great distances. Therefore, second best technologies regularly continued in operation and coexistence, complementing the newer innovation. (Ville, 1990)

It is possible to link the widespread use of new or improved forms of transportation to the five great surges of development. During the Industrial Revolution, a network of canals and waterways was built. Railways and steamships played a crucial part during the second and third revolutions. Personal automobiles and air travel became widespread in the fourth surge, where extensive networks of roads, highways, ports and airport were constructed. The most recent surge brought forth high-speed multi-modal physical transportation links by air, land and water. (Perez, 2010)

Of the various means of transport, air travel is likely to be the most technologically complex of the four main methods of travel (air, road, rail and water) and provides by far the quickest way to transport goods and people. For that reason, an indicator for the efficiency of air travel services is incorporated in the empirical part of this research.

3.3 ICT

Information and communication technologies (ICT) were at the centre of the most recent technological revolution and have dramatically redesigned modern societies. In terms of specific technologies, it has progressed through radio, television, the Internet and mobile technologies (Thapa, Sæbø, 2014). Globalization would not have happened without the ICT revolution. Transoceanic fibre optics, the Internet and satellites enabled the complete reshaping of the structures and behaviours of modern trade and finance. (Perez, 2010)

Measuring the overall effect of digital technologies on the economy and productivity is a difficult task. Nevertheless, Jorgenson, Ho and Stiroh (2008) claim, that the productivity surge in the second half of the 1990s was led by information technologies. Another line of research has looked at how ICT services may have affected trade. Freund and Weinhold (2004) offered empirical evidence that the internet has stimulated trade largely through cost reduction. Gomez-Herrera, Martens and Turlea (2014) also determined that distance-related trade cost have notably decreased in comparison to the traditional store trade in the same goods. This is supported by Goldfarb and Tucker (2019) who claimed that the development of ICT has lowered transportation costs of information and digital goods, as well as physical goods. The rise of digital purchasing technologies has meant that customers are inclined to purchase physical goods online, especially when offline buying is difficult or costly. Moreover, the internet has facilitated buying in bulk, particularly when goods are on sale, because customers do not have to be concerned about having to carry large amounts of purchases, further lowering the overall cost of transportation.

While current discussions on development recognize ICT as integral for economic growth and the betterment of social conditions, ICT has also opened the “digital divide”, a noteworthy contemporary issue facing developing countries. The scarcity of ICT, especially restricted internet connectivity, deprives developing countries the significant growth opportunities and life improvement that are available to advanced countries. ICT services provide the means to participate in the global market and endeavours to develop them in poor areas provide great potential for economic development. (Avgerou, 2003) According to Thapa and Sæbø (2014), despite large yearly investments in ICT development projects in developing countries, major gains have not been reported. Poor management, lack of know-how and no political will due to resistance to change have severely undermined this undertaking.

Harindranath and Sein (2007) argue that the outcome of ICT interventions hinges on how national and local governments as well as development agencies and organizations conceptualize ICT and development. Pertaining to the idea that ICT is merely a tool to automate processes in order to improve governmental efficiency is a major reason why important developmental objectives have not been reached, as a large portion of the potential of ICT is left unrealised. One of the frameworks Harindranath and Sein (2007) introduced was initially suggested by Malone and Rockart (1991) and it states, that society can be impacted by ICT through three effects. The primary effect entails the substitution of old technology by the new. The secondary effect involves an increase in the phenomenon enabled by the technology. The tertiary effect entails societal change and the generation of new technology-related businesses. The first two effects are necessary but not sufficient conditions for development, while the tertiary effect is key for understanding the potential reach of the ICT influence and is instrumental for the sustainability of the developmental impact.

Based on what we established in section 3, we have grounds to claim that a notable portion of technology adoption can be attributed to the sectors of energy, transport and ICT, which in turn suggests that they are highly influential in determining economic development. This assertion is tested in the empirical part of this paper.

4 Data and method

In order to determine if and how technology affects economic development, an instrumental variable regression (IV) was conducted and indicators for energy, transport and ICT were used as instruments for technology. For the reasons detailed earlier, we assert that those three sectors can determine a significant portion of a country's technology adoption and in doing so, can indirectly account for a large share of economic development. For two-stage least-squares (2SLS) we treat the technology indicator as endogenous and model the equations

$$\log\left(Y_I/L_i \right) = \alpha + \beta t_i + \gamma' X_i + \varepsilon_i, \qquad (1)$$

where Y_i/L_i is output per capita in country i, t_i is technology adoption, X_i is a set of controls, and ε_i is a random error term and

$$t_i = \lambda + \mu E_i^2 + \nu TR_i^2 + \xi I_i^2 + \delta' X_i + \eta_i, \quad (2)$$

where E is energy efficiency regulation in country i, TR is efficiency of air transport services in country i, I is fixed-broadband internet subscriptions in country i and η_i again a random error term.

A standard ordinary least squares (OLS) estimate of equation (1) will be included into the analysis as well, but we argue that using the IV method in the manner detailed will provide a much more informative and layered approach. It will enable us to incorporate the influence of energy, transport and ICT provide, as those sectors summarize most of the information on technology adoption. An important distinction must be made, while we argue that the energy, ICT and transport sectors can summarize a large portion of technology adoption and, in turn, economic development, instrumental variable regression relies on the assumption that the three technological indicators have no effect on economic development other than as a measure of the technology adoption. Considering the nature of our instruments, as we utilize really narrow sub-indicators from our sectors of interest, which are likely not to have a notable direct effect on GDP per capita on their own, the exclusion restriction is reasonable and plausible.

The indicator used to describe economic development or Y_i/L_i in this paper is GDP per capita, based on purchasing power parity (PPP). The data was retrieved from World Bank and is for the year 2017, in current US dollars. The data for technology adoption (t_i) came from a rich dataset originally created by Bockstette et al (2002) and then developed by Borcan et al (2017). The key figure utilized is a technology adoption indicator, which incorporates ten different technologies (each weighted equally): electricity, trucks, cars, tractors, cargo and passenger aviation, the internet, PC's, cell phones and telephones, in per capita terms. It is in terms of years of usage of each technology relative to the number of years since the technology was invented. The measure was calculated capturing one minus the gap in the average intensity of technology adoption with respect to the US. The highest technology adoption figures can be found in Canada (0.93) and New Zealand (0.92) and the lowest in Mali (0.17) and Ethiopia (0.22).

The technological indicators for energy, transport and ICT were retrieved from the Global Competitiveness Report dataset, which also uses World Bank databases. All three indicators are also for the year 2017. Energy efficiency regulation was chosen as an indicator for technological aptitude in the energy sector since it assesses a country's performance in energy efficiency as well as its policies and regulation to promote efficiency. Therefore, the indicator also incorporates an institutional element and can demonstrate the implications of lock-ins and surpassing them. The score is based on 13 individual indicators that are scored between 0 and 100 and weighted equally. They are: national energy efficiency planning; energy efficiency entities; information provided to consumers about electricity usage; energy efficiency incentives from electricity rate structures; incentives and mandates: industrial and commercial end users; incentives and mandates: public sector; incentives and mandates: utilities; financing mechanisms for energy efficiency; minimum energy efficiency performance standards; energy labelling systems; building energy codes; transport; and carbon pricing and monitoring. As argued in previous sections, more straightforward measures of, for example, energy production, are not broadly informative nor indicative of technological prowess. The countries with the highest indicators for energy efficiency are Italy (84) and Canada (83) and with the lowest are Mozambique (25) and Burundi (29).

We chose the indicator of the efficiency of air transport services to represent transport. It describes efficiency in the sense of frequency, punctuality, speed and price, from extremely inefficient to extremely efficient. Air transport can be considered as the pinnacle of technological accomplishment in conventional means of transport, therefore an indicator relating to it was preferred to, for example, road or rail infrastructure. The countries with the most efficient air transport services are the Netherlands (90) and Finland (88) and with the most inefficient are Lesotho (6) and Mozambique (33).

Thirdly, a fixed-broadband internet subscriptions variable was used as an indicator for information and communication technologies. It refers to the number of subscriptions for high-speed access to the public internet (TCP/IP connection), including cable modem, DSL, fibre, and other fixed (wired)-broadband technologies per 100 population. The countries with the most fixed-broadband internet subscriptions are Switzerland (46) and France (45) with the lowest are Guinea (0.01) and Burundi (0.04).

To illustrate that other instruments from our fields of interest can be included to produce similar results and add value to our findings, alternative technological indicators were also used in another specification of the model, namely electrification rate, quality of roads and internet users. Electrification rate represents the percentage of the population with access to electricity. It is an estimate for the year 2017 and it entails a household having access to sufficient electricity to power a basic bundle of energy services. For example, a minimum of several lightbulbs and a phone. To represent transport, the quality of roads was chosen. It measures the quality of road infrastructure in the sense of extensiveness and condition, from extremely poor to extremely good and is the weighted average of 2018-2019. The number of internet users is another measure of ICT adoption in a country. It represents the percentage of individuals who, in the last three months, used the internet from any location for any purpose, regardless of the network or device used. Those instruments were also retrieved from the Global Competitiveness Report dataset.

When testing the functional form of the first phase of the 2SLS (equation 2), the Regression Equation Specification Error Test (RESET) determined that the instruments should be squared. This finding indicates that the net effect on technology adoption is greater than the linear increases of our technology sector indicators.

The set of controls used in both equations of our baseline specification include technology adoption in the year 1500, urbanisation and regional dummies (America, Asia, Africa and Oceania, Europe, as the base, was omitted from the model). Technology adoption in 1500 CE summarizes information across the 4 sectors of transportation, military, industry and communications, and purposely excluding agriculture and incorporating 20 technologies. The overall measure was obtained by averaging across the sectors. The measure was included, as Comin et al. (2010) claimed, that "old technology matters" and illustrated that past technology adoption has a positive effect on per capita incomes today. In addition, technology adoption in 1500 CE can potentially summarise information on technology adoption prior to the technological revolutions, which we consider as a starting point for our key sectors. Regional dummies were included to capture broad geographical factors. Both the technology adoption indicator in 1500 CE and regional dummies were additionally retrieved from Borcan et al (2017). Lastly, an urbanisation figure was also retrieved from World Bank, specifically urban population as a percentage of overall population for the year 2018. Urbanisation was included as a control, as it is thought to be linked with economic development because it fosters human capital accumulation (Bertinelli, Zou, 2008).

The descriptive statistics of all the variables used in the main results of the paper are detailed in Appendix A, Table 5. Most of the data was for 94 countries. Those countries are also depicted in Appendix A, in Table 6, according to their regional dummy variable. A temporal analysis on GDP per capita was also conducted to illustrate that although we use cross-section data, our indicator is representative of the long-term development of a state. The descriptive statistics of average yearly growth rates of GDP per capita for 1990-2000 and 2000-2017 can be found in Appendix A, Table 7. As can be seen, the growth rates are stable across countries (China is the notable exception), which indicates, that using GDP per capita for the year 2017 is appropriate for measuring longstanding economic development.

To test the robustness of our models, in an alternative specification, GDP per capita was replaced by GDP per worker as the dependent variable. That figure was calculated using World Bank data for GDP and total labour force. Furthermore, to address any potential endogeneity concerns, three alternative controls (detailed info in Appendix B) we incorporated into the analysis.

5 Results

To illustrate how technology adoption and the squared technological sub-indicators relate to each other, a scatterplot with a smoothed conditional mean with a 0.95 confidence interval is included in Figure 1.

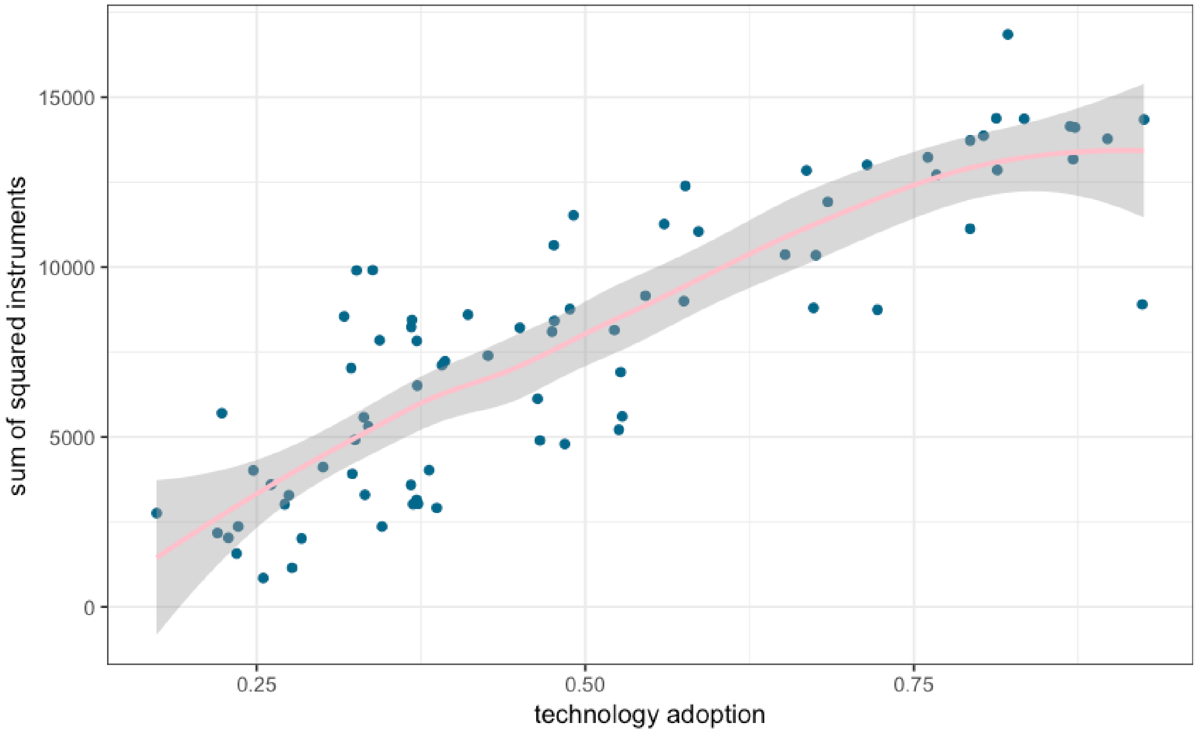

Figure 1. Relationship between technology adoption and the sum of squared energy, transport and ICT instruments
Source: author

As can be seen, a positive relationship exists between technology adoption and summed squares of energy efficiency regulation, efficiency of air transport services and fixed-broadband internet subscriptions. This informative relationship is used to instrument technology adoption in the two-stage least squares (2SLS) estimation. The indirect relationship between the squared instruments and log GDP per capita is illustrated in Figure 2. Once again, a smoothed conditional mean with a 0.95 confidence interval was added.

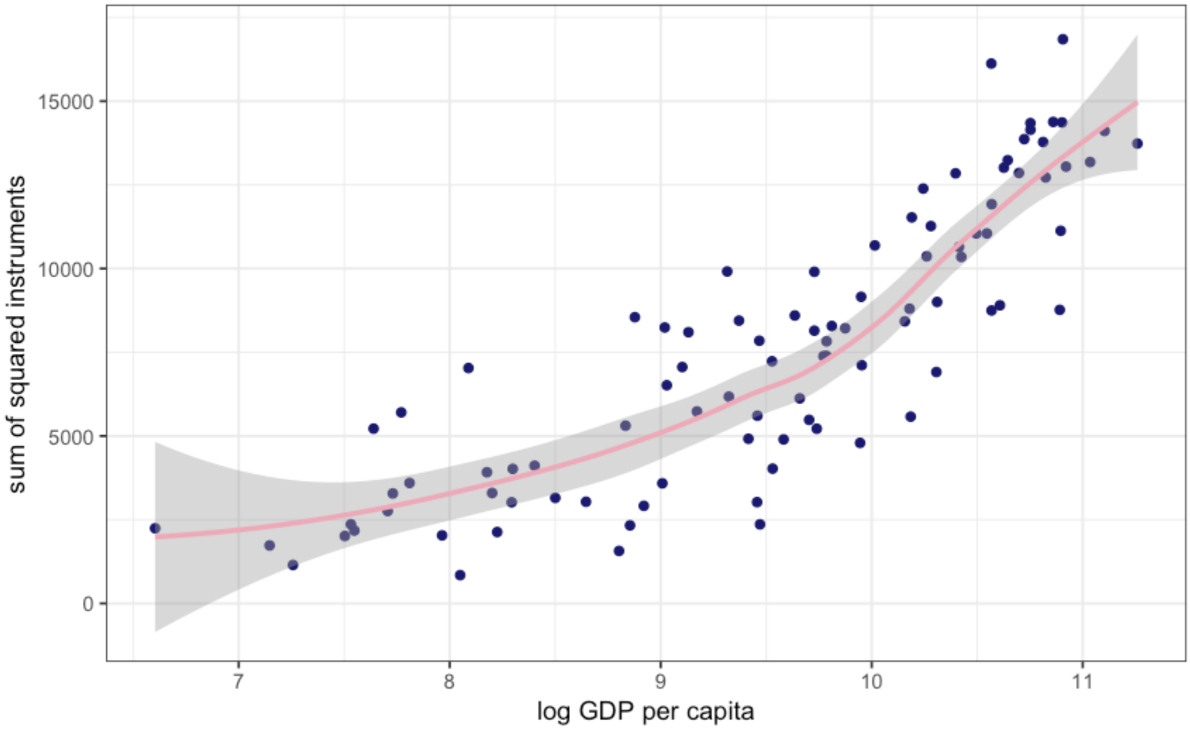

Figure 2. Indirect relationship between log GDP per capita and the sum of squared energy, transport and ICT instruments
Source: author

A clear, positive relationship between log GDP per capita and the sum of squared instruments is present, albeit it is not a direct relationship, but through technology adoption. The instruments can be utilized to describe economic development well. This will now be described in detail and shown quantitatively.

Table 2 shows the results of the two-stage least squares (2SLS) estimation for equations 1 and 2 with various specifications. Panel A presents the 2SLS estimates of our coefficient of interest from equation 1, β, and Panel B the corresponding first stages (equation 2). In Panel C, as a comparison, the results of a simple OLS estimation of equation (1) is shown, where technology adoption is treated as exogenous. The columns represent models with different controls, but regional dummies were included in all specifications of the models to capture broad geographical factors. Column 1 shows strong positive relationships between the first-stage instruments and technology adoption, all significant at the 1% level. The corresponding 2SLS estimate of the effect of technology adoption on GDP per capita is 3.87, also significant at the 1% level. Column 2 illustrates that adding

Table 2. 2SLS estimation of GDP per capita

	(1)	(2)	(3)	(4)
	log(Y/L)	log(Y/L)	log(Y/L)	log(Y/L)
Panel A: second stage				
Technology adoption	3.87***	3.95***	2.58***	2.11***
	(0.445)	(0.521)	(0.548)	(0.564)
Technology adoption in 1500 CE		-0.424		-0.135
		(0.443)		(0.350)
Urbanisation			1.62***	2.18***
			(0.409)	(0.400)
Regions	Yes	Yes	Yes	Yes
	Technology adoption	Technology adoption	Technology adoption	Technology adoption
Panel B: first stage				
Energy efficiency regulation squared	0.0000153***	0.0000167***	0.0000109**	0.0000136***
	(0.00000527)	(0.00000508)	(0.00000501)	(0.00000507)
Efficiency of air transport squared	0.0000349***	0.0000385***	0.0000273***	0.0000332***
	(0.00000725)	(0.00000719)	(0.00000702)	(0.00000730)
Fixed-broadband internet subs. squared	0.000176***	0.000159***	0.000160***	0.000145***
	(0.0000266)	(0.0000276)	(0.0000250)	(0.0000272)
Technology adoption in 1500 CE		-0.141**		-0.106
		(0.0673)		(0.0666)
Urbanisation			0.208***	0.148**
			(0.0573)	(0.0633)
Regions	Yes	Yes	Yes	Yes
P-value	0.0000	0.0000	0.0000	0.0000
Adjusted R2	0.806	0.816	0.853	0.888
Observations	79	66	79	66
Panel C: ordinary least squares				
Technology adoption	3.61***	3.70***	2.23***	1.97***
	(0.382)	(0.450)	(0.432)	(0.447)
Adjusted R2	0.807	0.816	0.854	0.888

Standard errors in parentheses
*** Significant at 1%; ** significant at 5%; * significant at 10%

technology adoption in 1500 into the baseline regression does not alter the highly significant and positive relationships present in column 1. The new variable is statistically significant only in the first stage, where it illustrates a negative relationship with technology adoption, alluding to the possibility of past technological lock-ins that hamper technological development in the present. Additionally, this result could refer to colonist setting extractive institutions to countries that were relatively well developed at that time, hampering further progress, like argued by Acemoglu and Robinson (2012). A negative relationship between technology adoption in 1500 and GDP per capita is present in Panel A too, but as it is statistically insignificant, no conclusive deductions can be drawn from it.

Adding urbanisation to the model in column 3 yields similar results, but notably both the coefficient for technology adoption and for efficiency of air travel services experienced a noticeable decrease. Urbanisation itself is statistically significant (at the 1% level) in both stages of the 2SLS, exhibiting a positive relationship with GDP per capita and technology adoption. Incorporating both technology adoption in 1500 CE and urbanisation in column 4 yields a model with the most descriptive power. Of the two, only urbanisation retains its statistical significance and positive relationship with technology adoption in the first stage, as it does in the second stage with GDP per capita. The coefficients of the instruments remain similar to those in column 1, but the corresponding 2SLS estimate of the effect of technology adoption on GDP per capita is lower, at 2.11.

All of our squared instruments possess statistically significant positive relationships with technology adoption. Their quadratic nature suggests that the net effect on technology adoption and, in turn, GDP per capita is greater than their linear increases. However, comparing the coefficients of the three is not quite straightforward, because while they all share a scale of 0 to 100, fixed-broadband internet subscriptions varies differently from energy efficiency regulation and efficiency of air travel services, as was detailed in the descriptive statistics in Table 6. We can still draw some conclusions. Energy efficiency regulation has the smallest coefficient of the three and is the only instrument to partially have statistical significance at only the 5% level (in column 3), while the remainder have statistical significance at the 1% level. Energy cannot be overlooked as a production input and while globally the limiting effect of energy scarcity has lessened, it is undoubtedly intrinsic for technological and economic development. Energy efficiency highlights why breaking away from energy-intensive patterns and technological lock-ins is vital. Efficiency of air transport services, has the second biggest effect on technology adoption and, indirectly, on GDP per capita according to the models. Therefore, providing reliable, fast and affordable mobility to people and goods is surely an impactful factor on development. ICT, represented by fixed broadband internet subscriptions, provides the biggest opportunity for growth, both due to its biggest impact on technology adoption and in terms of where there is the most room for improvement. As the mean and median for fixed broadband internet subscriptions (per 100 people) is around 15 and the maximum, in Switzerland, is 46, there is yet ample room for improvement and much potential for technological and economic development.

All four specifications of the models are statistically highly significant. The adjusted R^2 coefficients reveal that our approach is highly descriptive. The model in column 4 can account for 88% of the variation in GDP per capita. Diagnostics tests were conducted on all specifications of the model and they too revealed, that everything was in order. We could clearly reject the null hypothesis (at 1% statistical significance level, as for all) of the Weak instruments test, which states that all instruments have no effect for all four specifications. The Wu-Hausman test for endogeneity revealed that our estimates are efficient and that our model corresponds to the data. Overidentification was checked by the Sargan test and we could not reject the null hypothesis for columns 1-3, meaning that all instruments were valid, but not for column 4, meaning there were too many instruments, leading to some being invalid.

The 2SLS coefficient estimates are all larger than OLS estimates, which suggests that the noisiness of the technology variable might generate a typical problem of measurement error. This indicates that negative attenuation bias could be more relevant than the positive biases caused by reverse causality and omitted variables. Disentangling the multitude of clusters of political and economic institutions that influence economic development is a difficult undertaking and any one measurement can only account for just a part of the whole effect of the relevant cluster.

To judge whether the magnitude of the 2SLS estimates are sensible, we use Bulgaria and Poland as examples. Bulgaria has a slightly above average technology adoption index of 0.55 and increasing it by 0.1 would result in a 21%-39% increase of GDP per capita (if we use the range of estimates from table 2), specifically from 20,950 to about 25,400-29,100, bringing it in range of Greece (28,580), who has a technology adoption index of 0.65. Overall, Table 2 suggests a large, but probable impact of technology adoption on economic development and illustrates the three sector instruments can account for a significant part of economic development.

In Table 3 alternative instruments were added to our baseline specification. They were included to illustrate that other instruments from our fields of interest, energy, transport and ICT can be deployed to produce similar results and add merit to our findings. Specifically, electrification rate, quality of roads and internet users were used as instruments for technology adoption.

Table 3. 2SLS estimation with alternative instruments

	(1)	(2)	(3)	(4)
	log(Y/L)	log(Y/L)	log(Y/L)	log(Y/L)
Panel A: second stage				
Technology adoption	4.62***	3.85***	3.47***	3.15***
	(0.496)	(0.685)	(0.706)	(0.677)
Technology adoption in 1500 CE			-0.290	-0.254
			(0.34)	(0.372)
Urbanisation		0.936*	1.499***	1.658***
		(0.481)	(0.468)	(0.451)
Regions	Yes	Yes	Yes	Yes
	Technology	Technology	Technology	Technology
Panel B: first stage				
Electrification rate	-0.00000579			-0.0000064
	(0.00000646)			(0.00000623)
Quality of roads	0.0000331***	0.0000329***	0.0000283***	0.0000281***
	(0.00000649)	(0.00000609)	(0.00000713)	(0.00000712)
Internet users	0.0000431***	0.0000254***	0.0000303***	0.0000325***
	(0.00000703)	(0.00000737)	(0.00000812)	(0.00000838)
Technology adoption in 1500 CE			-0.0447	-0.0317
			(0.0780)	(0.0790)
Urbanisation		0.242***	0.150*	0.171*
		(0.0750)	(0.0835)	(0.0860)
Regions	Yes	Yes	Yes	Yes
P-value	0.0000	0.0000	0.0000	0.0000
Adjusted R2	0.788	0.830	0.866	0.875
Observations	79	79	66	66

Standard errors in parentheses
*** Significant at 1%; ** significant at 5%; * significant at 10%

Sticking with the controls that were included in Table 2, namely technology adoption in the year 1500, urbanisation and regional dummies, Table 3 validates our results, as a statistically highly significant (all at the 1% level) and positive relationship between technology adoption and GDP per capita was found. The coefficients for GDP per capita are somewhat higher compared to table 1, but in the same region. However, electrification rate as an instrument for technology adoption proved to be statistically insignificant in the first stages of the two-stage least squares estimations, which meant it was dropped from the models presented in columns 2 and 3. This finding is consistent with the theoretical foundation on which this paper is based. 46 countries out of the possible 94 had an electrification rate of 100%, which means it is not a reliable indicator for technological progress for most countries, even though it remains a development constraint for poor countries.

The quality of roads proved to be significant at the 1% level in all four specifications, as did the number of internet users. Both exhibited a strictly positive relationship with technology adoption, meaning that they have an indirect positive effect on economic development represented by GDP per capita.

While urbanisation remains statistically significant and exhibits a positive relationship with technology adoption in the first phase of the 2SLS, technology adoption in the year 1500 proves to be statistically insignificant in both phases.

All in all, Table 3 presents us four models, each statistically significant at the 1% level and with high descriptive powers, that range from 79% to 88%. The weak instruments diagnostic tests revealed no issues, but the Wu-Hausman test indicates that there are endogeneity issues with column 1 and 4. Moreover, a statistically significant Sargan test statistic alluded to overidentification problems in column 4.

6 Robustness

To examine the robustness of our previous findings and address any potential endogeneity concerns, we use four alternative controls and replace GDP per capita by GDP per worker as the dependent variable. The validity of the 2SLS findings in Tables 2 and 3 depends on the assumption that our energy, transport and ICT instruments have no direct effect on GDP per capita. While we judge this assumption to be plausible, we will now conduct an additional test on it by controlling for other potential variables that might be correlated with both our instruments and GDP per worker and examining whether adding those variables affects our estimates. Although this undertaking cannot totally rule out endogeneity concerns, we find in Table 4 that our central results are robust to the new controls. Detailed information and descriptive statistics for the alternative controls are in Appendix B.

The 2SLS estimates for GDP per worker in Table 4 were close to twice the value of GDP per capita (Table 2), which is proportional to the size of the workforce of most countries, as it amounts to less than half of the whole population on average. La Porta et al. (1998) argue that legal origins had an important role in shaping current institutions. For that

Table 4. 2SLS estimation with alternative controls and of GDP per worker

	(1)	(2)	(3)	(4)
	log GDP per worker	log GDP per worker	log GDP per worker	log GDP per worker
Panel A: second stage				
Technology adoption	6.242***	6.381***	6.13***	6.280***
	(0.333)	(0.392)	(0.474)	(0.391)
Military technology in 1500 CE			0.207	
			(0.226)	
State hist.				0.521
				(0.391)
Legal origins	No	Yes	Yes	Yes
	Technology adoption	Technology adoption	Technology adoption	Technology adoption
Panel B: first stage				
Energy efficiency regulation squared	0.0000120**	0.0000149**	0.0000171**	0.0000170***
	(0.00000580)	(0.00000606)	(0.00000644)	(0.00000613)
Efficiency of air transport squared	0.0000378***	0.0000317***	0.0000343***	0.0000328***
	(0.00000838)	(0.00000865)	(0.00000918)	(0.00000857)
Fixed-broadband internet subscr. sq.	0.000194***	0.000194***	0.000208***	0.000193***
	(0.0000269)	(0.0000278)	(0.0000299)	(0.0000275)
Military technology in 1500 CE			-0.0807**	
			(0.0386)	
State hist.				-0.105
				(0.0643)
Legal origins	No	Yes	Yes	Yes
P-value	0.0000	0.0000	0.0000	0.0000
Adjusted R2	0.833	0.842	0.854	0.845
Observations	79	79	79	79

Standard errors in parenthesises

*** Significant at 1%; ** significant at 5%; * significant at 10%

reason, the alternative 2SLS models in columns 2-4 were compiled with the regional dummies being replaced by legal origins dummies (Socialist, French, Scandinavian, German), British legal origins, as the base, was omitted. That change had little impact on our key estimates.

Dincecco and Prado (2012) argued, that to wage past wars, states made fiscal innovations to raise revenues, which in turn improved long-term fiscal capacity and economic development. To account for this potential effect, we include a variable for military technology in the year 1500 on the basis that states with the most advanced militaries needed to raise the most funds to support it, which helped to shape more efficient fiscal institutions on the long-term basis. Column 3 includes the military technology in 1500 CE measure in the baseline specification. We find the impact of technology adoption unchanged. As can be seen in Panels A and B, past military technology is statistically significant only in the first stage of the 2SLS, not having an apparent effect on GDP per worker directly. It has a negative effect on technology adoption, suggesting that past military technology could indeed have improved fiscal institutions, but might also have subjected states to technological lock-ins. The estimates for our instruments remain similar to previous specifications.

Borcan et al (2017) claimed that a hump-shape relationship exists between accumulated state history (measured by a normalized aggregate index of state history) and economic development, as accrued state experience increases productivity, while younger states have the potential to reach higher maximums. Therefore, in the long-run, for the mature states, the link between state experience and productivity is predicted to turn negative. To account for this potential factor, we include a state history variable in column 4, where it can be seen not to exhibit any meaningful effect nor statistical significance. Moreover, the Wu-Hausman test showed that there are endogeneity issues and a model of this specification does not correspond the data. An additional model was estimated where, in order to capture the potential hump-shaped effect, both linear and squared terms of the state history variable were included, but neither proved to be statistically significant.

In summary, Table 4 presents us with four highly statistically significant (at the 1% level) models with high degrees of descriptiveness (around 84%). While including the alternative controls cannot rule out endogeneity issues in their entirety, our central results still all remained highly significant and robust, which reinforces the claim that our energy, transport and ICT indicators are credibly exogenous.

7 Conclusion

While the integral part technology plays in economic development is widely recognized, too often an unwarranted one-directional approach is adopted. We argue that although it is very difficult to fully disentangle the countless variables that potentially influence growth, a significant portion, of economic and technological development can be attributed to three key technological areas – energy, transport and ICT. Those sectors can be used to summarize crucial information on technology adoption, making excellent instruments, as was evidenced by modelling more than 80% of technology's effect.

In our empirical analysis, we used the source of variation that arose from the strong positive correlation between our energy, transport and ICT measures and the technology adoption indicator to estimate substantial effects of technology adoption on GDP per capita. Those findings proved to be robust to a variety of specifications and controls. Since the narrow industry indicators of energy efficiency regulation, efficiency of air transport services and fixed-broadband internet subscriptions are not likely to have a direct effect on GDP per capita and are therefore exogenous, they make for plausible instruments.

The results indicate, that ICT offers the most potential for further growth and has the biggest effect on economic development. This finding is supported by Perez (2010), who maintained that the maturity of the current ICT revolution has not yet been reached. Transport technology has been very impactful on technology adoption and, in turn, economic development so far as well. This is in line with the assertions made by Cigu et al. (2019) and Ville (1990). The availability of affordable energy is an extremely robust growth constraint for developing countries, but the issue (developed) countries grapple with the most today is energy efficiency, since past investments have locked many states into energy-intensive paths, producing much inefficiency and making them vulnerable, which reinforces the findings of Benthem (2015) and Fouquet (2016). It is evident, that in order to promote economic development, states should recognize the crucial role technology plays and invest accordingly, as well as doing the upmost to support innovation. The frequency and severity of existing technological paradigms hampering the adoption of more advanced ones is regularly underestimated and calls for state intervention. Replacing existing technological paradigms can be difficult and painful processes but will be a major source of growth.

Technological lock-ins were a part of this analysis, albeit not in the forefront, but more effort to measure its effects could be a valuable avenue of further research, to which the implications reached here could provide a starting point. This paper does not identify the precise technological advancement processes to guide economic development and a specific investigation into the exact channels could be another potential area of future research.

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Appendix A

Table 5. Descriptive statistics of the variables used

	Obs	Mean	Median	SD	Min	Max
GDP per capita, in PPP USD	94	21734	16577	18323	738	77596
Technology adoption	79	0.49	0.45	0.21	0.17	0.93
Energy Efficiency Regulation	94	53.30	57.27	23.20	5.77	89.15
Efficiency of air transport service	94	59.9	61.0	15.0	6.04	89.9
Fixed-broadband Internet subs.	94	16.50	13.45	14.80	0.0093	46.33
Europe (dummy)	94	0.33	0	0.47	0	1
America (dummy)	94	0.17	0	0.378	0	1
Asia (dummy)	94	0.21	0	0.41	0	1
Africa (dummy)	94	0.27	0	0.44	0	1
Oceania (dummy)	94	0.02	0	0.15	0	1
Technology adoption in 1500 CE	67	0.53	0.53	0.33	0	1
Urbanisation	94	0.63	0.64	0.21	0.13	0.98
British legal origin (dummy)	94	0.26	0	0.44	0	1
Socialist legal origin (dummy)	94	0.21	0	0.41	0	1
French legal origin (dummy)	94	0.46	0	0.50	0	1
Scandinavian legal origin (dummy)	94	0.032	0	0.18	0	1
German legal origin (dummy)	94	0.04	0	0.20	0	1
GDP per worker, PPP USD	94	33093	16394	39092	473	174169
Electrification rate	94	86.0	99.998	25.2	10.09	100
Quality of roads	94	4.06	4.00	1.05	2.04	6.43
Internet users	94	61.2	68.7	26.6	2.66	99.01

Source: author, based on data from World Bank and Borcan et al (2017)

Appendix A cont.

Table 6. Countries used in the paper according to their regional dummy variable

Region	Represented	Countries
Europe	31	Albania, Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, North Macedonia, Moldova, Netherlands, Norway, Poland, Portugal, Romania, Russian Federation, Spain, Switzerland, United Kingdom
America	16	Argentina, Barbados, Bolivia, Brazil, Canada, Chile, Colombia, Costa Rica, Dominican Republic, Guatemala, Honduras, Jamaica, Mexico, Nicaragua, Paraguay, Peru
Asia	21	Armenia, Azerbaijan, Bangladesh, Cambodia, China, Georgia, India, Indonesia, Islamic Rep. of Iran, Israel, Japan, Jordan, Kazakhstan, Kyrgyzstan, South Korea, Lebanon, Malaysia, Mongolia, Nepal, Philippines, Saudi Arabia
Africa	24	Angola, Benin, Botswana, Burkina Faso, Burundi, Cape Verde, Cameroon, Egypt, Ethiopia, Gabon, Gambia, Ghana, Guinea, Kenya, Lesotho, Madagascar, Malawi, Mali, Mauritius, Morocco, Mozambique, Namibia, Rwanda, Senegal
Oceania	2	Australia, New Zealand

Source: author, based on data from World Bank and Borcan et al (2017)

Table 7. Descriptive statistics of average yearly growth rates of GDP per capita

	Obs	Mean	Median	SD	Min	Max
Average yearly growth of GDP per capita between 1990 and 2000	87	0.0178	0.0170	0.00332	-0.0558	0.142
Average yearly growth GDP per capita between 2000 and 2017	94	0.0354	0.0290	0.00346	-0.00554	0.184

Source: author, based on data from World Bank

Appendix B

Data appendix for the alternative controls used in Table 5.

Legal origins: dummy variables for English, French, Socialist, Scandinavian and German legal origins. States with English legal origins comprised the default group. Source: Borcan et al. (2017).

Military technology in 1500 CE: indicator for military technology in the year 1500. Source: Borcan et al. (2017).

Statehist: normalized aggregate index of state history, defined as the sum of all 50-year period state history scores, adjusted by a 1% discount factor. Takes into account if there is a government above a tribal level, is the government based locally or foreign and how much of the territory of the modern country was ruled by it. Reaches back to 3500 BCE and is for the year 2000. Source: Borcan et al. (2017).

Table 8. Descriptive statistics of the alternative controls

	Obs	Mean	Median	SD	Min	Max
British legal origins	94	0.223	0	0.419	0	1
French legal origins	94	0.234	0	0.426	0	1
Socialist legal origins	94	0.447	0	0.499	0	1
Scandinavian legal orgins	94	0.043	0	0.203	0	1
German legal orgins	94	0.054	0	0.227	0	1
Military technology in 1500	67	0.420	0.375	0.396	0	1
Statehist	94	0.246	0.227	0.164	0.0186	0.743

Source: author, based on data from World Bank and Borcan et al (2017)

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