UiO : University of Oslo

TIK

Centre for technology,
innovation and culture
P.O. BOX 1108 Blindern
N-0317 OSLO
Norway

Eilert Sundts House, 5th floor
Moltke Moesvei 31

Phone: +47 22 84 16 00
Fax: +47 22 84 16 01

http://www.sv.uio.no/tik/
info@tik.uio.no

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Senter for teknologi, innovasjon og kultur
Universitetet i Oslo

Technological Revolutions, Structural Change & Catching-Up

by

Jan Fagerberg (TIK, University of Oslo & UNU-MERIT) and Bart Verspagen (UNU-MERIT)

Abstract

Technological revolutions, i.e., clusters of technologies that collectively have a transformational impact on the global economy, are rare events that dramatically influence the opportunities facing countries at different levels of development. A central suggestion in the relevant literature is that countries that manage to adopt the new technologies associated with a specific technological revolution benefit economically from it. This is also assumed to go together with a changing specialization pattern in international trade. The paper considers the empirical merits of these suggestions, drawing on GDP and trade data for a large number of countries on different levels of development from the post-second-world-war period. The empirical analysis reveals a major divide in the global economy between a group of modern, industrialized countries, specialized in technology-based production, and another group of countries, specialized in commodities and resource-based products, and lagging behind both in terms of technology and income. More to the future, the paper also discusses the extent to which a new green technological revolution, with renewable energy as a central element, is currently emerging, and what impact this possibly might have for catching-up, structural change and economic growth for countries at different levels of development, e.g., China.

Keywords: Technological revolutions, catching up, specialization, renewable energy, China

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1. Introduction

This paper focuses on the role of technological revolutions in structural change and economic growth, with special emphasis on catching-up based growth. As explained in section 2 of this paper, technological revolutions, i.e., clusters of technologies that collectively have a transformational impact on the global economy, are rare events that dramatically influence the opportunities facing countries at different levels of development (Freeman and Perez 1986; Perez and Soete, 1988; Perez 2002).

As will be argued below, especially in section 3, successive technological revolutions also created a major divide in the global economy. Countries that managed to adopt the main technologies associated with technological revolutions, also managed to rapidly increase their standard of living. Countries that did not manage to adopt the new technologies were largely left with low development levels. As we will show below, this is associated strongly with the specialization pattern in foreign trade, see also chapters by Alcorta and Cantore, and by Porcile, in this volume. Developed countries are specialized in technology-based sectors and export the associated products. Less-developed countries are stuck in a specialization pattern of commodities and natural resource-based products. Since 1950, few countries were able to make the transition from the latter to the former category.

A common characteristic of the succession of technological revolutions from the 18th century onwards is that they use energy provided by fossil fuels intensively. However, burning of fossil fuels leads to emission of greenhouse gases, global warming and potentially very damaging effects, particularly for the poor part of the world (Stern 2015). To avoid this outcome, emissions of greenhouse gases from human activities need to be reduced to almost zero well before the end of this century, a goal almost all countries in the world are now committed to. This is very challenging indeed, as 80% of global energy currently comes from fossil fuels. Thus, nothing less than a technological revolution in the production and use of energy will be required. Section 4 develops the case for a renewable energy revolution, which it is argued is well underway, while section 5 considers the implications for catching up and economic growth.

2. A Schumpeterian Perspective: Technological Revolutions and Comparative Growth

2.1. Technological Revolutions

Technological change is an important driver of structural change. New technologies are associated with new consumer demand, new investment goods, and new materials as inputs to production. When new technologies diffuse through the economy, new production capabilities need to be developed. This leads to opportunities for new firms and countries to grow by supplying the new goods and services that the economy needs.

New technologies affect structural change by an interaction of radical and more incremental change. Radical technological breakthroughs create opportunities for a series of cumulative incremental innovations. Industrial history abounds with examples of this kind of interaction and the structural change that it leads to. For instance, the development of the steam engine with separate condenser by James Watt in the late 19th century (radical innovation) was followed by numerous improvements in steam engine technology (incremental innovation), enabling diffusion of the technology to a variety of application areas such as mines, factories, railways and steam ships (structural change) (see Von Tunzelmann, 1978; Nuvolari, 2006).

The interaction between radical and incremental technological change on the one hand, and structural change on the other hand, has been analyzed from a variety of perspectives. For example, in Schumpeter's business cycle theory (Schumpeter 1939), the main idea is that radical innovations will cluster in time, and that such clusters provide an upswing in economic growth. As a result, economic growth is distributed unevenly over time, giving rise to long cycles of economic prosperity followed by (relative) decline. In this way, the long waves of Van Gelderen (1913) and Kondratiev (1925) were connected to innovation. This is also where Schumpeter's notion of creative destruction becomes relevant: innovation causes structural change in which innovations (and the entrepreneurs that apply them) destroy incumbent market positions and the economic rents associated with them.

Freeman (1982), Freeman et al. (1982) and Freeman and Perez (1988) further developed Schumpeter's ideas. In their view, while some radical innovations may influence a specific sector or industry only, others may affect a whole range of sectors or even the entire economy. Freeman and Perez coined the term "technological revolutions" (or – alternatively – "changes in techno-economic paradigm") for "changes in technology systems (that) are so far reaching in their effects that they have a major influence on the behaviour of the entire economy" (Freeman and Perez 1988, p. 46-7). The defining feature of a technological revolution, they argue, is the emergence of a set of technologies developed around a cheap key input with very broad applicability (ibid, p, 48). Examples of such key inputs are oil during much of the twentieth century and microelectronic components more recently. The application of these innovations leads to learning effects, new innovations of various kinds, rapid exploitation of available technological opportunities, and as a result high productivity growth. This makes the new technologies attractive to apply, and leads to a virtuous circle, in which both the industry producing the key input and industries using it extensively (the "carrier" branches) grow very rapidly, resulting in extensive structural changes in the economy as the new technologies gradually take over a leading role.

According to Freeman and Perez, for such path-breaking innovation to come to (full) fruition, a number of complementary factors need to be in place, both in the form of an appropriate infrastructure, but also involving new ways of organizing economic activities and society at large. However, such complementary factors take time to develop, and a mismatch between the requirements of an emerging technological revolution and the existing socio-economic framework may therefore occur. This may lead to "structural crises of adjustments" (Freeman and Perez 1988), in which the potential of a new set of technologies is (yet) to be fully exploited, although the old technologies are already running out of steam. Nevertheless, in the course of time, technological, economic, organizational and social factors are expected to coevolve into a tightly integrated and mutually reinforcing system or, as they call it, a "dominant technological regime" (ibid, p. 47).

However, although a technological revolution may be quite dynamic for a prolonged period, sooner or later much of its extraordinary growth potential will be exhausted. Freeman (1982) points to Wolf's (1912) "law of retardation of progress" as the main explanation behind the decline of a technological regime. The law states that opportunities of any application in the technology domain will eventually run out due to physical limits. This leads to a decline in productivity growth. Abernathy and Utterback (1978) also pointed to such limits in the development of what they call a "dominant design". At this stage, the technological regime will be characterized by a high degree of inertia, and consequently acts as powerful barrier to new, radical initiatives that challenge the system. This is an important reason for the structural crises of adjustment highlighted by Freeman and Perez in their theory of economic development. More recently, Unruh (2000, 2002) suggests the term "techno-institutional complex" for this phenomenon, which he argues contributes to lock-in actors and resources to the existing, fossil-fuel based system ("carbon lock-in") and hamper the development and diffusion of more novel, climate-friendly technologies.

Much of the literature on the impact of radical technological breakthroughs focuses on the characteristics and delineation of successive technological (or industrial) revolutions from a historical perspective (see, e.g., von Tunzelmann 1995; Perez 2002). Freeman and various co-authors (Freeman and Louçã, 2001; Freeman and Soete, 1997; Freeman and Perez, 1988) distinguish five broad periods, starting with what is commonly known as the Industrial Revolution, and ending with the still ongoing ICT-age. The intermediate three periods are associated with steam power and railways (contrary to many popular accounts of the period, Freeman follows Von Tunzelmann, 1995, in associating the Industrial Revolution with water power); with steel and electrification, and with fossil fuels, the internal combustion engine, plastics and mass production.

A periodization that has recently gained popularity (see, e.g., Schwab, 2017) is to look at current developments in robotization, artificial intelligence and machine learning as a fourth industrial revolution. In Schwab's scheme, the first industrial revolution refers to the process of mechanization under the impact of steam power, with special roles for the iron and textiles industries. Broadly speaking, this encompasses Freeman's first and second periods. The second industrial revolution is associated with steel, oil, electricity and mass production. Again, this combines two of Freeman's periods. Finally, the third industrial revolution refers to the digital age, i.e., the rise of ICT, which is similar to Freeman's fifth period.

More recently, Perez (2016) has used the technological regime perspective in a forward-looking discussion of economic development. According to Perez, the global economy currently is in the middle of the ICT revolution and there are still large potential gains to be reaped. However, the prospects for succeeding in this depend crucially on policy-makers' abilities to give the ICT-revolution an appropriate direction, which she suggests calling "green", implying among other things a transition to a sustainable (circular) economy. We will delve deeper into these matters in Section 4 below.

2.2. Catching Up-Based Growth and the Global Income Distribution

Technological revolutions, irrespective of the precise periodization scheme being used, impact comparative growth dynamics. By and large, countries that manage to master the technological capabilities of the technological regime that dominates the global economic frontier, will be able to enjoy comparatively high living standards, while those countries that do not possess these capabilities will be lagging behind. Catching up to the economic frontier typically takes the form of acquiring the capabilities needed to participate in the current or emerging technological regime (Perez and Soete, 1988).

A theoretical framework that is useful to analyze these dynamics is the so-called Technology Gap Theory of economic development (Fagerberg, 1987, 1994). This theory starts from the idea that the international diffusion of technological knowledge can be a source for convergence of country income levels. Countries that are at a low level of income can benefit from the application of modern technologies that are available in the more advanced (rich) countries (Gerschenkron, 1962). But such diffusion is far from automatic, because it also depends on a number of factors in the knowledge-receiving country.

These factors have been dubbed social capability and technological congruence (Abramovitz, 1986, 1994 a,b). Technological congruence, or rather a lack of it, refers, among other things, to the idea that knowledge available in advanced countries is often of limited relevance to poor countries. One reason is that this knowledge refers to the current technological regime, and hence to modern sectors such as manufacturing and services, while the poor countries' economies are mostly dependent on sectors where this technological regime is less relevant, primarily agriculture. Other reasons include the capital intense nature of modern sectors and the need for economies of scale.

Social capability refers to the idea that in order to absorb foreign knowledge, the domestic economy needs capabilities, both at the agent level (e.g., human capital or education) and at the collective level (e.g., a well-working financial and legal system, and a competent and uncorrupt bureaucracy). Often, these capabilities are not sufficiently developed in countries far behind the global technological and economic frontier. Significant efforts may be necessary to develop the social capabilities required for catching up.

The need to invest in technological congruence and social capability to absorb international knowledge flows easily makes for a development trap (Verspagen, 1991). Countries that operate far behind the technological frontier usually do not have the resources to invest in these factors, nor the expertise to implement a successful policy to make absorption of knowledge possible. This is why they have a high probability to remain at low levels of development.

When countries do break out of the development trap that is created by lack of social capability and insufficient technological congruence, they often do so through capability-building in combination with significant public and private investment in the "modern" sectors that can facilitate development. Manufacturing used to be the primary modern sector (e.g., Korea, Taiwan), while natural resources could also be successful (Botswana, Oman), particularly driven by the seemingly unlimited demand for fossil fuels in the post Second World War period. Possibly, the services sector (e.g., in India) may take over this role in more recent times. But no matter what the primary "modern" sector is, significant capability-building, investment and structural change will be necessary.

However, successful cases of capability building for catching-up-based growth are rare. A number of countries in South-East Asia (first Japan, later Korea, Taiwan, Hongkong, Singapore) managed to achieve this during the second half of the 20th century, often by means of strong government involvement. Such active government policy towards structural change and knowledge absorption has been dubbed the developmental state model (e.g. Wade 1990; Amsden 1989; Kim 1997; Nelson and Pack 1999). Arguably, several other countries, primarily in Asia (e.g., China; Vietnam, are currently going through the same process.

3. An Historical Narrative

We will now empirically illustrate the theoretical ideas of the previous section by an historical narrative of global economic history since 1950. We start by looking at comparative levels of income between countries, and then address the interaction between technological regimes and structural change.

3.1. Catching Up and Convergence

We use the Maddison database on GDP per capita to summarize developments in income levels at the country level since 1965. The database covers almost all countries in the world on a yearly basis. Thus, we can analyze the global income distribution at the country level in a detailed way.

In terms of the countries in the database, 1990 marks a major change. This is the first year for which we have data for countries that came into existence after the breaking up of the Soviet Union and the Eastbloc, thus enlarging the number of countries from 134 (up to 1989) to 154 (from 1990 onwards). We therefore analyze the data separately for these two periods. For each period we present a graph of initial GDP per capita vs the growth rate of this variable. A negative relation between these two variables indicates convergence of catching-up based growth (initially poor countries growing faster than initially rich countries).

Figure 1 shows this relation for 1965 – 1989, which is the cold war period, with only a few communist countries included in the analysis. Countries are distinguished by groups (mostly geographically defined). We see a mix of experiences at the country level, including both convergence and divergence, often very specific to the country grouping. The group of developed countries, which includes non-Communist Europe and what Maddison calls the Western Offshoots (USA, Canada, Australia and New Zealand), shows clear convergence (a negative relation between the initial level and the subsequent growth rate of GDP per capita). The same holds for the group of five so-called Asian Tigers, which here includes not only Hong Kong, Korea, Singapore and Taiwan, but also Japan. Finally, Oman and Botswana also fit the convergence relationship, having low levels of GDP per capita, but the highest growth rates in the sample.

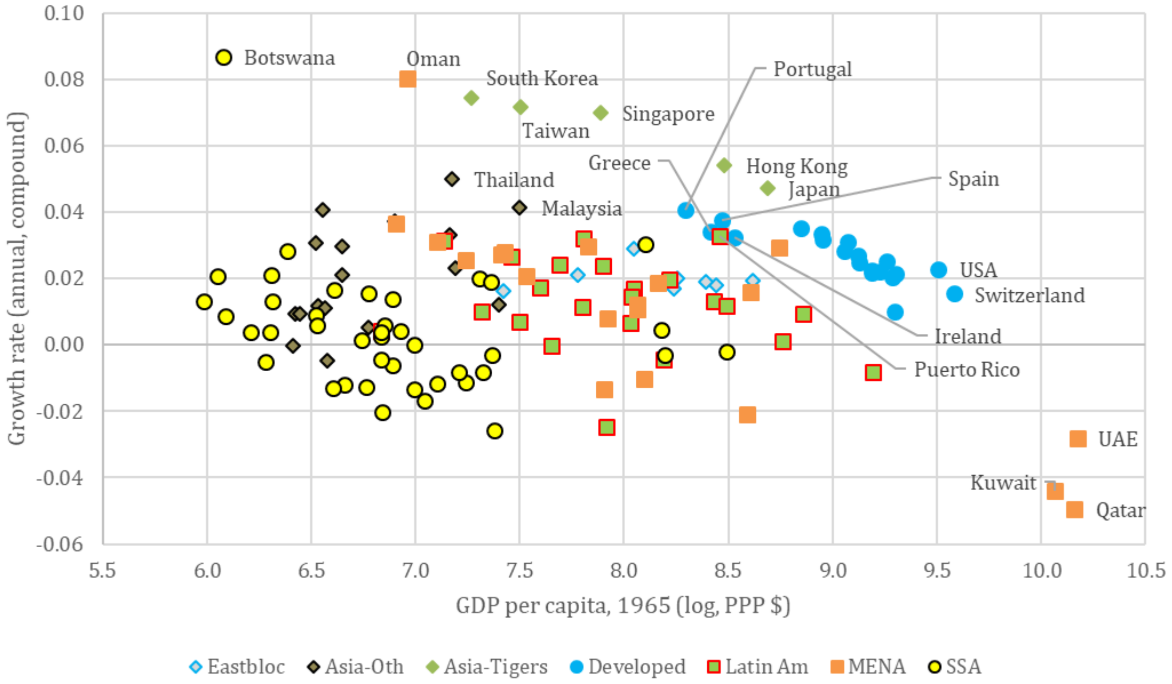

Figure 1. Convergence and divergence in the global economy, 1965 – 1989

By and large, the other groups of countries do not fit the convergence picture. There are a few isolated examples of countries, notably Thailand and Malaysia in the other Asia group, and Puerto Rico in the Latin America group, that could be argued to be part of the convergence relationship. But as a whole, Latin America, other Asia and especially sub-Saharan Africa show no convergence to the global frontier. Their moderate or low growth rates do not enable them to close the gap (in terms of GDP per capita) with the developed world.

Some countries in the Middle East and North Africa (MENA) group show a rather special pattern. These are the three oil-rich and small countries in the bottom-left of the graph. They have a very high initial level of GDP per capita, due to their oil wealth and small population, but show negative growth rates. Although they fit the convergence pattern, they will not be the main interest of our subsequent analysis.

We see significant change in this relationship during the post-cold war period (Figure 2). One major change compared to the cold war period is that growth in the developed countries is now much slower. As a consequence, there are now a much larger number of countries that are growing faster than the developed countries. Thus, we see more convergence in this post-cold war period than in the cold war period. But convergence is no longer defined very clearly in terms of the geographical groupings. Also, divergence (poor countries with low growth rates) remains a widespread phenomenon in this period as well.

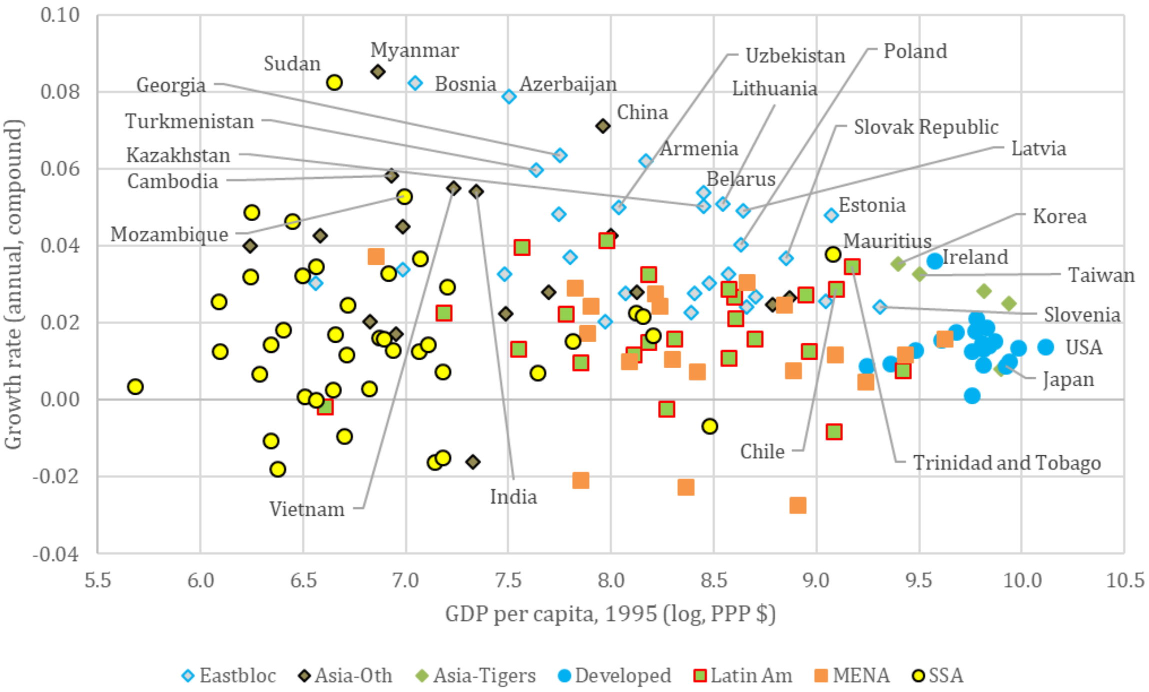

Figure 2. Convergence and divergence in the global economy, 1995 - 2016[1]

The Asian Tigers, with the exception of Japan (which grows very slowly in this period), are still on a converging trend and so are a number of developed countries. However, we also see that a fairly large number of formerly communist countries ("Eastbloc") now join the converging relationship, although at different degrees. In this group, the ex-Soviet republics are generally growing faster than the Eastern European countries, many of which joined the European Union after 1990. There are also two countries from the other Asia group (China and Myanmar), joined by Mauritius and Sudan from the sub-Saharan Africa group that are now rapidly converging. Other Asian countries that are growing rapidly are Vietnam, India and Cambodia. In Latin America, and MENA, we see

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[1] Libya, with initial level 7.75 and growth rate -0.068 is an outlier and has been excluded from the graph.

fewer countries with very high growth rates, and in sub-Saharan Africa performance is very diverse (some countries with rather high growth, some with low and even negative growth rates).

3.2. Structural Change and Technology

We will now investigate to what extent structural change, especially in relation to technological change, plays a role in the convergence and divergence trends of Figure 1 and Figure 2. For this purpose, we use a database that provides information on export value (in current US$) for 201 product categories. The reason for focusing on exports rather than production is mainly that data, especially for earlier years and less-developed countries, are better.[2] However, it may also be justified by the key role that structural change exports is generally assumed to play in catching-up processes. The database is based on the SITC rev. 1 trade classification. Although databases using different product classifications may provide us with much more detailed information, we prefer to use the SITC-1 database because it allows us to go back in time to 1965, i.e., much further back than the more detailed classifications, which typically start in the 1990s. For our analysis of structural change, such a long-run perspective is essential, and the 201 products still provide a reasonably detailed picture of export performance. The availability of countries differs greatly by year, and we focus on three particular years in the analysis: 1965, 1995 and 2010. This allows us to distinguish two periods, 1965 – 1995 and 1995 – 2010, that broadly correspond with our analysis of the cold war world and post-cold war worlds above. Unfortunately, the trade database does not cover all countries in Figure 1 and Figure 2. The 1995 – 2010 sample (102 countries) includes some formerly communist countries, while the 1965 – 1995 sample (63 countries) includes only countries from the non-communist world.

In both periods, the correlation between the average annual compound growth rate of GDP per capita and the same growth rate for export value (in current US$) is high: 0.83 for 1965 – 1995 and 0.51 for 1995 – 2010. This indicates that economic growth and export growth are intimately related. Because we are particularly interested in the role of technology, we apply the Lall classification (Lall, 2000), which assigns the 201 product classes in our database to one of six categories: commodities, resource-based manufactures, low-tech manufactures, medium-tech manufactures, high-tech manufactures, and other products.[3] Especially the distinction between the three technology based categories on the one hand and the commodities/ resource-based categories on the other hand will be of interest to the analysis here.

The Lall classification is relevant to our analysis because its broad categories are closely related to technological revolutions, especially the three technology-related groups of products. The group of commodities does not rely (much) on technology of any sort, and the resource-based group is mostly of a low-tech nature. In contrast, the high-tech class includes many products related to recent technological revolutions, such as ICT products. The medium-tech group also contains several products related to the technological revolutions that we are interested in, such as motor vehicles. Low-tech products, on the other hand, are based on relatively old technologies that are easily imitated.

Table 1 provides the breakdown of total export value into the five broad categories of the Lall classification. We omit the “other” category (also from the subsequent analysis) as it is very small.

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[2] A possible downside with using trade data, which are measured in values, is that we may underestimate structural change, because products with rapid productivity growth may see (relative) price falls.

[3] The implementation of the Lall taxonomy to SITC rev. 1 was downloaded from the World Bank’s Integrated Trade Solution website, https://wits.worldbank.org, August 2016.

Table 1. Shares of Lall-categories of products in total export value (current prices)

	Cold war world of 63 countries		*Post-cold war world of 102 countries*	
	1965	**1995**	**1995**	**2010**
Commodities	0.219	0.096	0.114	0.150
Natural resource-based manufactures	0.237	0.183	0.181	0.193
Low-tech manufactures	0.182	0.164	0.179	0.158
Medium-tech manufactures	0.283	0.395	0.372	0.344
High-tech manufactures	0.070	0.153	0.146	0.146

Note: categories do not add up to unity because category "Other transactions" has been left out (this is typically around 1% of the total).

We see that the three technology-based categories are always far more than half of total export value. During 1965 – 1995, these three categories rise from a 54% share to 71% share, while during 1995 – 2010, they fall from 70% to 64%. The share of low-tech manufactures falls in both periods, while that of medium-tech and high-tech rises strongly in the first period and remains stable (high-tech) or falls (medium-tech) in the last period. Commodities and natural resource-based manufactures are a falling share during 1965 – 1995 and a rising share during 1995 – 2010.

The increase of the share of commodities since 1995 is probably strongly related to movements of the oil price. During 1965 – 1995, the oil price rose by about 25% over the entire period, although there was a much higher spike in the middle of the period (1980). In the much shorter 1995 – 2010 period, the oil price roughly tripled.[4] Prices for other commodities (such as ores) also rose strongly over the 1995 – 2010 period. For countries exporting oil, such price increase represents an increase in income, so we must not dismiss this as mere inflation.

The importance of individual product classes in growth of total trade is distributed rather unequally. We calculate the contribution of an individual product class by multiplying its share at the start of the period with the growth rate of its trade value over the period (adding up this measure over all product classes gives growth of total export value). Table 2 provides an overview of the top-20 product classes in each period in terms of their contribution to export value growth. In both periods, these 20 classes (i.e., roughly 10% of all classes) provide over half of total export value growth (0.57 during 1965 – 1995, 0.59 during 1995 – 2010, as can be seen by adding up values in the share column).

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[4] Oil prices for West Texas Intermediate at mid-year (June) price levels, taken from https://www.macrotrends.net/1369/crude-oil-price-history-chart.

Table 2. Contribution of product classes to growth of total export value

rank	Product class	Lall	Share
1965-95			
1	Road motor vehicles	M	0.103
2	Other electrical machinery	M	0.064
3	Other non-electrical machines	M	0.061
4	Calculating machinery and other office machines	H	0.051
5	Raw iron & steel	L	0.030
6	Clothing, except fur	L	0.026
7	Plastic materials	M	0.026
8	Other telecom equipment	H	0.024
9	Organic chemicals, basic	R	0.024
10	Paper	R	0.017
11	Pharmaceuticals	H	0.017
12	Aircraft	H	0.017
13	Gasoline and refined oils	R	0.016
14	Oil, crude and partly refined	C	0.015
15	Electric circuit apparatus	M	0.015
16	Musical instruments, recordings	M	0.014
17	Internal combustion engines	M	0.013
18	Other chemicals	M	0.013
19	Measuring apparatus	H	0.011
20	Electric power machinery	H	0.010
1995-2010			
1	Road motor vehicles	M	0.079
2	Oil, crude and partly refined	C	0.057
3	Other non-electrical machines	M	0.054
4	Gasoline and refined oils	R	0.052
5	Other electrical machinery	M	0.049
6	Pharmaceuticals	H	0.038
7	Calculating machinery and other office machines	H	0.031
8	Raw iron & steel	L	0.029
9	Clothing, except fur	L	0.025
10	Organic chemicals, basic	R	0.025
11	Plastic materials	M	0.024
12	Natural and manufactured gas	C	0.019
13	Other telecom equipment	H	0.017
14	Ships and boats	M	0.015
15	Electric circuit apparatus	M	0.014
16	Other chemicals	M	0.013
17	Electric power machinery	H	0.013
18	Internal combustion engines	M	0.011
19	Measuring apparatus	H	0.011
20	Furniture	L	0.011

Notes: Lall column gives Lall product category (C = Commodities, R = Natural resource-based manufactures, L = low-tech, M = medium-tech, H = High-tech); Share column gives the contribution to growth of total export value (values of all 201 products add up to one in each period).

The medium-tech category dominates this list in both periods: eight products in both periods, adding up to 0.31 in the first period and 0.26 in the second period. High-tech is the second-largest category in both periods. Commodities and natural resource-based manufactures show a rising share in the second period. There is also a large degree of persistence between both periods: 17 of the 20 product classes in each period also appear in the other period. In the list of all 201 product classes, the correlation of the growth contribution in the two periods is 0.87, i.e., very high.

The list in Table 2 also shows a strong presence of product classes associated with the dominant technological regimes of the postwar world, as discussed in the previous section. For example, the top product class in both periods is road motor vehicles, while motorization is an important part of the post-1950 technological regime. The product class internal combustion engines (rank 17 and 18, respectively) also fits this pattern. ICT, another important element of the technological regime after 1950, is present in the form of several product classes, such as calculating machinery (rank 4 and 7), (other) telecom equipment (8 and 13), as well as in somewhat broader classes such as other electrical machinery, electric circuit apparatus, and measuring apparatus. Plastic materials, basic organic chemicals and other chemicals are other product classes present in Table 2 associated with the paradigm of mass production. Crude and refined oil, gasoline and natural gas, the fossil-based fuels associated with the major postwar technology regimes, are all present in Table 2 in both periods. In addition, Table 2 also includes some products related to "previous" technological regimes, such as iron and steel and electric power machinery (both featuring in Freeman's age of electricity and steel). Thus, almost all product classes in Table 2 can be identified in the narratives of major technological breakthroughs summarized above.

In order to investigate the relationship between structural change and catching-up based growth more closely, we look at the changes in specialization patterns at the country level. Table 3 summarizes these changes for the 63 countries of the cold war period (1965 – 1995). The table summarizes changes in specialization in terms of the five broad Lall categories of products. We define specialization in terms of the commonly used revealed comparative advantage (RCA) indicator.

About half (30 out of 63) of all countries is persistently (i.e., in 1965 and 1995) specialized in commodities or natural resource-based manufactures, or a combination of the two, i.e., these countries are not specialized in any of the three technology based categories in either year. This includes 13 (out of 16) Latin American countries, and all (13) sub-Saharan countries in the sample. There are also four developed countries and one MENA country in this group (the large oil producers from the MENA region are not included in the sample because data are missing).

There are three groups with a total of 22 countries in Table 3 that can be considered as technology-upgraders: either from an exclusive commodities or resource-based specialization into low-tech (9 countries), or from a low-tech specialization into medium-tech (three countries), or from low/medium-tech into high-tech (10 countries). All Asian Tiger countries are included in this broad group of upgraders (we do not have data for Taiwan). The latter two groups, which can be seen as the more radical upgraders, include only Asian countries (the Tigers plus Malaysia and Thailand, which showed high growth rates in Figure 1) and developed countries. In the less radically upgrading group (from commodities/natural resource-based to low-tech), we also find some countries from Latin America or the MENA region.

Table 3. Structural change in exports (current US$ value), 1965 – 1995

Countries without specialization in any of the technology-based categories in both years, i.e., specialized only in commodities and/or resource-based manufactures (n = 30)

Latin America: Argentina, Bolivia, Chile, Colombia, Costa Rica, Ecuador, Guatemala, Honduras, Nicaragua, Panama, Peru, Paraguay, Venezuela
Sub-Saharan Africa: Benin, Burundi, Burkina Faso, Central African Republic, Côte d'Ivoire, Cameroon, Congo-Brazzaville, Madagascar, Mauritius, Niger, Sudan, Togo
Developed: Australia, Canada, New Zealand, Norway
MENA: Jordan

Countries without tech-based specialization in 1965, but developing a specialization in low-tech (but not medium-tech or high-tech) in 1995 (n = 9)

Latin America: Brazil, El Salvador
MENA: Egypt, Morocco, Tunesia, Turkey
Developed: Denmark, Greece
Asia: Philippines

Countries with low-tech-based specialization and without medium-tech or high-tech specialization in 1965, but developing a specialization in medium-tech (n = 3)

Developed: Austria, Spain
Asia: Korea

Countries with low-tech or medium-tech-based specialization and without high-tech specialization in 1965, but developing a specialization in high-tech (n = 10)

Latin America: Mexico
Asia: Hong Kong, Japan, Malaysia, Singapore, Thailand
Developed: Finland, Ireland, Sweden
MENA: Israel

Countries with unchanging specialization that includes a tech-based category (n=5)

Developed: Belgium/Luxemburg, France, Netherlands, Portugal, USA

Other countries (n = 6)

Loosing medium-tech or high specialization: Germany, Italy
Loosing resource-based specialization: India, Pakistan
Loosing low-tech and medium-tech specialization: Switzerland
Gaining resource-based and low-tech specialization: United Kingdom

This suggests that structural change in the direction of technology-intensive exports (especially medium-tech and high-tech) is strongly related to catching-up based growth in the cold war era. To investigate this further, and to analyze the role of products related to the main technological regimes of the cold war era, Table 4 looks at structural change of the top-20 growth products (as in Table 2). The table lists the countries that develop new comparative advantages in each product, i.e., countries that do not have comparative advantage in the product in 1965 but do have comparative advantage in 1995.

Table 4. Top-20 growth products and the country that develop new comparative advantage in them, 1965 – 1995

rank	Product class/ countries with new comparative advantage	Lall
1	Road motor vehicles Canada, Japan, Mexico, Spain, Sweden	M
2	Other electrical machinery Korea, Malaysia, Philippines, Singapore, Thailand	M
3	Other non-electrical machines Japan	M
4	Calculating machinery and other office machines Hong Kong, Ireland, Japan, Malaysia, Netherlands, Singapore, Thailand	H
5	Raw iron & steel Brazil, Egypt, Finland, Greece, India, Italy, Spain, Turkey, Venezuela	L
6	Clothing, except fur Colombia, Egypt, El Salvador, Greece, India, Morocco, Mexico, Malaysia, Pakistan, Panama, Peru, Philippines, Thailand, Tunisia, Turkey	L
7	Plastic materials Belgium/Luxemburg, Colombia, Korea	M
8	Other telecom equipment Finland, Hong Kong, Israel, Korea, Mexico, Malaysia, Philippines, Singapore	H
9	Organic chemicals, basic Belgium/Luxemburg, Ireland, Israel, United Kingdom	R
10	Paper Brazil, Germany, New Zealand, Portugal	R
11	Pharmaceuticals Austria, Belgium/Luxemburg, Costa Rica, Guatemala, India, Jordan, Panama, El Salvador, Sweden	H
12	Aircraft Bolivia, France, Israel, Malaysia, Sweden	H
13	Gasoline and refined oils Argentina, Australia, Côte d'Ivoire, Congo-Brazzaville, Colombia, Ecuador, Finland, Greece, Korea, Morocco, Norway, Peru, Portugal, Sweden	R
14	Oil, crude and partly refined Argentina, Australia, Benin, Bolivia, Cameroon, United Kingdom, Guatemala, Mexico, Malaysia, Norway, Peru	C
15	Electric circuit apparatus Hong Kong, Japan, Mexico, Malaysia, Singapore, Thailand, Tunesia,	M
16	Musical instruments, recordings Hong Kong, Ireland, Korea, Mexico, Malaysia, Nicaragua, Singapore, Thailand	M
17	Internal combustion engines Austria, Brazil, Japan, Mexico, Portugal, Spain, Sweden	M
18	Other chemicals Belgium/Luxemburg, Colombia, Guatemala, Ireland, Israel, Jordan	M
19	Measuring apparatus Denmark, Japan, Sweden	H
20	Electric power machinery Denmark, Finland, Hong Kong, Mexico, Malaysia, Singapore, Thailand, Tunisia	H

Most of the 63 countries in the sample appear at least once in the table, but some countries appear rather often: Japan, Malaysia, Mexico, Singapore, Sweden and Thailand appear four or more times. Of these, only Mexico is not on a converging trend in Figure 1, its presence in Table 4 is probably mostly related to the strong growth of the *Maquiladora* industry after the signing of the NAFTA agreement. Note that Oman and Botswana, the most rapidly growing countries in this period, are not present in our sample. Anecdotal evidence suggests that their growth was mostly commodities based (oil for Oman and diamonds for Botswana).

Table 4 also provides insight into the role of products related to the main technological trajectories of the cold war era. The role of the Asian Tigers (including Japan) plus Malaysia and Thailand (which are also rapidly growing East Asian countries in this period) is notable in this respect: these countries are always prominent among the new "entrants" in product classes that relate to ICT. This is the case for other electrical machinery, with entrants from Asia only, and all entrants except Philippines from the high-growth group; for calculating machinery, with seven entrants, five of which are from the high-growth Asian group; other telecom equipment, with eight entrants of which four are high-growth Asia; and electric circuit apparatus, with five out of seven entrants from the high growth Asia group.

This evidence suggests that entry into product classes that are associated with new technological regimes can lead to high growth and catching up to the global economic frontier. However, such structural change is not a sufficient condition for catching up, as, for example, Mexico and the Philippines show. Both countries enter into similar product classes as Singapore, Malaysia, Thailand and Korea, but did not achieve similarly high growth rates. An explanation for this may be the fact that the specialization of these countries is mostly related to assembly, and that this adds little value (Castillo, 2018 shows that this is the case for the Mexican *Maquiladora*).

Table 4 also shows that a variety of other countries "enter" in products related to older technological regimes, such as iron and steel, or textiles. We see several countries from Latin America, other (low growth) Asia and MENA entering into these product classes, but none of these (except Malaysia and Thailand in clothing) show particularly high growth. A similar pattern can be observed in the high-tech product class pharmaceuticals, although in this case there are also many developed countries that enter.

Do these results carry forward to the post-cold war period? This is the question with which we will conclude our narrative in this section. Table 5 documents the broad structural changes (or lack of it) in terms of specializations in the Lall categories, for the post-cold war period. This uses mostly the same groupings as in Table 3, although there are a few changes arising from the difference in observed trends. One similarity with the cold war period is the large group of countries (40) that are persistently specialized in the commodities and/or resource-based categories. Like before, this includes mostly sub-Saharan African and Latin American countries, as well as the same four develop countries as before. We also now have a larger number of MENA countries in the sample, and these are largely found in this category.

Table 5. Structural change in exports (current US$ value), 1995 – 2010

Countries without specialization in any of the technology-based categories in both years, i.e., specialized only in commodities and/or resource-based manufactures (n = 40)

Sub-Saharan Africa: Benin, Burundi, Burkina Faso, Cameroon, Central African Republic, Congo-Brazzaville, Côte d'Ivoire, Ethiopia, Malawi, Mauritius, Mozambique, Niger, Sudan, Uganda, Zambia
Latin America: Argentina, Bolivia, Chile, Colombia, Costa Rica, Ecuador, Honduras, Nicaragua, Panama, Paraguay, Peru, Trinidad and Tobago, Venezuela
Developed: Australia, Canada, New Zealand, Norway
MENA: Algeria, Oman, Qatar, Saudi Arabia, Syria, Yemen

Countries without tech-based specialization in 1995, but developing a specialization in low-tech (but not medium-tech or high-tech) in 2010 (n = 6)

Sub-Saharan Africa: Kenya, Madagascar, Togo
Latin America: Guatemala
MENA: Jordan
Formerly communist: Kyrgyz Republic

Countries with low-tech-based specialization and without medium-tech or high-tech specialization in 1965, but developing a specialization in medium or high-tech (n = 8)

Formerly communist: Czech Republic, Hungary, Poland, Slovak Republic, Slovenia
Asia: China, Philippines
Developed: Denmark

Countries with low-tech specialization but not medium-tech and/or high-tech, in both years (n = 18)

Formerly communist: Croatia, Estonia, Latvia, Lithuania, Macedonia, Romania
Asia: Bangladesh, India, Nepal, Pakistan
MENA: Egypt, Tunisia, Turkey
Sub-Saharan Africa: Mauritania, Mauritius
Latin America: Dominican Republic, El Salvador
Developed: Portugal

Countries with medium and/or high specialization both years (n = 18)

Developed: Austria, Germany, France. Ireland, Italy, Netherlands, Spain, Switzerland, United Kingdom, USA
Asia: Japan, Korea, Malaysia, Singapore, Thailand
MENA: Israel
Latin America: Mexico

Countries with low and/or medium and/or high-tech specialization in 1995 and without any such specialization in 2010 (n = 11)

Latin America: Brazil, Jamaica, Uruguay
Developed: Finland, Greece
Formerly communist: Kazakhstan, Moldova
Sub-Saharan Africa: Gambia, South Africa, Zimbabwe

Other countries (n = 1)

From low-tech and high-tech to resource-based and low-tech: Hong Kong

There is now a smaller number (six) of countries that change from purely commodities and/or resource-based specialization to a low-tech specialization., but also a relatively large group (18 countries) that is persistently specialized in low-tech (without a specialization in medium or high-tech). This latter group includes six formerly communist countries, but also countries from various other groups. The group of countries with a persistent specialization in medium-tech and/or high-tech is also relatively large (18 members), and this includes mostly developed countries as well as the dynamic Asian countries from the cold war period. In addition, there is a group of 11 countries that loses the specialization in the tech-based categories. Finally, the group of countries that develops new specializations in medium and/or high-tech (the clearest form of upgrading) is relatively small (8 countries) and consists mostly of formerly communist countries in Eastern Europe. China is another notable member of this group.

In summary, these results repeat two important features from the previous period: first, a clear lock-in of some countries (mostly in Africa and Latin America) in commodities and resource-based production, and, second, upgrading in terms of technological specializations by a limited group of countries. But whereas in the cold war period this role was mostly played by the dynamic Asian economies, in the post-cold war period the role is taken over by formerly communist countries in Europe. Note that this latter group had higher growth than the developed world in this period, hence showed convergence.

Table 6 looks at the more detailed product level of the top-20 product classes in terms of their contribution to the growth of the value of total trade. We see the formerly communist European countries also in this table, where they appear as “entrants” in many of the medium and high-tech product classes, especially those related to ICT (calculating machines, other telecom equipment, electric circuit apparatus, measuring apparatus), as well as motor vehicles and other non-electrical machines. China is also a frequently listed entrant in Table 6, especially so in the ICT related product groups.

Summing up the evidence in this section, we find that structural change in the direction of medium-tech and high-tech exports is positively related to catching-up based growth. Countries with high productivity growth rates tend to specialize in technology-intensive products, which are the products that are related to the major technological breakthroughs of the era. Thus, our findings suggest suggests that entry into product classes that are associated with new technological regimes may lead to high growth and catching up to the global economic frontier. This seems to be true for the entire post-World War II period, but while initially a small number of dynamic Asian economies played this role, more recently it was taken over by formerly communist countries in Europe.

The major lessons are as follows: Because of the difficulties in adopting foreign technology, and realizing large structural changes as a result of this adoption, we see a major divide in the global economy between one group of modern industrialized countries specialized in technology-based production, and another group of countries lagging behind in terms of technology and income, and specialized in commodities and resource-based products. Although we see some changes to the role of commodities and resource-based production in the recent period, due to price increases of commodities, the basic duality in the global economy remains intact.

Table 6. Top-20 growth products and the country that develop new comparative advantage in them, 1995 – 2010

rank	Product class/ countries with new comparative advantage	Lall
1	Road motor vehicles Argentina, Czech Republic, Hungary, Korea, Poland, Portugal, Romania, United Kingdom, Slovak Republic, Thailand, Turkey, USA, South Africa	M
2	Oil, crude and partly refined Brazil, Côte d'Ivoire, Sudan	C
3	Other non-electrical machines Czech Republic, Finland, Slovak Republic, Slovenia	M
4	Gasoline and refined oils Cameroon, India, Jamaica, Kyrgyz Republic, Madagascar, Macedonia, Pakistan, Spain, United Kingdom, USA, Yemen	R
5	Other electrical machinery China, Costa Rica, Israel	M
6	Pharmaceuticals Spain, Greece, Hong Kong, Israel, USA	H
7	Calculating machinery and other office machines China, Costa Rica, Czech Republic, Hungary, Mexico, Philippines	H
8	Raw iron & steel Colombia, Nepal, Togo, USA	L
9	Clothing, except fur Denmark, Guatemala, Jordan, Kenya, Kyrgyz Republic, Moldova, Madagascar, Spain	L
10	Organic chemicals, basic Finland, India, Jamaica, Korea, Oman, Singapore, Trinidad and Tobago	R
11	Plastic materials Austria, Finland, Greece, Japan, Lithuania, Portugal, Singapore, Sweden, Thailand	M
12	Natural and manufactured gas Congo-Brazzaville, Croatia, Egypt, Honduras, Kazakhstan. Mozambique, Oman, Peru, Saudi Arabia, Yemen	C
13	Other telecom equipment China, Estonia, Hungary, Romania, Slovak Republic	H
14	Ships and boats China, Côte d'Ivoire, Congo-Brazzaville, India	M
15	Electric circuit apparatus China, Costa Rica, Estonia, Macedonia, Morocco, Philippines, Romania	M
16	Other chemicals Argentina, China, Denmark, Egypt, Japan. Macedonia, Norway	M
17	Electric power machinery Estonia, Hungary, Italy, Spain, Philippines	H
18	Internal combustion engines Czech Republic, Finland, Hungary, Italy, Poland, Thailand, Turkey	M
19	Measuring apparatus Finland, France, Hong Kong, Hungary, Israel, Moldova, Mexico, Malaysia, Norway, Singapore	H
20	Furniture Turkey	L

Commodity price booms do provide some countries with the opportunity to grow fast, but when commodity prices turn low again, or when a country has no natural resources like oil or ores, technology-based catch up is the way to rapid growth. This implies structural change in the direction of production that is related to the major technological regimes of the era, like ICT and motor cars in the post-1950 period. Catch up in products related to older technologies (such as raw iron and steel, or textiles) is also a possible channel for upgrading or production capabilities for some countries, but this is not co clearly associated with high growth.

Because only few countries manage to make this transition, we continue to see a clear and very persistent division at the global level between one group of countries who produce technology-based products, and another group of countries who produce commodities and resource-based products.

Will this pattern of potential catching up continue in the years to come, when the global economy needs to transform away from burning fossil fuels, pollution and non-sustainable resource use? Because this transition is very much based on new and emerging technologies, we may expect that countries able to quickly jump on the sustainable technologies bandwagon to be best placed for rapid development. The remainder of the paper explores on these questions. We will particularly focus on technologies related to sustainable energy as a main carrier of a potential technological revolution in the making, and ask which countries are best positioned to play a lead role?

4. A renewable energy revolution?

The high income that major technological breakthroughs brought to the developed world is not only based on knowledge but also on energy provided in the form of fossil fuels (Fouqet 2016). Whether it was steam, electricity, or direct burning of oil, gas and coal, energy provision in successive technological revolutions has almost exclusively based on burning fossil fuels. But as is now abundantly clear, burning fossil fuels leads to emissions of greenhouse gases into the atmosphere, temperature rise and broader climate change, with potentially very harmful economic and social effects, particularly for the poor part of the world (Stern 2015). Thus, the present development path of the global economy is clearly not sustainable. To change this will require major changes in production, consumption, resource use, and ways of life. An important part of this, and where changes are already taking place, concerns provision and use of energy. This is why we conclude this chapter by a brief discussion of how the ongoing revolution in renewable energy technologies fits in the pattern of technological change and structural change as we know it from previous technological revolutions. Mathews (2013, 2014) and Stern (2015) have indeed suggested that there is evidence of a "green" technological (or industrial) revolution in the making.

The sun is an abundant source of energy. Only a tiny share of the sunshine that reaches earth during a year would be sufficient to cater for all human needs. The sun is the ultimate source of hydroelectric energy (rain), bio-energy (photosynthesis), wave energy, wind energy and solar energy. Hydroelectric energy is traditionally considered clean[5] and relatively inexpensive, but the prospects for massively scaling up production of it globally are bleak. Bio-energy may not play a major role either because the photosynthesis is a relatively inefficient way to convert sunshine to other, usable forms of energy; it demands a lot of water (which is a scarce resource); and it competes with producing food (which also is in limited supply) to a growing global population (Seba 2014). Wave energy has not really caught on but wind and solar have, particularly during the last few decades (Seba 2014, Goodall 2016).

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[5] More recently, scientists have pointed to a fair amount of CO2 emissions due to hydroelectric energy, see, e.g., https://www.newscientist.com/article/dn7046-hydroelectric-powers-dirty-secret-revealed/.

Can renewable energy from wind and solar, complemented with other renewable sources, be sufficient to cater for humanity's needs? This will to an important extent depend on the price of these forms of energy. As experience from previous technological revolutions suggests, the price of core inputs tends to fall rapidly over time, due to dynamic increasing returns to scale that lead to large increases in efficiency.

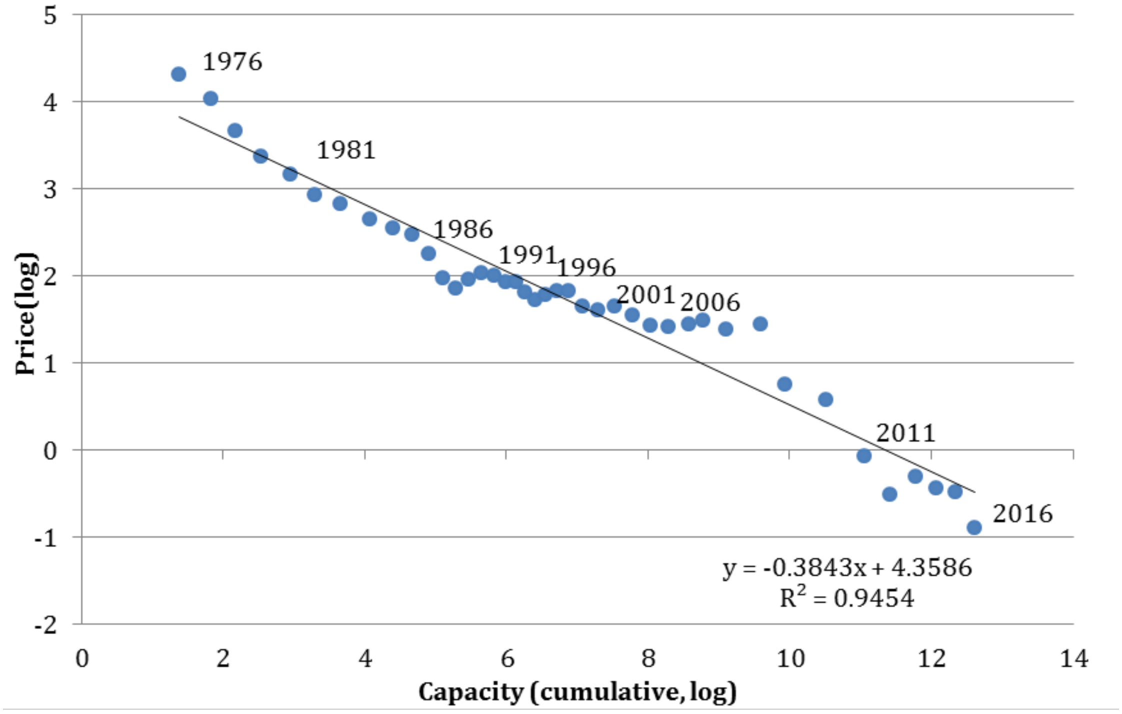

Figure 3. Price of generating electricity by solar power, per watt

Note: Price per watt is the average price of a photovoltaic (PV) module (in constant 2016 US dollars) divided by its rated DC output power in watts. Capacity (cumulative) in a specific year is the sum of the rated DC output power in watts of all PV modules produced prior to that year (starting in 1976). The regression underlying the trend-line is included in the lower right of the figure. Source: Own calculations based on data from Bloomberg New Energy Finance (with contributions from IEA and Paul Maycock).

It has been argued, though, that while the core technologies of previous technologies revolutions offered significant benefits to users, leading to rapid adoption and increasing scale associated with price drops, the same does not hold for renewable energy because of its high costs compared to fossil alternatives (Pearson and Foxon 2012). In their view, continuing diffusion of renewable energy will be totally dependent on subsidies, i.e., policy, and this makes it very different from prior technological revolutions. However, while this may be an accurate description of the situation a few years back, it is arguably not true anymore. Today, cost-levels for renewables are substantially lower than those of e.g., nuclear energy plants (Seba 2014)[6], and - in many if not

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[6] In the early post-second-world-war period nuclear energy was widely considered as the most promising technology for producing electricity but safety concerns and increasing costs have since undermined the public trust in the technology. It is now generally regarded as "too expensive, too dangerous and too dirty"

most locations world-wide - on par with or below plants producing electricity by burning fossil fuels even when the social costs associated with greenhouse gas emissions are not accounted for (Goodall 2016). Consistent with this, the first contracts for the development of renewable energy plants without public subsidies have already been signed.

Figure 2 and Figure 3 provide evidence that the prices of energy generated by renewable sources have dropped rapidly over time. Certainly these patterns, with no apparent slowdown yet, seem to fit the bill of price drops of key material and energy inputs observed in previous technological revolutions.

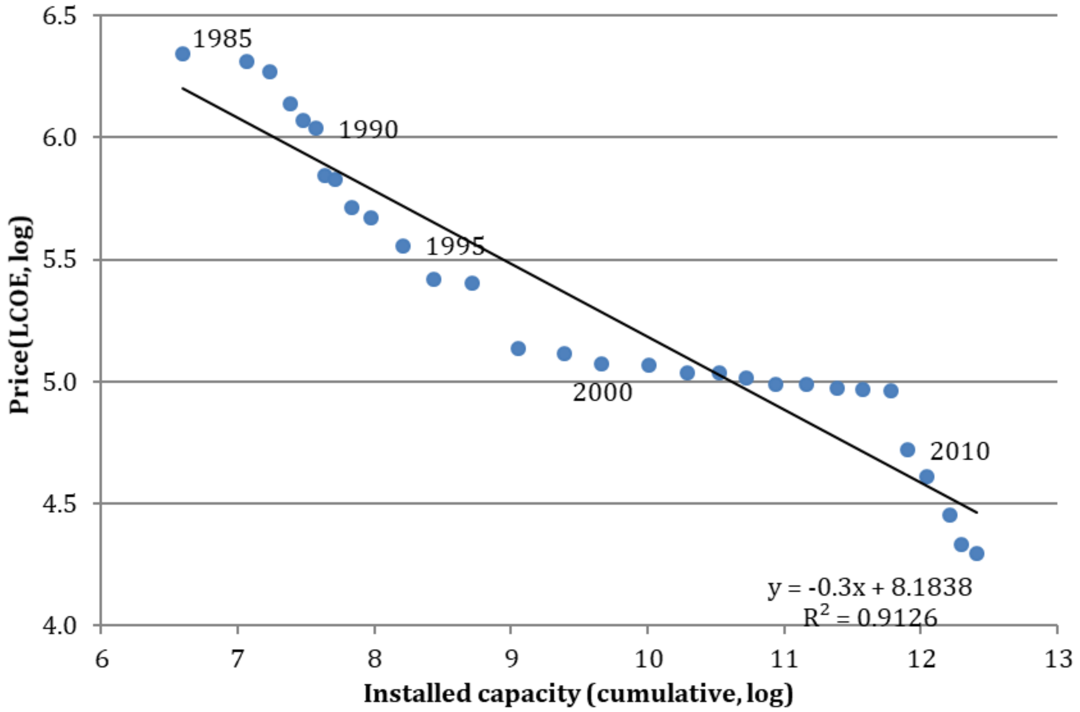

Figure 4. Price of generating electricity from wind power

Note. The figure plots the levelized cost of electricity (LCOE, vertical axis, in logs), which is the cost to build and operate a power-generating asset over its lifetime divided by its output, against cumulative installed capacity in MW (horizontal axis, in logs). Source: Own calculations based on data from Bloomberg New Energy Finance

Moreover, it might be argued that Pearson and Foxon underestimate the co-benefits that renewable energy technologies offer to adopters and the role that this has placed in the diffusion of these technologies. Burning fossil energy for electricity production, heating, powering machinery, vehicles etc. not only leads to global warming, it also creates serious environmental damage at the local level. Substituting fossil fuel with renewable energy may lead to significant improvements in well-being and health locally. Such concerns have certainly played an important role in the diffusion of renewable energy in countries like Germany and Denmark (see later) and continue to do so in e.g. China today.

(Seba 2014, p. 171) As a consequence, many old nuclear plants are now being retired, while very few new ones are built.

Perez (2010) points to two further crucial aspects of a technological revolution. The first has to do with how closely the technological systems that together make up the revolution are related, while the second – that she emphasizes as being very important – concerns the capacity to transform the rest of the economy (and eventually society) in a way that allows the new technological systems to deliver on their promise. With respect to these criteria, the renewable energy revolution is made up of, first, a series of technological systems (wind, solar etc.) that exploit the same (abundant) source (the sun) to produce the same product, i.e., energy (mostly electricity) and, second, of a number of systems using this (cheap and abundant) product to deliver new and existing goods and services in an environmentally more benign way than what was possible before.

Arguably, a global energy-system based on renewables, particularly wind and solar, implies that the whole world will have to go electric, with electricity produced by renewable energy. This means, first, that renewables have to substitute for fossil fuel in production of electricity worldwide. Moreover, the entire transport-sector – a major emitter of greenhouse-gases worldwide – would have to be electrified, either battery-driven or by using fuels, such as hydrogen, derived from renewable energy. The same goes for heating of buildings, and a number of industrial processes that today depend on energy from fossil fuels. Nevertheless, a severe challenge in an energy system based on renewables is what to do when the wind doesn't blow and/or the sun doesn't shine. To alleviate such problems, energy-storage, distribution and management systems will have to be radically improved through innovation, e.g., the development of very advanced smart grids. As this example shows, the transition from fossil fuels to renewable energy will depend on – and give raise to – numerous innovations in other parts of the economy. Thus, the transition will require extensive changes in technology, business models and ways of life more generally, just as the theory of technological revolutions predicts. It should be noted, however, that substituting burning fossil fuels with renewable energy is arguably just one – albeit very important – step towards a sustainable economic system, which also will require radical changes in a number of other dimensions, e.g., food production, resource use and management, and the way we live and work (Laestadius 2015).

It is important to note that wind- and solar-based systems for producing electricity are not recent inventions. Wind was a traditional source of energy in mills and sailing ships. In more modern reincarnations, both solar and wind energy have been around for at least half a century. As for many radical innovations, the first modern versions were costly, unpractical devises that in most instances were unable to compete with other ways to produce electricity and therefore attracted few users. Nevertheless, the oil-crises of the 1970s led to increasing attention to energy security and hence also to other possible sources of energy supply than fossil fuels in several Western economies. Wind-energy attracted special attention in Denmark, which – fuelled by public policies supporting technology diffusion (deployment)[7] - became a global hotspot for innovation in this area, and home to leading technology providers such as Vestas. Later such diffusion-oriented policies were adopted in Germany as well as a key part of the so-called Energiewende. As a result the share of renewable energy in electricity consumption displayed in Figure 5 - and total energy consumption - increased rapidly in both countries and in Europe as a whole.[8]

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[7] The original approach in Denmark was to subsidize the price of the wind turbine itself. This turned out to be not very effective, however, so later this gave way to a guaranteed right for producers of renewable energy to connect to the grid and sell excess electricity to a "fair" price (a so-called feed-in tariff). Subsequently this policy instrument became adopted in Germany as well, as a key element in the so-called "Energiewende".

[8] Source for the underlying data in the figure is Eurostat [nrg_ind_335a], accessed on August 3, 2017.

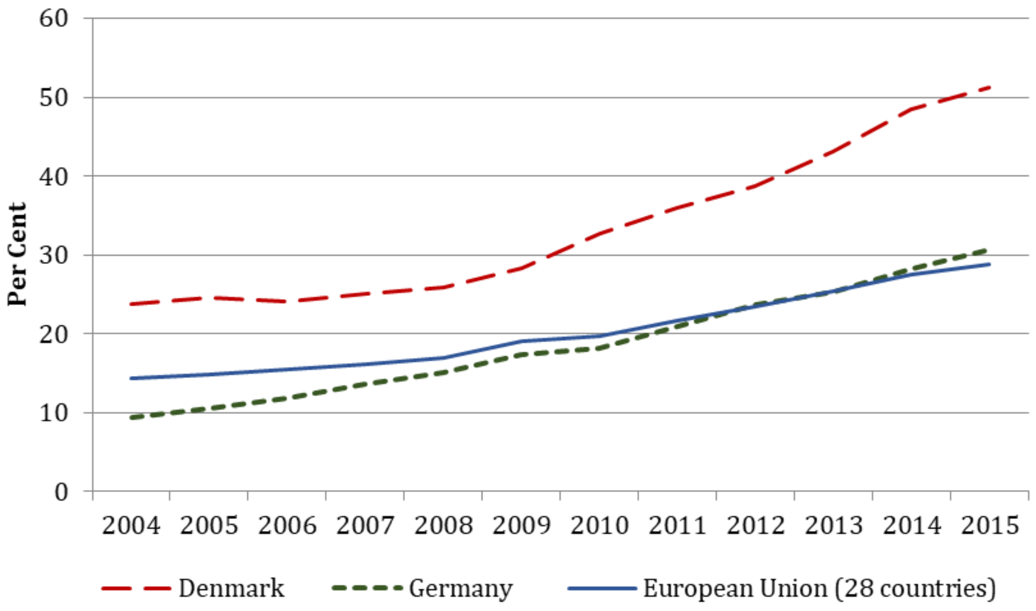

Figure 5. Share of renewable energy in electricity

Energy research has shown that previous energy transitions have taken several decades if not more to unfold (Wilson 2012, Smil 2016), but also that change may occur much faster when advantages for end-users are sufficiently large (Grubler 2012, Pearson and Foxon 2012) and/or there are proactive policies in place (Sovacool 2016). The policies towards renewable energy pioneered in Denmark, Germany and other European countries from the 1980s onwards met both these criteria. The essence of the policy was to compensate users for the higher costs of investing in renewable energy when compared to conventional, fossil alternatives, with the expectation that the larger (and rapidly growing) user base that this leads to would spur technological progress and reduce costs, so that need for subsidies gradually would be reduced and eventually cease altogether. While pioneered in Denmark, the policy became particularly pro-active in Germany from around the turn of the century onwards, after the coming to power of a new red-green government. The German approach had a much broader focus, targeting technologies at different stages of maturity with technology-specific feed-in tariffs, this came to have a particularly large effect in the case of solar (Figure 6).[9]

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[9] Source for the underlying data of the figure is Own calculations based on data from *Bundesminister für Wirtschaft und Energie*, (http://www.bmwi.de/DE/Themen/Energie/Energiedaten-und-analysen/Energiedaten/gesamtausgabe), accessed on 1.10.2016.

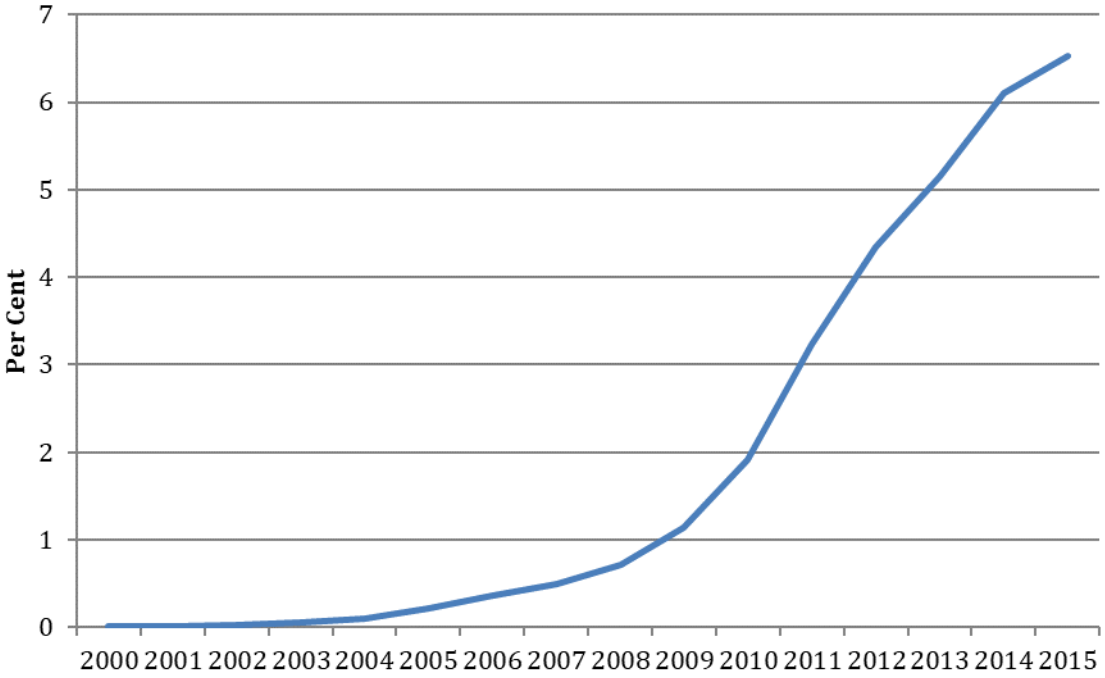

Figure 6. Germany: Share of solar energy in electricity

Similar policies were also to a varying degree adopted in other European countries, and an important European industry serving the rapidly expanding demand for capital goods for the renewable energy sector gradually evolved. However, the growing market also attracted the attention of Chinese firms, particularly for solar panels, which led to increased competition and declining prices, and eventually several bankruptcies in Germany and other countries. On a global scale, though, lower prices led to increased demand, and stronger growth in the deployment of renewable energy. Another development was increased demand for renewable energy technologies in China itself, particularly after the advent of the financial crises, which led to a weaker demand in Western markets and steps by the Chinese government to compensate for this by spurring domestic demand. Increased deployment of renewables was also embraced by the Chinese leadership as a welcome alternative to the polluting, fossil fuel-based technologies on which China until then had relied on, which had led to numerous health problems (and potentially also social and political unrest). As a result, China quickly developed into the largest market globally for renewable technology. In fact, it's per capita investments in renewables overtook those of the European Union in 2015, and it uses three times as much as Europe on investments in clean energy when measured as a share of GDP (Mathews 2017). What are the possible implications of this for global catching-up and economic growth? This is the question to which we now turn.

5. Implications for catch up and convergence

We have in this chapter made use of a theoretical perspective that identifies not only continuous change, but also major discrete events in the form of a technological revolutions, as major drivers of technological and economic progress. As explained in section 3 above, technological revolutions, although rare, evolve through interactions between major technological, social and institutional changes and give rise to technological regimes, which define the characteristics required for succeeding in catching-up processes.

Catching-up to the global economic frontier from a relatively backward position is a demanding process. It requires the adoption of technological knowledge of the dominating techno-economic system, and this comes with deep structural change, both in the direct economic sense (new sectors and activities) and in a broader societal sense. A stable technological regime may make it easier for countries with the required characteristics to succeed. For example, as Abramovitz (1994 a,b) explains, during the post 2nd World War years a number of European countries (and Japan as well) managed to exploit a window of opportunity by developing adequate social capabilities and making the economic environment more congruent by the conditions prevailing in the leader country (through trade liberalization for instance). Similarly, as was shown in section 3 above, in the era of ICTs, a number of countries, particularly in Asia, succeeded to join the catching-up path by developing capabilities of specific relevance for entering the ICT sector, while simultaneously benefitting from access to huge the US and European markets. As pointed out earlier, the larger the gap, the greater importance did dedicated catch-up policies by the government play, as evidenced by Japan in the early post-2nd World War period (Johnson 1982) and Korea and Taiwan more recently (Amsden 1989, Wade 1990).

However, a technological revolution also means that the rules of the game change, changes that become codified with the evolution of a new technological regime. The question addressed here is if a new green technological revolution, with renewable energy as a central element, is developing, what impact might it have for catching-up, structural change and economic growth? At the centre of attention is the role of China, which hitherto has caught up mostly by adapting to conditions based by the existing ("pre-green") technological regimes. A sizeable gap remains though. Can China reduce this gap further by leading the way in the emerging renewable energy revolution? Our assessment is that this is indeed possible (see also Mathews 2014, 2017). First, China's leadership has very strong incentives for engaging with renewable energy, not only because of climate concerns, but also for reducing local pollution and the possible social and political unrest it might lead to. Second, the sheer size of its domestic market implies scale advantages as well as the possibility of influencing regulations, standards etc. and hence the further development of the push to a sustainable economy, of which renewable energy is a central element. Nevertheless, other advanced Asian economies are very concerned about these opportunities, e.g., Korea's green growth strategy (Mee Lie 2017), so it is possible that the Asian involvement in this new path will extend beyond China itself.

What will be the role of extant technological leaders in the coming technological revolution? The USA is home to relevant capabilities and resources, but its political leadership is hostile to the emerging revolution, and nostalgic about the polluting system of the past. Europe has played an important role in generating the new path and is home to important industrial actors. Until the financial crisis Europe seemed destined to emerge as the leader in this area. The Chinese push into this area during the crisis years, and similar cutbacks in Europe, leaves the European industrial presence in this area vulnerable. Perhaps the situation will be one of cooperation to the mutual benefit of all concerned rather than cut-through competition (Schmitz and Lema 2015) but that remains to be seen.

What about the developing part of the world? Will the emerging technological revolution make catch-up easier or more difficult? The answer is that these are very promising developments for the poor part of the world. This is so because renewable energy opens up for local initiatives and decentralized solutions in contrast to the very centralized, capital-intensive systems that characterize electricity production and distribution today. Much in the same way as the transition from wired to mobile telephony made investments in costly infrastructure unnecessary and made telephony and other ICT-based services available to people who would otherwise have been excluded from them. And access to cheap renewable energy makes this a whole lot easier of course. Hence, the interaction between the renewable energy revolution and the ICT revolution offers great opportunities for developing countries.

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