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Do Lead Markets for Clean Coal Technology Follow Market Demand? A Case Study for China, Germany, Japan and the USA

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Abstract

Despite the high CO2 emission intensity of fossil and especially coal-fired energy production, these energy carriers will play an important role during the coming decades. The case study identifies the main technological trajectories concerning more efficient fossil fuel combustion and explores the potentials for lead markets for these technologies in China, Germany, Japan and the USA taking into account the different regulation schemes in these countries. We concentrate on supercritical (SC) and ultra-supercritical (USC) pulverized coal technologies that are already established.

The case study shows that lead markets may not be always stable. During the 1960s and 1970s, the USA can be identified as a lead market for SC und USC technologies. Japan was still a lag market but it surpassed the USA in the early 1980s especially because of its technological capabilities. It can also be observed that other advantages ? such as price and demand advantage ? are shifting to China. China is practicing a leapfrogging strategy and has already become a leader in the market segment of low and middle quality boilers, whereas Japan and Germany still dominate the world turbine market.
The conclusion is that lead markets may switch over time to markets with high growth rates, although first mover advantages exist for some knowledge and innovation-intensive products such as turbines. First movers profit from the growth in lag countries by exporting and co-operation activities. Less knowledge-intensive products such as boilers are attractive for leapfrogging strategies, and emerging countries have already caught up.

Jelcodes:Q31,Q39

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The case study shows that lead markets may not be always stable. During the 1960s and 1970s, the USA can be identified as a lead market for SC und USC technologies. Japan was still a lag market but it surpassed the USA in the early 1980s especially because of its technological capabilities. Besides the demand-oriented lead market model push factors such as R&D activities also seem to play an important role.

It can also be observed that other advantages – such as price and demand advantage – are shifting to China. China is practicing a leapfrogging strategy and has already become a leader in the market segment of low and middle quality boilers, whereas Japan and Germany still dominate the world turbine market.

The conclusion is that lead markets may switch over time to markets with high growth rates, although first mover advantages exist for some knowledge and innovation-intensive products such as turbines. First movers profit from the growth in lag countries by exporting and cooperation activities. Less knowledge-intensive products such as boilers are attractive for leapfrogging strategies, and emerging countries have already caught up. Thus, international technology cooperation is a beneficial process for all involved parties.

Keywords: Lead Markets, Coal Power Plants, Energy Technology, Energy Policy

JEL: Q31, Q37, Q43

1 Introduction

Despite the high CO_2 emission intensity of fossil and especially coal-fired energy production, these energy carriers will play an important role during the coming decades. In Germany, nuclear energy has to be replaced and in countries such as China or India the high and still growing energy demand requires the use of coal in addition to renewable energy sources. The existing resources of coal are with 14.800 billion tons still sufficient for the next century (Löschel 2009). 44% of the hard coal resources may be assigned to the USA, 28% to China and 18% to Russia. The resources of lignite (brown coal) are also considerable: 4.200 billion tons (33% USA, 31% Russia, 15% China, 1% Germany). A further argument for coal consists in the fact that it is in most countries cheaper compared to the use of natural gas.

In Germany, hard coal (22.8%) and brown coal (25.5%) contributed to nearly half of the whole electricity production in 2007. Following a scenario of IEA (2007), the relevance of the use of coal will not shrink until 2030, for the EU 27 the share of 30% will remain at the same level, in China we will still observe a value of around 80% concerning the electricity production. Even if we consider a scenario with a higher use of energy efficiency improvements, China will produce more than 60% of its electricity by the use of coal (Löschel 2009).

Against this background, cleaner and more efficient coal-fired power plants will have an important role to play for both global energy and climate policy in the future. This study will identify the lead market strategies of four major countries in the global coal power plant market (China, Germany, Japan and the USA) regarding the main innovations of clean coal technology. The lead market approach for environmental innovations as developed by Beise and Rennings (2005) has identified six success factors for lead markets: comparative price and demand advantages, a high reputation in environmental technology (transfer advantage), similar market conditions (export advantage), a competitive market structure and ambitious environmental regulation. We will also take further supply side aspects into account (see also Rennings and Cleff 2011, and Tiwari and Herstatt 2011). Our ex-post analysis identifies the existence of lead markets for the most important efficient, “clean coal” technologies.

The most important technological trajectory of fossil fuel power plants is the pulverized combustion with a share of 90% of coal-fired capacity worldwide (WCI 2005, Rennings and Smidt 2010), so that this technology will be in the focus of our case study. Another reason is that we want to concentrate on technologies that have already left the demonstration phase. This is the case for subcritical, super- and ultra-supercritical pulverized coal technologies that are already established whereas for technologies such as Carbon Capture Storage (CCS) no diffusion curves can be derived yet due to their early phase of innovation.

The paper is structured as follows: Section 2 describes the relevant clean coal technologies and their diffusion curves for Germany, China, Japan and the USA. Section 3 applies the lead market approach to the case of efficient coal technologies by developing and quantifying indicators for lead market factors. Section 4 takes additionally supply side factors into account. In Section 5, we validate our results with expert interviews with German firms. Section 6 summarizes the results and concludes.

2 Coal Power Plant Technology and Diffusion Curves

In general terms, a clean coal technology may be defined as a "technology that, when implemented, improves the environmental performance and efficiency as compared to the current state-of-the art in coal-fired power plants" (Buchan and Cao 2004). Coal-fired power stations with pulverized bed combustion are characterized by the steam conditions when entering the turbine, the condenser pressure or the efficiency of the turbine (RWE Power AG 2011, IEA 2010a).

The steam conditions are divided in subcritical, supercritical and ultra-supercritical-conditions. Steam is called supercritical when the steam parameters exceed the critical point. The higher the temperature and pressure of the steam, the higher is the efficiency of the power plant. A subcritical power plant works with a steam temperature of about 540 °C or less and a pressure of about 160 bar, which lies under the critical point. This technology is obsolete and was removed by the supercritical power plants. Here, the steam temperature lies between 540 °C and 600 °C and the pressure between 230 bar and 270 bar. Temperatures of 600 °C with a pressure of 270 bar are state of the art and are called ultra-supercritical. Applying this technology, an efficiency of 40% - 43% can be achieved. Technologies characterized by temperatures of 700°C and pressures of 375 bar will be called advanced ultra-supercritical.[1] The so-defined advanced ultra-supercritical power plants that are able to reach an efficiency of 50% or more are currently applied in some projects only because of the high costs of materials that are able to resist high temperatures and pressures (IEA, 2010).

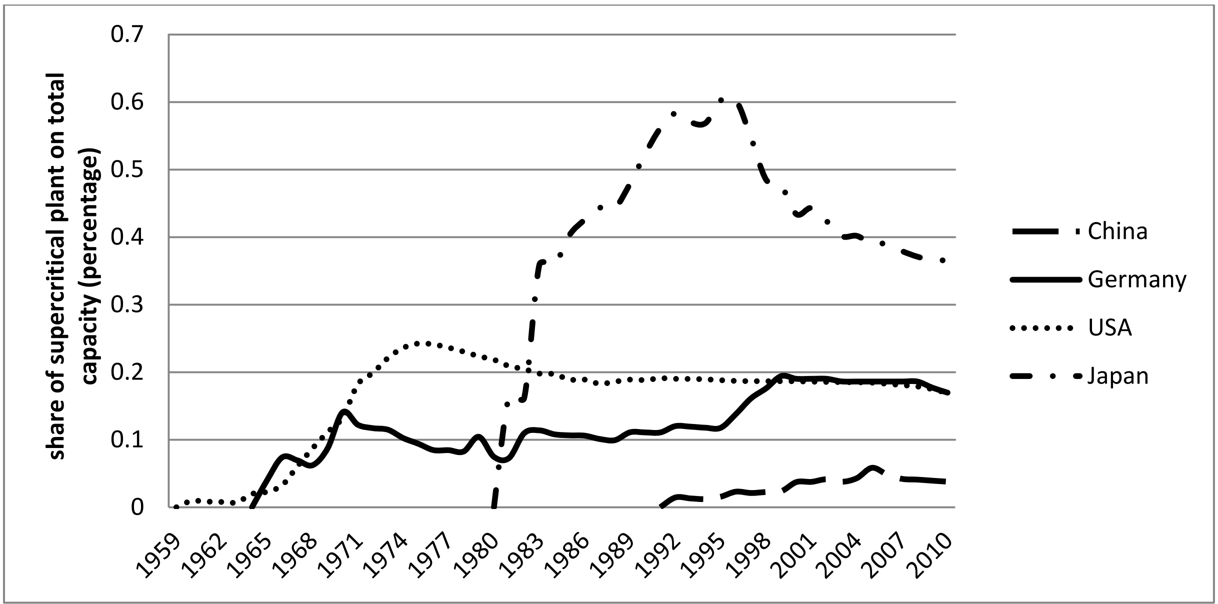
The diffusion of new technologies in coal-fired power plants is slow due to a long average life time of 35-40 years and the risk of the high investments which leads to risk-averse investment decisions (Rennings et al., 2010). Our case study analyzes the diffusion of supercritical and ultra-supercritical power plants as innovative solutions compared to the older subcritical

[1] The IEA coal database already defines technologies as ultra-supercritical that are characterized by a steam pressure of more than 250 bar combined with a steam temperature of at least 550 °C. The diffusion curves (Figure 1 and 2) are calculated following this definition.

plants.

The supercritical pulverized coal technology has been introduced in 1959 in the USA. Figure 1 shows the development of the share of supercritical power plants on the entire installed capacity of coal-fired power plants in a country from 1959 to 2010.

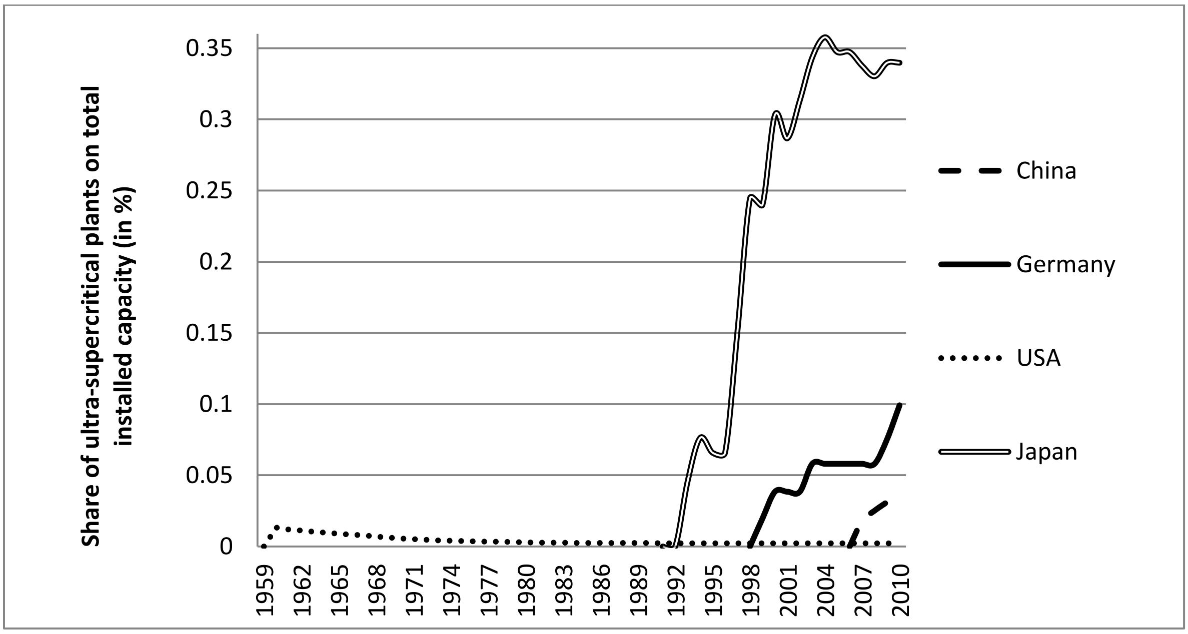
Figure 1: Diffusion curve of supercritical pulverized coal technology in selected countries



Source: IEA (2011a), own calculations.

The United States was the leader in designing and manufacturing (ultra-) supercritical pulverized coal technology in the late 1950s (Rennings and Smidt, 2010). The first ultra-supercritical (USC) plant in the world was Ohio Power's (now American Electric Power) Philo unit 6 in 1960. Not as expected, the United States decided to abandon this technology on the domestic market in 1960. Germany followed the USA in adopting supercritical power plants in 1965. Just like in the United States, the diffusion of supercritical plants seemed promising in the beginning. However, just after reaching a market share of 14.1% in 1970, the diffusion of supercritical power plants stopped and declined again to about 7.3% in 1981. After the German reunification in 1990, the relative importance of supercritical technologies compared to subcritical power units increased. Beginning in 1999, Germany concentrated on the construction of ultra-supercritical plants characterized by steam temperatures of 550 °C and more (following the definition of the IEA coal database, see Figure 2).

Figure 2: Diffusion curve of ultra-supercritical coal-fired power plants



Source: IEA (2011a), own calculations.

Japan started constructing supercritical plants in the 1970s. Influenced by the oil price crisis, the share of supercritical power plants in Japan rose from zero in 1980 to 60.2% in 1996 at an annual growth rate of 27.3%. Japan picked up ultra-supercritical pulverized coal technology in 1993. As a second mover, Japan was the major driver for USC technologies during the 1990s and became the technology leader before 2005.

China is the last country regarding the development of supercritical pulverized coal technology of the four countries. China started using supercritical technology in the 1990s with the procurement of ten units from Russia. Since then, many more supercritical units have been built and approximately 27 were in operation at the end of 2010. Sixty percent of the new plants that started construction after 2005 and represent a total of 37.8 GW (600 MW each) are supercritical. From 2010 to 2020, new power plants with unit capacities of 600 MW and more will all be required to be supercritical and about half of the newly built power generating units will be ultra-supercritical. Consequently, supercritical units will account over 30% by 2020 (Huang 2008).

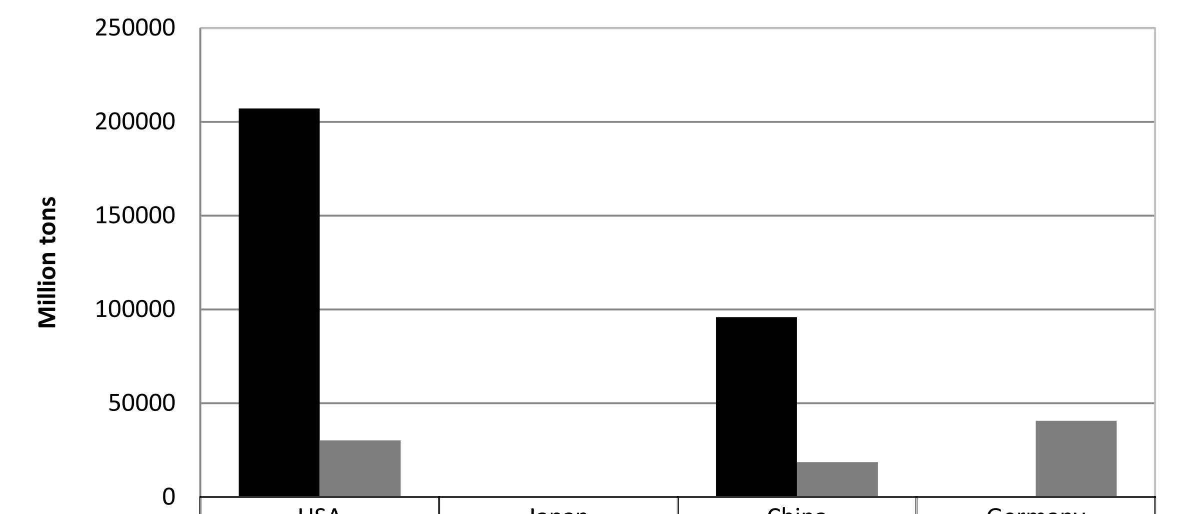
It seems that the USA first took over the role of a lead market in the 1960’s and during the following 20 years. Germany in the 1960’s and Japan in the 1970’s followed the innovation design in the USA. The traditional view of stable lead markets has been supported for many examples such as the diffusion of cellular phones, the facsimile machine or diesel motors with direct injection, etc. (Beise 2001, Beise and Rennings 2005, Rennings and Smidt 2010). However, in our case of clean coal, the diffusion curves overlap by Japan in the early 1980's since America stopped to build new supercritical power plants (Rennings and Smidt, 2010).

3 Lead Market Factors

3.1 Price advantage

The price advantages can be measured by using different indicators: proved reserves, fuel costs, absolute and comparative cost advantage. First, proved reserves are defined by the IEA (2007:9) as all resources "…that are not only confidently considered to be recoverable but also can be recovered economically, under current market conditions." It is an indicator of the supply side for relative cost advantages regarding resources.

Figure 3: Proved hard and brown coal reserves in 2008 of selected countries



	USA	Japan	China	Germany
■ Hard coal	207119	340	95900	99
■ Brown coal	30176	10	18600	40600

Source: IEA (2011b).

If it is assumed that importing fuels is more expensive than extracting own reserves, then the endowment of a country regarding coal reserves decides whether it has a price advantage or not. The usefulness of proved resources as an indicator for price advantages is however limited. It is possible that a country is not able to make use of its reserves because it is not permitted by the national energy policy.

The United States own by far the largest coal reserves in the world (IEA 2011, Figure 3). The structure of coal reserves in both USA and China is similar. 87% of total reserved coal is hard coal in the USA and 84% in China. Germany has only abundant brown coal reserves and Japan's total proved coal reserves are negligible. Following Beise's argumentation (Beise 2001), the USA have a price advantage caused by their abundant coal reserves compared to the other countries.

Fuel prices also give information about the price advantage of a country, but tax reductions and other privileges may distort the picture. Following the IEA (2011c), the USA have a price advantage compared to Japan and Germany.

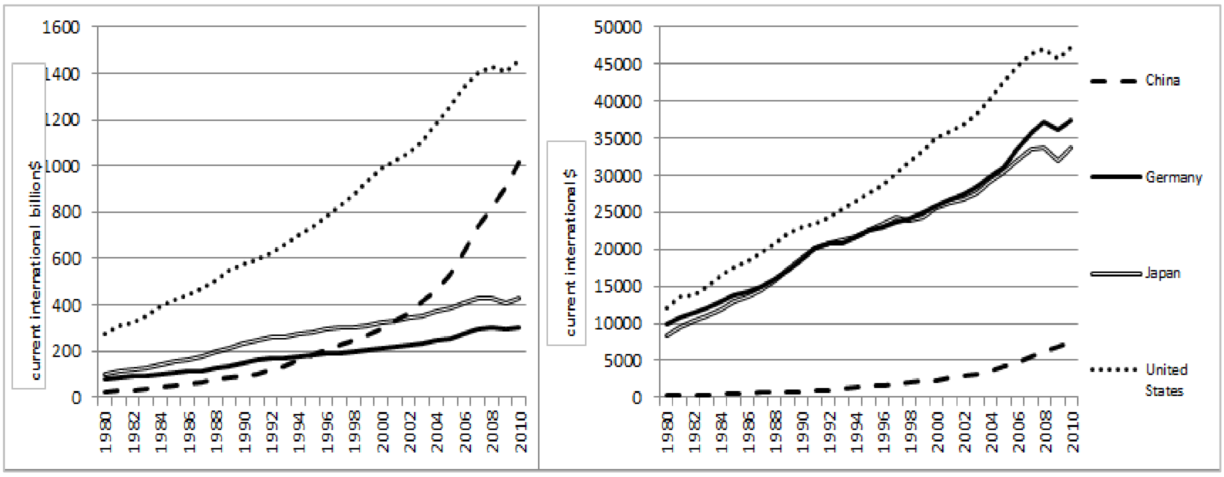
3.2 Demand advantage

Per capita income can be used as an indicator for demand advantages. The wealth of a nation plays a positive role on the rate and time of adoption of innovations (Dekimpe et al. (1998) and Vernon (1979)). From a supply perspective, it may increase the motivation to invest in new technologies and from a consumer perspective it reflects a greater willingness to pay for new products. However, the correlation between income and the rate and time of adoption of innovations has been mostly proven for consumer goods (Beise 2001:91), whereas the innovative behavior of firms strongly depends on further factors such as the existence of innovative capacities or highly qualified staff.

Among the four countries examined in this study, the USA shows the highest total and per capita GDP. China´s total GDP has grown rapidly during the last two decades and passed Germany in 2007 and Japan in 2009, but it´s income per capita in 2010 was only 4354 $ (see Figure 4).

Figure 4: Total GDP and GDP per capita (current international $, in PPP) of selected countries

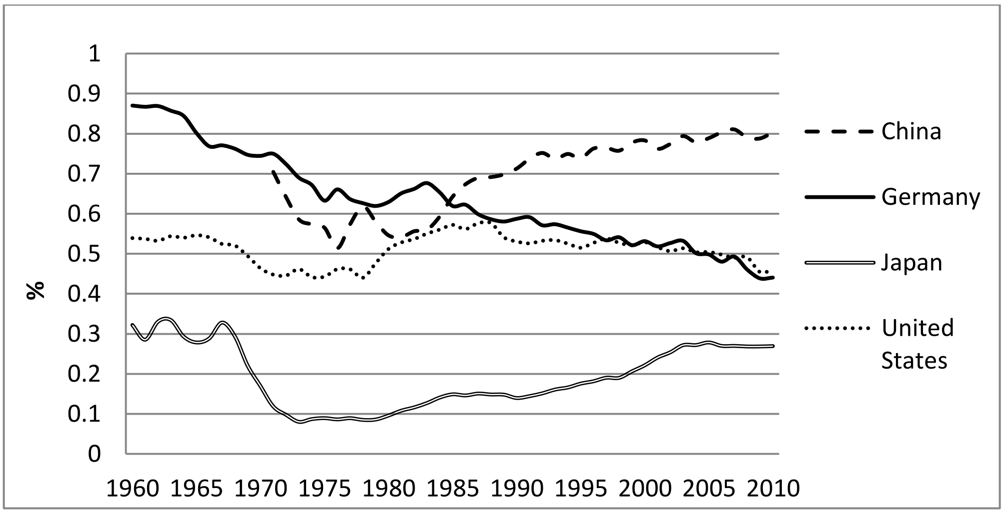
Total GDP　　　　GDP per capita



Source: Word data bank (2011a).

The relevance of coal-based electricity production in a country can be used as a further indicator for demand advantages. Countries highly relying on the CO_2-intensive coal are more and more willing to introduce efficient coal technologies because they are put under high political pressure by other countries to improve their CO_2 performance. China shows the highest coal-based electricity production and already surpassed the USA in 2006 (World Bank database 2011b).

Figure 5: Share of coal on total electricity output of selected countries



Source: World bank database (2011b).

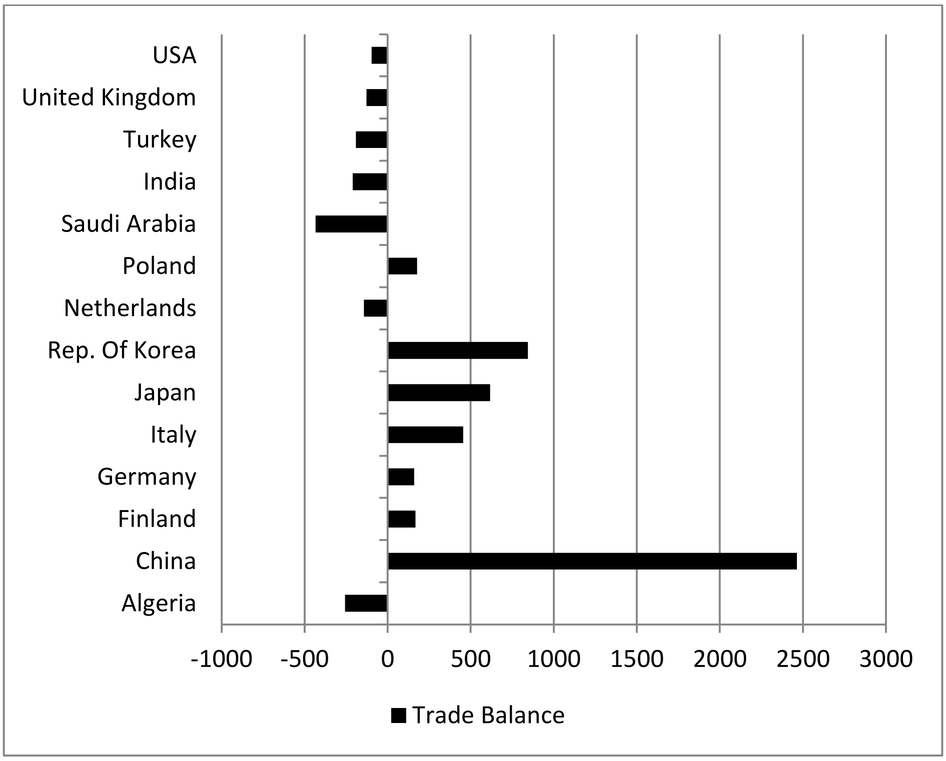
Furthermore, China shows the highest coal share on total electricity output (80%) compared to the other three countries (see Figure 5).

Countries characterized by a high average plant age may also have a demand advantage since the power plants can be expected to be replaced soon. The United States has the highest average age of their coal-fired power plants, but looking at the energy policy in the USA, favoring gas-fired power plants and renewables, this demand advantage will not play an important role (IEA 2011a). To sum up, China seems to have a clear demand advantage for coal-fired power plant technologies.

3.3 Export advantage

In the following, we try to assess which countries are specialized in the production of clean coal technologies and successful in selling clean coal equipment to other countries. To measure the export advantage, we use the trade balance (exports – import) in 2010 and the development of the export/import ratio from 2007 to 2010. The UN Comtrade data basis provides such data not explicitly for clean coal technologies but for the product groups "steam boilers" and "steam turbines".

Figure 6: Trade Balance Steam Boilers in 2010, in millions US $



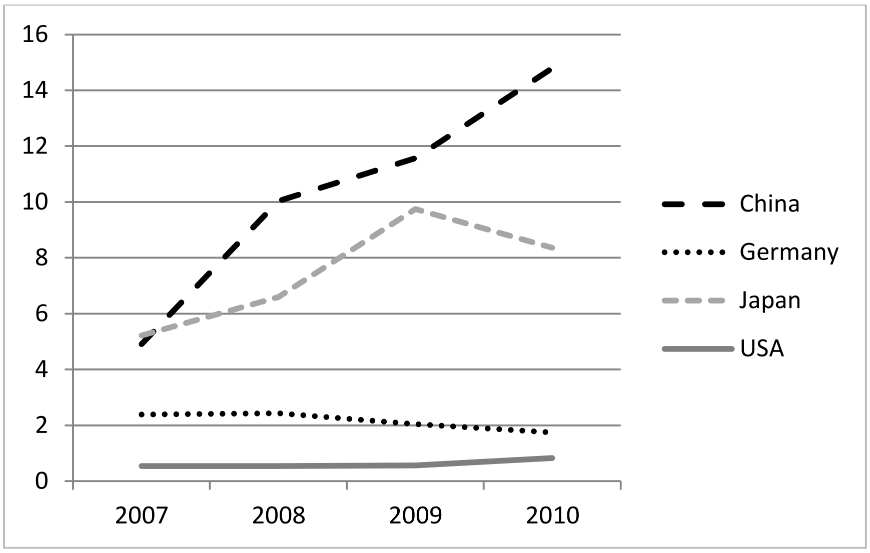
Source: UN (2012).

Figure 6 shows that China is highly specialized in the production of steam boilers, even dominating the Republic of Korea and Japan. Following the results of expert interviews with power plant and component producers, this statistic does not tell the whole story because China predominantly exports parts of boilers that have to be completed by the high-tech products of

Japanese or German firms. Japan and Germany are also net exporters of steam boilers, whereas the USA is even a net importer.

The development of the export/import ratio from 2007 to 2010 confirms these results: From 2008, China shows the highest export/import ratio followed by also high values for Japan. For Germany, this value even declined slightly from 2007 to 2010, confirming the lower importance of Germany as a production location for these products. In the USA, we observe a slight increase, but the ratio remains below the value one.

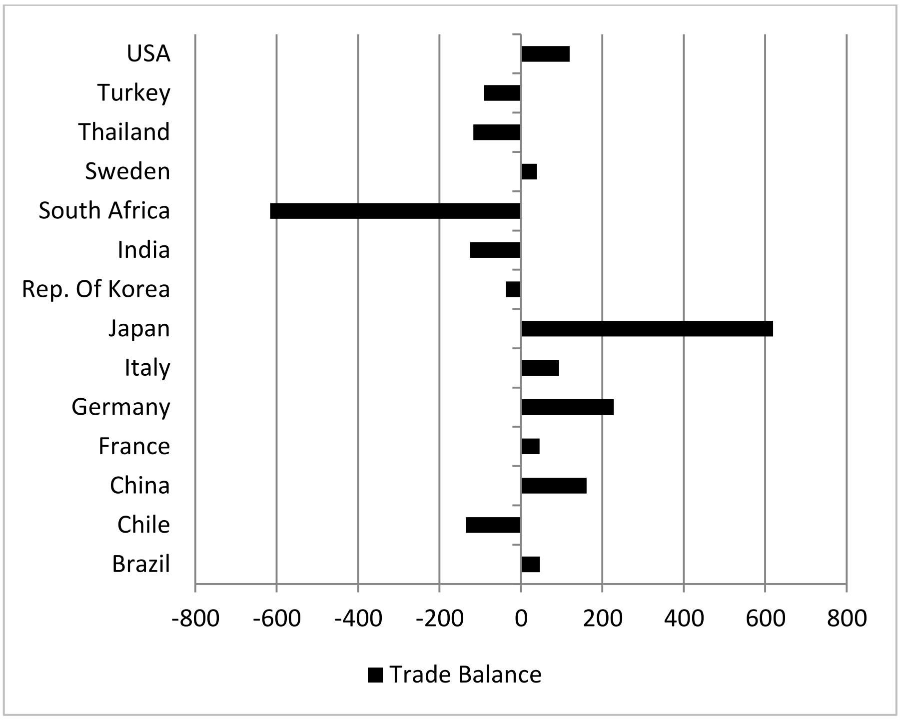
Figure 7: Steam Boilers: Development of export-import ratios from 2007 to 2010



Source: UN (2012).

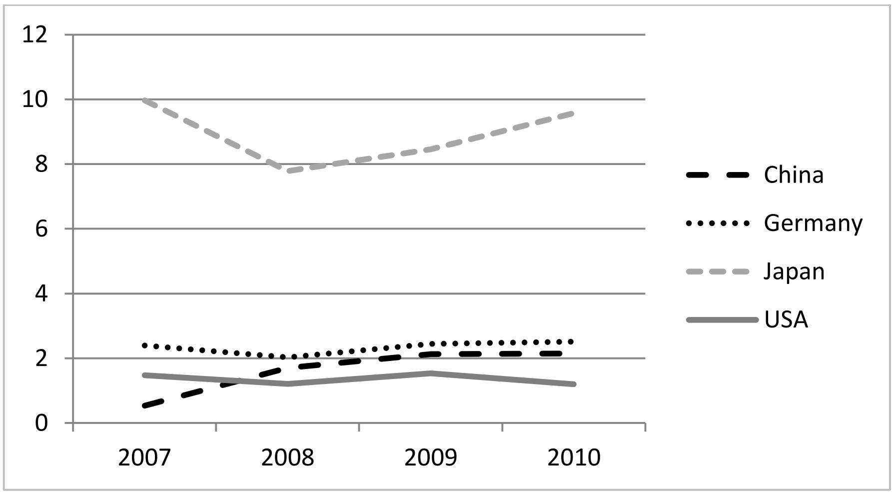
Concerning steam turbines, Japan seems to be the most specialized country documented by a high trade surplus in 2010 (Figure 8) and very high export/import ratios from 2007 to 2010 (Figure 9) compared to the other countries. Especially Germany, but also China and the USA also show high net exports in 2010 for steam turbines. As concerns the trade balance and the export/import ratio, Germany still remains beyond China whereas the export/import ratio of the USA is now lower than that of China.

Figure 8: Trade Balance Steam Turbines in 2010, in millions US $



Source: UN (2012).

Figure 9: Steam Turbines: Development of export-import ratios from 2007 to 2010



Source: UN (2012).

Summing up, China seems to have an export advantage for steam boilers, whereas Japan holds this position for steam turbines. Due to the growing importance of highly efficient coal power plants requiring “high-tech” steam boilers, the Chinese producers will only keep their export advantage if they are able to improve the technical quality of their boilers.

3.4 Transfer advantage

On the one hand, the transfer advantage describes the capability of a country to be or to become a lead market in the respective technology. On the other hand, but closely correlated to the capability, a country shows a high transfer advantage if the international reputation and attention regarding the specific technology is high (Rennings and Smidt 2010).
To measure the transfer advantage for efficient coal technologies, we use the following indicators:

- Degree to which R&D matters in a country;
- R&D related to coal technologies and CCS (Carbon Capture Storage);
- Number of demonstration plants in a country;
- Efficiency of coal fired power plants (Output of electricity sector/input electricity sector).

Table 1: Indicators Transfer Advantage

Country	R&D in general (2007/8/9) in % of GDP	R&D related to coal and CCS (2010) in % of GDP	Number of demonstration plants (2007)	Average Efficiency of coal fired power plants (2005)
Germany	2.82	0.00086	8	39.0
Japan	3.44	0.00267	21	42.0
USA	2.79	0.00256	12	36.4
China	1.5	-	9	31.0

Source: OECD (2012), IEA (2011a), Rennings and Smidt (2010).

The results for our indicators (Table 1) show a clear transfer advantage for Japan where the average efficiency of coal-fired power plants is the highest. Furthermore, Japan is characterized by the highest number of demonstration plants and percentage of R&D in general and also related to coal technologies.

Table 2: Total R&D related to Coal Technologies (including Carbon Capture Storage) and renewable resources in million US $ (2010 prices and exchange rates)

Countries and Technologies	**2005**	**2008**	**2010**
Germany			
Coal (production, preparation, transport)	10.5	41.4	12.0
CO_2 capture and storage	5.6	3.9	17.1
Renewable energy sources	127.8	160.6	248.4
Japan			
Coal (production, preparation, transport)	160.8	90.5	18.3
CO_2 capture and storage	-	42.2	127.4
Renewable energy sources	277.8	223.2	236.9
USA			
Coal (production, preparation, transport)	269.1	349.3	148.0
CO_2 capture and storage	69.5	196.3	225.0
Renewable energy sources	277.1	456.7	1310.0

Source: IEA (2012).

Compared to renewable energy sources, the total R&D expenses related to coal technologies are very small in Germany (Table 2). In Japan, the research for renewables has also a high importance, but the R&D expenses for clean coal technologies are still very high, supporting the result that Japan has a transfer advantage. From 2005 to 2010, interestingly, the R&D expenses in Japan shifted significantly from coal production technologies to CCS which is also the case in the USA.

3.5 Regulation advantage

In the following, we analyze indicators describing the regulation environment for the realization of clean coal technologies in the USA, Germany, Japan and China. As Rennings and Smidt (2010:324) describe it: “Along with the economic incentives of rising fuel prices and the development of other fossil fuel power plants, the political objective of reducing CO_2 emissions is one of the main reasons why coal fired power plants should be improved.” To analyze a regulation advantage for clean coal technologies indicators such as the existence of carbon-taxes and/or an emissions trading system, also the importance of renewable energy electricity production and the social acceptance of coal technologies are relevant aspects.

Because of the high relative CO_2 emissions of coal compared to other energy sources, the introduction of carbon taxes or the implementation of an emissions trading system seems to be a very important driver of clean coal technologies. Furthermore, a high proportion of renewable energy electricity production may exert a pressure on the coal sector to become more efficient and less CO_2-intensive. At least in the long run, energy policy decisions are dependent on the acceptance of society – the story of nuclear power being an excellent example for this argument. On the one hand, a low social acceptance for coal may trigger activities to develop cleaner coal technologies. But on the other hand, due to the fact that it is difficult to explain to a non-technician that coal may be "clean", the low social acceptance may also lead to a resistance against all "dirty" and "clean" coal technologies.

Germany

The general policy background for coal technologies in Germany is characterized by a low societal acceptance, whereas renewable energies are in the focus of energy policy. The coal policy strategy has strongly changed from 1970 to 2011, but the sixth energy research program of the German government from 2011 still contains important elements to promote clean coal technologies (Bundesministerium für Wirtschaft und Technologie, 2011). Furthermore, European initiatives play an important role. Already in 1998, a group of major suppliers of the power industry and some of the major utilities in Europe started a 17-year demonstration project that was financially supported by the European Commission (European Commission 2011:74), namely the so-called Thermie 700°C supporting the introduction of advanced ultra-supercritical technologies.

As regards the German innovation policy, the sixth energy research program shows that coal technologies are not in the focus of innovation policy and subsidies because of the high attention towards renewables, but the program confirms that the improvement of the use of coal for electricity production is necessary despite a low societal acceptance. In fact, environmental policy goes in a similar direction. Renewable energy is highly subsidized, on the other side, eco-taxes and the European Emissions Trading System (EU ETS) lead to a higher burden of fossil fuel energy suppliers and energy consumers. The negative effect of environmental policy (e. g. ETS) is moderated because the amount of permits for energy suppliers were high and mainly costless due to the grandfathering allocation system still in use. Furthermore, there are still exceptions for energy suppliers concerning eco-taxes. From the perspective of industrial policy, too, the liberalization of the electricity market led to a higher competition for fossil fuel energy suppliers.

In a nutshell, Germany lost much of its regulation advantage for clean coal technologies during the last ten years because of a clear cut change of paradigm towards renewables. It may be true that this new strategy also triggers the development of more efficient coal technologies, but on the other hand, the coal sector lost much of its financial support by the state in favor of renewables. In the long run, it can be expected that the low societal acceptance of coal will lead to a further loss of regulation advantage for clean coal technologies.

China

The general policy conditions for the use of coal power plants in China are – against the background of a still growing energy demand – favorable, despite a growing consciousness of politicians and the population for environmental protection. Following Hong et al. (2009), China has tightened its environmental protection laws and standards during the recent years. For example, the 11th Five-Year Plan of the Chinese government aims at restructuring the energy sector by shutting down high polluting and energy-consuming small thermal power plants. The industrial policy of the Chinese government aims at increasing the energy efficiency in energy-intensive sectors such as steel and electrolytic aluminum industries (Hong et al., 2009). In Article 31 of the law on Energy Conservation, "…the state encourages industrial enterprises to adopt highly efficient and energy-saving motors, boilers, furnaces, fans and pumps, and to employ co-generation technology, residual heating and pressure utilization, clean coal technology and advanced energy monitoring and control technologies." (Hong et al., 2009:20).

In general, the regulation situation in China is positive for clean coal technologies. On the one hand, because of the high and still growing energy demand together with enormous coal reserves, China will not renounce the use of coal. On the other hand, a growing environmental consciousness of politicians and parts of the population trigger the development of cleaner coal technologies. The construction of ultra-supercritical coal-fired power plants during the last years confirms this argumentation.

Japan

Especially the Japanese innovation policy seems to be favorable for the development of clean coal technologies because of the focus on highly efficient power plants. The R&D subsidies are high and co-operations between universities and the industry are actively supported (Fuchs et al. 2011). The relatively high amount of ultra-supercritical power plants constructed during the last twenty years confirms this picture. In fact, Japan is forced to develop and use highly efficient coal technologies because the country is highly dependent on imports of energy. In the future, against the background of the high risk of nuclear power plants in Japan, efficient clean coal technologies may still play a more important role.

USA

The development of efficient energy technologies is mainly market-driven, there is only few public R&D support. Concerning coal technologies, the USA show a concentration on IGCC and Fluidized Bed Combustion. Despite the fact that the first ultra-supercritical power plant was constructed in the USA in 1959, this country abandoned this technology. Furthermore, the environmental policy regarding a CO_2 emission reduction strategy is quite lax (Fuchs et al. 2011). In fact, there seems to be no regulation advantage for the USA for clean coal technologies. To sum up, compared to the USA, Germany and Japan, China seems to have a clear regulation advantage.

4 Market Structure, Lead Suppliers and Technological Capability

The recent literature on lead markets (e.g. Rennings and Cleff 2011 or Tiwari and Herstatt 2011) accentuates the role and the importance of supply side aspects for the development of lead markets. A competitive market structure combined with the existence of highly innovative lead suppliers may be the basis of the leadership of a country in a specific technology. Therefore, we firstly analyze the market structure for coal technologies. Secondly, we analyze the framework conditions for competition and innovation in our four countries followed by a deeper analysis of the technological capabilities using patent indicators.

The question which market structure is best for the realization of innovations has a long tradition in the theoretical literature on innovation behaviour of firms. Following Arrow (1962), firms in competitive markets have higher incentives to invest in R&D because they may get – at least for a limited period of time - the full economic rent from an innovation. Contrary to that, Schumpeter (1943) argues that big firms in monopolistic markets are more likely to solve the appropriation problem, namely to keep the rents of their innovation. Therefore, the role of the market structure remains an empirical question. Many empirical analyses support the view of Arrow, but especially the more capital-intensive the industry and the respective innovation activities, the more innovative large firms in monopolistic markets may also be (Martin 2006). Concerning coal technologies, the markets in our four countries seem to be highly concentrated. Table 3 shows the shares of the "big five" producers of whole components, turbine and boiler suppliers. Following this indicator, the markets in Japan and the USA are characterized by the highest concentration whereas the situation in Germany seems to be a bit more competitive.

Table 3: Number of Clean Coal Technology Suppliers

Country	Producers of coal power plants		Turbine suppliers		Boiler Suppliers	
	Number	Share* of "big five" in %	Number	Share* of "big five" in %	Number	Share* of "big five" in %
China	23	81	27	83	22	80
Germany	17	71	18	87	19	63
Japan	6	99	7	99	6	99
USA	20	96	12	95	20	96

* Related to the number of plants.
Please note that the IEA Coal database contains many missing values concerning the names of the producers. The "shares of the big five" are calculated without missing values implicitly assuming that the plants without producer information show the same distribution.

Source: IEA (2011a).

Against the background of the above mentioned controversial theoretical debate and the fact that the development and the construction of new clean coal-based power plants is capital-intensive, the identification of a market structure advantage of any of the four countries is - following our concentration indicator - not possible.

Therefore, it is furthermore useful to explore the general competition conditions in the four countries on the basis of the Global Competitiveness Report of 2011. This report contains a rich set of indicators on innovation and the respective framework conditions.

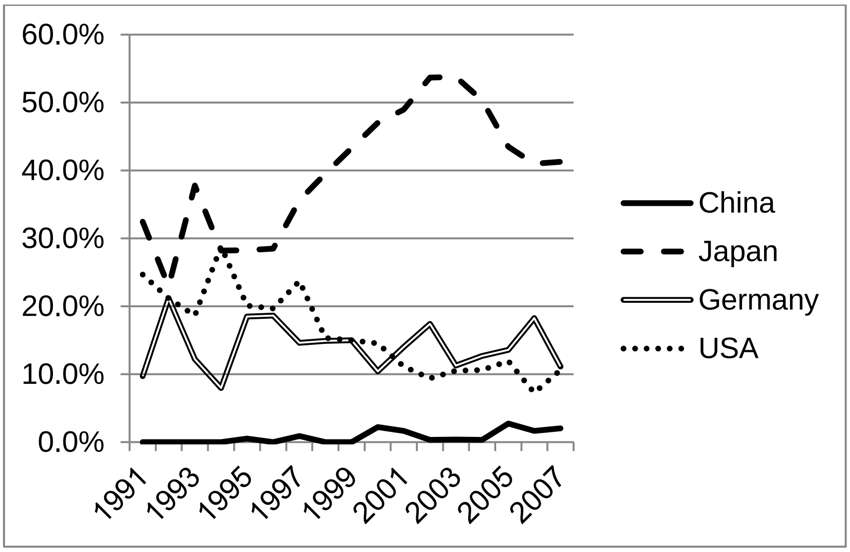
The innovation indicators show a dominant role of Japan which ranks first in the capacity of innovation, company spending on R&D and second in the availability of scientists and engineers. Concerning the patents granted, the state of the cluster development and for the firm-level technology absorption, Japan also attains the highest values of the four countries. Besides variables on trade barriers and rules on FDI, Japan shows high values for the variables on good market efficiency, too. The intensity of local competition and the effectiveness of anti-monopoly policy also seem to be very high in Japan.

The USA also reaches high ranks, but mostly behind Japan except e.g. in terms of quality of scientific research institutions, the government procurement of advanced technical products, the availability of latest technologies and the venture capital availability.

Germany also shows high innovation capacities and a high quality of scientific research institutions. Comparing the four countries, Germany reaches the best positions regarding the quality of the educational system, the quality of the overall infrastructure and the intellectual property protection. Concerning this indicator, China only attains a low rank. This is also the case for the effectiveness of anti-monopoly policy and especially for the existence of bureaucratic barriers in this country measured by the number of procedures to start a business. Compared to the other three countries, the innovation capacities in China still seem to be quite low.

The technological capabilities of the different countries with respect to coal technologies can be measured by the importance of the respective patent activities. Figure 10 shows the world market shares of coal-fired power plant technologies in the four countries documenting the high technology capabilities of Japan with a share of 40% in 2007. In the USA, the market share declined from 1991 to 2007 showing the diminishing interest and capability of this country in the development of clean coal technologies. In Germany, the patent shares are stagnating, whereas the figures for China are rising but starting at a very low level.

Figure 10: World Market Share Patents: Coal-fired Power Plant Technologies



Source: ISI (2012).

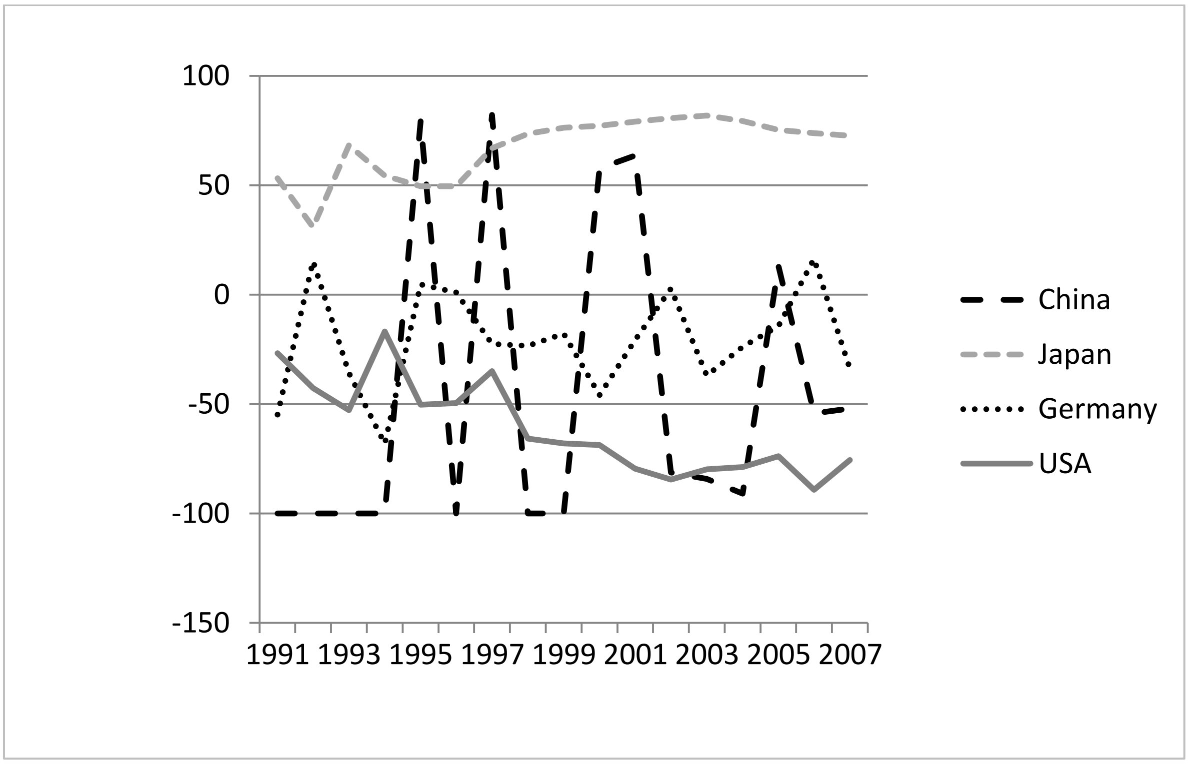
Furthermore, the Relative Patent Advantage is calculated for each country i and each technology field j according to Walz and Marscheider-Weidemann (2011):

$RPA_{ij} = 100 * \tanh \ln\{(p_{ij}/\sum_i p_{ij})/(\sum_j p_{ij}/\sum_{ij} p_{ij})\}$

The RPA indicates if the world patent share of clean coal technologies of a country is bigger or smaller than the country's world patent share for all technologies.

For all years from 1991 to 2007, only Japan shows positive figures documenting its leading technological capabilities for clean coal technologies (Figure 11). The RPA values also confirm the decline of the importance of coal technologies for the USA. Because of low absolute values for the number of coal-related patents the figures for China do not yet show a clear picture. The stagnating situation for Germany regarding clean coal technology capabilities is confirmed.

Figure 11: Relative Patent Advantage for Coal-fired Power Plant Technologies



Source: ISI (2012).

To sum up, all countries are characterized by high concentration values for coal technology suppliers so that further indicators have to be analyzed to assess a market structure advantage. Japan seems to be on top of the four countries because of its high innovation capacities and the high availability of scientists and engineers.

5 Firm Views and Strategies – Results from Expert Interviews

To analyze the strategies of firms regarding the development and use of new efficient coal technologies against the background of a growing political support of renewables expert interviews were carried out. A producer of components for coal-based power plants (Saarschmiede), a power plant producer (Hitachi Power Europe) and an energy supplier (Vattenfall) were interviewed.

Saarschmiede produces components for (coal-fired) power plants (e. g. turbine & generator shafts, turbine & compressor rings, parts for plant construction or high pressure vessels). Germany remains the main market (37%) followed by Europe (23%), Asia (23%) and the USA (15%). Whereas the construction of completely new power plants plays an important role in China and India, in Germany and especially in the USA, the refurbishment of existing power plants dominates. Hitachi Power Europe is one of the main constructors of fossil-fired power plants. Whereas the rapidly growing market of China is supplied by other firms of the Hitachi group, Hitachi Power Europe concentrates on the construction of new power plants in Europe (especially Poland, Turkey and Russia), India and South-Africa. In Germany, the company increasingly concentrates on services and refurbishment for existing power plants because, at the moment, nearly no new coal-fired power plant projects are planned. Vattenfall is an energy supplier mainly producing electricity by lignite (80%). Concerning electricity production, Vattenfall has a market share of 16% in Germany. The main constructors of the power plants of Vattenfall are Hitachi Power Europe, Alstom and Siemens.

Currently, the market for (clean) coal technologies in Germany is negatively assessed because of the high political support of renewables in combination with uncertainties concerning the future role of coal technologies. Nevertheless, the experts of Hitachi and Vattenfall are optimistic that coal technologies will play even a growing role to assure the energy supply in Germany, especially by the use of lignite-based highly efficient power plants. At the moment, only the refurbishment of existing coal power plants and services are important business areas whereas nearly no new projects are realized. In Japan, the future role of nuclear power is uncertain, but the experts do not expect a dynamic development concerning coal-fired power plants. The market in China is very dynamic, around 50 new power plants are built every year leading to extensive possibilities to implement highly efficient technologies (ultra-supercritical). In the USA, at present, only a few new coal-fired power plants are constructed because of the high availability of gas, but the high age of coal-fired power plants leads to high refurbishment potentials and markets.

Japan and Germany seem to have clear first mover advantages concerning the highly innovative parts of clean coal technologies and in general for 600 °C power plants, whereas China has second mover advantages in manufacturing boilers. Following the experts, Germany has highly profited from these first mover advantages in terms of export success and technological leadership. The crucial question remains if the German firms are able to keep the first mover benefits against the background of the shrinking importance of coal technologies in Germany. Saarschmiede as a component producer is at least optimistic that the R&D units ("innovative cells") will not leave Germany or Japan despite declining markets in these countries because of the lack of highly educated and innovative staff in China.

The experts of Hitachi and Vattenfall are more pessimistic. Germany and also Japan may lose their first mover advantages because a considerable part of innovation activities occurs when a power plant is constructed in close cooperation with the client. Due to the fact that nearly no new coal-fired power plants are projected in Germany, this country may lose a part of these first mover advantages. On the other side, the high market volume in China leads to more innovation activities in this country. It is unclear if Chinese firms will be able to build a 700 °C power plant as intended in the five-year-plan, but they will gain experiences and may get a technological leadership. An important pre-condition for keeping the technological leadership for efficient coal technologies would be the reduction of the high uncertainty regarding the future use of coal.

Following the opinion of the experts, the market situation in Germany for clean coal technologies requires far reaching changes of firm strategies. For Saarschmiede, an increasing concentration on foreign markets is necessary because of the uncertainty regarding coal power plants in Germany. Therefore, the firm will more and more concentrate on the Chinese market. At present, Hitachi Power Europe extends its business fields services, the refurbishment of existing power plants or the deconstruction of nuclear power plants because in Germany the construction of new coal power plants will only be relevant in 5-10 years. Furthermore, the firm extends its activities in new markets such as Poland, Turkey or Romania, whereas the Chinese market is not an option for Hitachi Power Europe. Despite these activities, Hitachi was forced to cut jobs. On the one hand, Vattenfall will extend the use of renewable energies, on the other hand, the firm will still rely on lignite because, under the condition of current and expected CO_2 prices, this energy carrier will be competitive. A further option is the extension of R&D for CCS.

6 Summary and Conclusions

Despite the high CO_2 emission intensity of fossil and especially coal-fired energy production, these energy carriers will play an important role during the coming decades. The case study identifies the main technological trajectories concerning more efficient fossil fuel combustion and explores the potentials for lead markets for these technologies in China, Germany, Japan and the USA taking into account the different regulation schemes in these countries.

An analysis of the diffusion of efficient coal technologies shows that the USA took over the role of a lead market in the 1960's and during the following 20 years. Germany in the 1960's and Japan in the 1970's were followers. The diffusion curves overlap by Japan in the early 1980's since America stopped to build new (ultra-) supercritical power plants. Although China is still the last country that introduced ultra-supercritical technologies in 2007, commercial adoption of this technology is expanding rapidly. The analysis shows that the typical pattern of a stable lead market only applies to a limited extent because Japan has surpassed the USA although it started as a typical lag market.

Concerning the different lead market factors, our results show a clear price advantage for the USA and China because of their high coal reserves. Japan holds the last position because of the lack of reserves and high prices. High income per capita in the USA, Japan and Germany point to a demand advantage of these countries but high electricity intensity and the highest share of coal in electricity production (80%) favors China. To describe the export advantage, the indicators "export minus import" and the "development of export/import ratio" have been used. China seems to have an export advantage for steam boilers, whereas Japan holds this position for steam turbines. Japan seems to have a clear transfer advantage. The country is characterized by the highest number of demonstration plants and percentage of R&D in general and also related to coal technologies. Germany lost much of its regulation advantage for clean coal technologies during the last ten years because of a clear cut change of paradigm towards renewables. In China, the regulation situation seems to be positive for the implementation of clean coal technologies. Compared to the USA, Germany and Japan, China seems to have a regulation advantage concerning clean coal technologies.

Concerning supply side factors, Japan seems to be on top of the four countries because of its high innovation capacities and the high availability of scientists and engineers and because of its leadership regarding clean coal patent activities.

All in all, Japan has caught up in terms of supply factors, China in terms of price, demand and regulation advantage. The fact that Japan is now the leading country for super and ultra-supercritical coal technologies supports the hypothesis that - apart from the demand-oriented lead market model - push factors such as R&D activity play a strong role as well. It can also be observed that some other advantages - such as price and demand advantage - are shifting to China. China is practicing a leapfrogging strategy and has already become a leader in the market segment of low and middle quality boilers, whereas Japan and Germany still dominate the world turbine market.

Expert interviews confirm that Japan and Germany seem to have clear first mover advantages concerning the highly innovative parts of clean coal technologies and in general for 600 °C power plants whereas China has second mover advantages in manufacturing boilers. The crucial question remains if the German firms are able to keep the first mover benefits against the background of the shrinking importance of coal technologies in Germany. Saarschmiede as a component producer is at least optimistic that the R&D units ("innovative cells") will not leave Germany or Japan despite declining markets in these countries because of the lack of highly educated and innovative staff in China.

Following Hitachi and Vattenfall, Germany and also Japan may lose their first mover advantages because a considerable part of innovation activities occurs when a power plant is constructed in close cooperation with the client.

The clean coal market situation in Germany requires far reaching changes of firm strategies. An increasing concentration on foreign markets such as China, Poland, Turkey or Romania is one option because of the uncertainty regarding coal power plants in Germany. For Hitachi Power Europe an extension of business fields, the refurbishment of existing power plants or the deconstruction of nuclear power plants is necessary. Vattenfall will extend the use of renewable energies, but the firm will still rely on lignite because, under the condition of current and expected CO_2 prices, this energy carrier will be competitive.

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