Do Investments in Clean Technologies Reduce Production Costs? Insights from the Literature

Govinda R. Timilsina[a] and Sunil Malla[b]

ABSTRACT

In response to growing environmental concerns, governments have encouraged innovation and adoption of green or clean technologies through various policy measures. At present more than half a trillion US$ is being invested annually in clean technologies. This study analyzes if investments in clean technologies increase productivity and reduce production costs based on the existing literature. The findings are, however, mixed. Most ex-post studies show a positive relationship between clean investments and energy-intensive manufacturing firms' productivity. In transportation, buildings, and power sectors, empirical evidence between the adoption of clean technologies and the cost of energy services is highly limited. Ex-ante studies find cleaner vehicles that use electricity or hydrogen are still more expensive than gasoline and diesel vehicles, while in the buildings sector, clean technologies reduce the cost of energy services. In the power sector, increased investments in renewable energy have not yet decreased the average costs of grid electricity supply.

Keywords: Green energy, Clean energy technology, Energy efficiency (EE), Cleaner production, Clean investment, and productivity

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1. INTRODUCTION

In response to growing concerns to address climate change, one of the biggest challenges to human development, development financing institutions including national governments, international financial institutions, bi-lateral donors, non-governmental organizations, and the private sector have channeled hundreds of billions of dollars toward green or clean or low carbon economic development. Investment in clean energy in recent years particularly has significantly increased around the world. The International Energy Agency (IEA) estimates that about US$600 billion was invested in clean energy technologies in 2019, of which US$343 billion in renewable energy production technologies and US$249 billion in energy-efficient technologies were invested (IEA 2021a). The total investment in clean energy in 2019 accounted for 34% of the global investments in entire energy technologies, including fossil fuel technologies. The multilateral development banks (MDBs) allocated, on average, US$51.2 billion annually for low carbon development over the last five years (EBRD 2021). A study by (McCollum et al. 2018) estimates that in addition to current plans and policies, meeting current Nationally Determined Contributions (NDC) pledges globally will require US$130

[a] Corresponding author. Senior Research Economist, Sustainable Development and Infrastructure Unit, Development Research Group, World Bank. E-mail: gtimilsina@worldbank.org.
[b] Short-term consultant, World Bank.

billion per year of further investment in low-carbon technologies by 2030. It is likely that most development institutions, including the World Bank Group, would prioritize clean or low carbon technologies in their assistance for infrastructure development in developing countries. However, a question emerges—has the increased deployment of clean and low-carbon technologies helped decrease the overall cost of production? Is there concrete evidence of lowered production costs in various energy-consuming sectors, such as industries, power utilities, transportation, buildings, and agriculture, due to the increased adoption of clean technologies?

This study aims to answer this question by reviewing existing literature. The authors are not aware of any review study investigating this question. We analyze the issues from national as well as sectoral perspectives. The review includes ex-post econometric and ex-ante modeling studies. Multiple databases and numerous keywords are used in retrieving articles that have an empirical analysis. The databases include EconLit, Scopus, Web of Science, Google Scholar, JSTOR, and organizational databases such as IEA and the World Bank Group. It includes peer-reviewed journal articles, academic literature, and documents produced by international organizations, research institutions, and government departments. The keywords used are 'clean energy', 'clean energy investment', 'clean energy and productivity', 'low carbon technologies', 'economics of clean energy', 'green energy', 'green energy technologies', 'modern energy', 'energy technology and economy', R&D in energy technologies', 'energy and total factor productivity', 'clean energy and total factor productivity'.

The ex-post studies examine the relationships between investments in green or clean technologies and production costs or productivity of firms using observed data from the field. The ex-ante analyses examine the economic or financial viability of a clean technology using current or projected information on technological and economic variables (e.g., energy efficiency and costs of technologies, fuel prices). The former technique is more common in firm-level analysis. The latter is widely used at the technology level. The ex-post analysis can directly relate investment in clean technologies with production costs of the firm or productivity. The ex-ante analysis focuses on whether investments in clean technologies reduce the costs of energy service delivery. For example, if investments in green technologies or renewable energy technologies (e.g., solar, wind, hydro, geothermal) have helped reduce the average electricity supply costs. Similarly, in the transportation sector whether investments in cleaner vehicles, such as electric, hydrogen, and hybrid vehicles, reduce the cost of transportation services. Finally, in the buildings sector (residential or commercial) if the adoption of energy-efficient appliances or devices causes net economic gains for households or business owners.

The study carries out an extensive review of existing empirical literature to understand the relationship between green/clean technologies and production costs in general and energy service costs in particular sectors: manufacturing, transportation, electricity, buildings, and agriculture. The findings of the existing studies are mixed and inconclusive. Most studies examining the relationships between green/clean technologies and productivity show a positive relationship. However, the channels through which the investments are translated into productivity gains are not clear. Studies at the sectoral level (e.g., electricity and transportation) do not provide clear evidence of cost reductions in transportation services and electricity supply due to renewable energy technologies and electric or hydrogen vehicles. A similar outcome is observed in the buildings sector. However, investments in energy-efficient technologies, particularly in energy-intensive industries, in most cases, reduce production costs or improve productivity.

The remainder of this paper is structured as follows: Section 2 presents the trends of green/clean investment. Section 3 discusses the findings of the existing studies that examine the relationship between investments in green/clean technologies and productivity in general. It also highlights some factors influencing the relationship. In Section 4, the effects of green/clean investment on production costs in specific sectors, such as manufacturing, power, buildings, and transportation are analyzed. This is followed by the discussions of other factors that drive private sector investments in green/clean technologies (Section 5). Finally, key conclusions are drawn in Section 6.

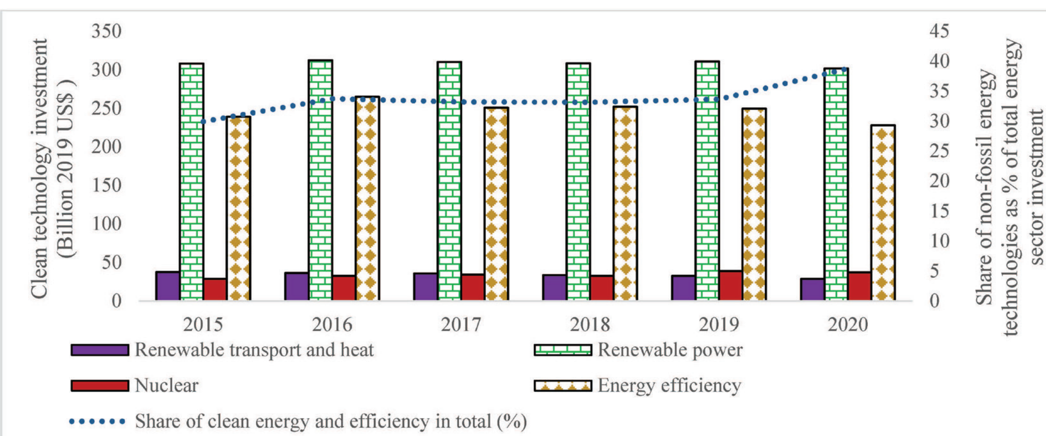
2. CLEAN TECHNOLOGIES—INVESTMENT AND EXPANSION

Over the last two decades, clean energy technologies, including both on the energy supply side and energy demand side, have attracted a large investment each year. Government policies to promote green/clean energy technologies to address global climate change and local air pollution problems are the main drivers of these investments. The IEA estimates that about US$308 billion was invested in renewable electricity technologies in 2015 (Figure 1). It increased to US$311 billion in 2019. Investments in renewable fuels for transportation (i.e., liquid biofuels) have, however, decreased from US$38 billion in 2015 to US$33 billion in 2019. These investments are also reflected in Figure 2 which portrays the expansion of renewable electricity generation capacities vis-a-vis fossil-fuel-based capacities since 2000. Yet, the global share of electricity generation from renewable technologies in total electricity generation accounted for about 10% if hydropower is excluded. Including hydropower, the share of renewable electricity generation in total electricity generation stands at 28% in 2020 (Figure 2a). Including nuclear, non-fossil fuel-based technologies produced 38% of the total electricity globally in 2020. In terms of capacity to generate electricity, the shares of renewables, renewables including hydro, and non-fossil fuels technologies are 20%, 37%, and 43%, respectively (Figure 2b). The reason for the lower share of generation from renewables compared to that of capacity is that renewables electricity plants (e.g., solar, wind, hydro) can operate fewer hours in a year than fossil fuels-based plants.

Although the share of renewables is relatively small in total installed capacity, they are the largest in terms of new capacity addition. For example, from 2010 to 2020, the capacity

FIGURE 1

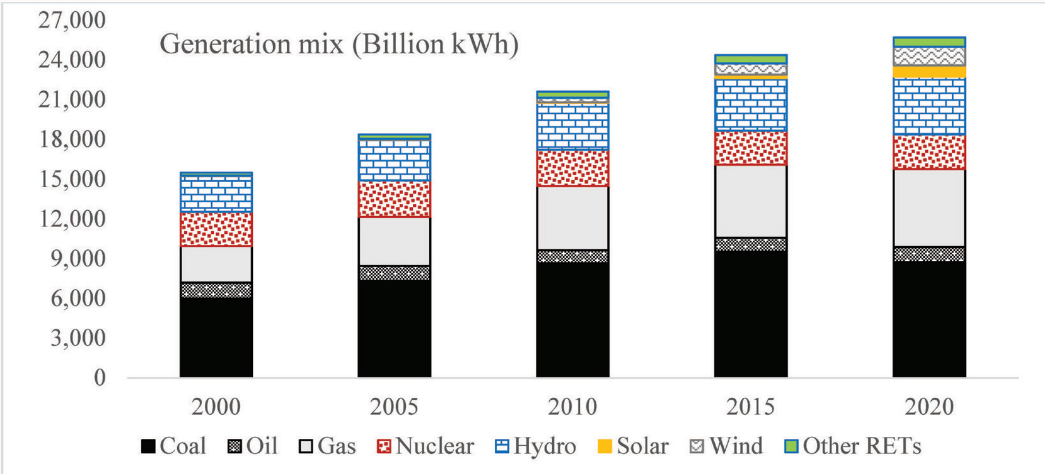
Investments (Billion US$) in non-fossil fuel-based technologies and their share (%) in total energy investment (2015-2020)



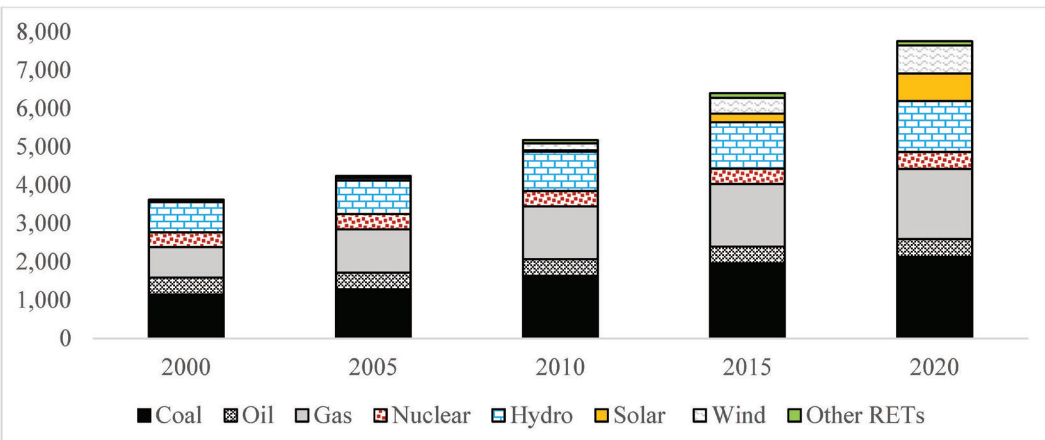
Source: IEA 2020c

FIGURE 2
Global electricity generation and capacity mix

(a) Annual generation mix (Billion kilowatt-hours)



(b) Total installed capacity mix (GW)



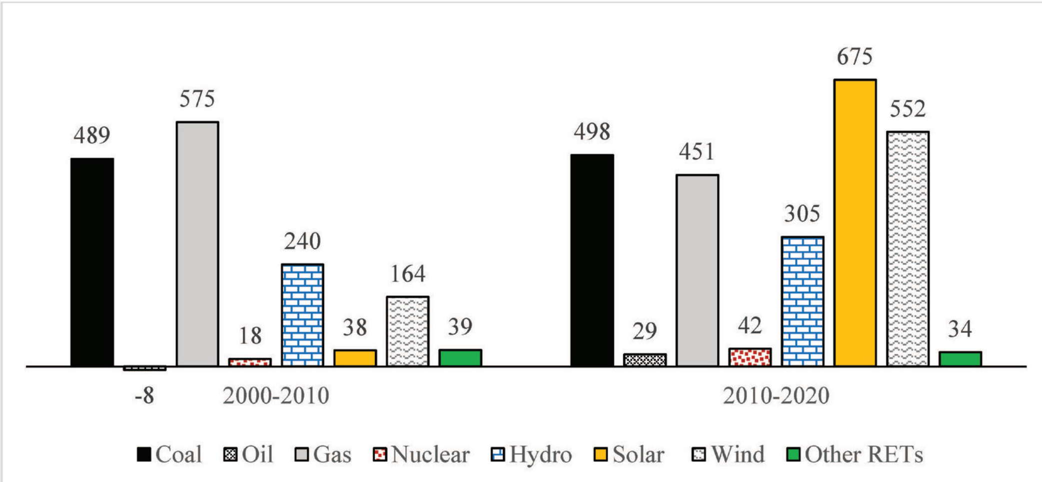
(continued)

addition of solar power is the largest (675 GW) followed by wind power (552 GW) (Figure 2c). Solar and wind together accounted for almost half of the total capacity added during the 2010-2020 period. Due to the stringent climate change targets, particularly if the net-zero path is followed, the share of renewables (solar, wind, hydro, and other renewable energy technologies) would be much higher by 2030.

Investments in renewables are expected to accelerate due to the current debate on the net-zero target (i.e., a goal to have net-zero GHG emissions globally) by the middle of this century. The net-zero target is consistent with the 1.5 °C targets—limiting the increase in the global mean surface temperature of the earth's surface to 1.5 °C above the pre-industrial level--. To stay on the path to meeting this target, the IEA estimates that the world needs 630 GW of solar PV and 390 GW of wind to be added annually by 2030 (IEA 2021a). It also projects that two-thirds of the total energy supply should be met from wind, solar, bioenergy, geothermal, and hydro energy by 2050 to realize the net-zero target.

FIGURE 2 *(continued)*
Global electricity generation and capacity mix

(c) New capacity or capacity added during the 2000-2010 and 2010-2020 period (GW)



Other RETs refer to other renewables, including biomass, geothermal, tidal, etc.
Source: IEA 2021b

There is a sharp rising trend in the number of corporations joining the 100% renewable energy consumption (RE100) group, which brings together organizations that have set a target to source 100% of their power from renewables by a particular date in the future. The number of corporate members of RE100 increased from 12 in September 2014 to 222 in January 2020 (FS et al. 2020). The RE100 includes prominent companies such as Apple, Facebook, and Microsoft. The list includes 19 of the world's 100 largest companies by revenue.

The total investment in clean technologies, including renewables and energy efficiency (EE), has remained stagnant at around US$600 billion during the 2015-2019 period. It dropped to US$562 billion in 2020 due to the COVID pandemic (Figure 1). One key reason for the downward trend of investment despite the continued expansion of clean technology adoption is falling unit costs for key renewable technologies (e.g., solar PV, wind, and electric vehicles).

The EE improvement means using technology that requires less energy to perform the same task. It has multiple benefits, including reducing energy bills[1], mitigating climate change, reducing air pollution, improving energy security, and increasing energy access (IEA 2020a). The IEA estimates that the efficiency gains since 2000 in IEA member countries resulted in the avoidance of over 15% or US$600 billion more energy expenditure for fuels for heating, road transport, and a wide range of other energy end-uses (IEA 2020b).

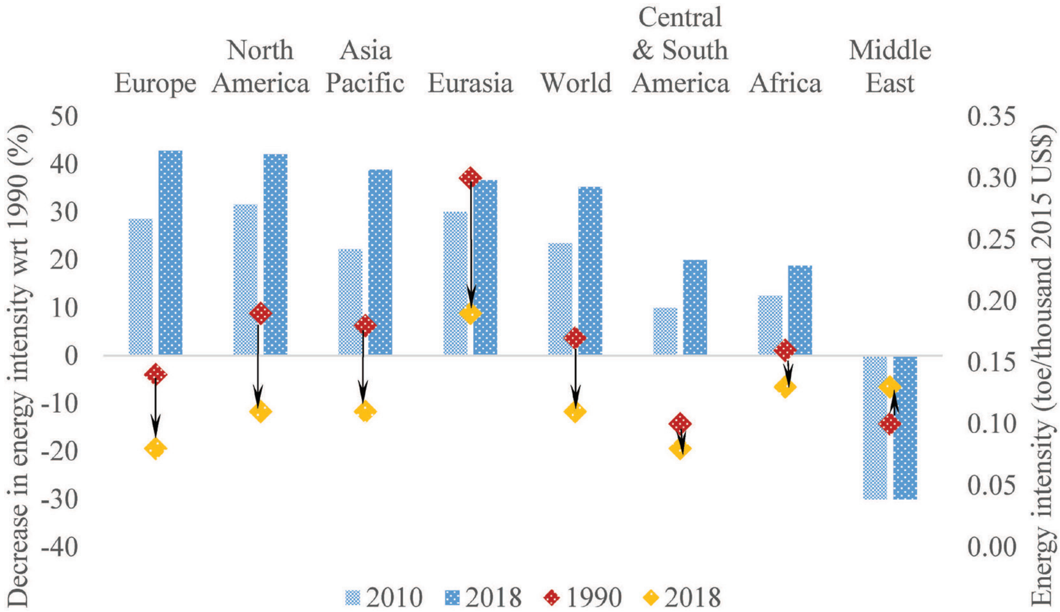
The improvement of EE is one of the main drivers of reducing energy intensity (EI) in many countries and regions around the world.[2] For instance, excluding the Middle East, the worldwide EI of the economy—the amount of energy used to generate a unit of GDP—has decreased in the past, ranging from a low of 19% in Africa to a high of 43% in Europe between 1990 and 2018 (Figure 3 bar graph). The increasing trend in EI in the Middle East is mainly

1. In some cases, EE improvements might not reduce energy consumption due to rebound effect. See e.g., Stapleton et al. 2016.
2. Lower (or higher) EI could indicate that energy is being used efficiently (or inefficiently) but not always.

due to the dominance of expanding energy-intensive industries, commodity exporting-based economies, and low energy prices. In absolute values, the EI is the highest in Eurasia (0.19 toe per thousand 2015 US$) to the lowest in Europe and Central and South America (0.08 toe per thousand 2015 US$) (Figure 3 scatter plot).

FIGURE 3

Energy intensity (EI) in 2010 and 2018 relative to 1990 (bar, left axis) and EI in 1990 and 2018 (scatter plot, right axis) by world regions



Source: IEA 2021b

3. GREEN/CLEAN INVESTMENTS AND FIRM'S PRODUCTIVITY IN GENERAL

Many empirical studies investigate the relationship between investments in cleaner or greener technologies and the cost of production or productivity. In general, productivity measures the efficiency with which firms, organizations, industry, and the economy convert inputs (e.g., labor, capital, and raw materials) into output. Productivity grows when output grows faster than inputs when both inputs and outputs are measured at the same or constant prices. Depending upon the input in consideration, there are many different measures for productivity, such as single-factor productivity (e.g., labor productivity or capital productivity) or multifactor (e.g., capital and labor or capital-labor-energy-materials) productivity. It can be measured at the firm or industry, or the organization or country-level (OECD 2001). Unless specified otherwise, productivity in this study refers to total factor productivity (TFP)[3]. In this section, the literature that presents overall relationships between green/clean energy investment

3. The TFP, also known as multi-factor productivity, is a measure of the output of a firm or industry or economy relative to the size of all its primary factor inputs. It measures the residual growth that cannot be explained by the rate of change in the services of labor, capital and intermediate outputs of firms or industries or economy as whole. It is often interpreted as the contribution to productivity growth made by factors such as new knowledge, technologies, and experience.

and productivity at the industry level is discussed, followed by the section on various attributes, such as firm size, ownership, and regulations, that can influence the relationship.

3.1. Relationship between green/clean investment and productivity

Existing studies argue and demonstrate empirically that stricter environmental regulations cause firms to invest in innovation and adoption of cleaner technologies, which would eventually lead to increased productivity. There is a strong argument that environmental regulations cause technological innovation that will increase productivity and that the productivity gain offsets the costs of environmental regulations (Porter 1991; Porter and van de Linde 1995). This hypothesis, popularly known as 'Porter's hypothesis'[4], has been tested empirically by many studies that are discussed in this paper. The empirical results are, however, ambivalent. While earlier studies do not necessarily prove Porter's hypothesis, more recent studies do. For example, investments in pollution control technologies (i.e., clean technologies) in the US manufacturing industries during the 1980s had a significant positive effect on R&D expenditures (Jaffe and Palmer 1997). However, the evidence of whether the striker environmental regulations in the US manufacturing industries during that period spurred R&D activities (i.e., increased patents of green/clean technologies) is not strong. This is sometimes referred to as a "weak" version of Porter's hypothesis in the literature because it does not confirm whether innovation or the use of clean/green technologies is good for firms. The result is not surprising, though, as the large-scale deployment of cleaner or greener technologies in local air pollution control occurred after the 1990s. Moreover, increased deployment of greener energy technologies, such as wind and solar, accelerated more recently, after 2005.

Some studies also examine impacts on the productivity of green/clean investment resulting from environmental regulations in China. For example, Chinese regulated firms are more motivated (or obligated) to invest in green/clean technologies to meet existing environmental regulations (Cao et al. 2021). Using sample data from environmentally dirty industrial firms (e.g., coal mining and washing, oil and gas mining, petroleum processing, coking and nuclear fuel processing, power, thermal production and supply, and gas production and supply) for the 2000-2007 period, they find that investments in green/clean technologies led to an increase firms' productivity. Likewise, there is evidence of a positive relationship between the deployment of new green/clean technologies resulting from flexible environmental regulations and the productivity of Chinese industrial firms during the 1998-2007 period (Peng et al. 2021). Also, green investment has a significant and positive correlation with the financial performance of Chinese energy firms during the 2008-2017 period, that is, increasing green investment helps improve financial performance (Chen and Ma 2021). They also find that green investment helps reduce environmental violations and promotes the environmental performance of these energy firms.

Several studies directly examine whether an investment in green/clean technologies increases firms' productivity or production costs (Böhringer et al. 2012; Hamamoto 2006; Horváthová 2012; Lanoie et al. 2008; Leoncini et al. 2019; Palmer and Truong 2017; Rath et al. 2019; Rubashkina et al. 2015; Sohag et al. 2021; Stucki 2019; Tugcu and Tiwari 2016).[5] For

4. Discussion of Porter's hypothesis is relevant here because it suggests environmental regulations cause technological innovation that will increase productivity. The increased productivity could lead to decreased production costs.

5. See Appendix A.1 for a summary of methods used and the main findings and arguments of these selected studies.

example, in the case of Japanese manufacturing industries, pollution control expenditures have a positive relationship with R&D expenditures and a negative relationship with the average age of capital stock (Hamamoto 2006). The investments in pollution-control technologies, as a proxy for stringent environmental regulations, also resulted in modest, long-term gains in TFP in the case of 17 Quebec (Canada) manufacturing sectors (Lanoie et al. 2008). They find that this effect is more important in industries that are more exposed to international competition. Likewise, a positive relationship between new green technologies use and firms' profitability is found based on 79 global firms during the 2007-2012 period (Palmer and Truong 2017). However, in some cases, it is not always clear whether the effects of investments in clean technologies increase firms' productivity. For example, the relationship between environmental policies, including green/clean investment, and firms' productivity growth is not positive in the case of German manufacturing sectors during the 1996-2002 period (Böhringer et al. 2012). They, however, conclude that environmental policies or regulations should stimulate environmental investment to realize firms' productivity growth.

Several empirical studies also examine if the investment in renewable energy technologies promotes TFP. For example, a higher share of renewable energy in the production process significantly promotes TFP in the long run based on data from 25 OECD countries (Sohag et al. 2021). This is not necessarily the case in the short run. The increased human capital, innovations, and trade openness augment the positive relationship between renewable energy investment and TFP. However, they do not explain the channels through which increased renewable energy improves TFP. Similar effects are also observed in examining the relationship between the growth of renewable energy and TFP using panel data from 36 countries during the 1981–2013 period (Rath et al. 2019). They show that an increased TFP is associated with increased consumption of renewable energy, whereas the consumption of fossil fuels is negatively associated with TFP. Their findings, however, vary across different regions. Since increased consumption of renewable energy reflects increased investment in renewable energy technologies, their findings imply that green investments increase TFP at the aggregated level. There is also a positive effect of green technologies on a firm's productivity growth which is greater than that of non-green technologies based on the dataset of 5,498 manufacturing firms in Italy during the 2000-2008 period (Leoncini et al. 2019). Likewise, in the case of Japanese manufacturing industries, increases in R&D investment stimulated by regulatory stringency have a significant positive effect on TFP growth (Hamamoto 2006).

There exists no consensus, however, on the relationship between investment in green/clean technologies and productivity. For instance, there is a significant upfront innovation expenditure that led to firms' lower productivity in the case of Czech Republic firms (Horváthová 2012). However, this negative effect also tends to fade over time and transforms into a positive effect in the long run. There is also no evidence of a positive relationship between pollution abatement and control expenditures, as a proxy for clean/green technology investment, and productivity based on the cross-country sector-level panel data of 17 European countries during the 1997-2009 period (Rubashkina et al. 2015). They also find a positive impact of environmental regulation, as proxied by patents, on productivity. Likewise, there is no remarkable causal link between renewable energy consumption and TFP growth in the power sector in BRICS countries[6] during the 1992-2012 period (Tugcu and Tiwari 2016). Instead, they find a positive relationship between non-renewable energy (fossil-fuels) consumption and TFP

6. BRICS refers to the group of countries that include Brazil, Russia, India, China, and South Africa.

in Brazil and South Africa.[7] In some cases, there are significant positive productivity effects of an investment in green energy technologies in firms with high energy costs but not in firms with medium energy costs based on the firm-level data in Austria, Germany, and Switzerland (Stucki 2019). They also find significantly negative effects for firms with low energy costs.

3.2 Factors affecting the relationships between clean investments and productivity

Several factors influence whether investments in green/clean technologies increase a firm's productivity. These factors include the size of firms, their ownership, the presence of different policy instruments including environmental regulation, and activities for investments (development vs adoption of technologies). Firm size is one of the key factors that influence whether green/clean investment impacts a firm's productivity. This is mainly because large firms have a higher investment capacity, especially in the case of energy-intensive firms. Therefore, they tend to invest in green/clean technologies. On the other hand, small firms, particularly less energy-intensive ones, may not find it beneficial, as suggested by some literature (Stucki 2019). For example, large firms which are energy-intensive and exposed to international competition are more likely to invest in energy-efficient technologies (Hrovatin et al. 2016). Large firms also have financial resources for investment in clean or energy-efficient technologies. Similar results are seen in Irish firms during the 2008-2016 period, i.e., larger firms, importers, and firms that are part of an enterprise group are more likely to invest in clean energy technologies (Siedschlag and Yan 2021). In China, small-scale firms are notably less likely to invest in the development (or innovation) of clean technologies (measured in terms of patents) because of budget constraints (Chen et al. 2021). On the other hand, large-scale firms in China can invest in innovation (R&D) because of their access to finance and innovation risk diversification capabilities. With environmental regulations, small firms choose to reduce their output rather than increase investment in technologies to meet the regulations. Firm size is also an important factor to influence the productivity effects of green investment in the case of investment in water pollution control technologies in China (Qi et al. 2021). They find that large firms can install clean technologies without impacting their outputs as the fixed costs of clean technologies are relatively small, while small firms that do not invest in clean technologies face higher costs due to different regulatory costs. They also argue that the fixed costs associated with the installation of clean technology led to increasing returns to scale above a threshold size of a firm (i.e., large firms). That is the reason why large firms are less pollution-intensive than small firms in China.

The ownership of firms is another factor affecting the relationships between clean investments and productivity. However, not enough empirical evidence is available that indicate the influence of ownership of firms. Large-scale multinational firms usually have private ownership (i.e., multinational companies). Such firms invest in green/clean technologies if they are energy-intensive and exposed to international competition. They normally do not face financial constraints. Similarly, large state-owned companies, such as electricity utilities, have financial resources for green/clean investment (e.g., adoption of renewable technologies for power generation). Therefore, the size of the company appears to matter more than the ownership regarding investment in green/clean technologies. Yet, some studies attempt to differentiate the impacts of green/clean investment based on ownership. For example, the impacts on the pro-

7. Note, however, that expansion of renewable energy is happening more recently. Therefore, this finding is not surprising as the data used in this study were for the period when there was little expansion of renewable energy.

ductivity of green investments to meet the existing regulatory policies (i.e., cleaner production standards) are greater for state-owned firms than that for non-state-owned firms in China (Cao et al. 2021; Peng et al. 2021). Their findings, again, boil down to the size of the firms because state-owned firms in China account for a significant proportion of large-scale energy firms, and cleaner production standards have greater effects on the improvement of productivity of state-owned firms.

Another factor that influences whether investments in green/clean technologies increase a firm's productivity is the presence of policy instruments, including environmental regulation. Environmental regulation increases the cost burden of firms because firms have to internalize environmental costs. At the same time, it also incentivizes firms to invest and innovate in green technology that may have financial benefits. In the case of Spanish manufacturing firms for the 2010–2017 period, the relationship between policy instrument and energy-saving investments that increases the firm's productivity is mixed (García-Quevedo and Jové-Llopis 2021). They find that there is not enough evidence of a positive relationship between policies such as environmental taxes, tax credits and regulation, and saving energy investments, while subsidies show significant and positive influence. Based on 188 manufacturing firms In China, the relationship between green innovation and firm performance is inconclusive (Tang et al. 2018).

3.3 Effects of innovation vs. adoption of green/clean technology on the productivity

It is also important to understand whether the firm's productivity change due to green investment is caused by the investment in the deployment of green/clean technologies or by their development (i.e., R&D investment). While the increased adoption of green/clean technologies directly affects productivity even in the short run, innovation of new technology through R&D investment does so in the long run. However, the development of new technology does not guarantee its adoption. The discussions earlier are related mostly to investment in the adoption or deployment of clean technologies. In general, the countries with greater energy R&D investment intensity show higher levels of investment in green technologies (Popp et al. 2011). Some existing studies empirically show that environmental knowledge spillover or the knowledge created through R&D investment in environmental or clean technologies is positively related to firms' performance.

For instance, there is a positive but only slightly significant effect of process or product innovation on productivity based on a survey of small and medium-sized Italian manufacturing firms over the 2004-2006 period (Aldieri et al. 2021). They find that positive and strongly significant effects if it is an organizational innovation.[8] Also, the investment in environmental or clean technologies or knowledge, measured in terms of registered patents, affects firms' productivity significantly and positively based on the firm-level data on inputs, outputs, and their patents registered from Japan, the USA, and European countries (Aldieri et al. 2020). Likewise, there is a positive relationship between innovation (investment in clean/green technology R&D) and productivity (TFP) based on the firm-level panel data of Dutch manufacturing firms over the 2000-2008 period (van Leeuwen and Mohnen 2017).

However, in some cases, the green/clean technology innovations hurt firms' productivity, mainly due to additional direct costs associated with R&D investments to innovate and modify production design and process, and increasing financial constraints due to the fixed

8. Generally, product innovation includes new products, process innovation includes new technologies and organizational innovation includes new business practices (OECD 2005).

budget for investment in innovation activities (Zhang et al. 2019; Zhang et al. 2020). There is also a weak and highly heterogeneous relationship in the evidence a relationship between R&D investment, both green/clean and other R&D investments, and firm or industry productivity based on a review of 65 different studies in OECD countries (Ugur et al. 2016). They find that the sources of heterogeneity are the size of the firms (small or large), funding sources of R&D (private or public), and the magnitude of R&D investment (low or high).

4. GREEN/CLEAN INVESTMENT AT THE SECTORAL LEVEL

This section explores green/clean investment effects on production costs in specific sectors, such as manufacturing, power, buildings, and transportation. The indicators used for productivity here differ across sectors and they are not necessarily the TFP considered earlier. For the manufacturing sectors, we still use the TFP as the measure of productivity. Where TFP data is not available or not relevant, we use the cost of energy services because manufacturing sectors, particularly the energy-intensive ones, invest in energy-efficient technologies to reduce their production costs. Private firms invest in energy-efficient devices or processes if the investment is profitable (or it saves overall production costs). Therefore, a reduction in energy costs can be interpreted as a reduction in production costs. For the power sector, we look at whether an expansion of renewable sources of electricity generation (hydro, solar, wind) reduces the overall costs of electricity supply from a grid. In the transportation sector, the indicator is cost reduction for transportation services due to clean or alternative vehicles. For the buildings sector, for example, we look at whether the EE measures reduce households' or businesses' utility (energy or electricity) bills. However, studies examining the impacts of the adoption of clean energy technologies are limited in the agriculture sector.

4.1 Manufacturing sector

Energy is an important input to manufacturing industries. Costs of fuels and electricity constitute a major share of the total cost of production in energy-intensive industries, such as iron and steel, aluminum, cement and glass, pulp and paper, chemicals, and fertilizers. These industries often invest in energy-saving technologies to reduce their energy bills. Some countries have regulations that mandate improvements in EE in industrial establishments. In such a case, Porter's hypothesis would hold if the investments in EE improvements reduce overall production costs or improve productivity.

Several recent studies provide empirical evidence to support the positive relationship between improvements in EE and productivity (Arriola-Medellín et al. 2019; Filippini et al. 2017, 2020; Haider and Bhat 2020; Hasanbeigi et al. 2012; Huang and Wu 2021; Li et al. 2021a; Morrow et al. 2014; Unver and Kara 2019; Xylia et al. 2017; Zuberi et al. 201). For example, the impact of a national EE program on the TFP growth of firms in China's iron and steel industry is positive and statistically significant based on the firm-level survey data collected through the Chinese Annual Industrial Survey for the 2003-2008 period and using multiple empirical strategies and identifications (Filippini et al. 2020). In the chemical industry, adopting clean technologies would reduce more than 40% of the production costs for the same output level from the industry using a simulation model (Li et al. 2021a). In the Taiwanese cement industry, similar results are seen, i.e., there is a reduction in production costs due to the adoption of energy-efficient technologies (Huang and Wu 2021).

Several studies also show positive impacts of clean or energy-efficient technologies on productivity, but the impacts vary across the studies.[9] Some studies explain how an increased EE enhances the productivity of a firm, presenting an example of the glass industry, which is an energy-intensive industry (Boyd and Pang 2000). Other studies find that investments in the development or deployment of clean technologies also increase labor productivity. For example, in the case of firms involved in developing and adopting energy-efficient technologies during the 2012-2014 period in Austria, Germany, and Switzerland, investments in clean technologies increase labor productivity (Arvanitis et al. 2017). Likewise, there is a positive and causal relationship between the EE investment and the labor productivity of the firms in 27 EU member states and the UK during the 2018-2019 period (Kalantzis and Niczyporuk 2021). They find that investment in EE improves labor productivity by 16 percentage points and that the labor productivity gains are higher in foreign-owned firms than in domestic firms and in exporting firms.

However, the positive relationship between the adoption of clean technologies and a firm's productivity could be conditional on other policies or activities. For example, firms gain productivity by adopting environmental technologies only in the presence of supportive organizational structures (Hottenrott et al. 2016). Using the panel data on the adoption of environmental technologies in German manufacturing and service firms for the 2000-2008 period, they find firms that adopted green technologies together with changes to their organizational structures utilize green technologies better than those firms that only adopted green technologies without having supportive organizational structures. In some cases, the adoption of clean technologies (1000 Energy-Consuming Enterprises Program, or T1000P) in China had negative impacts on TFP change, a decrease of an annual 0.923% on average, in the chemical industry (Ai et al. 2021).

4.2 Transportation sector

It is not straightforward to measure productivity in the transportation sector because of the mixed ownership of vehicles between households and businesses. Automobiles (e.g., cars, SUVs, motorcycles, small trucks) are usually owned by private households, whereas bigger vehicles (e.g., busses, big trucks) are owned by private companies or government utilities. In this study, we use the costs of providing transportation services as an indicator to compare the economics of road vehicles. It measures the unit costs of delivering comparable transportation services.[10] The costs are the life-cycle costs that include costs of owning and operating the vehicles (Comello et al. 2021). This measurement is commonly used in the literature. It is also referred to as 'total cost of ownership (TCO)' to compare the overall cost of clean and alternative vehicle technologies (e.g., BEVs, PHEVs, and FCEVs) with that of conventional vehicles (i.e., ICEVs).[11] With advances in technologies, the TCO of clean vehicles has been

9. See Appendix A.2 for the summary of results of these studies.

10. In the case of transportation service providing firms, the TFP can be measured dividing output (e.g., transport sector value added) by a weighted set of inputs (e.g., labor hours, fuel, equipment, and materials). It can also be measured as average revenue per passenger-mile for passenger transportation, and average freight revenue per ton-mile for freight transportation (BTS 2021; Davis and Boundy 2021).

11. Road transportation vehicles can be broadly categorized as conventional internal combustion engine vehicles (ICEVs) and alternative electric vehicles (EVs). The ICEVs are powered by fossil fuels (gasoline, diesel, LPG, and natural gas) and in some cases, biofuels (biodiesel and bioethanol) are blended with fossil fuels. The EVs are powered by electricity. There are two basic types of EVs: all electric vehicles and plug-in hybrid electric vehicles (PHEVs). All electric vehicles include Battery Electric Vehicles (BEVs) and Fuel Cell Electric Vehicles (FCEVs). The PHEVs run on electricity for shorter ranges, then switch over to an ICE running

falling significantly in recent years. For this reason, we focus on empirical studies examining the TCO of clean vehicles published in the past five/six years.

The economic analyses of transportation services analyzed by existing studies are differentiated by the type and size of vehicles. These include studies analyzing the economics of passenger cars (Ajanovic and Haas 2021; Breetz and Salon 2018; Hamza et al. 2021; Lévay et al. 2017; Ouyang et al. 2021; Palmer et al. 2018; Weiss et al. 2019), commercial vehicles (Falcão et al. 2017), buses (Ally and Pryor 2016; Comello et al. 2021; Li and Kimura 2021), trucks (Vora et al. 2017) and combination of different vehicles (Gambhir et al. 2015). In general, most of these studies show that the TCO of an average passenger EV is currently higher than an equivalent ICEV.[12] However, EVs are projected to be cost-competitive in the future because of a series of efforts and commitments in place to improve EV's battery technology, which constitutes a major cost of EVs. Meeting the climate change targets, mainly the net-zero carbon target by the mid-century, require a massive investment in the transportation sector. The sector needs to undergo a transition towards massive electrification across the different modes; production of zero-carbon synthetic fuels derived from renewable energy and massive improvements in vehicle EE. Some studies project when alternative or cleaner (i.e., EVs, BEVs, hydrogen vehicles) vehicles will be economically competitive through technological innovations and market development. For example, FCEVs would be competitive with conventional vehicles by 2035 (Whiston et al. 2021). Another study indicates that small BEVs will reach parity with ICEVs by 2025, and medium-sized and large BEVs will do so around 2030 (Ouyang et al. 2021). However, they find that even though BEV and PHEV purchase costs will fall by 31%–36% and 16%–18%, respectively, between 2020 and 2030, most EV models will still not reach purchase cost parity by 2030.

A few studies report cost-effectiveness of alternative or cleaner vehicles, particularly when they account for environmental benefits. For example, electric buses are cheaper than diesel and CNG buses in urban metro areas in the US (Holland et al. 2021). They find that compared to new diesel or CNG buses, the per-mile net benefit (or cost savings) of an electric bus is \$0.04 and \$0.01, respectively, on average. Although significant spatial heterogeneity exists across different urban areas within the country, the environmental benefit of electrifying the entire bus fleet in Los Angeles relative to a new diesel fleet is estimated at US\$65 million per year; relative to a diesel bus, the benefits of purchasing and operating an electric bus over its lifetime are about US\$8,000 at a 3% discount rate. Likewise, electric buses are more cost-effective than the existing diesel buses in Belgium, mainly because the TCO is around €730 thousand for electric buses and €803 thousand for diesel buses (Lebeau et al. 2013). Similar results are seen for Malaysia (Teoh et al. 2018), India (Majumder et al. 2021), and Sweden (Borén 2020). In Malaysia, they find that the annual cost (i.e., energy, maintenance, and fuel costs) for electric buses is around US\$4.5 million, which is 68% less than that of a diesel bus. In India, depending on how electricity is supplied (grid or solar off-grid or a combination of both), they find that the present value of the total cost of an electric bus system by the end of 2030 ranges from US\$314 thousand to US\$370 thousand. In contrast, it is US\$377 thousand for the conventional diesel bus system. In Sweden, they find that electric and alternative fuels

on gasoline when the battery is depleted. PHEVs could also use hydrogen in a fuel cell, biofuels, or other alternative fuels as a back-up instead of gasoline.

12. See Appendix A.3 for studies that show the cost disadvantage of alternative (or cleaner) vehicles as compared to their conventional counterparts.

(biogas and HOV) fueled buses will be cheaper than diesel vehicles if the societal cost of emissions and noise are considered.

Although some of these existing studies (see Appendix A.3) show alternative or green/clean transportation systems are relatively cheaper than existing fossil fuel-based transportation services, the actual deployment of clean vehicles faces several barriers. First, the economic analysis of the green/clean transportation system may not necessarily reflect the true economic costs as these analyses include financial incentives (i.e., subsidies provided under the various government programs to promote green/clean transportation systems) (Li et al. 2021b). Some studies include environmental benefits in the analysis (Holland et al. 2021). Including the environmental costs of fossil fuels or the environmental benefits of clean fuels is a correct approach in an economic analysis of clean/green transportation. However, private vehicle owners do not account for these social benefits while making a vehicle purchase decision. Some studies (Ouyang et al. 2021; Ruffini and Wei 2018) also make optimistic assumptions about the technological evolution of clean/green transportation systems, which could be unrealistic due to a series of uncertainties around the assumptions. Moreover, even if some cleaner vehicles are economically attractive under a certain set of data and assumptions, adoption of these vehicles may not occur due to several barriers, including lack of infrastructure (e.g., charging stations for electric vehicles).

4.3 Power sector

The electric power sector offers the highest opportunities to invest in green or clean infrastructures, particularly renewable electricity (RE) generation technologies, including hydro, solar, and wind. The critical question is whether investments in green/clean power generation technologies help reduce the total electricity supply costs and prices. The answer is mixed.[13] In some cases, the expansion of renewable electricity reduces the cost of electricity supply and eventually electricity prices. On the other hand, it would result in the opposite in many cases. Even though costs of renewable sources for electricity generation are falling rapidly, their initial investment (capital) costs are still high as compared to the conventional technologies to produce electricity (e.g., natural gas combined cycle technology). On a levelized cost basis, renewables are becoming more and more competitive with conventional power generation technologies (Timilsina 2020). However, intermittent renewables cannot be compared with existing technologies that supply uninterruptible electricity (or firm capacity). Therefore, increased penetration of renewable energy technologies is likely to increase the average costs of electricity supply unless the cost of energy storage drops significantly. Even if carbon pricing is introduced to penalize fossil fuels, renewables could still increase the average costs of the electricity supply of a grid (Steckel and Jakob 2018).

There are two types of studies analyzing the relationships between the penetration of renewable electricity into a grid and its average costs of electricity supply. The first set of studies conducts ex-ante analysis using power sector expansion models, which use optimization techniques. These models find the least-cost mix of electricity generation resources for a given time-horizon satisfying all constraints specified by the modelers. For example, some studies (Mai et al. 2021; Liang et al. 2019; Kumar 2016) have employed this approach to examine the effects of expanding renewable electricity on the costs of electricity supply from grids. The second type of study is ex-post studies using econometric techniques to relate the expansion of

13. See Appendix A.4 for a summary of methods used and the main findings and arguments of these selected studies.

renewables with electricity prices (Würzburg et al. 2013) and several studies referred by them fall into this category.

Many studies also investigated the impacts of increased penetration of renewable electricity on the average costs of electricity grids and, ultimately, electricity prices. For example, replacing coal-fired power plants with renewables in Italy would increase the electricity supply costs because the benefits from coal phase-out are smaller than electricity system costs due to increased intermittent renewables and natural gas (Vellini et al. 2020). Renewables also pose a threat to the viability of base-load generation in the long term; therefore, cheaper, and relatively cleaner fossil-fuel sources, such as natural gas, are needed for the reliable supply of electricity for many decades to come (Adelman and Spence 2018). Some studies (Liang et al. 2019; Kumar 2016) also find that large-scale integration of renewable energy would cause an increase in electricity system costs and price. However, if the declining trends of costs of renewables and storage technologies continue, and if the value of carbon reduction is accounted for, integration of renewable technologies may not increase the long-term costs of electricity supply from a grid.

Some studies examine the impacts of meeting renewable energy portfolio standards introduced or planned by various states in the USA and find that an expansion of non-fossil electricity generation that accounts for 45% of the total generation would increase electricity system costs by 0.4% to 0.8% depending upon the discount rate (Mai et al. 2021). They also find that if the share of non-fossil fuels in the total generation reaches 78%, the system costs will increase by 2.7% to 3.6%. In China, increasing the share of renewable electricity capacity by 23.6 percentage points in 2050 (from 27.1% in the BAU scenario to 50.7% in RE expansion scenario) would increase the electricity system costs by 7% (Liang et al. 2019). In Indonesia, expanding renewables to account for 40% of the total electricity generation by 2050 (or increasing renewable capacity by 1.3 times from the business-as-usual case) would increase the electricity system costs by 40% from the BAU case (Kumar 2016). They also find that increasing renewable capacity to account for 39% of the total capacity by 2050 (increasing renewable capacity by 3.4 times from the BAU case) would increase the electricity system costs by 82% (from the BAU case) in Thailand. In some cases, the cost of attaining RE penetration in a grid above a threshold or inflection point (the point at which the penetration of RE begins to exceed hourly load) also gets very expensive for retail utility customers (Schulte and Fletcher 2021). They find that at this point, REs must be turned down or curtailed which may lead to diminishing returns for REs. This could be a technical barrier to achieving a 100% clean energy goal for an electricity grid.

In certain circumstances, the expansion of renewable electricity could reduce the average costs of an electricity supply system or grid and electricity prices. Such cases arise when the electricity market is well-interconnected and is fully deregulated; electricity prices are based on short-run prices, which reflect variable costs of the network at a given time, such as day-ahead price. In the EU electricity market, which represents a well-interconnected system of electricity grids, increased penetration of renewables could reduce electricity prices at certain points in time (i.e., certain hours in a day). Several studies cited in (Würzburg et al. 2013) report a reduction in short-term costs of electricity in the EU and the corresponding prices due to the increased penetration of renewables. However, some caution needs to be taken as to whether RE sources have enjoyed subsidies or premium prices (feed-in-tariff). The price reduction could be a result of these subsidies. On the other hand, one could also argue that if carbon prices are introduced, the price reduction effects of RE sources hold even if they do not receive any subsidies. It should also be noted that the studies cited in (Würzburg et al. 2013) are relatively old. Further, costs of electricity from RE sources were much higher a decade ago than now and the average prices of electricity are higher now than a decade ago. For example, between 2010 and 2021, the global weighted average levelized cost of electricity of solar PVs fell by 88% and onshore wind fell by 68% (IRENA 2022). Timilsina (2021) calculates levelized costs of electricity from 11 technologies considering hundreds of sensitivity analyses in all input variables. It shows that renewables, particularly hydro, solar PV, and onshore wind are relatively cheaper than other technologies for power generation.

4.4 Buildings sector

Many studies examine the economics of energy-efficient technologies, particularly heating and cooling devices, insulations, lighting devices, cooking appliances, and electronic and computer devices in residential and commercial buildings. These technologies reduce the demand for energy and save energy costs; they reduce emissions of GHGs and local air pollution (e.g., indoor air pollution). Globally, a large investment is made annually in clean technologies in buildings. In 2018, it accounted for the largest share (58%) of the total US$139 billion invested in energy-efficient technologies globally (IEA 2019).[14] Several empirical studies show significant savings in energy consumption and energy bills in the household sector (a sub-set of the buildings sector). For example, based on a review of 100 existing studies that analyze EE improvements in the household sector, a wide variation of reduction in electricity use is observed ranging from a low of 0.5% to a high of 80% of total electricity use, with a median value of 7.9%. (McAndrew et al. 2021).[15]

In the Amman and Zarqa regions of Jordan, the net saving by implementing EE measures (refrigerators and freezers) from 2011 to 2020 ranges from 4,451 GWh to 17,807 GWh, which is equivalent to saving electricity bills by Jordanian Dinar 320 million to 1,282 million, respectively, roughly US$450 million to 1,808 million in the current exchange rate (Abd Alfattah et al. 2017). The low-temperature and condensing boilers, as well as floor insulation, are found to be the most cost-effective EE measures based on data from 1,400 dwellings in France (Belaïd et al. 2021). They find that the percentage of total energy saved by using each type of these measures is about 29% for floor insulation and 38% for both low-temperature and condensing boilers. In some other cases, the cost-effectiveness of energy renovation measures is widely dependent on energy prices. For example, residents in low-income areas of Salt Lake City, Utah saved approximately US$18,219 annually in electricity bills, an equivalent of about US$100 per household, through the exchange program of replacing inefficient bulbs with LED (Witt et al. 2019). This translates to savings of about 2.6% of the total electricity consumed by each household. In Australia, most low-income households save, on average, 53% of their energy consumption in refrigeration through the replacement of old refrigerators with energy-efficient ones under the appliance replacement offer program (Ren et al. 2021). However, they also find that some portion of the energy savings could be compromised if the size of a new refrigerator is larger than the old one. There is also a case where cooking time for pizza could be reduced by 50% which corresponds to a reduction of 27% in energy consump-

14. EE investments in buildings sector include building envelopes, heating, ventilation, and air conditioning (HVAC), appliances, and lighting.
15. See Appendix A.5 for a summary of selected studies.

tion while retaining the desired quality properties of the pizza using a combination of efficient cooking technologies (Mastrascusa et al. 2021).

It is not necessarily true that the adoption of clean or energy-efficient technologies reduces energy consumption. For example, households in Ireland that have adopted micro renewable energy systems, such as PV panels, micro wind turbines, solar thermal water heaters, wood pellet boilers, geothermal heat pumps, and combined heat and power (CHP) units, have increased their electricity (Chester et al. 2019). In Japan, households began spending more electricity on space cooling and food preservation after the implementation of the EE program that sets efficiency standards for major home appliances (Inou and Matsumoto 2019). They find that the large size and increased stock of home appliances contributed to an increase in electricity use. Similar results are seen from residents in the Greater Boston area who received weekly feedback on their water consumption (a proxy for environmental measures) and lowered their water use by an average of 6%, an equivalent of 0.5 kWh/person/day, but at the same time, they increased their electricity consumption by 5.6%, an equivalent of 0.89 kWh/person/day (Tiefenbeck et al. 2013). They also find that the energy saved by reduced (hot) water consumption is offset by the increased electricity consumption by nearly a factor of two. In Memphis (Tennessee), households using the minimum threshold level (150 kWh per month) of the green electricity program (a proxy for environmental measures) have increased their electricity consumption by 2.5% (Jacobsen et al. 2012).

Several studies also use economic or financial analysis to evaluate investments in clean technologies (e.g., EE and solar home systems). For example, in Ghana, the cost savings from reduced electricity consumption by adopting energy-efficient air conditioning (AC) systems is about US$1.96 billion from 2018 to 2030 (Opoku et al. 2019). In Mexicali, Mexico, 39% of all households use oversized ACs, and replacing these ACs with more energy-efficient ACs would save them 32% in energy consumption annually (Suástegui et al. 2018). In the US, up to 60% of annual HVAC (heating, ventilation, and air conditioning), related energy is saved without compromising occupants' thermal comfort by setting optimal HAVC temperature setpoints in office buildings (Papadopoulos et al. 2019). In a single-family house in Maryland (USA), 13.1% to 14.7% of energy savings are observed with more efficient HVAC (e.g., ground-source heat pump with two and three boreholes) compared to conventional HVAC (e.g., air-source heat pump) (Wu et al. 2018). They find that the estimated value of operation cost saved is about US$186 to US$191 per household annually. However, for the same net electricity generation, the ground-source heat pumps required US$7,934 (2 boreholes) and US$9,739 (3 boreholes) higher initial cost than the air-source heat pump.

Some studies examine net energy savings (or net benefits) due to the adoption of clean energy supply systems in buildings. For example, the benefits of distributed photovoltaics (DPV) system in Bangladesh would be more than 1.5 times in residential and commercial buildings (Timilsina 2021). In the Waukegan area of Illinois, when energy efficiency and solar energy are combined, a household could save 66% annually on its electricity bill (Baek et al. 2020). Some studies show that refrigerator electricity consumption can be reduced by about 50% and 70% using commercially available energy-efficient components at an incremental cost of about US$45–US$60 and US$100–US$120 per unit, respectively (Park et al. 2019). They find that the total annualized cost of an off-grid solar home system together with an efficient refrigerator can be decreased by about 50%. This is mainly due to the additional cost of the efficient refrigerator which is significantly lower than the cost savings due to smaller capacity requirements for panels and batteries. In Australia, individual households could save 25% to 43% of their energy use when solar PV and battery systems are used for refrigerators (Roberts et al. 2019). In Cyprus, the benefit-to-cost ratio of replacing storage type electric water heaters with solar PV-based water heaters is an attractive option, ranging from 3.7 to 7.5 (Atikol et al. 2013). In Italy, retrofitting with EE measures and integrated rooftop PV in the office building results in potential energy savings of 54%, an equivalent to 8.8 TWh, with total implementation costs of €19 billion (Luddeni et al. 2018).

Not all case studies or economic/financial analyses show investments in clean technologies reduce the costs of energy services delivered. Whether investments in clean technologies pay off or not depends on several factors. While the detailed discussion of these factors is beyond the scope of this study, we present a few examples below. Energy price is the key factor influencing the economics of clean technology investment in the building sector. For example, the investment in energy-efficient technologies (e.g., high-performance glazed windows) in small office buildings in Thailand is unprofitable under current economic conditions (Lohwanitchai and Jareemit 2021). In Israel, the electricity savings from building envelopes (e.g., external insulating wall) of a typical apartment in the hot and humid climate is only one-third of the total retrofit cost (Friedman et al. 2014). Another example includes retrofitting the HVAC system and insulation of office buildings in China which could reduce annual energy consumption by 57% compared to the national average of office buildings (Zhou et al. 2016). They find that electricity consumption savings of 53% for heating and 64% for cooling with similar scale buildings elsewhere in China. They also find that 30% of the operation cost can be saved by replacing the HVAC system operation with a water storage system (energy-efficient retrofitting). While retrofitting wall insulation and replacing old ACs with energy-efficient ones offer higher financial viability, replacing windows is not the case for residential villas in Dubai (Rakhshan and Friess 2017). Likewise, retrofitting heating system is cost-effective, while building envelops (e.g., retrofitting external walls) is not economically beneficial in residential buildings in Beijing, China (Liu et al. 2018).

4.5 Agriculture sector

Unlike in other sectors, studies examining the impacts of the adoption of clean energy technologies are limited in the agriculture sector. Some studies show the application of solar water pumps for irrigation in remote areas increases farmers' yields by as much as three-fold compared to relying solely on rainfall (EAC 2020). They find that majority of the farmers (75%) in three African countries (Kenya, Tanzania, and Uganda) have increased their productivity, such as working less time, increased yields, lower farm operating costs, and improved income, since using their solar water pump. In Kenya, solar irrigation shows a high return on investment for horticultural crops compared to diesel alternatives (IFC 2019). They find that for a typical farm in Kenya, the total cost over five years to irrigate a one-acre area is estimated at US$3,000 when using a solar water pump compared to US$6,000 when using an equivalent diesel pump. In Hubei province, China, the energy used by efficient tillage mode (ridge cultivation with no-till) compared to conventional cultivation with intensive till used in rice fields is 24.7% lower (Li et al. 2021c). They find that the net ecosystem economic efficiency, which is calculated by subtracting agricultural inputs cost and carbon cost from grain yield cost, is higher for the efficient tillage mode (CHY16,419.9 ± 1,186.0 per hectare) compared to the conventional one (CHY9,881.8 ± 217.0 per hectare). A similar study in north-western Indo-Gangetic plains in India shows that efficient no-tillage in maize reduced energy input by 38.4% and 20.1% compared to deep tillage and conventional tillage, respectively (Nisar et al. 2021). They also find that per tonne of maize grain production, no-tillage saved 1,044 MJ of energy (41%) and increased grain yield by 35.3% compared to conventional tillage. Based on the levelized cost of heat, (Çiftçioğlu et al. 2020) find that solar thermal (glazed and unglazed solar air collectors) used for drying agriculture, marine, and meat products are cost-effective compared to electricity and fossil fuels (natural gas and LPG) options over the long run. Another example includes a two-fold increase in agricultural productivity between 1961 and 2010, mainly due to energy conversion efficiency improvements and agricultural yields (Harchaoui and Chatzimpiros 2017). They also find that the overall livestock energy conversion efficiency[16] increased by 45% from 1961 to 2010; poultry gained 84%, pork by 17%, sheep & goats by 67%, and cattle by 27%.

There is a wide difference in agricultural yields between developing and developed countries mainly due to the different levels of technologies used. For example, yields for maize, which is a major staple crop in many parts of sub-Saharan Africa, are about 2 tons per hectare compared to commercial yields of about 8 tons per hectare in the Americas (OECD and FAO 2018). Also, some clean technologies that are used in milling are not always efficient. For example, a PV solar-powered motor system for milling maize in East Africa yields (a throughput) of about 32.7 kg/hr, which is much lower than the diesel mill, which yields 120 to 150 kg/hr (EAC 2020). Some studies show the use of digital technologies in enhancing agricultural activities and increasing productivity. For example, South African households using information and communication technologies (e.g., internet connection and mobile telephone) have positive and significant impacts on their agricultural production (food) (David and Grobler 2019). Likewise, using efficient automated irrigation with advanced wireless sensor networks shows that the quantity of water used is smaller compared to a conventional one (Nikolidakis et al. 2015). There is also a significant positive relationship between the adoption of information and communication technology (ICT) and agricultural productivity based on the data for the 1995-2000 period from 81 countries (Lio and Liu 2006). They find that returns from ICT in agricultural production of the richer countries are about two times higher than those of the poorer countries.

5. OTHER FACTORS DRIVING VOLUNTARY INVESTMENT IN GREEN/CLEAN TECHNOLOGIES

Unlike the general perception that the private sector does not have an interest to invest in new green/clean technologies because of their cost disadvantage as compared to conventional or non-green technologies, some empirical literature shows otherwise. For example, returns or payoffs are not the only criteria investors use to make decisions on green/clean investments (Fama et al. 2007). They argue that investors can buy assets as consumption goods rather than strictly based on returns or payoffs. Many information technology companies (e.g., Google, Facebook, and Twitter) think, during the initial public offerings, that the market for clean technologies will expand in the future even if they are expensive and not profitable for now. Some studies also provide empirical evidence by comparing the investors' demand between 99 green energy companies and 93 matching samples of non-green energy Fortune 500 firms (Ng and Zheng 2018). They show that green energy portfolios perform comparably or better than a matching non-green energy portfolio. Contrary to the traditional perception that full filling

16. Energy conversion efficiency in livestock production is the ratio of output products to feed inputs both expressed as energy.

social responsibility is costly for firms, they find meeting environmental objectives does not affect firms' market performance.

There is also a positive impact of innovation on the market value of firms (Colombelli et al. 2020). Using sample data of firms from France, Germany, Italy, the Netherlands, and the UK during the 1985-2011 period, they find that firms operating in sectors with a high propensity for green technologies yield a significant positive effect along with the stock of green technologies. Likewise, green investment promoted by renewable energy policies in OECD countries improves firms' financial performances based on the financial performance data of 420 energy firms in OECD countries over four years (2013-2016) (Hassan 2019).

Based on findings by (Dangelico and Pujari 2010; Berrone et al. 2013), green technologies lead to increased profitability for firms (Palmer and Truong 2017).[17] Using 1,020 press releases on green technology products introduced by 79 global firms between 2007 and 2012 and their operational profitability, they show a positive relationship between green technology and firm profitability. In some cases, investments in green technologies or innovations benefit firms as it creates a positive image, which eventually leads to an improvement in their market valuation (Palčič and Prester 2020.). Also, firms with green information technology receive higher subsequent returns on assets and the market-to-book values of assets ratios (Przychodzen et al. 2018). There is also a case that investment in green operations and preservation technology could significantly improve the retailer's financial performance (Saha et al. 2017).

Some studies report that green/clean investments do not necessarily improve the financial performance or market values of firms.[18] Investors, such as venture capital firms, would be interested in making investments in the early stages (e.g., R&D expenditure) of green/clean technology companies. But some studies find the other way around (Gaddy et al. 2017). Using the investment data from venture capital firms for the 2006-2011 period, they find clean technologies poorly suited for venture capital investment. They find that materials and hardware industries have a longer payback period than venture capital firms normally expect. The size of capital requirement is normally big for large-scale green/clean technology development or adoption. Venture capital firms see the green/clean technology market as risky and yield low returns because the potential acquirers of these technologies (e.g., utilities and large industrial corporations) are reluctant to buy risky startups.

6. CONCLUSIONS AND FINAL REMARKS

Investments in green and clean technologies are rapidly increasing, particularly in renewable energy and energy-efficient technologies, over the last decade. The primary factors behind the growth of green/clean investment are policies and measures introduced by the government in response to environmental concerns, particularly global climate change. The investment is, however, financed mainly by the public sector. The investment is also financed by the private sector if they are financially incentivized or mandated through regulatory measures. The private sector will also invest in green/clean technologies if the adoption of clean technologies reduces production costs. This paper aims to understand whether or not clean or green tech-

17. Dangelico and Pujari (2010) show new products based on green/clean technologies result in higher commercial values due to a higher visibility of these products to market actors, and Berrone et al. (2013) report new products based on green/clean technologies help attract more customers at higher premiums as a result from a long-term investment on R&D.

18. See Appendix A.6 for selected empirical studies on the relationship between green investment and the financial performance of firms or industries.

nologies increase productivity and reduce production costs. To fulfill this objective, we search for empirical or numerical evidence from the literature. The review includes ex-post empirical studies as well as ex-ante economic analysis or technological/sectoral modeling.

The findings from the literature appear to be sensitive to two aspects: the type of studies (ex-post vs. ex-ante) and the level of studies (firm or technology). We find in the literature that the ex-post studies to analyze the impacts of clean/green technologies on the production costs or costs of energy service delivery use empirical (econometric) techniques that derive the evidence from observed data. The ex-ante studies use economic/financial (e.g., benefits-cost analysis) at the technology level (e.g., electricity vehicle, refrigerator) or modeling at the network or sectoral level (e.g., solar and technologies for power generation). Most of the ex-post or econometric studies we reviewed, particularly the more recent ones, show a positive relationship between investments in clean technologies and firms' productivity. Several studies also support Porter's hypothesis that state environmental regulations incentivize innovation, ultimately reducing firms' production costs. Some factors, such as the size of firms and types of investments (i.e., investments for development vs. deployment of technologies), influence the relationships.

At the sectoral level, except for some manufacturing and the buildings sectors, most studies are found to use ex-ante economic analysis or sectoral modeling instead of ex-post econometric approaches. Ex-post studies are focused either on the manufacturing industries or the buildings sector. Ex-ante studies at the sectoral level examine the impacts of green/clean investments on the cost of energy services instead of sectoral productivity. The findings of the studies are mixed. In the buildings sector, existing studies mostly report that adopting clean (both energy efficient and clean energy supply technologies, such as solar home systems) saves energy and energy services. The findings are, however, sensitive to several variables, particularly the cost of technologies and fuels. On the other hand, studies for the transportation sector show that vehicles utilizing cleaner fuels (electricity, hydrogen) are not yet economically attractive compared to conventional vehicles unless their environmental benefits (value of GHG and local air pollution reduction) are quantified. Moreover, even if vehicles using clean or non-fossil fuels are economically attractive under certain assumptions, they face many barriers, mainly supporting infrastructure, such as charging stations for electric vehicles. In the future, however, clean or zero-emitting vehicles could be economically attractive, as shown by several studies. Nevertheless, it depends on the improvement of the battery technology and provision of required infrastructure at much smaller costs than that today. Note that battery constitutes the main cost of electric vehicles.

Studies on the power sector suggest that the expansion of greener/cleaner renewable energy technologies, which is happening rapidly more recently, also has mixed effects on electricity supply costs from electricity grids. Despite rapid drops in their costs, renewable energy technologies, particularly solar and wind, do not necessarily reduce the average costs of electricity supply because of their intermittency. Moreover, the level of their penetration in most countries around the world is still small. If the costs of renewable electricity and storage technologies drop further, increased penetration of renewables will reduce the average costs of electricity.

Since the existing studies using the observed data (i.e. empirical studies), in general, agree that adopting clean technologies reduces production costs and harmful environmental externalities, the adoption of clean and green technologies should be enhanced further. Policies to support the adoption of clean technologies should be continued or increased. Our study also reveals that reducing production costs is not the only incentive for the private sector to invest in green/clean technologies. Adopting green/clean technologies increases private companies' social image and market values. Since investments in green/clean technologies increase productivity and enhance market values by improving social image, the private sector should increase investments in green or clean technologies.

Although the existing ex-post empirical studies generally agree on the positive contribution of clean technologies in improving productivity, further studies are needed, particularly in the transportation, power, and building sectors. Further firm-level empirical studies across the globe will contribute to a better understanding of the relationship between clean technologies and productivity as well as production costs in various sectors.

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Appendix A.1. Selected empirical studies examining the relationship between green/ clean investment and productivity

Study	Method	Main findings and argument
Qi et al. (2021)	An econometric method is applied to 39 Chinese manufacturing industries.	Firm size plays a key role in clean technology adoption. Environmental regulations eliminate some firms with low production efficiency through market competition and increase the overall productivity level.
Sohag et al. (2021)	CS–ARDL technique is used in 25 OECD countries from 1980 to 2015.	A higher share of renewable energy in the energy mix in the production process significantly promotes TFP in the long run, while it is inconclusive in the short run.
Cao et al. (2021)	PSM-DID method is applied to Chinese energy firms from 2000 to 2007.	The cleaner production regulations increased regulated firms' TFP, especially small firms. Also, the impact of cleaner production regulations on state-owned firms was greater than that of non-state-owned firms.
Peng et al. (2021)	A DID method is used to a panel data of Chinese industrial enterprises for the 1998-2007 period.	The market-based environmental regulation exerted significant productivity-enhancing effects across all types of industrial enterprises, with stronger effects associated with privately owned, more productive, and less pollution-intensive enterprises.
Aldieri et al. (2020)	The empirical method uses panel data on firms' patents on environmental innovation from 9 European countries, Japan, and the USA for the 2002-2007 period.	Green technology innovation and its knowledge spillovers affect firms' TFP significantly and positively in all the investigated economic areas.
Leoncini et al. (2019)	A quantile regression method is used for 5498 manufacturing firms in Italy from 2000 to 2008.	There is a positive effect of green technologies on a firm's growth. A firm's experience appears important for the growth benefits of green technologies.
Stucki (2019)	The ordinary least square model is applied using firm-level data in Austria, Germany, and Switzerland in 2014.	Firms with relatively high energy costs show significantly larger marginal effects of green technology investments on TFP than firms with low energy costs. However, this effect is observed only for 19% of firms with the highest energy costs.
Rath et al. (2019)	The panel cointegration tests and dynamic OLS are applied to panel data of 36 countries from 1981-2013.	Generally, the increase in renewable energy consumption positively affects TFP growth in the long run, while the increase in fossil fuel consumption has a mixed effect on TFP growth.

Study	Method	Main findings and argument
Zhang et al. (2019)	The modified fixed investment model is applied to data from 34000 Chinese firms in 2013.	The environmental abatement crowds out innovation investment and decreases firms' productivity due to financial constraints.
Palmer and Truong (2017)	Data on 1020 technological green products between 2007 and 2012 by 79 global firms are used.	The relationship between technological green new product introductions and firm profitability is positive.
Hrovatin et al. (2016)	The probit and bivariate probit models are applied to the panel data set of 848 Slovenian manufacturing firms during 2005-2011.	Large firms with high energy costs tend to invest both in EE and green technology to increase productivity and improve their competitive position in the market. Non-environmental investments by the firms do not crowd out green/clean technology investments.
Tugcu & Tiwari (2016)	A panel bootstrap Granger causality analysis of Konya is used for BRICS countries from 1992 to 2012.	The relationship between green technology and TFP growth is less substantial than that between non-green technology and TFP growth. In some cases, green technology has a positive effect on TFP growth.
Hottenrott et al. (2016)	A two-stage least squares regression analysis of firm-level panel data of Germany covering the period from 2000 to 2008.	Firms can achieve higher TFP gains from adopting new technologies if they adapt their organizational structures. Such complementarity effects may be of particular importance for the adoption of GHG abatement technologies.
Rubashkina et al. (2015)	The instrumental variable estimation approach is used for manufacturing sectors of 17 European countries between 1997 and 2009.	There is a positive impact of environmental regulation on the output of innovation activity, as proxied by patents, thus providing support in favor of the "weak" Porter hypothesis.
Horvathova (2012)	A measure of environmental performance is applied to the firm-level data from the Czech Republic.	The effect of environmental performance on financial performance is negative in the short run but it is positive in the long run.
Böhringer et al. (2012)	Econometric analysis is used for a panel dataset of German manufacturing sectors.	The environmental regulations stimulate environmental investment to be compatible with the pursuit of production growth.
Lanoie et al. (2008)	An econometric approach is used for 17 sectors in the Quebec manufacturing industry from 1985-1994.	The impact of environmental regulation on productivity is negative in the short run but it is positive in the long run. This effect is stronger in a subgroup of industries that are more exposed to international competition.

Study	Method	Main findings and argument
Hamamoto (2006)	A reduced-form econometric model is used for 5 Japanese manufacturing industries in the 1960s and 1970s.	The pollution control expenditures have a positive relationship with the R&D expenditures and a negative relationship with the average age of capital stock. Also, increases in R&D investment have a significant positive effect on the growth rate of TFP.

Appendix A.2. Selected empirical studies examining the relationship between clean investment and cost of production in the manufacturing sector

Study	Method	Findings
Li et al. (2021a)	Simulation method using Aspen Plus software for the chemical industry.	Retrofitting the coal chemical industry (CCI) with more efficient petrochemical technologies reduced the total annual costs (operating and capital expenditure) of CCI by 41.3% with total product yield almost unchanged.
Huang & Wu (2021)	Simulation methods using extended energy conservation supply and extended MAC curves are applied to the cement industry in Taiwan.	Using energy-efficient technologies, by 2025, the total annual fuel savings could reach 1828 TJ, equivalent to 6% of the energy used for cement production in 2018.
Zhang et al.(2021)	A network Epsilon Based Measure model and Tobit regression are applied to the Chinese construction industry from 2000–2017.	In the construction industry, market-friendly environmental regulations have a positive effect on green technology innovation, while rigid and mandatory environmental regulations (e.g., command and control) hurt green technology innovation.
Wan et al. (2021)	A generalized method of moments regressions is applied to Chinese energy firms for 8 weeks before and after the pandemic.	Although the impact of COVID-19 on firms' financial performance is negative for both types of firms (clean energy and fossil-fuel firms), investor attention to the disruptive effects of the pandemic had a significant and positive effect on clean energy stocks' returns.
Haider & Bhat (2020)	An econometric technique is used in the paper industry in 21 states in India from 2001-2013.	An increasing level of TFP is associated with a lower level of EI or better EE. Better skills and capacity utilization have a positive impact on EE performance of the paper industry, while the heterogeneity within the structure of the industry hurts EE performance.
Filippini et al. (2020)	The two-stage approach of translog cost function and DID approach are applied to 5340 Chinee iron & steel firms for 2003 and 2008.	The national EE program had a positive and statistically significant effect on productivity in iron & steel firms. The EE program increased annual productivity growth by 3.1% points, with approximately equal contributions from technical change and scale efficiency change.

Study	Method	Findings
Palčič & Prester (2020)	A four-step OLS is applied to survey data collected from 232 Croatian and Slovenian manufacturing firms during 2018-2019.	Green innovation has an impact on firms' competitive advantage through their image, and not necessarily through financial gains. Advanced manufacturing technologies also contribute to both the firm's productivity and green innovation.
Gong et al. (2020)	An OLS method is applied to high-pollution firms (Shanghai and Shenzhen) in China from 2009 to 2018.	The influence of rising labor costs on green technology innovation has a threshold effect. The effects of the rise of labor costs on the green technology innovation of high-pollution firms illustrate an "inversely U-shaped" variation trend with the increase of the degree of market monopoly.
Haas et al. (2020)	The least-cost optimization model is applied to the electricity supply of copper mines in Chile, Peru, China, the USA, Austria, Indonesia, and Mexico from 2020 to 2050.	At present, it is attractive for copper mines to have a solar generation of 25% to 50% of the yearly electricity demand. In the future, the expected electricity costs range from 60 to 100 Euro per MWh for 2020 and from 30 to 55 Euro per MWh for 2050, with the lower bound in sunny regions such as Chile and Peru.
Zuberi & Patel (2019)	EE cost curves are applied to the Swiss chemical and pharmaceutical industry from 2000 to 2012.	Electricity savings by improving motor systems is estimated at 15% of the total electricity demand in 2016. The EE potential also varies with different energy prices.
Unver & Kara (2019)	A regression analysis using AMPL Software is applied to a steel forging facility in Turkey.	Correct regulation of the production process through increased EE would result in 65% energy savings in the unit production of a steel forging facility. Considering the total annual production of the facility, 7,639 kWh of energy may be saved in a year, which is equivalent to €3,686 per year or 6.6 tons of oil equivalent per year.
Arriola-Medellín et al. (2019)	An energy management system is applied to the oil and gas processing center in Mexico.	Investment in EE at the oil and gas processing center reduced the consumption of natural gas and electricity consumption by 75% and 98%, respectively.
Shapiro & Walker (2018)	Statistical decomposition is applied to the manufacturing industry in the United States from 1990 to 2008.	Overall, between 1990 and 2008, air pollution emissions from US manufacturing fell by 60% despite a substantial increase in manufacturing output mainly due to changes in environmental regulation (pollution tax) rather than changes in productivity or the composition of products produced (trade).

Study	Method	Findings
Zhu et al. (2018)	A global data envelopment analysis (DEA) is applied to the mining& quarrying industry in China from 1991 to 2014.	The TFP of China's mining & quarrying industry increased by 71.7%. Technological progress was the most important contributor, and the decline in scale efficiency and management efficiency were the two inhibitors. However, the green TFP growth and the returns to scale of the sub-sectors within the industry are mixed.
Wurlod & Noailly (2018)	A trans-log cost function and decomposition analysis are applied to a set of 14 industrial sectors in 17 OECD countries from 1975-2005.	Green innovation contributed to the decline in EI in most sectors. The median elasticity of EI to green patenting is estimated at −0.03, i.e., a 1% increase in green patenting activities in a given sector is associated with a 0.03% decline in EI. Overall, half of the decrease in EI is related to changes in input prices and half to changes in production technologies.
Xylia et al. (2017)	A cost-benefit analysis is applied to Swedish energy-intensive industries.	The benefit-to-cost ratio of the impact of implementing the EE obligation scheme for Swedish energy-intensive industries ranges from 1.56 to 2.17 and the break-even cost ranges from 83.3 to 86.9 Euro per MWh. The estimated annual energy savings potential is 1.25 TWh per year.
Morrow III et al. (2013)	A bottom-up energy conservation supply curves model is applied to the Indian cement industry for 2010-2030.	The cumulative cost-effective plant-level electricity savings potential for the Indian cement industry for 2010-2030 is estimated to be 83 TWh, and the cumulative plant-level technical electricity saving potential is 89 TWh during the same period.

Appendix A.3. Selected empirical studies assessing the economics of alternative vehicles

Study	Methods	Findings and argument
Holland et al. (2021)	Damage valuation using the IAM model, and the social cost of carbon are used for an electric urban bus in the USA.	Compared to a diesel bus fleet, the environmental benefit of operating an electric bus fleet is about US$65 million per year in Los Angeles and above US$10 million per year in six other metropolitan areas in the USA. Relative to diesel, the NPV benefit of an electric bus is positive in about two-thirds of urban counties. Relative to CNG, the NPV benefit is negative in all counties.
Whiston et al. (2021)	Based on 31 experts' assessments of expected future costs and capacities of storage systems in the US.	Given technical and fuel price uncertainty, FCEV costs ranged from US$0.38 to 0.45 per mile in 2020, US$0.30 to 0.33 per mile in 2035-2050, and US$0.27 to 0.31 per mile in 2050. Depending on fuel, electricity, and battery prices, FCEVs could compete with conventional and alternative fuel vehicles by 2035.

Study	Methods	Findings and argument
(Li et al. (2021b)	A life cycle cost model is used for BEV and FCEV in China.	BEVs and FCEVs in most cities in China are incomparable to conventional ICEs in terms of tangible cost. But government subsidies, purchase and driving restrictions, and environmental taxes, greatly increase the intangible and external costs of CVs, making consumers more inclined to purchase BEVs and FCEVs.
He et al. (2021)	A levelized cost of driving for light duty FCEV is applied from 2017 to 2030 in China	Assuming decreased costs for both hydrogen production and FCVs in 2030, the levelized cost of driving for wind-electrolysis light-duty FCEVs pathway (US$0.31/km) could approach that for gasoline (US$0.29/km) and BEVs (US$0.30/km). The vehicle purchase cost ranges from US$23,999 for ICEV to 55,292 for BEV in the reference case for the 2017 model, while purchase cost ranges from US$25,612 for ICEV to 37,039 for BEV for the 2030 model.
Comello et al. (2021)	The time-driven life-cycle cost model is used for mobility services of an electric transit bus in the USA.	Based on the LCC of diesel and battery-electric transit buses, electric buses entail higher upfront acquisition costs, but they obtain lower LCCs once utilization rates exceed only 20% of the annual hours (i.e., 1300 hours).
Ouyang et al. (2021)	The consumer-oriented TCO approach is used for ICEVs, PHEVs, and BEVs in China from 2020 to 2030.	Under the 5-year holding period scenario, small BEVs will reach parity with ICEVs in terms of the TCO by 2025, while medium-sized and large BEVs will do so around 2030. Even though BEV and PHEV purchase costs will fall by 31%–36% and 16%–18%, respectively, between 2020 and 2030, most EV models will still not reach purchase cost parity by 2030.

Study	Methods	Findings and argument
Tarei et al. (2021)	Best-Worst Method is used to filter out the critical EV barriers out of a total of eighteen barriers obtained from the existing literature in India.	The five main EV barriers are technical, infrastructure, financial, behavioral, and external barriers. Technical barriers include relatively lesser known technology than ICEV, unknown driving and durability range, the unreliability of suppliers, and not well-known development of alternative fuel technology. Infrastructure barriers include shortage of charging stations, low availability of maintenance, service, and repair, lack of EV manufacturers, and unavailability of reliable electricity. Financial barriers include high upfront purchase price, unknown resale value, and TOC. Behavioral barriers include consumer perception of EVs such as lack of awareness, skepticism on safety and reliability, perceived benefits, and dealer understanding reluctance to push EVs. External barriers include dependence on external sources for raw materials, wastage and recycling of batteries, and limited EV incentives and advertisements by the government.
Ajanovic & Haas (2021)	The TCO approach is used for FCEV.	Based on a driving range of 12,000 km per year over 7 years, the TCO of FCEVs is currently very high, about three times, compared to conventional ICEVs. Three major challenges that the passenger FCEVs to be in strong competition with conventional ICEVs and BEVs are reduction of investment costs of cars, infrastructure development, and stable policy framework conditions.
Hamza et al. (2021)	The bottom-up approach for TCO is applied in the USA.	In 2018, the costs of plug-in vehicles (BEVs and PHEVs) are approximately US$7,000, 8,000, and 11,200 more than the conventional ICEVs in the size categories of car, crossover, and SUV, respectively. Even with an expected reduction in battery cost in 2030, plug-in vehicles are approximately US$1,800, 2,500, and 3,500 more than conventional ICEVs for cars, crossovers, and SUVs, respectively.
Hasan et al. (2021)	TCO per km approach is used in New Zealand.	The TCO of a new EV is much higher compared to conventional ICEV mainly due to the high initial purchase price and the cost of battery replacement. However, with the proposed "clean car discount", the TCO per km of EV vehicle (Nissan Leaf) is expected to reduce by 6 NZ cents and becomes competitive with new conventional ICEV (Toyota Corolla). In 2018, the TCO per km of new EV is 45.6 NZ and the new conventional ICEV is 38.8 NZ cents.

Study	Methods	Findings and argument
Li & Kimura (2021)	TCO per km approach in EVs in ASEAN countries.	Based on TCO per km, the FCEVs are the least competitive option among the alternative powertrains. BEVs appear to be the most competitive, except for passenger vehicles. The TCO per km varies from low US$0.55 in Thailand to high US$0.75 in Malaysia for FCEV passenger cars.
Mustapa et al. (2020)	TCO analysis is used in Malaysia.	The TCO per km of Nissan leaf (BEV), BMW i3s (BEV), Hyundai Ioniq HEV plus (PHEV), Honda jazz 1.5 (PHEV), and Perodua Myvi 1.5 High AT (ICEV) are 1.75, 2.5, 1.0, 0.71, and 0.52, respectively, based on 28,188 km over 20 years period. The TCO per km of the BEVs is higher compared with the PHEVs and the ICEV. This implies that the cost of owning EVs in Malaysia is not competitive compared to the HEVs and the ICVs.
Cox et al. (2020)	TCO analysis is used in Europe.	Vehicles with smaller batteries and longer lifetime distances have the best cost and climate performance. If a very large driving range is required or clean electricity is not available, hybrid powertrain and compressed natural gas vehicles are good options in terms of both costs and climate change impacts. Alternative powertrains containing large batteries or fuel cells are the most sensitive to changes in the future electricity system as their life cycles are more electricity intensive.
Nassif & Almeida (2020)	Advanced Vehicle Simulator (ADVISOR) is used.	The costs and fuel economy results of the different configurations (different degrees of hybridization, DOH) of FCEV are compared to those of the original vehicle. The configuration with the highest DOH (61.2%) shows an 8.3% increase in fuel economy and a total cost reduction of 13.2% compared to the original vehicle. In 2019, the purchase price of Nissan Leaf (40 kWh) and Hyundai Ioniq Electric ranges from US$30,000 to 37,000, and Toyota Mirai FCEV costs US$58,500.
Dreier et al. (2019)	Advanced Vehicle Simulator (ADVISOR) is used in Brazil.	Analyzing the influence of passenger load, driving cycle, fuel price, and four different types of buses on the cost of transport service for one bus rapid transit route in Curitiba, Brazil, the lowest fuel cost ranges for the passenger load are plug-in (0.198–0.289 US$/km), followed by two-axle (0.255–0.315 US$/km), articulated (0.298–0.375US$/km), and conventional (0.552–0.809 US$/km) buses. The capital cost of the bus ranges from US$103,669 to 276,563.

Study	Methods	Findings and argument
Bekel & Pauliuk (2019)	Life cycle assessment is used in Germany.	Considering mid-size vehicles like the VW e-Golf, BEVs have today better environmental and financial performance than FCEVs. However, the range of the BEV is lower than the range of the FCEV (200km vs 530 km) and both technologies have different stages of maturity.
van Velzen et al. (2019)	Literature review and interview methods are used.	The production costs of EVs will go down in the future, but this does not mean that the TCOs of EVs will continue to go down as well. It is argued that EVs are sold at or below production costs. This is a common strategy in the automotive industry, as initial investments are high, and no markup is covered by the BEV's retail price. This may change in the future and BEV retail price may increase to recoup investments. This directly negatively influences the TCO of BEVs, suggesting that the ongoing TCO of BEVs in the future may not decrease.
Thompson et al. (2018)	Design for Manufacture and Assembly (DFMA®) analysis is used.	Total system cost ranges from US$50/kWnet to produce 100,000 FCEVs to US$45/kWnet to produce 500,000 FCEVs per year in 2017 based on the comparison with the fuel cell system in the commercially available Toyota Mirai. Decreasing system cost to US$30/kWnet will be needed for cost competitiveness with ICEVs.
Ruffini & Wei (2018)	Learning The learning rate approach and life cycle cost analysis are used.	The fuel cell system is the key factor in making FCEV life cycle costs comparable to ICEV costs. With an 18% learning rate, FCEVs are estimated to be cost-competitive with ICEVs by 2025, but with an 8% learning rate, this cost-competitive point is pushed out for almost 25 years.
Breetz & Salon (2018)	TCO approach is used for conventional, hybrid, and electric vehicles in 14 cities in the USA from 2011 to 2015.	BEVs cost substantially more than conventional and hybrid vehicles mainly due to their higher purchase price and rapid depreciation outweighed their fuel savings. Based on 10 years of TCO, to bring the EV (Nissan Leaf) to cost parity with the ICEV (Toyota Corolla), the Leaf's purchase price would need to drop by US$5,091 (15%) under full electricity prices, US$3,192 (10%) with half-priced electricity, and US$1,292 (4%) with free electricity.
Ally & Pryor (2016)	TCO is based on the life cycle assessment of FCEV (buses) compared with diesel, CNG, and hybrid buses in Australia from 2012 to 2014.	At the current level of capital and operation costs and with the current performances of hydrogen and fuel cell technologies, the TCO of a fuel cell bus is 2.6 times that of a conventional diesel bus.

Study	Methods	Findings and argument
Simmons et al. (2015)	Vehicle model-specific approach and sales-weighted average approach are used in the USA.	Consumers realize, on average, 17.3% fuel economy improvement and save US$1,070. Most new technologies (hybrid electric vehicles) become financially attractive to consumers when average fuel prices exceed US$ 5.60/gallon, or when annual miles traveled exceed 16,400.
Gambhir et al. (2015)	MACC and decomposition analysis is used for low-carbon vehicles in China.	The substitution of low-carbon fuel-driven trucks (fuel cell and battery) for their business-as-usual alternatives (ICEV) results in cost savings by 2050. In contrast, the low-carbon fuel-driven passenger cars are, in most cases, significantly costly—20 to 60 percent more expensive than ICE vehicles in 2050.

Appendix A.4. Selected empirical studies showing impacts of renewable energy on electricity supply costs

	Methods	Findings
Schulte & Fletcher (2021)	Useful clean energy analysis in the USA.	Due to intermittency, RE leads to diminishing returns for useful clean energy. Every utility has a hypothetical "inflection point" where increasing high levels of renewables begin to exceed hourly load and must be turned down or otherwise curtailed. Utilities would "stall out" in useful energy when RE reaches levels at about 60 %–80 % of their annual load.
Mai et al. (2021)	Optimization-based capacity expansion model and Regional Energy Deployment System are applied in the USA from 2020 to 2050.	The expansion of non-fossil electricity generation to account for 45% of the total generation would increase electricity system costs by 0.4% to 0.8% depending on the discount rate. If the share of non-fossil fuels in the total generation reaches 78%, the system costs would increase by 2.7% to 3.6%.
Vellini et al. (2020)	Cost-effective estimation of mitigation costs of the power sector in Italy.	The mitigation costs of CO_2 emissions reduction in the Italian electricity sector in 2030 vary widely ranging from null up to €140 per ton. The larger the use of gas and electricity generation from the solar source, the higher the mitigation costs. The complete phase-out of coal exhibits the highest migration costs that are not as beneficial from an economic perspective.
Liang et al. (2019)	A simulation method using the LEAP model is applied in China from 2015 to 2050.	Increasing the share of renewables in total electricity generation capacity from 27.1% to 50.7% in 2050 would increase the electricity system costs for the 2015-2050 period by 7%. It would reduce 41% of the power sector's CO_2 emissions in 2050.

	Methods	Findings
Adelman & Spence (2018)	Low-cost electricity generation optimization is applied in the USA from 2016 to 2031.	The low natural gas prices—below US$3.50/ MMBtu through 2023 and below US$4.50/ MMBtu through 2031—inhibit the construction of new renewable capacity. The significant impact of inexpensive gas is likely to be limiting the entry of renewables. This is mainly due to two phenomena: 1) renewables pose a much greater threat to the viability of base-load generation in the long term than natural gas-fired generation; and (2) when gas prices set market prices, they also determine the economics of renewables, and thereby the volume of new renewable capacity that enters the market.
Kumar (2016)	A simulation method using the LEAP model is applied in Indonesia and Thailand from 2020 to 2050.	In implementing renewables at a large scale in both these countries the cost of production increases substantially. For example, the total electricity production costs in 2050 increases by 40% in Indonesia and by 82% in Thailand.
Würzburg et al. (2013)	A multivariate regression model is used in Germany and Austria.	The changed electricity mix due to the German nuclear electricity generation exit did not affect the size of the merit order effect, where price decreases occur because (additional) RE-based electricity bids into the market at lower marginal costs. It also lists several earlier studies analyzing the impacts of RE on the EU electricity market.

Appendix A.5: Selected studies on the economics of clean technologies in the buildings sector

Study	Method	Main findings and argument
Belaid et al. (2021)	A multivariate statistical approach and cost-benefit analysis are used in 1,400 dwellings in the French residential sector in 2013.	Low-temperature and condensing boilers, as well as floor insulation, are the most cost-effective EE measures. Also, the cost-effectiveness of energy renovation measures is widely dependent on energy price and the discount rate.
Lohwanitchai and Jareemit (2021)	A cost-benefit analysis is used for three representative six-story office buildings in Thailand.	The investment in high-performance glazed windows in small office buildings is unprofitable (NPVs = −14.77–−46.01).
McAndrew et al. (2021)	A literature review based on 153 papers published between 1990 and 2019 is used to examine the EE interventions in advanced economies' households.	A review of one hundred papers reported a positive impact of EE intervention, i.e., a reduction in electricity use by households, ranging from 0.5% to 80%, with a median measured electricity reduction of 7.9%.

Study	Method	Main findings and argument
Ren et al. (2021)	The artificial neural networks and empirical models are used for a sample of 16 household refrigerator replacements under the Appliance Replacement Offer in low-income households in Australia.	Most households achieved substantial energy savings from the replacement program. The average annual energy cost savings of refrigerator replacements is 53%. However, the energy savings could be compromised if the size of the new refrigerator were much larger than the old unit.
Timilsina (2021)	Economic analysis of distributed PV (DPV) in the residential, commercial, and industrial sectors using a model that allows electricity exchange between the consumers and the national electricity utility	The benefits of DPV to the consumers are more than 1.5 times as high as their costs
Baek et al. (2020)	An hourly load profile simulation is used for solar-plus-storage applications for three types of buildings: a secondary school, a supermarket, and a typical single-family home in Waukegan, Illinois.	In most cases, investing in solar PV resulted in significant electricity bill savings for consumers that paid back the initial capital cost of the system in 11–12 years. Most homes and businesses in the Waukegan area in Illinois could cut their electricity bills by more than half.
Chesser et al. (2019)	A Logit regression model is used based on the 2010 household budget survey of Ireland.	Households that have adopted micro-renewable energy systems do not result in a reduction in electricity use, rather it increases electricity use.
Inoue and Matsumoto (2019)	Conditional demand analysis is used based on micro-level data from the National Survey of Family Income and Expenditure in Japan.	Although EE of home appliances significantly improved after the implementation EE program (Top Runner), households began spending more electricity on space cooling and food preservation.
Opoku et al. (2019)	Technical data from a national survey is analyzed to study the EE of ACs used in the offices of public and commercial buildings in Ghana.	The estimated annual electricity savings potential is 260 GWh in 2020 and 1,770 GWh in 2030, and savings of US$1.96 billion during 2018-2030 using more efficient inverter ACs instead of ACs currently in use.
Roberts et al. (2019)	Financial analysis is used for PV solar and battery storage system in 5 Australian apartments.	There is a financial benefit to the deployment of embedded networks with combined solar and battery storage systems for apartment buildings. The cost of these measures ranges from 400—750 AUD per kWh for embedded networks as compared to 750–1000 AUD per kWh for the individual household system.

Study	Method	Main findings and argument
Papadopoulos et al. (2019)	Simulation-based multi-objective optimization is used to fine-tune HVAC setpoints of office buildings in 7 climate zones across the US.	Locations with mild climates, such as San Francisco, CA, can realize up to 60% of annual HVAC-related energy savings without compromising the occupants' thermal comfort.
Park et al. (2019)	A bottom-up approach is used to estimate the energy consumption and cost of small (50 L and 100 L) refrigerators.	The refrigerator's electricity use can be reduced by about 50% and 70% using commercially available energy-efficient components at an incremental cost of about \$45–\$60 and \$100–\$120 per unit, respectively.
Witt et al. (2019)	Based on a project of exchanging LED bulbs for 181 households in low-income areas in Salt Lake City, Utah over 8 months.	A saving of approximately US\$18,219 is estimated in electricity bills for the residents. This is the equivalent of about US\$100 in savings per household per year.
Alfattah et al. (2017)	An econometric approach is used for the field survey of the residential sector in Amman and Zarqa, Jordan.	The net saving by implementing EE measures (refrigerators) from 2011 to 2020 is estimated at 4451 GWh which translates into a saving on electricity bills of 320 million JD.
Krati and Dubey (2017)	An optimization analysis is used to evaluate the economic and environmental benefits of a wide range of EE technologies for new and existing buildings in Oman.	The implementation of a government-funded large-scale energy retrofit program for the existing residential building stock is highly cost-effective and provides a reduction of 957 GWh in annual electricity consumption.
Jacobsen et al. (2012)	A cross-sectional probit model is used based on a green electricity program for households in Memphis, Tennessee from 2003 to 2008.	Participating households that enroll at the minimum level (i.e., 150 kWh/month) of the green electricity program, increase their electricity consumption by 2.5%.
Kneifel (2010)	A life cycle cost analysis is used for a total of 576 energy simulations run for 12 prototypical buildings in 16 cities, with 3 building designs for each building-location combination.	EE technologies, such as the installation of smaller and cheaper HVAC equipment, can be used to decrease energy use in new commercial buildings by 20-30% on average and up to over 40% for some building types and locations.

Appendix A.6. The selected empirical literature on indicating the relationship between clean/green investment and financial performance of firms

	Method	Findings
Chen & Ma (2021)	Regression analysis is applied to 90 Chinese energy firms from 2008 to 2017.	Green investment has a significant and positive correlation with financial performance. Green investment helps reduce environmental violations and promote environmental performance, and environmental performance can strengthen the impact of green investment in improving the long-term performance of firms.
Colombelli et al. (2020)	A market value approach is used on a sample of firms from France, Germany, Italy, the Netherlands, and the UK from 1985-2011.	The stringency of the environmental regulatory framework yields a positive and significant impact, as does the stock of green technologies vis-a-vis non-green technologies. Moreover, the environmental regulatory framework positively moderates the positive effect of the stock of GTs. Also, the quality of firms' knowledge stocks is found to positively influence firms' MV.
Hassan (2019)	The natural capital inventory approach is used for 420 energy firms in OECD countries from 2013-2016.	Most renewable energy incentive policies deployed in OECD countries stimulate improved accounting-based measures of financial performance. Substituting renewable energy for fossil fuels, incentivized through RE policies, stimulates improved financial performance of energy companies in OECD countries.
Przychodzen et al. (2018)	Content analysis is used for corporate disclosures and financial data of 162 companies listed on the Frankfurt Stock Exchange for 2007-2016.	Firms with green information technologies are characterized by higher subsequent returns on assets and the market-to-book values of assets ratios. Also, firms introducing green information technology solutions experience permanently lower operating margins and higher costs of goods sold to net sales ratios.
Saha et al. (2017)	An optimization and simulation analysis is used.	Continuous investment in green operations and preservation technology can significantly improve the retailer's financial performance. Results also show that the higher price sensitivity of the market always discourages the retailer from investing in green operations. The retailer needs to invest more in green operations for products with relatively high unit value.

	Method	Findings
Gaddy et al. (2017)	A comparison is made between the risk and returns profiles of clean energy technology investments against those of other sectors in the USA from 2006 to 2011.	The investment in clean energy technologies underperformed compared to investments in other sectors. Among the clean energy technology investments, investments in companies that develop new hardware, materials, chemistries, or manufacturing processes consumed the most capital and yielded the lowest returns.