Energ. Ecol. Environ. (2020) 5(6):470–495
https://doi.org/10.1007/s40974-020-00190-2

ORIGINAL ARTICLE

Does ICT trade facilitate renewable energy transition and environmental sustainability? Evidence from Bangladesh, India, Pakistan, Sri Lanka, Nepal and Maldives

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Received: 12 March 2020 / Revised: 1 September 2020 / Accepted: 4 September 2020 / Published online: 23 September 2020

Abstract Consumption of fossil fuels has triggered the worldwide awareness to attain socioeconomic and environmental sustainability, particularly by enhancing renewable energy use and mitigating the environmental adversities, in tandem. Against this background, this paper aimed to investigate the impacts of promoting ICT trade, through liberalization of the associated trade barriers, on the prospects of undergoing renewable energy transition and limiting environmental degradation by curbing CO_2 emissions across six South Asian economies. The overall results from the econometric analyses, in a nutshell, confirm that higher degrees of openness to ICT trade lead to greater consumption of renewable energy, improve energy use efficiency levels and enhance access to cleaner cooking fuels. However, ICT trade fails to elevate the renewable energy shares in aggregate final energy consumption figures in South Asia. Besides, ICT trade is also seen to boost CO_2 emissions across this region; although the impacts seem to reverse upon enhancement in renewable energy consumption levels along with liberalization of the ICT trade barriers. Thus, these results impose key policy implications for the South Asian governments for simultaneously ensuring energy security and sustaining environmental well-being across South Asia.

Keywords ICT · Renewable energy transition · Carbon emissions · Cross-sectional dependence · South Asia

JEL Classifications O13 · O14 · P28 · Q2 · Q42

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1 Introduction

The traditional monotonic dependency on the consumption of non-renewable fossil fuels has eventually triggered a consensus, among the global economies, for ensuring energy security and simultaneously mitigating the environmental adversities stemming from fossil fuel combustion worldwide. Conventionally, such predominant reliance on fossil fuels has resulted in brisk exhaustion of their reserves; thus, the global energy sustainability goals have largely been jeopardized (Asif and Muneer 2007; Vivoda 2010). Besides, the finite supplies of these primary energy resources have attributed to the unreliability of the secondary energy supplies as well. A particular reason behind this phenomenon could be due to the global power generation volumes often lagging behind the corresponding installed capacities particularly due to the acute primary energy supply constraints (Xue et al. 2014). Apart from the persistent depletion of the non-renewable energy (NRE) reserves, the aggravating world energy demand has also had its toll on the global energy crises (Chapman et al. 1972; Smil and Knowland 1980). Furthermore, the underdeveloped economies, in particular, have obstinately been unable to meet their respective energy demands with their indigenous energy supplies. As a result, energy resource diversification is thought to be a critically important energy sector reform for ensuring energy security across the globe. The paramount importance of energy inputs for economic expansion and attaining economic welfare is unopposed (Ferdaus et al. 2020). However, inrtegration of renewables into the energy systems is crucial keeping in the sustainability of socioeconomic and environmental development into cognizance (Murshed 2018). Besides, enhancement of the efficiency of energy use, especially within the third world countries, has also become a prioritized agenda (Yang and Yu 2015).

On the other hand, the predominant use of the NRE resources has also played an uncompromising role in deteriorating the global environment (Omer 2008; Saboori and Sulaiman 2013). Ecological economists often allege the combustion of these environmentally-unfriendly energy resources to be responsible for the surging trends in the global greenhouse emission levels which, in turn, have contributed to the exacerbation of the surface temperatures worldwide. As a consequence, the global warming phenomena had resulted in the rapid meltdown of the natural glaciers to drive up the world sea levels (Hoel and Kverndokk 1996; Boden et al. 2009). Under such climate change driven environmental adversities, transition from the consumption of NRE to the relatively cleaner and environmentally-friendly renewable energy (RE) alternatives is postulated to reverse the aggravating greenhouse emission trends (Droege 2011; Murshed 2018). Augmentation of renewable resources into the global energy-mix is believed to be aligned with the policies aimed at de-carbonization of the world atmosphere (Luderer et al. 2012; Rockström et al. 2017). More importantly, the substitution of fossil fuels by the RE alternatives is anticipated to complement the energy diversification policies that are undertaken to safeguard the ensure energy security targets of the energy-deficit economies, in particular (Asif and Muneer 2007; Valentine 2011).

Environmental sustainability refers to the protection of environmental resources and persistent betterment of environmental quality (Kasayanond et al. 2019; Murshed and Dao 2020). Thus, taking into consideration global energy security and environmental sustainability concerns, the United Nations (UN) had called for international commitments from the global stakeholders to ensure greater access to affordable, reliable, sustainable and modern energy supplies all over the world. The 7th Sustainable Development Goal (SDG 7), in this regard, precisely targets to substantially elevating the shares of renewables in the global final energy consumption levels while simultaneously doubling the levels of the energy-use efficiencies. However, attainment of these targets, especially within the underdeveloped economies, is often impeded by the multidimensional constraints; among these, technological redundancy within these economies is often hypothesized to have detrimental roles in bottlenecking the fulfillment of the energy and environmental sustainability targets (Mirza et al. 2009; Urmee et al. 2009).

Against this backdrop, international trade of Information and Communications Technology (ICT) commodities can be presumed to overcome the technological barriers that have traditionally inhibited the prospects of improving the energy-use efficiencies within the developing economies. Development of the ICT sector is likely to uplift the energy-use efficiencies through better management of the energy resources consumed (Kramers et al. 2014; World Energy Council 2018). Moreover, it has been predicted that ICT penetration into the global energy sectors can possibly curb the global energy demand by around 3.5–6.3% without marginalizing the growth of the world economies (Rodríguez Casal et al. 2005). Besides, ICT-based applications are also believed to complement the policies aimed at increasing the shares of renewables in total energy consumption levels which, in turn, can also enhance the energy-use efficiencies further. This notion of RE leading to higher energy-use efficiencies is based on the fact that the RE resources, in comparison to the NRE resources, are relatively more energy intensive in nature. Thus, promoting ICT trade can justifiably be linked to the adoption of RE technologies within the energy systems of the developing economies.

The RE supplies, particularly wind and solar, are asserted to exhibit unpredictability due to these resources being largely dependent on nature. Thus, the development of the ICT sector can be vital in this regard. The application of ICT could ensure the maximum harvest of these unreliable RE resources at their respective peak periods. Besides, ICT can also be tapped to facilitate the storage of electricity generated from these primary RE resources (Ahmed et al. 2017). On the other hand, the application of ICT within the power sector can also attribute to electricity conservation by smartening the conventional grids that are prone to experiencing abrupt failures and shutdowns (Murshed 2020a). Also, imports of ICT commodities are hypothesized to reduce the costs associated with renewable power generations within the developed economies that face comparative disadvantages in producing them domestically. Furthermore, the greening of the ICT applications can be decisive in reducing the global emissions of greenhouse gases as well, particularly by boosting the RE shares worldwide (Wang et al. 2015).

Hence, keeping these potentially favorable outcomes of ICT trade on energy and environmental sustainability into cognizance, this paper aims to evaluate the impacts of liberalizing the ICT-trade barriers on the prospects of undergoing renewable energy transition (RET) and mitigating the greenhouse emissions across selected South Asian economies, namely Bangladesh, India, Pakistan, Sri Lanka, Nepal and Maldives. RET specifically refers to the transition from use of non-renewable to renewable energy resources within an economy whereby its monotonic dependence on fossil fuels, in particular, can be gradually phased out (Murshed 2018). The central motivation behind this paper has been sourced from the fact that the majority of these South Asian economies are predominantly reliant on the use of NRE for electricity generation purposes (World Bank 2020). Simultaneously, technological redundancy within these economies has bottlenecked their prospects of enhancing the respective shares of renewables in the aggregate energy consumption figures. Under such unappealing circumstances, promoting ICT imports, in particular, is hypothesized to lay the foundation for the South Asian economies to augment RE resources into the national energy-mixes (Murshed et al. 2020b). It is worth mentioning that the South Asian economies considered in this paper have traditionally been net importers of ICT commodities. Thus, trade liberalization decisions are likely to boost ICT imports further. Besides, higher volumes of ICT imports by the South Asian economies are likely to result in technological advancement for better monitoring and management of the environmental attributes in South Asia. In this regard, the use of ICT in South Asia can be hypothesized to limit greenhouse emissions across this region.

This paper contributes to the literature in a couple of aspects. Firstly, this is the only study that evaluates the impacts of ICT trade on the RET, using a linear econometric model, in the context of South Asia. Although a wide array of the preceding studies have probed into the overall trade openness-RET nexus in the South Asian context (Murshed 2018; Murshed et al. 2020a), the potential impacts of promoting ICT trade in this regard are yet to be extensively explored. Secondly, the impacts of ICT trade on environmental quality in South Asia are scrutinized. The existing studies have primarily focused on the impacts of ICT use on environmental quality (Higón et al. 2017; Amri et al. 2019). However, to the best of knowledge, the specific impacts of the ICT-trade liberalization on the environmental well-being in South Asia have not been empirically evaluated before. As far as environmental quality is concerned, this paper uses the Carbon dioxide (CO_2) emission figures of the South Asian economies as a proxy variable for environmental sustainability in South Asia. CO_2 emission is particularly chosen in this regard because CO_2 accounts for a major proportion of the aggregate greenhouse emissions worldwide and is therefore recognized as the major greenhouse gas (IPCC 2014). Keeping the colossal potentials of ICT trade for the attainment of RET and environmental sustainability across South Asia into cognizance, the following questions are addressed in this paper:

1. Does the trade of ICT commodities facilitate the RET phenomenon in South Asia?
2. Can the energy-use efficiencies be enhanced by promoting ICT trade across South Asia?
3. Does ICT trade ensure environmental sustainability by reducing CO_2 emissions in South Asia?

The remainder of this paper is organized as follows. Section 2 provides a trend analysis of ICT trade across the selected South Asian economies and sheds light on the relevant energy consumption and environmental quality indicators as well. A critical review of the literature review is presented in Sect. 3. The econometric models and the dataset used in this paper are explained in Sect. 4, while Sect. 5 briefly describes the methodology of the research. Section 6 discusses the findings from the econometric analyses and Sect. 7 concludes.

2 Some stylized facts on ICT trade, energy consumption and CO_2 emission trends in South Asia

Figure 1 illustrates the trends in the trade of ICT goods across the selected South Asian economies. It is evident from the graphical illustrations that the percentage shares of ICT goods trades in the respective GDP figures, also referred to as the ICT-trade openness indices, of India, Bangladesh and Nepal have on average exhibited progressive trends between 2000 and 2016. In contrast Sri Lanka, Pakistan and Maldives have registered declining projections. However, among the selected South Asian economies, the fluctuations in Nepal's ICT-trade openness indices depicted a great deal of volatility over the aforementioned period. A particular reason behind this phenomenon can be attributed to the nation's robust growth in the volumes of ICT trade during the early-2000 period, peaking around 2008 before experiencing a sharp downfall. Between 2000 and 2016, the average ICT-trade openness indices of Bangladesh, India, Pakistan, Sri Lanka, Maldives and Nepal were 0.77%, 1.47%, 0.95%, 1.49%, 3.27% and 1.65%, respectively. These comparative ICT-trade openness trends portray a significant amount of heterogeneity in the indices across these nations. Besides, the fact that all the South Asian economies are net importers of ICT commodities, it can be assumed that the ICT sectors of the economies are yet to be developed. Therefore, liberalizing the associated trade barriers can be beneficial for the development of the ICT sectors which, along with facilitating RET and ensuring environmental sustainability can also be expected to boost the future ICT export volumes as well.

The predominant monotonic NRE dependency among the South Asian nations is evident from the energy consumption figures reported in Table 1. It can be seen that Nepal leads among the other five South Asian economies in terms of the average RE shares. This can be primarily attributed to Nepal's immense prospects of generating hydropower (Agrawala et al. 2003). In the post-2000 period, the average RE share in Nepal stood at 88.08% followed by Sri Lanka, Pakistan, Bangladesh, India and Maldives, having corresponding RE shares of 60.50%, 47.50%, 45.74%, 43.28% and 1.40%, respectively. The low RE shares in Maldives certify the failure of this nation to undergo RET due to being overwhelmingly reliant on imported petroleum for electricity generation purposes

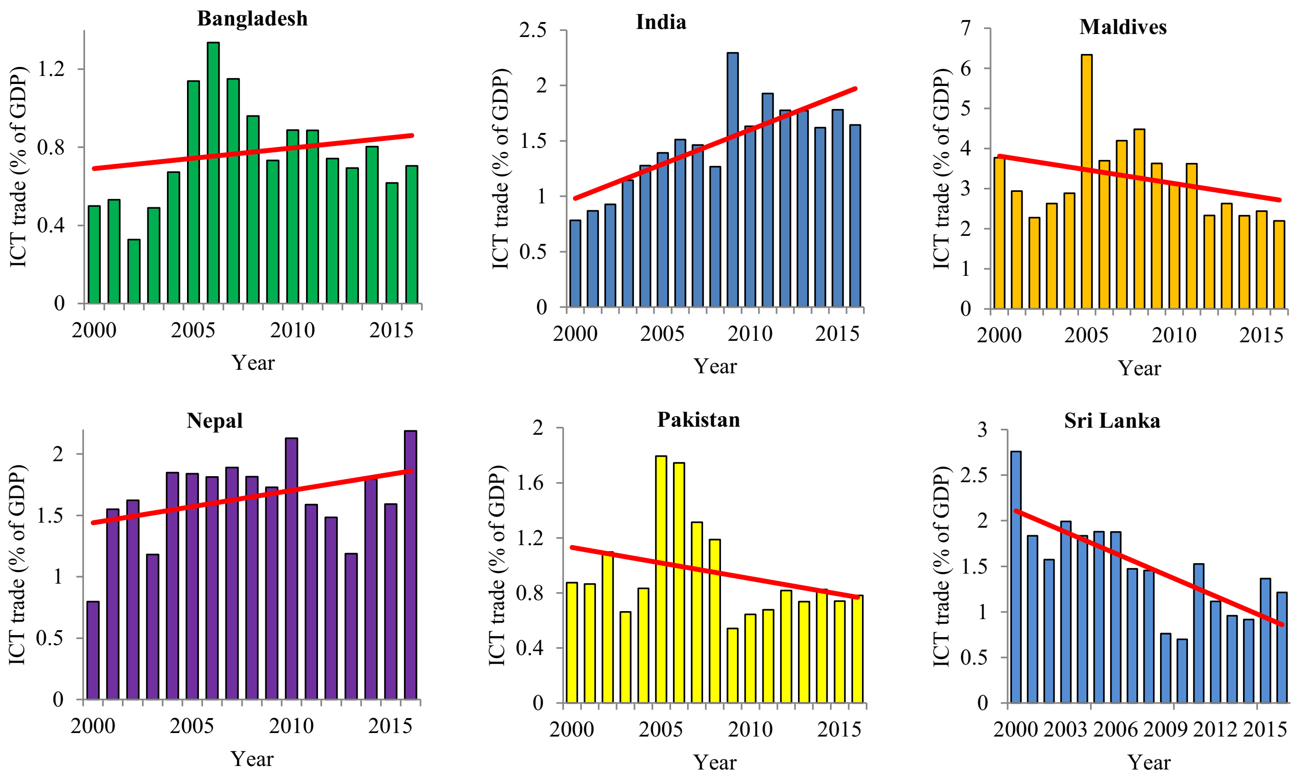

Fig. 1 Trends in the ICT-trade openness across South Asia (2000–2016). *Source*: World Development Indicators (World Bank 2020)

Table 1 Renewable energy consumption across South Asia. *Source*: World Development Indicators (World Bank 2020); Authors' own compilation from British Petroleum (2018)

Panel A: Renewable Energy shares (% in total final energy consumption levels)						
Period	India	Bangladesh	Nepal	Pakistan	Sri Lanka	Maldives
2000-04	50.90	54.78	89.14	50.12	62.42	1.86
2005-08	46.38	48.19	90.64	46.07	61.00	1.49
2009-12	39.39	40.70	86.97	46.27	61.32	1.15
2013-16	36.84	37.05	85.30	46.85	56.78	0.98

Panel B: Types of Renewable Energy use across the South Asian economies	
India	Biomass energy, hydropower, wind power, solar power, biofuel energy
Bangladesh	Solar power, wind power, ocean wave energy, biogas energy, geothermal energy, biomass energy, hydropower
Nepal	Hydropower, solar power, wind power
Pakistan	Solar power, wind power, tidal power
Sri Lanka	Hydropower, wind power, solar power, biomass energy
Maldives	Wind power, solar power, biomass energy, geothermal energy

(van Alphen et al. 2007). Moreover, the statistical figures reported in Table 1 also reveal that the average RE shares in all the selected South Asian economies have declined between the 2000-2016 period; the average RE shares in India, Bangladesh, Nepal, Pakistan, Sri Lanka and the Maldives have declined by 14.06, 17.73, 3.84, 3.27, 5.64 and 0.88 percentage points, respectively. Hence, these appalling trends in the RE shares motivated the evaluation of the prospects of ICT-trade expansion on the RET phenomenon in South Asia. Besides, the types of RE resources consumed by respective South Asian economies are also presented in Table 1.

Figure 2 depicts the average levels of energy-use intensities across the selected South Asian nations. It is evident that all the South Asian economies have managed to become more energy-efficient over the years which can

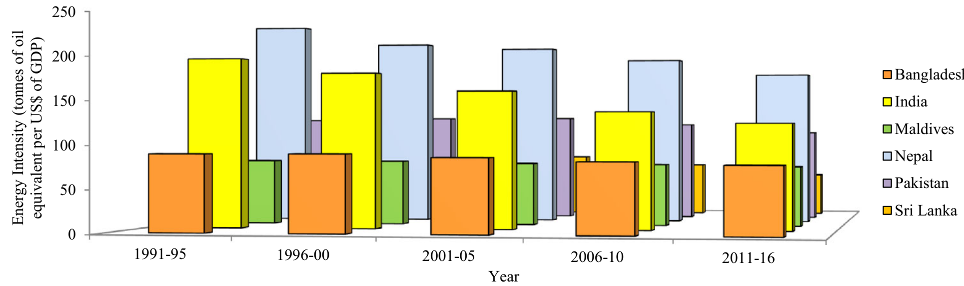

Fig. 2 Energy-use intensity trends in South Asia (1991–2016). *Source*: World Development Indicators (World Bank 2020)

be perceived from the declining trends in their average energy-use intensities between 1991 and 2016. Sri Lanka currently is referred to as the most energy-efficient economy due to its energy-use intensity being the lowest within the South Asian region. The nation's average level of energy-use intensity was around 86 tonnes of oil equivalent per US dollar of its GDP in 1991, which went down to almost 53 by the end of 2016. Hence, Sri Lanka has managed to enhance its energy-use efficiency by almost 37%. In contrast, Nepal has unfortunately languished behind its regional neighbors due to registering the highest level of energy-use intensity among the concerned South Asian economies. On the other hand, India, despite not matching Nepal in terms of the level of energy-use efficiency, has outpaced all the other five South Asian economies by registering the highest energy efficiency gains between 1991 and 2016. As oppose to Nepal's 37% efficiency gain, India improved its energy-use efficiency level by almost 39%.

On the other hand, Fig. 3 illustrates the trends in Access to Clean Fuels and Technologies (ACFT) for cooking purposes between 2000 and 2016 in South Asia. It can be seen that both India and Pakistan have managed to exhibit identical trends in their respective ACFT levels, while the corresponding trends in the cases of Nepal and Sri Lanka have also coincided for a large period between 2000 and 2016. Besides, Maldives demonstrated significant improvements in its ACFT levels, registering almost a threefold increase in the ACFT figures during the post-2000 period. However, Bangladesh has been the least successful among the six South Asian nations with respect to ensuring greater ACFT for cooking purposes for its people. Between 2000 and 2016, the average ACFT level in Bangladesh was merely 11.9% which was significantly lower than the corresponding ACFT figures across South Asia.

CO_2 emissions are referred to as the major greenhouse gas which is most responsible for the climate change adversities linked to the greenhouse emissions. Besides, almost two-thirds of the global greenhouse emissions are presumed to be CO_2 (Field 2014). Thus, it is critically important to analyze the CO_2 emission trends keeping South Asia's environmental sustainability into cognizance. As far as the intensities of CO_2 emissions across South Asia are concerned, India is currently labeled as the most polluted South Asian economy followed by Maldives and Pakistan (World Bank 2020). However, statistical figures reveal that Pakistan, in recent times, has fared well in mitigating its CO_2 emission intensities which is not the case for the Maldives. In contrast, Sri Lanka and Nepal have done considerably well in limiting their respective levels of CO_2 emission intensity (World Bank 2020). On the other hand, the per capita CO_2 emissions in Bangladesh and Nepal are the lowest in South Asia (World Bank 2020). The low per capita CO_2 emissions in Bangladesh can be attributed to the nation's monotonic reliance on the

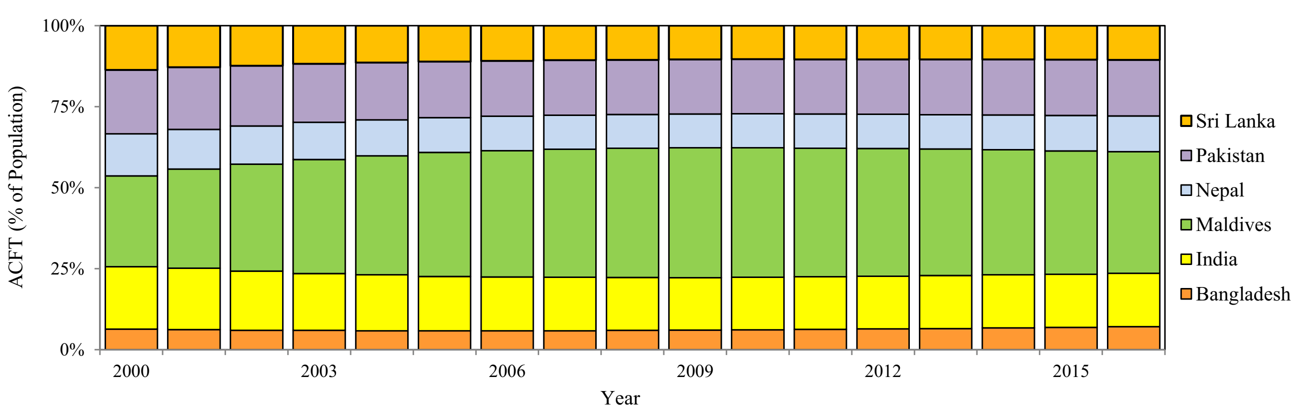

Fig. 3 The ACFT for cooking trends in South Asia (2000–2016). *Source*: World Development Indicators (World Bank 2020)

indigenous natural gas supplies for power generation purposes which, in comparison to the traditional oil-based electricity outputs, emits relatively less amount of CO_2. The low levels of per capita CO_2 emissions in Nepal could be credited to the nation's predominant use of the primary RE resources for generating electricity. Conversely, Maldives and India are the two topmost emitters of CO_2 which is evident from their respective per capita CO_2 emission levels (World Bank 2020).

3 Literature study

This section is classified into two subsections. The former provides a theoretical framework to explain how the facilitation of ICT trade can ensure RET and environmental sustainability within an economy. The latter discusses the corresponding empirical evidence documented in the literature.

3.1 Theoretical framework

It has been acknowledged in the literature that greater international trade is pertinent for the attainment of economic growth (Salman et al. 2019). Therefore, with relevance to promoting growth within the economy, it is ideal for economies to gradually open up and engage in bilateral and multilateral trade activities. The rationale behind the pertinence of liberalizing the trade barriers, in general, can be understood from the Heckscher–Ohlin–Vanek theory of international trade (Vanek 1968). This theory postulates that keeping the relative factor endowments across two countries into cognizance, a country will be a net exporter of those goods which intensively employ its relatively abundant factors endowments and be a net importer of those goods which intensively employ the relatively less-abundant resources. Accordingly, a reduction in the barriers that inhibit ICT goods trade would ideally facilitate the cross-border flows of ICT commodities into the countries that have comparative disadvantages in producing them locally.

Moreover, enhancing openness to ICT trade would also lead to the development of the ICT sector within the developing economies, in particular, which can be anticipated to improve their energy infrastructures. Hence, such ICT-trade-induced energy infrastructural development is likely to stimulate the RET phenomena across the trading economies. It is acknowledged in the literature that inappropriate energy infrastructure often bottlenecks the prospects of RET within the underdeveloped countries in particular (Murshed 2020b; Murshed et al. 2020b). Besides, the relatively greener ICT commodities, in particular, are said to have the capacity to incorporate the RE resources into them which can also be effective in elevating the overall levels of RE consumption (Andreopoulou 2012). Additionally, the ICT applications can also account for the inefficient consumption of electric power through the smartening of the conventional grids (Murshed 2019a). As a result, electricity wastages can also be significantly reduced (Panajotovic et al. 2011). Furthermore, the use of ICT can also be linked to off-grid electrification through the employment of RE resources for power generation purposes. Consequently, the pressures on the national grids for power supply can also be expected to diminish (Alstone et al. 2015).

Conversely, incorporation of RE resources into the national energy-mix, through the application of ICT in particular, could also reduce the intensity of the CO_2 emissions. Although the trade of ICT goods may at times trigger emissions of CO_2, particularly via boosting the production of electricity from the NRE sources, it is believed that trade of the relatively greener ICT products can reverse this trend (Despins et al. 2011). Accordingly, greater openness to ICT trade can be anticipated to foster the overall RET phenomenon which, in turn, is likely to exhibit critically imperative roles in simultaneously safeguarding energy security and mitigating the CO_2 emissions-induced environmental hardships as well.

3.2 The empirical literature on ICT and RET

Although the trade of ICT goods and services is envisioned to display critically important roles for facilitating green growth (Mensah et al. 2019), particularly by amplifying the RE consumption levels within the trading economy, a few of the existing studies have empirically explored the specific impacts of ICT trade on the RET phenomenon. However, a plethora of studies in the literature did document the impacts of higher openness to trade, in general, on the RE consumption responses within the developing economies in particular (Amri 2019). Thus, considering ICT trade as a subset of the overall volume of international trade, these existing studies can be expected to provide an understanding of the dynamic associations between ICT trade and RET across the globe. Alam and Murad (2020), in the context of 25 Organization for Economic Co-operation and Development (OECD) countries, concluded that enhancing international trade openness, along with economic growth and technological progress, can attribute to the elevation of the RE consumption levels. Hence, trade of ICT goods, in this context, could be expected to stimulate technological spillover which, in turn, is likely to facilitate RET within the technologically backward economies. In addition, Alam and Murad (2020) also referred to the long-run dynamics between trade openness and RE consumption being similar for all the OECD countries, while some country-specific variations were also observed from the statistical findings. Likewise, Murshed (2020b) found statistical evidence in favor of trade openness accounting for higher RE consumption within the low-income economies but not in the context of countries belonging to the lower and upper-middle-income groups. Besides, the author also referred trade liberalization decisions to be key policy interventions that assist in enhancing the energy use efficiency levels. On the other hand, in a study on the determinants of China's renewable electricity output, Lin et al. (2016) referred to trade openness undermining the share of renewable electricity in the nation's aggregate electricity outputs.

Although the analysis of the impacts of ICT-trade promotion for boosting the RE consumption levels has attracted minimal interest in the energy and environmental economics narrative, a plethora of the existing studies have documented the potential mechanisms through which use of ICT commodities can harness the targets of uplifting the shares of renewables in the global energy consumption figures. Ahmed et al. (2017) showed how ICT penetration can catalyze technological innovation within the energy sector to foster the RET phenomenon by particularly facilitating the optimal storage and distribution of power produced from renewable resources. Likewise, Stallo et al. (2010) claimed ICT development is a pre-requisite for augmenting RE into the global energy-mixes; hence, ICT can be referred to be a credible means of attaining SDG7. Besides, Arnone et al. (2013) highlighted the significance of using ICT goods to develop ICT-based energy management systems within buildings, particularly for generating electricity from photovoltaic and wind sources. On the other hand, linking ICT development to RET, Abid et al. (2017) discussed the potential channels through which ICT can smarten the conventional energy systems. Besides, the authors also pointed out how ICT penetration can attribute to the greening of traditional energy systems.

Traditionally, the global energy systems were centralized and, therefore, more vulnerable to in-grid inefficiencies and adverse grid failures. Thus, a more decentralized approach to generation, transmission and utilization of electric power is recommended to avoid the abrupt grid failures and also to negate system shutdowns. The Internet of Energy (IOE) facilitates this energy decentralization process through the application of wireless technologies involving a wide range of smart mini-grid applications. Therefore, the critically important roles of ICT development for achieving RET can be better understood from the processes driving global energy transitions through the internet (He et al. 2020). There are several aspects through which ICT development, under the concept of IOE, can be linked to RET:

3.2.1 *Smart gridding technology*

ICT is believed to play a central role in decentralizing the conventional centralized energy systems across the globe, particularly by smartening these traditional grids. Smart grids are asserted to be the long-term solution to the global energy crises in the twenty-first century (Murshed 2019a). However, the sustainability of smart gridding techniques is conditional on technological innovations; particularly through the development of the ICT sector worldwide (Skea et al. 2019). Besides, Erlinghagen and Markard (2012) opined that ICT development stimulates the transformation of the orthodox mega grids into smart mini-grids that are relatively more efficient and less prone to energy wastage. Moreover, ICT-enabled smart gridding technology is hypothesized to curb inefficient use of energy through digitalized detection of power-theft to ensure optimal utilization of electricity (Jindal et al. 2020). In addition, ICT enables the development of the relevant smart grid infrastructure by provisioning for data and information exchange concerning inefficient use of electricity, that too in near-real-time (Shawon et al. 2019). More importantly, the incorporation of RE resources into the smart grids can be expected to enhance the overall energy efficiency levels. Panajotovic et al. (2011) showed that renewable smart grids ensure energy optimization within the telecommunications sector. In the same vein, Chavan and Chavan (2020) claimed that ICT-enabled renewable smart grid systems are effective in remotely monitoring the efficacies of power plants and real-time detection of in-grid inefficiencies in a relatively cheap and user-friendly manner. Besides, Worighi et al. (2019) argued that photovoltaic penetration into the smart grids can improve grid reliability through the facilitation of storage of solar power inside batteries. Similarly, Bourhnane et al. (2019) showed how ICT can be utilized for controlling and real-time monitoring of the energy produced within the renewable smart grids. These facilities can be expected to improve the operational efficiency of these intelligent, flexible and relatively cleaner mini-grids.

3.2.2 *Demand-side management of energy*

ICT development can be related to demand-side energy management whereby the use of ICT commodities is expected to induce behavioral changes among the end-users of energy. Bastida et al. (2019) showed that ICT-interventions reduce energy use without compromising the energy need; thus, energy efficiency levels can be raised. Similarly, Doukas et al. (2019) demonstrated how ICT applications can be used to incentivize energy conservation policies to reduce energy consumption levels and elevate energy-use efficiencies. Nurulin et al. (2019) asserted that behavioral change-induced energy conservation decisions can improve energy efficiencies by up to 20%. The authors particularly emphasized the use of ICT applications to create awareness among the end-users to conserve energy for future use. Moreover, ICT development can also facilitate the home energy management systems particularly through the integration of RE resources like solar and wind into smart home appliances (Molla et al. 2019). Apart from enhancing energy efficiencies by nudging behavioral changes, several studies have also highlighted the use of ICT to promote RE consumption in a similar manner. For instance, Fung et al. (2010) conducted a study to demonstrate how ICT-based applications like smart meters can stimulate the adoption of RE resources among the end-users of electricity. Similarly, ICT has the said to influence household behavior for adopting relatively cleaner fuels as well. Evans et al. (2017) remarked that ICT can work as an awareness-building tool to disseminate knowledge regarding the advantages of employing cleaner cookstove options. Besides, Yasmin and Grundmann (2019) showed that internet use and electronic media played a defining role in facilitating the adoption of biogas for cooking in the state of Punjab in Pakistan. Similarly, Acharya et al. (2017) demonstrated how ICT-enabled wireless technologies can enhance the efficiency levels of biogas generation plants which, in turn, would be ideal in elevating the share of cleaner fuels in the aggregate cooking fuel consumption figures.

3.2.3 Consumer to prosumers of energy

ICT has been acknowledged to enable the energy consumers to become prosumers as well. A prosumer is referred to as an individual or firm that consumes energy and produces energy as well (Espe et al. 2018). The energy conserved, through the use of ICT by enhancing energy-use efficiencies and reducing energy wastes simultaneously, can either be transferred to the grid or privately shared (Murshed 2019a). Zafar et al. (2018) claimed that energy sharing through smart grid applications enables prosumers to manage peak loads and ensure energy sustainability as well. In a study by Gautier et al. (2018), the authors explained how energy prosumers can effectively transfer the surplus energy produced within the grid-connected smart grids to the national grid. Besides, Ożadowicz (2017) proposed how energy-efficient prosumer microgrids can be useful in demand-side management of energy as well. Moreover, Weiller and Neely (2014) argued that ICT can facilitate the use of relatively cleaner and renewable fuels inside plug-in hybrid electric engines to generate power within automobiles which, in turn, can be transmitted into the grid. The feasibility of similar ICT-enabled vehicle-to-grid technologies with respect to the integration of renewable electricity into the energy systems was also analyzed by Goebel and Callaway (2012). On the other hand, Zhang et al. (2018) and Sousa et al. (2019) discussed how ICT applications can be tapped to ensure peer-to-peer energy trading through renewable smart microgrid connectivity. Similarly, El-Baz et al. (2019) asserted that ICT development could facilitate the emergence of small-scale private energy markets between peers whereby the surplus energy produced within the smart mini-grids can be transferred to other personal mini-grids.

3.2.4 Rural off-grid electrification

Several existing studies have recommended the use of ICT for electrification of the rural communities (Bhattacharyya and Palit 2016). In a study on the Sub-Saharan African economies, Mekonnen and Sarwat (2017) discussed the potential ways through which ICT-enabled smart grids can amplify rural electrification rates. Besides, the authors asserted that setting up smart mini-grids across rural areas can generate electricity from solar power to provide off-grid electrification for rural societies. Similar conclusions in the context of the rural solar power generation within the rural communities were also made by Baurzhan and Jenkins (2016) for Sub-Saharan African nations and Roche and Blanchard (2018) for Kenya. Likewise, Rajbongshi et al. (2017) analyzed the roles of photovoltaic and biomass powered hybrid energy generation systems for off-grid rural electrification purposes. The authors mentioned that technological advancement in this regard can manage peak loads to bridge the rural electricity demand. Furthermore, in the South Asian context, where there is a substantial amount of disparity in electrification rates across the urban and rural areas, the use of ICT for enhancing access to off-grid renewable electricity for the rural community is believed to be extremely important (Palit and Bandyopadhyay 2016). Figure 4 illustrates how ICT-trade-enabled IOE technologies address energy management issues and facilitate the RET phenomena.

3.3 The literature on ICT and CO_2 emissions

Emission of CO_2 into the atmosphere is not a problem that is confined within the particular nation or the region that is directly responsible for the emissions. Rather, it is a global issue since it affects the entire environment worldwide. Hence, reducing the emissions of CO_2 and other greenhouse gases are critically pertinent in ensuring environmental and ecological sustainability across the globe. Although the advancement of technology is often prescribed to reduce CO_2 emissions (Long et al. 2015a), the impacts of ICT-trade-induced technological improvement for lowering the emissions are yet to be broadly

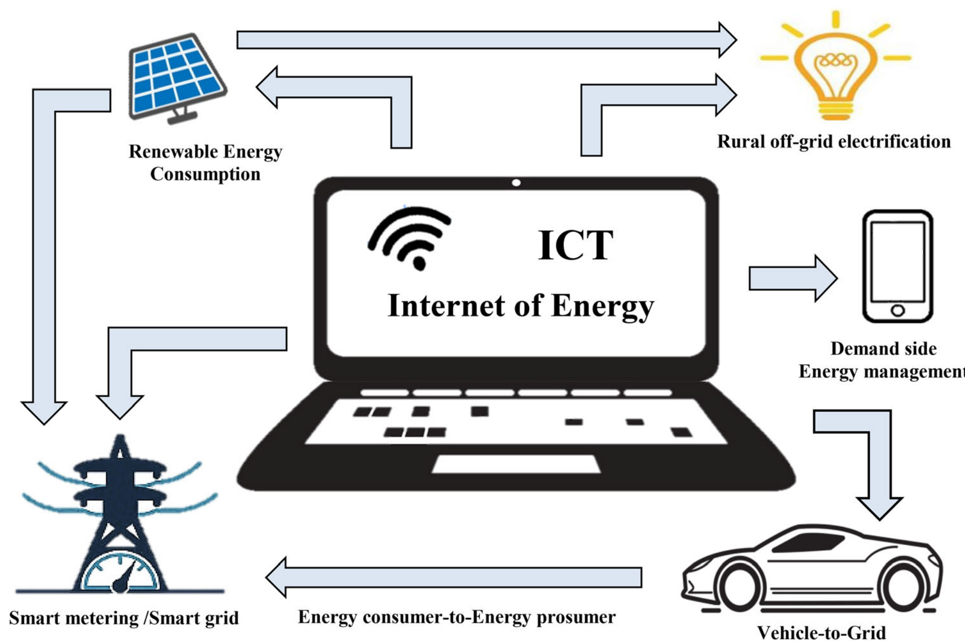

Fig. 4 A graphical illustration of the ICT-trade-enabled Internet of Energy, RET and energy management. *Source*: Authors' own

documented in the literature. However, several preceding studies have highlighted the dynamic associations between consumption of ICT goods and the corresponding responses in the CO_2 emissions (Lee and Brahmasrene 2014; Park et al. 2018).

The nexus between consumption of ICT commodities and CO_2 emissions has received equivocal empirical evidence in the existing literature. For instance, Khan et al. (2018) found statistical evidence regarding the negative impacts of ICT on the environment in the context of the Next 11 emerging economies. The empirical findings showed that the use of the internet increased CO_2 emissions within these nations. Also, when interacted with financial development, the negative impacts of ICT use were accentuated. However, at higher levels of economic growth, the interacted impacts of ICT use were found to reduce the CO_2 emission levels which implied that economic growth led to the greening of the ICT sectors whereby the emissions have been reduced to a large extent. In particular, green ICT development through provision for use of the relatively cleaner energy resources could be effective in curbing the CO_2 emissions stemming from the booming global ICT sectors. The logical explanation behind such an aspiring hypothesis can be aligned with the findings documented in the existing studies that have concluded that use of the cleaner energy resources can account for lower emission of CO_2 into the atmosphere. In a relevant study on China, Long et al. (2015b) opined that the consumption of coal and oil resulted in higher CO_2 emissions in China. However, the use of the relatively cleaner natural gas resources attributed to lower emission of CO_2 in China.

Similarly, in a study concerning 116 developing and 26 developed world economies, Higón et al. (2017) concluded that the use of ICT commodities impedes environmental sustainability in the early stages, thus, emitting higher volumes of CO_2 into the atmosphere. However, with time, the relationship is reciprocated whereby in the latter stages ICT can be tapped to curb the CO_2 emission levels. The statistical estimates from the regression analyses provided statistical evidence in favor of a nonlinear inverted-U-shaped association between consumption of ICT goods and per capita CO_2 emissions. The authors quantified ICT consumption in terms of use of fixed telephone subscriptions, mobile cellphone subscriptions, personal computers, internet and fixed broadband subscriptions.

Conversely, in a study on the BRICS countries, Haseeb et al. (2019) opined in favor of ICT having a positive impact on the environment through mitigation of CO_2 emissions. Using internet use and mobile subscriptions to proxy for ICT goods consumption, the authors found that a 1% increase in the number of internet users and mobile phone subscribers, per 100 people, attributed to reductions in the per capita CO_2 emissions by 40 and 66 percentage points, respectively. However, the results from the country-specific analysis depicted the heterogeneity of the findings. Consumption of both the ICT commodities was found to reduce CO_2 emissions in Brazil and Russia but not for India and China. On the other hand, internet use and mobile subscription were found to, respectively, reduce and elevate the per capita CO_2 emission levels in South Africa. In a similar study by Zhang et al. (2019), the authors concluded in favor of the consumption of these two ICT products being effective in reducing CO_2 emissions across the high and middle-income countries but increasing it within low-income economies.

4 Model specification and data

This paper modifies the econometric model used by Murshed (2018) to evaluate the impacts of trade of ICT goods on RET and environmental sustainability in the South Asian context. The model used in the study by Murshed (2018) considered the in-general trade openness index as the principal regressor of interest. However, since this paper aims to specifically address the impacts of ICT trade, the ICT-trade openness index is used instead. Besides, this paper also assesses the impacts of ICT trade on environmental quality which is proxied by the CO_2 emission figures. The corresponding empirical models used in this paper can be specified as:

$$\ln REC_{it} = \partial_0 + \partial_1 \ln IOPEN_{it} + \partial_{jt} X_{j,it} + \varepsilon_{it} \quad (1)$$

$$\ln RES_{it} = \delta_0 + \delta_1 \ln IOPEN_{it} + \delta_{jt} X_{j,it} + \varepsilon_{it} \quad (2)$$

$$\ln EI_{it} = \theta_0 + \theta_1 \ln IOPEN_{it} + \theta_{jt} X_{j,it} + \varepsilon_{it} \quad (3)$$

$$\ln ACFT_{it} = \alpha_0 + \alpha_1 \ln IOPEN_{it} + \alpha_{kt} Y_{k,it} + \varepsilon_{it}, \quad (4)$$

where the subscripts i, t and ε refer to the individual cross-sectional units (countries), time (years) and the error terms, respectively. The parameters ∂, δ, θ and α are the intercepts and the elasticities to be estimated. The dependent variables used in models 1, 2, 3 and 4 are used as indicators of RET within the selected South Asian economies. The variable REC refers to renewable energy consumption level measured in terms of terajoules. RES stands for the percentage shares of RE in total final energy consumption levels. EI denotes the intensity of energy-use which is expressed as the amount of energy used to produce one unit of GDP. This particular variable captures the efficiency of energy use whereby higher values of EI refers to lower energy-use efficiencies and vice versa. Finally, ACFT abbreviates for access to clean fuels and technologies for cooking which is given by the percentage of the population having access to these clean cooking fuels.

The principal regressor of interest IOPEN abbreviates for the ICT-trade openness index which is measured in terms of the sum of imports and exports of ICT goods expressed as a percentage of the GDP of the respective South Asian nations. A higher value of this index can be interpreted as higher volumes of ICT trade by the selected South Asian economies and vice versa. X is set of j (j = 1, 2, …, 7) control variables that are believed to influence REC, RES and EI. The control variables include carbon dioxide emissions (CO_2) in metric tons per capita, world real crude oil price (OIL) in US dollars per barrel, net inflows of foreign direct investments (FDI) in constant 2010 US dollars, net official development assistance (NODA) received in terms of 2010 constant US dollars, international remittance inflows (REMIT) in 2010 constant US dollars, Gross National Product per capita (GNIPC) measured in terms of 2010 constant US dollars and consumer price index (CPI) to proxy for the domestic inflationary rates. Y is a vector of k (k = 1, 2, …, 5) control variables that are expected to affect ACFT which includes CO_2, OIL, CPI, life expectancy at birth (LIFE) and secondary school enrollment rates (SSE).

Besides, following Murshed et al. (2020c), the per capita CO_2 emissions are used to quantify environmental quality across South Asia. The econometric models in this regard are given by:

$$\begin{aligned}\ln CO2_{it} = {} & \mu_0 + \mu_1 \ln IOPEN_{it} + \mu_2 \ln REC_{it} \\ & + \mu_3 (\ln IOPEN * \ln REC_{it}) + \mu_4 \ln OIL_{it} \\ & + \mu_5 \ln GNIPC_{it} + \mu_6 \ln GNIPC^2_{it} + \varepsilon_{it}\end{aligned} \quad (5)$$

$$\begin{aligned}\ln CO2_{it} = {} & \pi_0 + \pi_1 \ln IOPEN_{it} + \pi_2 \ln NREC_{it} \\ & + \pi_3 (\ln IOPEN * \ln NREC_{it}) + \pi_4 \ln OIL_{it} \\ & + \pi_5 \ln GNIPC_{it} + \mu_6 \ln GNIPC^2_{it} + \varepsilon_{it},\end{aligned} \quad (6)$$

where the parameters μ and π are the intercept and elasticities to be estimated. NREC refers to NRE consumption measured in terms of terajoules. In both models 5 and 6, REC and NREC are interacted with IOPEN to assess the combined impacts of openness to ICT trade and energy consumption on the CO_2 emissions which is pertinent to understand the heterogeneity of the impacts with respect to the type of energy resource consumed. $GNIPC^2$ is the squared term of the per capita GNI figures which are used to account for the possible nonlinear relationship between economic growth and CO_2 emissions. The signs of the elasticity parameters attached to GNIPC and its squared terms would provide statistical support to validate/invalidate the existence of the Environmental Kuznets Curve (EKC) hypothesis in the South Asian context. The EKC hypothesis postulates in favor of economic growth in the initial phases attributing to adverse environmental consequences which, beyond a certain growth threshold, phases out to ensure environmental welfare in the latter stages of growth (Pata 2018; Murshed et al. 2020b; Muhammad et al. 2020; Murshed 2020c, d).

All the variables have been transformed into their natural logarithms for the ease of the conditional bivariate elasticity estimations (Murshed et al. 2020d; Murshed 2020e). Annual time-series data from 2000 to 2016 is compiled in the context of all the six selected South Asian economies. Table 2 provides the description, units of measurement and their corresponding data sources.

Table 2 Description and sources of data

Variable	Description	Units	Source
REC	Renewable energy consumption levels	Terajoules	World Development Indicators (World Bank 2020)
RES	Renewable energy share on total final energy consumption figures	Percentage	World Development Indicators (World Bank 2020)
EI	Energy intensity levels which denote the amount of energy used to produce 1 US dollar worth of real GDP	kg of oil equivalent per US dollar	World Development Indicators (World Bank 2020)
ACFT	Access to clean fuel and technology for cooking among the population	Percentage	World Development Indicators (World Bank 2020)
IOPEN	Openness to ICT trade which is the percentage share of ICT goods imports and exports in total imports and exports of goods	Percentage	World Development Indicators (World Bank 2020)
CO2	Carbon dioxide emissions per capita	Metric tons	World Development Indicators (World Bank 2020)
OIL	Real crude oil price	Constant 2016 US dollars	British Petroleum Statistical Review of World Energy (British Petroleum 2018)
FDI	Real value of net inflows of foreign direct investments	Constant 2010 US dollars	World Development Indicators (World Bank 2020)
NODA	Real value of net official development assistance received	Constant 2010 US dollars	World Development Indicators (World Bank 2020)
REMIT	Real value of international remittances received	Constant 2010 US dollars	World Development Indicators (World Bank 2020)
GNIPC	Real gross national income per capita to proxy for national income level/economic growth	Constant 2010 US dollars	World Development Indicators (World Bank 2020)
GNIPC2	Squared term real gross national income per capita	Constant 2010 US dollars	World Development Indicators (World Bank 2020)
CPI	Consumer price index which proxied for the domestic inflation rate	Index	World Development Indicators (World Bank 2020)
SSE	Secondary school enrollment rates to proxy for education	Percentage	World Development Indicators (World Bank 2020)
LIFE	Life expectancy at birth to proxy for health	Years	World Development Indicators (World Bank 2020)
NREC	Non-renewable energy consumption levels	Terajoules	World Development Indicators (World Bank 2020)

5 Methodology

5.1 Cross-sectional dependency analysis

The econometric analysis starts by addressing the possible issues of cross-sectional dependency (CD) in the data that attribute to the estimation of biased and inconsistent stationarity and cointegrating properties. Hence, it is pertinent to investigate whether the cross sections are independent or not. The CD usually arises when one economic data of a particular country is influenced via the same economic data in another country whereby the countries within the panel dataset are referred to be either globally or regionally associated. Keeping the border-sharing aspect and trade and financial integration among the South Asian economies into cognizance, the CD issues in the panel data can be expected. Hence, following Zafar et al. (2019) and Dong et al. (2020), this paper taps the CD tests proposed by Pesaran (2004) and Breusch and Pagan (1980). Both these methods predict test statistics under the null hypothesis of cross-sectional independence against the alternative hypothesis of CD. For a model comprising of N number of cross sections for the time period T, the test statistics of the Pesaran CD and the Breusch–Pagan Lagrange Multiplier (LM) tests can be written as:

$$CD = \sqrt{\frac{2}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} T_{ij}\hat{\rho}_{ij}^{2} \rightarrow N(0,1) \quad (7)$$

$$LM = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} T_{ij}\hat{\rho}_{ij}^{2} \rightarrow \chi^{2} \frac{N(N-1)}{2}. \quad (8)$$

For robustness check, the CD analysis is also performed using the techniques introduced by Friedman (1937) and Frees (1995).

5.2 Panel unit root analysis

The unit root analysis denotes whether the variables considered within the econometric model are mean-reverting (stationary) or not (non-stationary). Analysis of the possible unit root problem in the data is pertinent since the stationarity of the variables nullifies the possibility of the spurious regression analysis (Murshed 2019b). Besides, identification of the order of integration of the variables, using appropriate unit root estimating techniques, is key to assessing whether there are any cointegrating relationships between the variables included in the respective econometric model (Sharif et al. 2019). However, in the context of the panels being cross-sectionally dependent, the application of the first-generation panel data unit root estimation methods, such as the Harris–Tzavalis (1999) and Breitung (2000) unit root tests, is no longer appropriate due to these tests not accounting for the CD issues (Sharif et al. 2019). Thus, the second-generation panel unit root tests that are robust to handling CD issues. This paper uses the cross-sectionally Augmented Dickey–Fuller (CADF) and the cross-sectionally augmented Im–Pesaran–Shin (CIPS) unit root estimation techniques proposed by Pesaran (2007). The CADF statistic can be obtained from the model specified below:

$$\Delta y_{it} = a_i + b_i y_{i,t-1} + c_i \bar{y}_{t-1} + \sum_{j=0}^{s} d_{ij} \Delta \bar{y}_{t-j} + \sum_{j=1}^{s} \delta_{ij} \Delta \bar{y}_{i,t-j} + e_{it}, \tag{9}$$

where $\bar{y}$ and $\overline{\Delta y}$ are the cross-sectional averages of lagged levels and first differences, respectively, at time T for all countries. The estimated t-statistic from Eq. (9) is then used to compute the CIPS statistic which can be shown as:

$$\text{CIPS} = N^{-1} \sum_{i=1}^{N} \text{CADF}_i, \tag{10}$$

where CADF_i is the t-statistic estimated from the CADF regression model shown in Eq. (9). Both the CADF and CIPS tests are performed under the null hypothesis of non-stationarity of the variables against the alternative hypothesis of otherwise. Additionally, this paper also applies the bootstrap-panel unit root analysis proposed Smith et al. (2004) which particularly accounts for the CD issues by using bootstrapping techniques. Moreover, this technique ideally suits relatively shorter panel data sets. Furthermore, for comparability of the unit root findings, the Harris–Tzavalis (1999) and Breitung (2000) first-generation panel unit root tests are also applied.

5.3 Panel cointegration analysis

Likewise, the first-generation panel unit root tests, the conventional panel cointegration methods such as the Kao (1999) residual-based cointegration technique do not take the CD issues into account. Thus, the Westerlund (2007) panel cointegration analysis, which is robust to handling cross-sectionally dependent panel dataset, is employed to investigate the long-run associations between the variables. The CD problems are accounted for through estimation of the probability values of the test statistics via bootstrapping methods. A total of two group-mean tests and two panel tests are performed under the null hypothesis of no cointegration against the alternative hypothesis of cointegration among at least one cross-sectional unit. The Westerlund (2007) tests are structured in the context of an error-correction model which can be expressed as:

$$\Delta y_{it} = \delta_i' d_t + \alpha_i \left(y_{i,t-1} - \beta_i' x_{i,t-1} \right) + \sum_{j=1}^{p_i} \alpha_{ij} \Delta y_{i,t-j} + \sum_{-q_i}^{p_i} \gamma_{ij} \Delta x_{i,t-j} + e_{it}, \tag{11}$$

where d_t stands for the deterministic components and p_i and q_i are the lag lengths and lead orders which vary across individual cross sections. The two group-mean test statistics G_t and G_a and the two panel test statistics P_t and P_a within the Westerlund (2007) cointegration analysis can be expressed as:

$$G_t = \frac{1}{N} \sum_{i=1}^{N} \frac{\hat{\alpha}_i}{\text{SE}(\hat{\alpha}_i)} \tag{12}$$

$$G_a = \frac{1}{N} \sum_{i=1}^{N} \frac{T\hat{\alpha}_i}{\hat{\alpha}_i(1)} \tag{13}$$

$$P_t = \frac{\hat{\alpha}_i}{\text{SE}(\hat{\alpha}_i)} \tag{14}$$

$$P_a = T\hat{\alpha}. \tag{15}$$

Additionally, the Durbin–Hausman cointegration method proposed by Westerlund (2008) is also applied for the robustness check of the cointegration findings. The Westerlund (2008) is also efficient in the context of cross-sectionally dependent panels. Besides, the Kao (1999) first-generation panel cointegration analysis is performed for comparison purposes.

5.4 Panel regression analysis

This paper employs the Bai et al. (2009) Continuously Updated Fully Modified (CUP-FM) and the Continuously Updated Bias Corrected (CUP-BC) regression estimators that are suited for handling cointegrated panels. Both these techniques are said to generate robust results in the presence of endogeneity and cross-sectional dependency issues within the dataset and can also accommodate a mixed order of integration among the variables in the respective models. The regression function of a CUP-FM and CUP-BC model can be shown as:

$$\left(\hat{\beta}_{\mathrm{CUP}}, \hat{F}_{\mathrm{CUP}}\right) = \arg\min \frac{1}{nT^2} \sum_{i=1}^{n} (y_i - x_i\beta)' M_F (y_i - x_i\beta), \tag{16}$$

where $M_F = I_T - T^{-2} FF\prime$ and I_T and F are the identities of matrix dimension T, and the error term assumes a latent common factor. In the context of the continuously biased estimators being consistent, asymptotic bias may arise from the endogeneity and the CD problems. Although both the CUP-FM and the CUP-BC correct for this asymptotic bias, the difference between these two estimators is that the CUP-FM estimator corrects for the bias only in the final stage of the iteration, while the CUP-BC corrects it at each stage of the iteration. For robustness checks, the Feasible Generalized Least Squares (FGLS) estimator is also used to predict the long-run elasticities.

5.5 Panel causality analysis

The recently developed Dumitrescu–Hurlin panel causality estimation technique developed by Dumitrescu and Hurlin (2012) is applied to investigate the causal dynamics between openness to ICT trade and the RET and environment indicators considered in this paper. The conventional Granger (1969) causality test inappropriately assumes homogeneity across the cross sections whereby the test statistic is estimated using the null hypothesis that Granger causality does not exist between a pair of stationary variables belonging to all the cross sections against the homogenous alternative hypothesis of Granger causality existing between these variables in all the cross sections. Thus, this method does not take the heterogeneity across the cross sections into consideration which results in biased causality estimates. In contrast, the Dumitrescu–Hurlin causality technique allows for heterogeneity across the cross sections to estimate the Z-bar statistics under the null hypothesis that there does not exist a Granger causality between a pair of stationary variables in all the cross sections, referred to as the Homogenous Non-Causality (HNC) null hypothesis, against the non-homogenous alternative hypothesis of Granger causality existing between these variables in at least one of the cross sections. The mean statistic used to test the HNC null hypothesis can be given as:

$$W_{N,T}^{\mathrm{HNC}} = \frac{1}{N} \sum_{i=1}^{N} W_{i,T}, \tag{17}$$

where $W_{N,T}^{\mathrm{HNC}}$ is the mean value of the individual Wald statistic $W_{i,t}$. According to Dumitrescu and Hurlin (2012), under the assumption that the individual residuals are independently distributed across all the cross sections and their covariances are equal to zero, the mean statistic sequentially converges to the equation below when T and N tend to approach infinity:

$$Z_{N,T}^{\mathrm{HNC}} = \sqrt{\frac{N}{2K}}\left(W_{N,T}^{\mathrm{HNC}} - K\right)\overset{\vec{d}}{\underset{T,N\to\infty}{}} N(0,1), \tag{18}$$

where $Z_{N,T}^{HNC}$ is the z-statistic, N is the number of cross sections and K is the optimal lag length. According to Dumitrescu and Hurlin (2012), if T tends to infinity, the individual Wald statistics are independently and identically distributed with the mean individual Wald statistic being equal to K and its variance being equal to 2 K. A standardized Z-statistic ($\bar{Z}_{N,T}^{\mathrm{HNC}}$) is then approximately calculated for the mean Wald statistic of the HNC null hypothesis which can be shown as:

$$\bar{Z}_{N,T}^{\mathrm{HNC}} = \frac{\sqrt{N}}{\sqrt{\mathrm{Var}\left(\tilde{W}_{i,T}\right)}}\left[W_{N,T}^{\mathrm{HNC}} - E\tilde{W}_{i,T}\right]. \tag{19}$$

The statistical significance of the standardized z-statistics determines the causality between a pair of stationary variables in at least one of the cross sections. For robustness check, the Granger (1969) causality and the Geweke's (1982) measure of instantaneous feedback techniques are also used to deduce the causal associations.

6 Results and discussion

The results from the CD analysis are reported in Table 3. The statistically significant test statistics, for all the four methods, reject the null hypothesis of cross-sectional independence to confirm the presence of CD issues in the context of all six models considered in this paper.

Since there is evidence of CD among the panels, the second-generation panel unit root tests are to be appropriately applied. However, for comparability, the first-generation unit root techniques are also used. Table 4 presents the findings from the panel data unit root analysis. The results from the Harris–Tzavalis (1999) and the Breitung (2000) first-generation tests reveal a mixed order of integration among the variables. However, both the CIPS and CADF second-generation unit root tests suggest that all the variables are non-stationary at their respective level forms, but they become stationary at their first differences. Thus, a

Table 3 Results from the cross-sectional dependency analysis

Model Dependent variable Test	(1) $lnREC_t$ Test Stat.	(2) $lnRES_t$ Test Stat.	(3) $lnEI_t$ Test Stat.	(4) $lnACFT_t$ Test Stat.	(5) $lnCO2_t$ Test Stat.	(6) $lnCO2_t$ Test Stat.
Pesaran (2004)	− 1.731*	1.851**	− 1.617*	− 1.472*	− 1.172**	3.163***
Breusch–Pagan (1980) LM	52.517***	50.012***	39.970***	42.880***	64.903***	55.112***
Friedman (1937)	23.222***	20.399***	19.010***	24.221***	33.290***	38.290***
Frees (1995)	0.712***	0.632**	0.580**	0.611***	0.780***	0.810***

The optimal lags are based on Schwarz Information Criterion (SIC); the test statistics are estimated under the null hypothesis of cross-sectional independence against the alternative hypothesis of cross-sectional dependence; ***, ** and * denote statistical significance at 1%, 5% and 10% levels, respectively

common order of integration, at first difference [$I(1)$], among the variables is ascertained. The contrasting results from the first- and second-generation tests highlight the pertinence of performing the second-generation panel unit root analysis to account for the CD issues in the data.

The unit root exercises are followed by the panel cointegration analysis. Table 5 reports the test statistics from both the first- and second-generation panel cointegration methods. The results from the Kao (1999) first-generation cointegration analysis confirm cointegration in the context of models 1, 2, 5 and 6 but not for models 3 and 4. However, the results from both the Westerlund (2007) and Westerlund (2008) second-generation cointegration tests affirm cointegrating relationships among the concerned variables for all the empirical models. Hence, these contrasting findings once again reveal the importance of performing the second-generation panel cointegration tests that are robust to handling the CD issues in the data. The statistical evidence of cointegration implicates long-run associations between ICT trade, the renewable energy transition indicators, energy efficiency levels, CO_2 emissions figures and the variables controlled for within the respective empirical models. This fulfills the pre-requisite to predicting the long-run elasticities using appropriate panel data regression tools.

After confirmation of cointegration among the variables, the next step involves the estimation of the long-run elasticities using the appropriate panel data regression estimators that account for the CD problems. The CUP-FM, CUP-BC and FGLS panel regression techniques are applied to predict the long-run elasticities. The elasticity estimates in the context of models 1, 2 and 3 are reported in Table 6. The estimates, in general, portray the robustness of the results to the different regression techniques which is evident from the similarity of the predicted signs of the elasticity estimates.

In the context of model 1, the statistically significant long-run elasticities advocate in favor of a positive association between the trade of ICT goods and consumption of RE resources within the concerned South Asian nations. It is found that a 1% rise in ICT-trade openness attributes to a corresponding rise in the RE consumption figures by 0.04–0.11%, on average, *ceteris paribus*. Hence, it can be asserted that the liberalization of the barriers that impede the trade of ICT commodities could be ideal in augmenting RE into the national energy-mixes across South Asia. Moreover, it can be also said that the cross-border flows of ICT goods could also account for the technological constraints that have traditionally bottlenecked the prospects of undergoing RET across this region. Thus, promoting ICT trade can be effective in ensuring energy security in South Asia. Besides, the other results from the regression analysis indicate that RE consumption is also positively influenced by higher levels of economic growth, rising CO_2 emissions, inflows of international remittances, positive crude oil price shocks and higher rates of domestic inflation. On the other hand, the positive signs of the elasticity parameters attached lnFDI validate the pollution haven hypothesis (PHH) in South Asia. The PHH refers to adverse environmental conditions that result from incoming FDI, especially from the developed to the developing economies (Cole 2004).

However, although higher openness to ICT trade is found to enhance the RE consumption levels across the selected South Asian economies, it does not quite guarantee the overall RET phenomenon. This can be clearly understood from the negative signs of the estimated elasticities attached to lnIOPEN in the context of model 2. It is found that a 1% rise in openness to ICT goods trade reduces the average shares of RE in the total final energy consumption levels by 0.62–0.68%, *ceteris paribus*. This implies that trade of ICT commodities not only enhances the consumption of RE, but it boosts the overall consumption of NRE resources in South Asia. Consumption of ICT products is known to enhance the demand for electricity, whereby the conventional fossil fuel-generated

Table 4 The results from the first- and second-generation panel unit root tests

Variables	First-generation panel unit root tests				Second-generation panel unit root test					
	Harris–Tzavalis		Breitung		CIPS		CADF		Smith et al. (2004)	
	Level	Δ	Level	Δ	Level	Δ	Level	Δ	Level	Δ
lnREC	− 0.057***	− 0.396***	− 1.787***	− 1.914***	− 2.013	− 5.299***	− 2.388	− 3.798***	− 2.179	− 4.892***
lnRES	− 0.093***	− 0.579***	0.349	− 2.179***	− 2.004	− 4.238***	− 1.219	− 2.389*	− 2.285	− 5.340***
lnEI	0.337**	0.180***	− 0.361	− 4.714***	− 2.154	− 5.149***	− 2.001	− 3.634***	− 2.323	− 4.440***
lnACFT	0.987	2.901***	1.025	− 2.804***	− 1.854	− 4.775***	− 2.149	− 3.287***	− 1.301	− 4.290***
lnIOPEN	0.284***	− 0.371***	− 2.190***	− 4.295***	− 2.634	− 5.152***	− 2.281	− 3.346***	− 2.410	− 5.121***
lnCO2	0.531	1.291***	1.456***	− 4.916***	− 2.164	− 4.825***	− 1.307	− 3.302***	− 2.299	− 4.119***
lnOIL	0.972	1.210***	1.950	− 2.908***	1.719	4.701***	1.700	3.107***	− 2.182	− 3.782***
lnFDI	0.282***	− 0.269***	− 2.074**	− 3.751***	− 2.618	− 4.133***	− 2.436	− 3.364***	− 1.120	− 5.410***
lnNODA	0.271***	− 0.341***	− 2.384***	− 5.918***	− 2.578	− 5.658***	− 2.819	− 3.561***	− 2.277	− 5.499***
lnREMIT	0.651	0.109***	2.587	− 2.918***	− 1.969	− 3.169**	− 2.512	− 3.430***	− 2.390	− 4.228***
lnGNIPC	0.205***	− 0.337***	− 0.760	− 1.778**	− 2.298	− 2.760*	− 1.461	− 3.590***	− 1.320	− 4.721***
lnGNIPC2	0.112***	− 0.378***	− 0.861	− 1.798**	− 1.278	2.813**	− 1.449	− 3.781***	− 1.322	− 3.221***
lnCPI	0.439**	− 0.256***	− 1.040	− 6.519***	− 2.408	− 3.928***	− 2.236	− 3.685***	− 1.213	− 3.929***
lnSSE	− 0.128	1.898***	0.292	− 2.339***	− 1.897	− 3.088**	− 1.355	− 3.304***	− 2.121	− 4.290***
lnLIFE	0.831	1.910***	1.212	4.998***	− 1.181	− 4.723***	− 2.218	− 4.067***	− 1.282	− 4.232***
lnEC	0.139***	1.348***	− 0.682	− 4.985***	− 1.084	− 4.431***	− 2.410	− 3.640***	− 2.140	− 4.892***
lnIOPEN*lnREC	0.403***	− 0.338***	− 2.177**	− 4.889***	− 1.991	− 5.247***	− 2.248	− 3.476***	− 1.229	− 5.700***
lnIOPEN*lnNREC	0.283***	− 0.341**	− 1.091	− 4.226***	− 1.688	− 5.437***	− 2.314	− 3.482***	− 2.112	− 4.910***

Δ denotes first difference; the reported test statistics are calculated considering both constant and trends under the null hypothesis of non-stationarity against the alternative hypothesis of stationarity; optimal lags are based on SIC; the test statistics under the Smith et al. (2015) method are predicted using 5000 bootstrapped replications; ***, ** and** denote statistical significance at 1%, 5% and 10% levels, respectively

Table 5 The panel cointegration test results

Test model	First-generation test	Second-generation tests				
	Kao (1999)	Westerlund (2007)				Westerlund (2008)
	ADF Stat.	G_t	G_a	P_t	P_a	D–H test Stat.
(1)	− 4.487***	− 5.614***	− 5.706***	− 5.136***	− 3.543***	15.982***
(2)	− 7.221***	− 4.124***	− 6.519***	− 9.159***	− 6.690***	15.399***
(3)	− 1.210	− 1.800*	− 13.939***	− 10.721***	− 10.521***	14.214***
(4)	− 1.221	− 10.419***	− 13.434***	− 2.861	− 4.245**	10.219***
(5)	− 6.063***	− 4.500***	− 3.978**	− 3.593**	− 4.026***	11.889***
(6)	− 6.225***	− 4.721***	− 4.417*8	− 3.994**	− 1.776	9.489***

ADF refers to Augmented Dickey–Fuller test statistic; D–H refers to the Durbin–Hausman panel test statistic that has been estimated using 5000 bootstrap replications; The test statistics are estimated under the null hypothesis of no cointegration against the alternative hypothesis of cointegration among the variables in the respective models; The optimal lags are based on SIC; *** and ** denote statistical significance at 1% and 5% levels, respectively

Table 6 The long-run elasticity estimates in the context of models (1), (2) and (3)

Dep. var.	lnREC			lnRES			lnEI		
Model	(1)			(2)			(3)		
Estimator	CUP-FM	CUP-BC	FGLS	CUP-FM	CUP-BC	FGLS	CUP-FM	CUP-BC	FGLS
Regressors									
lnIOPEN	0.109**	0.061***	0.043*	− 1.761***	− 1.680***	− 0.615**	− 0.188***	− 0.223***	− 0.130**
	(0.050)	(0.012)	(0.019)	(0.329)	(0.268)	(0.006)	(0.016)	(0.041)	(0.050)
lnCO2	0.115**	0.132	0.038*	3.133**	3.422**	5.959***	− 0.103***	− 0.306***	− 0.220***
	(0.049)	(0.088)	(0.002)	(1.305)	(1.579)	(0.908)	(0.023)	(0.040)	(0.027)
lnOIL	0.102	0.429***	0.271***	1.486	6.115***	3.851***	0.07**	0.436***	0.035
	(0.096)	(0.130)	(0.068)	(2.565)	(2.933)	(1.241)	(0.026)	(0.079)	(0.053)
lnFDI	− 0.081*	− 0.373***	− 0.196***	− 4.356***	− 6.489***	− 3.56***	0.027	0.043	0.145
	(0.047)	(0.052)	(0.051)	(1.267)	(0.905)	(0.882)	(0.020)	(0.039)	(0.117)
lnNODA	− 0.519	− 0.051	− 0.017	− 5.320***	− 4.339*	− 2.180**	− 0.020	− 0.206***	− 0.030
	(0.716)	(0.149)	(0.049)	(2.038)	(2.013)	(0.898)	(0.017)	(0.063)	(0.050)
lnREMIT	0.458***	0.458***	0.439***	11.877***	11.44***	10.42***	0.049***	0.139***	0.055***
	(0.036)	(0.052)	(0.022)	(0.965)	(1.000)	(0.467)	(0.011)	(0.030)	(0.009)
lnGNIPC	0.641***	0.544***	0.263***	− 28.57***	− 5.182**	− 10.321***	− 4.484***	1.149***	0.379***
	(0.139)	(0.082)	(0.101)	(3.719)	(2.001)	(1.758)	(0.030)	(0.114)	(0.048)
lnCPI	0.015	0.047***	0.018***	0.239	0.754***	0.305**	− 0.004***	− 0.013	− 0.008
	(0.011)	(0.009)	(0.007)	(0.286)	(0.166)	(0.120)	(0.001)	(0.008)	(0.006)
Constant	15.135***	3.726	2.822***	171.35***	119.581**	101.129***	− 2.865***	− 9.529***	− 2.954***
	(1.554)	(2.602)	(1.017)	(45.651)	(51.02)	(17.948)	(0.361)	(1.278)	(0.912)
Wald Chi^2			2030.1***			1365.611**	2334.9***		
Adj. R^2	0.773	0.805		0.707	0.781			0.680	0.727
Observations	101	101	102	101	101	102	102	101	101

The standard errors are reported within the parentheses; ***, ** and* denote statistical significance at 1%, 5% and 10% levels, respectively

electric power is often tapped to meet the surging energy demand in South Asia. Consequently, the consumption of NRE resources can be expected to simultaneously go up in response to higher imports of ICT commodities. This is a key finding regarding the pertinence of greening the ICT goods that are traded. Hence, it is better off to reduce the trade barriers relatively more in the context of those ICT commodities that can operate by integrating RE resources rather than relaxing tariffs on the comparatively dirty ICT commodities that intensively use the NRE resources. These results are quite similar to the conclusions made by Murshed (2018) in which the author claimed that higher trade openness attributed to higher RE consumption levels but lower RE shares in selected South Asian economies.

The other key findings in the context of model 2 reveal that rising CO_2 emissions tend to induce the urgency in undergoing RET which can be perceived from the positive correlation found to exist between CO_2 emissions and the RE shares across South Asia. The corresponding elasticity estimates show that a 1% rise in CO_2 emissions is accompanied by an increment in the RE shares by 3.13–5.96%, on average, *ceteris paribus.* Similar impacts are also witnessed as rising crude oil prices in the world markets are found to elevate the shares of renewables in South Asia. This finding is parallel to the conclusions made by Murshed and Tanha (2020) in which the authors remarked in favor of a U-shaped association between crude oil prices and RE shares in net oil-importing South Asian economies. Besides, the FDI inflows are also found to aggravate the relative use of NRE resources which further establishes the validity of the pollution haven hypothesis in the context of the concerned South Asian economies. On the other hand, international remittance receipts seem to be conducive to enhancing the shares of RE across the concerned South Asian economies. This implies that the remittances received by the left-behind households of the expatriates tend to increase their household income levels; thus, financially empowering them to afford and consume the RE resources. As far as economic growth is concerned, it is found that rising income levels in South Asia adversely affect the RET processes since the marginal growth effects on RE shares are found to be negative. Hence, this particular finding asserts that the economic growth policies in South Asia are not aligned with the corresponding RET targets.

In the context of model 3, the elasticity estimates assert asserted that enhancing the trade of ICT goods can effectively enhance the efficiency of energy use within the selected South Asian economies. A 1% rise in the ICT-trade openness indices curbs the intensity of energy use by 0.09–0.22%, on average, *ceteris paribus.* Hence, from the perspective of energy conservation, liberalizing the trade barriers to facilitate cross-border flows of ICT goods can be ideal in reducing the energy consumption levels without compromising the overall energy demanded by the South Asian economies. A plausible explanation in this regard could be made in the sense that the development of the ICT sectors is often associated with technological advancement that can attribute to the smartening of the traditional power-grids. Consequently, the applications of smart gridding technologies can mitigate the inefficient use and wastage of electricity across South Asia (Murshed 2019a, b). Hence, it can be claimed that promoting ICT trade can be effective in reducing the system losses stemming from the transmission and distribution irregularities existent within the South Asian nations.

Table 7 reports the long-run elasticity estimates derived from regression analysis in the context of model 4. It is visible that the trade of ICT goods results in greater ACFT for cooking purposes. The marginal effect of a percentage increase in the ICT-trade openness index is predicted to elevate the ACFT levels by 5.05–6.72%, on average, *ceteris paribus.* This is an interesting finding because the conventional dependence on traditional cooking fuels not only has adversely affected the environmental balance in South Asia, but it had also triggered health misfortunes among the women in particular. Hence, higher volumes of ICT trade within South Asia can be expected to exhibit positive influences on the adoption of cleaner cooking fuel alternatives. Such transition in the cooking fuels is likely to improve the health conditions of the women who are the major stakeholders of the health-adversities resulting from inhalation of the harmful emissions that stem from the combustion of the traditionally combusted unclean cooking fuels. This finding is also supported by the positive correlation found between ACFT for cooking and the average life expectancies at birth in South Asia. Moreover, the adoption of such cooking fuels and technologies is also seen to be positively influenced by the rising CO_2 emissions. This implies that higher emissions of CO_2 tend to create a consensus among the South Asian economies to replace the traditional firewood by the relatively environment and health-friendly cooking fuels. Besides, the secondary school enrollment rates are also found to stimulate clean cooking fuel adoption across this region. This particular finding implies that better education generates awareness in understanding the negative impacts of using traditional cooking fuels which, in turn, motivates the switch in the cooking fuels.

The conditional impacts of higher openness to ICT trade on the quality of the environment in South Asia are evaluated via the impacts on the magnitudes of CO_2 emission. Table 8 reports the long-run elasticity estimates from the regression analysis in the context of models 5 and 6. It is evident from the elasticity estimates that ICT trade directly attributes to environmental degradation by triggering CO_2 emissions into the atmosphere. A percentage increase in the ICT-trade openness indices increases per capita CO_2 emissions by 0.32–0.36%, on average, *ceteris paribus*. Therefore, although ICT development is hypothesized to contribute to lower levels of environmental pollution, the results found in this paper contradict this notion. This can

Table 7 The long-run elasticity estimates in the context of models (4)

Dependent variable: lnACFT			
Estimator	CUP-FM	CUP-BC	FGLS
Regressors			
lnIOPEN	6.717***(1.513)	5.054** (1.750)	6.541*** (0.562)
lnCO2	9.966***(0.701)	8.891*** (0.421)	6.923*** (0.604)
lnOIL	4.511 (4.878)	3.726 (2.771)	2.911 (2.735)
lnLIFE	2.901*** (0.688)	1.773*** (0.414)	1.630*** (0.177)
lnSSE	2.002*** (0.083)	2.090*** (0.057)	1.089*** (0.241)
lnCPI	− 0.125 (0.217)	− 0.284 (0.210)	− 0.229 (0.140)
lnGNIPC	18.310*** (2.843)	17.517*** (1.283)	21.972*** (1.750)
Constant	− 50.369*** (20.134)	− 10.459*** (2.009)	− 50.314*** (10.881)
Wald Chi^2			1121.02***
Adj. R^2	0.674	0.749	
Observations	101	101	102

The standard errors are reported within the parentheses; ***, ** and * denote statistical significance at 1%, 5% and 10% levels, respectively

Table 8 The long-run elasticity estimates in the context of models (5) and (6)

Dependent variable: $lnCO_2$						
Model	(5)			(6)		
Estimator	CUP-FM	CUP-BC	FGLS	CUP-FM	CUP-BC	GFLS
Regressors						
lnIOPEN	0.349** (0.162)	0.339** (0.151)	0.310 (0.292)	0.321** (0.151)	0.361** (0.152)	0.214 (0.182)
lnREC	− 3.246*** (0.850)	− 0.924*** (0.100)	− 3.930*** (0.054)	–	–	–
lnIPOEN*lnREC	− 0.144* (0.087)	− 0.125*** (0.026)	− 0.100*** (0.008)	–	–	–
lnNREC	–	–	–	1.191*** (0.035)	1.138*** (0.211)	1.131*** (0.003)
lnIOPEN*lnNREC	–	–	–	0.024*** (0.009)	0.011** (0.006)	0.001*** (0.000)
lnOIL	− 0.617** (0.307)	− 0.374*** (0.111)	− 0.364*** (0.083)	− 0.697*** (0.164)	− 0.239** (0.115)	− 0.299*** (0.037)
lnGNIPC	350.253*** (37.211)	350.357*** (39.89)	87.873*** (21.271)	36.070*** (3.297)	3.959** (2.010)	10.859*** (2.826)
lnGNIPC2	− 398.146*** (55.819)	− 403.728*** (82.991)	− 101.498*** (32.119)	− 39.830*** (35.118)	− 3.599*** (0.318)	− 11.606*** (1.317)
Constant	− 0.966*** (0.028)	− 0.912 (1.219)	− 0.923 (0.846)	− 13.526*** (1.287)	− 10.730*** (2.100)	− 10.840) (0.289)
Wald Chi^2			494.791***			3466.1***
Adj. R^2	0.828	0.888		0.873	0.881	
Observations	101	101	102	101	101	102

The standard errors are reported within the parentheses; ***, ** and * denote statistical significance at 1%, 5% and 10% levels, respectively

be compared to the ICT paradox scenario whereby investments for ICT development fail to generate the expected outcomes. However, the elasticity estimates also reveal that the overall impacts of enhancing ICT trade on the CO_2 emission figures are conditional on the nature of the energy resource consumed by the South Asian economies. This can be understood from the statistically significant elasticity parameters attached to the interaction terms which tend to implicate that higher openness to ICT trade is effective in reducing CO_2 emissions provided the level of RE consumption goes up as well. On the other hand, greater openness to ICT trade and higher levels of NRE consumption are found to jointly attribute to higher CO_2 emission levels. Hence, these findings implicate that it is pertinent to facilitate cross-border trade of ICT goods that can make use of RE resources which, in turn, can effectively reduce the CO_2 emissions in South Asia. Besides, it can be asserted that provision for use of RE resources within the ICT commodities can be ideal in solving the ICT paradox to an extent; thus, causing environmental betterment by mitigating the CO_2 emission levels in South Asia. These results conform to the conclusions made by Inglesi-Lotz and Dogan (2018) in the context of 10 Sub-Saharan African nations.

The other important results reported in Table 8 reveal that CO_2 emissions across the selected South Asian economies are sensitive to exogenous shocks to the real prices of crude oil in the international markets. The results indicate that a 1% rise in the real prices of crude oil reduces CO_2 emissions on average by 0.30–0.70%, *ceteris paribus*. Moreover, controlling for ICT-trade openness, RE consumption, NRE consumption and crude oil prices, the results also provide statistical support to validate the EKC hypothesis in the context of the South Asian economies. This is evident from the positive and negative signs of the estimated elasticity parameters attached to GNIPC and its squared terms, respectively. Hence, it can be said that at the initial phases of economic growth there is a trade-off between economic and environmental welfares whereby CO_2 emissions are found to rise. However, beyond a certain level of growth, the trade-off tends to be phased out to establish a complimentary association between economic and environmental development whereby the CO_2 emissions tend to decline. Since the RE resources are cleaner sources of energy, greater consumptions of renewables can be associated with lower CO_2 emissions as well. Keeping this RE consumption-CO_2 emissions nexus into consideration, it can be asserted that higher openness to trade of the RE-intensive ICT goods and services can play a crucial role in bending EKC at lower levels of per capita GNI.

Finally, the Dumitrescu–Hurlin (2012) heterogeneous panel causality analysis is conducted to unearth the possible causal association among the variables of concern. The corresponding results from the causality analysis in the context of models (1), (2) and (3) are reported in Table 9, while those in the context of models (4), (5) and (6) are reported in Table 10. It is evident from the overall estimates that unidirectional causalities stem from ICT-trade openness to RE consumption, energy-use intensity levels and ACFT for cooking purposes in the context of the selected South Asian nations. However, a feedback causal association is found between the trade of ICT goods and the shares of RE in aggregate final energy consumption figures. Hence, keeping these causal linkages into cognizance and linking them with the corresponding elasticity estimates from the regression analysis, it can be asserted that liberalization of the barriers levied on the cross-border flows of the ICT goods could be effective in boosting the consumption of RE resources and also improving the efficiency of energy consumption across South Asia. However, the policymakers have to be cautious in reducing the trade barriers levied on the ICT goods that make intensive use of the NRE resources since liberalizing these barriers could amplify the NRE consumption levels at a faster rate than the RE consumption levels. Therefore, it can be affirmed that the ultimate impacts of higher openness to ICT trade on the RET phenomena are conditional on appropriate tariff policies which should preferably facilitate the cross-border flows of the green ICT commodities in South Asia.

On the other hand, the causality estimates presented in Table 10 certify the bidirectional causal association between the trade of ICT goods and CO_2 emissions in South Asia. This finding implies that not only does cross-border flows of ICT goods affect the emissions of CO_2, the intensity of the emissions also plays a critical role in determining the movements in the ICT-trade openness indices in the South Asian economies. Thus, in line with the corresponding positive signs of the predicted elasticity parameters, it can be said that enhancing openness to ICT trade degrades the environment through greater emission of CO_2. However, it can be expected that rising volumes of CO_2 emissions could stimulate awareness building for promoting trade of the relatively greener ICT commodities. Moreover, a unidirectional causality running from RE consumption to CO_2 emissions is also witnessed which further calls for effective energy sector reforms to ensure replacement of NRE resources by the renewable alternatives in order to ultimately reduce the CO_2 emission intensities. Once again, liberalization of the barriers to trade of the green ICT goods and services can be an appropriate policy intervention keeping the sustainability of the environment into cognizance.

The results from the Granger (1969) and the Geweke (1982) causality estimates are reported in Tables 11, 12, 13 and 14 in the "Appendix". The overall results show that these techniques are inferior compared to the Dumitrescu–Hurlin (2012) causality estimation method; which can be perceived from the failure of these methods to statistically establish causal linkages between the concerned variables.

Table 9 Dumitrescu and Hurlin (2012) heterogeneous panel causality test results

Model (1)			Model (2)			Model (3)		
Dep. Var.	Indep. Var.	*Z*-bar Stat.	Dep. Var.	Indep. Var.	*Z*-bar Stat.	Dep. Var.	Indep. Var.	*Z*-bar Stat.
lnREC	lnIOPEN	5.371***	lnRES	lnIOPEN	5.471***	lnEI	lnIOPEN	3.438***
lnIOPEN	lnREC	− 0.068	lnIOPEN	lnRES	4.211***	lnIOPEN	lnEI	0.582
lnREC	lnCO2	3.323***	lnRES	lnCO2	7.626***	lnEI	lnCO2	0.189
lnCO2	lnREC	0.275	lnCO2	lnRES	1.335	lnCO2	lnEI	2.712***
lnREC	lnOIL	3.140***	lnRES	lnOIL	6.684***	lnEI	lnOIL	5.103***
lnOIL	lnREC	0.638	lnOIL	lnRES	− 1.241	lnOIL	lnEI	0.503
lnREC	lnFDI	− 0.052	lnRES	lnFDI	2.774***	lnEI	lnFDI	0.386
lnFDI	lnREC	0.869	lnFDI	lnRES	2.285**	lnFDI	lnEI	4.720***
lnREC	lnNODA	2.248**	lnRES	lnNODA	3.541***	lnEI	lnNODA	1.298
lnNODA	lnREC	4.492***	lnNODA	lnRES	6.311***	lnNODA	lnEI	7.454
lnREC	lnREMIT	6.003***	lnRES	lnREMIT	7.786***	lnEI	lnREMIT	1.97**
lnREMIT	lnREC	19.956***	lnREMIT	lnRES	1.357	lnREMIT	lnEI	22.08***
lnREC	lnGNIPC	8.268***	lnRES	lnGNIPC	2.69*	lnEI	lnGNIPC	6.567***
lnGNIPC	lnREC	1.052	lnGNIPC	lnRES	3.101***	lnGNIPC	lnEI	1.510
lnREC	lnCPI	1.501	lnRES	lnCPI	1.91*	lnEI	lnCPI	− 1.031
lnCPI	lnREC	0.311	lnCPI	lnRES	− 0.096	lnCPI	lnEI	0.617

The estimated *z*-statistics are reported; ***, ** and * denote statistical significance at 1%, 5% and 10% levels, respectively

Table 10 Dumitrescu and Hurlin (2012) heterogeneous panel causality test results

Model (4)			Models (5) and (6)		
Dep. Var.	Indep. Var.	*Z*-bar Stat.	Dep. Var.	Indep. Var.	*Z*-bar Stat.
lnACFT	lnIOPEN	5.428***	lnCO2	lnIOPEN	8.031***
lnIOPEN	lnACFT	1.150	lnIOPEN	lnCO2	2.012**
lnACFT	lnCO2	− 0.715	lnCO2	lnREC	4.275***
lnCO2	lnACFT	3.755***	lnREC	lnCO2	3.324***
lnACFT	lnOIL	− 0.401	lnCO2	lnIOPEN*lnREC	4.265***
lnOIL	lnACFT	− 0.464	lnIOPEN*lnREC	lnCO2	1.116
lnACFT	lnLIFE	− 0.001	lnCO2	lnNREC	8.191***
lnLIFE	lnACFT	271.481***	lnNREC	lnCO2	13.272***
lnACFT	lnSSE	0.001	lnCO2	lnIOPEN*lnNREC	1.278
lnSSE	lnACFT	0.129	lnIOPEN*lnNREC	lnCO2	1.980**
lnACFT	lnCPI	3.453***	lnCO2	lnOIL	2.119**
lnCPI	lnACFT	− 1.023	lnOIL	lnCO2	− 1.041
lnACFT	lnGNIPC	− 0.177	lnCO2	lnGNIPC	4.848***
lnGNIPC	lnACFT	2.595	lnGNIPC	lnCO2	3.665***

The estimated *z*-statistics are reported; ***, ** and * denote statistical significance at 1%, 5% and 10% levels, respectively

7 Conclusion

In the contemporary era, economic development is believed to be conditional on the sufficiency of energy supplies and sustainability of the environmental attributes. In this regard, undergoing RET has become a global agenda that calls for adoption of appropriate energy policy reforms that augment RE resources into the global energy-mix. However, undergoing RET is particularly difficult in the context of the developing economies. Besides, RET is also expected to improve the quality of the environment through the mitigation of greenhouse emissions, in particular. Therefore, it is pertinent to unearth the macroeconomic aggregates that are conducive to facilitating RET and ensuring environmental well-being worldwide. Against this backdrop, this paper aimed to investigate the impacts of promoting ICT trade for the South Asian economies to undergo RET and enhance environmental quality through mitigation of the CO_2 emissions. This paper evaluated these impacts in the context of Bangladesh, India, Pakistan, Sri Lanka, Nepal and Maldives between 2000 and 2016.

The statistical findings from the panel data econometric analyses, accounting for the CD issues in the data, indicated that greater cross-border flows of ICT goods enhance RE consumption levels, improve the efficiency of energy use and increase the ACFT for cooking purposes. However, greater ICT-trade openness does not amplify the shares of renewables in the aggregate final energy consumption figures of the South Asian economies of concern. These results implied that the liberalization of the relevant barriers that impede ICT trade, despite exerting positive influences on the RE consumption levels, stimulates the cross-border flows of the dirty ICT commodities that intensively consume the NRE resources; thus, the shares of renewables in the total energy consumption levels tend to decline. Hence, it is recommended that trade barriers should only be reduced in the context of the relatively greener ICT commodities that can employ the RE resources. On the other hand, the promotion of ICT trade across South Asia is found to curb the CO_2 emission levels to a large extent provided the traded ICT commodities are relatively green.

Therefore, the results, in a nutshell, call for effective policy interventions to facilitate the cross-border flows of the relatively greener ICT commodities across South Asia. Such provisions for international trade of ICT commodities would go on to foster the RET phenomena within the selected South Asian economies which, in turn, would be ideal in safeguarding the prospects of attaining environmental sustainability across this region. In this regard, the ICT goods traded by the South Asian economies are to be extended preferential treatments whereby such trade policy interventions are likely to catalyze the ICT-trade volumes to a large extent. However, monitoring the nature of the ICT goods traded is essential, particularly for elevating the shares of renewable in the aggregate energy consumption figures of the South Asian nations. Based on these findings from the empirical exercises, the South Asian economies should finance research and development projects that are aimed at promoting RE use through the application of ICT. Such investments would not only solve the ICT paradox by curbing the CO_2 emission levels but would also be critically important in elevating the overall RE shares across South Asia.

Limited availability of data was the major limitation faced in conducting this study. This, to an extent, confined the econometric exercises in the manner that not all South Asian economies could be considered in the analyses. Moreover, due to the unavailability of long data series, the country-specific investigations could not be performed as well. Thus, as part of the future scope of research, this analysis can be extended to conduct country-specific studies to identify the possible heterogeneity of the findings. Moreover, other greenhouse emissions can also be included to assess the impacts of ICT trade on South Asia's environmental sustainability from a broader perspective. Besides, the empirical exercises can also be performed by augmenting nonlinear components into the empirical models for assessing the potential threshold impacts. Furthermore, this study can be replicated incorporating the possible structural breaks in the data for a robustness check of the empirical findings. Finally, a disaggregated analysis using the consumption of different types of ICT goods can also be undertaken to assess their respective impacts on the RET phenomena and CO_2 emission responses in South Asia.

Acknowledgements The authors express their gratitude to the anonymous reviewers for their efforts in reviewing the paper and suggesting key modifications that have enhanced the quality of the article. The authors also thank the editor for his cooperation during the review process.

Funding No funding was received to conduct this research.

Compliance with ethical standards

Conflict of interest The authors report no conflict of interest of any sort.

Appendix

See Tables 11, 12, 13 and 14.

Table 11 Panel Granger (1969) causality test results

Model (1)			Model (2)			Model (3)		
Dep. Var.	Indep. Var.	Chi^2-Stat.	Dep. Var.	Indep. Var.	Chi^2-Stat.	Dep. Var.	Indep. Var.	Chi^2-Stat.
lnREC	lnIOPEN	1.993*	lnRES	lnIOPEN	0.812	lnEI	lnIOPEN	1.985
lnIOPEN	lnREC	1.239	lnIOPEN	lnRES	1.631	lnIOPEN	lnEI	4.153
lnREC	lnCO2	0.664	lnRES	lnCO2	12.855***	lnEI	lnCO2	1.954
lnCO2	lnREC	1.267	lnCO2	lnRES	1.505	lnCO2	lnEI	0.885
lnREC	lnOIL	0.427	lnRES	lnOIL	5.637*	lnEI	lnOIL	14.065***
lnOIL	lnREC	0.286	lnOIL	lnRES	1.976	lnOIL	lnEI	0.194
lnREC	lnFDI	0.086	lnRES	lnFDI	6.479**	lnEI	lnFDI	0.546
lnFDI	lnREC	11.657***	lnFDI	lnRES	9.489***	lnFDI	lnEI	12.757***
lnREC	lnNODA	1.758	lnRES	lnNODA	2.563	lnEI	lnNODA	0.802
lnNODA	lnREC	1.792	lnNODA	lnRES	6.661*	lnNODA	lnEI	1.929
lnREC	lnREMIT	1.068	lnRES	lnREMIT	6.585**	lnEI	lnREMIT	4.588*
lnREMIT	lnREC	16.449***	lnREMIT	lnRES	17.113***	lnREMIT	lnEI	3.811
lnREC	lnGNIPC	0.324	lnRES	lnGNIPC	9.750***	lnEI	lnGNIPC	2.743
lnGNIPC	lnREC	3.129***	lnGNIPC	lnRES	0.525	lnGNIPC	lnEI	5.613*
lnREC	lnCPI	6.403***	lnRES	lnCPI	10.263	lnEI	lnCPI	1.252
lnCPI	lnREC	1.049	lnCPI	lnRES	5.882*	lnCPI	lnEI	0.672

The estimated Chi^2-statistics are reported; ***, ** and* denote statistical significance at 1%, 5% and 10% levels, respectively

Table 12 Panel Granger (1969) causality test results

Model (4)			Model (5)			Model (6)		
Dep. Var.	Indep. Var.	Chi^2-Stat.	Dep. Var.	Indep. Var.	Chi^2-Stat.	Dep. Var.	Indep. Var.	Chi^2-Stat.
lnACFT	IOPEN	1.966	lnCO2	lnREC	1.675	lnCO2	lnNREC	1.232
lnIOPEN	lnACFT	2.196	lnREC	lnCO2	1.443	lnNREC	lnCO2	1.160
lnACFT	lnCO2	4.111	lnCO2	lnREC*IOPEN	1.502	lnCO2	lnNREC*IOPEN	3.134
lnCO2	lnACFT	3.110	lnREC*lnIOPEN	lnCO2	6.818**	lnNREC*IOPEN	lnCO2	1.726
lnACFT	lnOIL	7.472**	lnCO2	lnOIL	5.269*	lnCO2	lnOIL	3.402
lnOIL	lnACFT	0.219	lnOIL	lnCO2	1.036	lnOIL	lnCO2	1.255
lnACFT	lnLIFE	5.372*	lnCO2	lnGNIPC	0.914	lnCO2	lnGNIPC	0.940
lnLIFE	lnACFT	33.258***	lnGNIPC	lnCO2	5.103*	lnGNIPC	lnCO2	1.058
lnACFT	lnSSE	5.398*						
lnSSE	lnACFT	1.167						
lnACFT	lnCPI	0.541						
lnCPI	lnACFT	4.998*						
lnACFT	lnGNIPC	2.589						
lnGNIPC	lnACFT	9.307***						

The estimated Chi^2-statistics are reported; ***, ** and * denote statistical significance at 1%, 5% and 10% levels, respectively

Table 13 Geweke's (1982) Measure of Instantaneous Feedback results

Model (1)		Model (2)		Model (3)	
Null Hypothesis[a]	Chi^2-Stat.	Null Hypothesis[a]	Chi^2-Stat.	Null Hypothesis[a]	Chi^2-Stat.
lnREC and lnIOPEN	0.425	RES and IOPEN	0.946	lnEI and IOPEN	2.177
lnREC and lnCO2	1.168	RES and CO2	1.240***	lnEI and CO2	0.364
lnREC and lnOIL	0.306	RES and lnOIL	0.025	lnEI and lnOIL	16.125***
lnREC and lnFDI	0.312	RES and lnFDI	7.714***	lnEI and lnFDI	0.002
lnREC and lnREMIT	0.266	RES and lnREMIT	0.015	lnEI and lnREMIT	0.815
lnREC and lnNODA	0.130	RES and lnNODA	2.564*	lnEI and lnNODA	0.953
lnREC and lnGNIPC	3.531*	RES and lnGNIPC	0.176	lnEI and lnGNIPC	2.013
lnREC and lnCPI	0.004	RES and CPI	1.134	lnEI and CPI	4.132

[a]Null Hypothesis of the presence of instantaneous feedback; ***, ** and * denote statistical significance at 1%, 5% and 10% levels, respectively

Table 14 Geweke's (1982) Measure of Instantaneous Feedback results

Model (4)		Model (5)		Model (6)	
Null Hypothesis[a]	Chi^2-Stat.	Null Hypothesis[a]	Chi^2-Stat.	Null Hypothesis[a]	Chi^2-Stat.
lnACFT and lnIOPEN	0.944	lnCO2 and lnREC	2.037	lnCO2 and lnNREC	3.670*
lnACFT and lnCO2	0.002	lnCO2 and lnREC*lnIOPEN	0.409	lnCO2 and lnNREC*lnIOPEN	0.629
lnACFT and lnOIL	1.834	lnCO2 and lnOIL	5.166**	lnCO2 and lnOIL	6.751*
lnACFT and lnLIFE	6.835***	lnCO2 and lnGNIPC	5.273**	lnCO2 and lnGNIPC	3.210*
lnACFT and lnSSE	1.440				
lnACFT and lnGNIPC	0.188				
lnACFT and lnCPI	1.433				

[a]Null Hypothesis of the presence of instantaneous feedback; ***, ** and * denote statistical significance at 1%, 5% and 10% levels, respectively

References

Abid MR, Lghoul R, Benhaddou D (2017) ICT for renewable energy integration into smart buildings: IoT and big data approach. In: 2017 IEEE AFRICON. IEEE, pp 856–861

Acharya V, Hegde VV, Anjan K, Kumar M (2017). IoT (Internet of Things) based efficiency monitoring system for bio-gas plants. In: 2017 2nd international conference on computational systems and information technology for sustainable solution (CSITSS). IEEE, pp 1–5

Agrawala S, Raksakulthai V, van Aalst M, Larsen P, Smith J, Reynolds J (2003) Development and climate change in Nepal: Focus on water resources and hydropower. Oecd, Paris, pp 14–28

Ahmed F, Naeem M, Iqbal M (2017) ICT and renewable energy: a way forward to the next generation telecom base stations. Telecommun Syst 64(1):43–56

Alam MM, Murad MW (2020) The impacts of economic growth, trade openness and technological progress on renewable energy use in organization for economic co-operation and development countries. Renew Energy 145:382–390

Alstone P, Gershenson D, Kammen DM (2015) Decentralized energy systems for clean electricity access. Nat Clim Change 5(4):305–314

Amri F (2019) Renewable and non-renewable energy and trade into developed and developing countries. Qual Quant 53(1):377–387

Amri F, Zaied YB, Lahouel BB (2019) ICT, total factor productivity, and carbon dioxide emissions in Tunisia. Technol Forecast Soc Chang 146:212–217

Andreopoulou Z (2012) Green Informatics: ICT for green and Sustainability. Agrárinformatika J Agric Inf 3(2):1–8

Arnone D, Bertoncini M, Rossi A, D'Errico F, García-Santiago C, Moneta D, D'Orinzi C (2013) An ICT-based energy management system to integrate renewable energy and storage for grid balancing. In: Proceedings of the fourth international conference on future energy systems. ACM, pp 259–260

Asif M, Muneer T (2007) Energy supply, its demand and security issues for developed and emerging economies. Renew Sustain Energy Rev 11(7):1388–1413

Bai J, Kao C, Ng S (2009) Panel cointegration with global stochastic trends. J Econom 149(1):82–99

Bastida L, Cohen JJ, Kollmann A, Moya A, Reichl J (2019) Exploring the role of ICT on household behavioral energy efficiency to mitigate global warming. Renew Sustain Energy Rev 103:455–462

Baurzhan S, Jenkins GP (2016) Off-grid solar PV: is it an affordable or appropriate solution for rural electrification in Sub-Saharan African countries? Renew Sustain Energy Rev 60:1405–1418

Bhattacharyya SC, Palit D (2016) Mini-grid based off-grid electrification to enhance electricity access in developing countries: what policies may be required? Energy Policy 94:166–178

Boden TA, Marland G, Andres RJ (2009) Global, regional, and national fossil-fuel CO_2 emissions. Carbon Dioxide Information

Analysis Center, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, Tenn., USA
Bourhnane S, Abid MR, Lghoul R, Zine-Dine K, Elkamoun N, Bakhouya M, Benhaddou D (2019). Real-time control of smart grids using NI CompactRIO. In: 2019 international conference on wireless technologies, embedded and intelligent systems (WITS). IEEE, pp 1–6
Breitung J (2000) The local power of some unit root tests for panel data. In: Baltagi BH (ed) Advances in econometrics, volume 15: nonstationary panels, panel cointegration, and dynamic panels. JAI Press, Amsterdam, pp 161–178
Breusch TS, Pagan AR (1980) The Lagrange multiplier test and its applications to model specification in econometrics. Rev Econ Stud 47(1):239–253
Chapman D, Tyrrell T, Mount T (1972) Electricity demand growth and the energy crisis. Science 178(4062):703–708
Chavan S, Chavan M (2020) Recent trends in ICT-enabled renewable energy systems. In: Information and communication technology for sustainable development. Springer, Singapore, pp 327–332
Cole MA (2004) Trade, the pollution haven hypothesis and the environmental Kuznets curve: examining the linkages. Ecol Econ 48(1):71–81
Despins C, Labeau F, Le Ngoc T, Labelle R, Cheriet M, Thibeault C, Mcneill J (2011) Leveraging green communications for carbon emission reductions: techniques, testbeds, and emerging carbon footprint standards. IEEE Commun Mag 49(8):101–109
Dong K, Dong X, Jiang Q (2020) How renewable energy consumption lower global CO_2 emissions? Evidence from countries with different income levels. World Econ 43(6):1665–1698
Doukas H, Marinakis V, Tsapelas J, Sgouridis S (2019) Intelligent energy management within the smart cities: an EU-GCC cooperation opportunity. In: Smart cities in the Gulf. Palgrave Macmillan, Singapore, pp 123–147
Droege P (2011) Urban energy transition: from fossil fuels to renewable power. Elsevier, Amsterdam
Dumitrescu EI, Hurlin C (2012) Testing for Granger non-causality in heterogeneous panels. Econ Model 29(4):1450–1460
El-Baz W, Tzscheutschler P, Wagner U (2019) Integration of energy markets in microgrids: a double-sided auction with device-oriented bidding strategies. Appl Energy 241:625–639
Erlinghagen S, Markard J (2012) Smart grids and the transformation of the electricity sector: ICT firms as potential catalysts for sectoral change. Energy Policy 51:895–906
Espe E, Potdar V, Chang E (2018) Prosumer communities and relationships in smart grids: a literature review, evolution and future directions. Energies 11(10):2528
Evans W, Johnson M, Jagoe K, Charron D, Young B, Rahman ASMM, Ipe J (2017) Evaluation of behavior change communication campaigns to promote modern cookstove purchase and use in lower-middle-income countries. Int J Environ Res Public Health 15(1):11
Ferdaus J, Appiah BK, Majumder SC, Martial AAA (2020) A panel dynamic analysis on energy consumption, energy prices and economic growth in Next-11 countries. Int J Energy Econ Policy. https://doi.org/10.32479/ijeep.9880
Field CB (ed) (2014) Climate change 2014–impacts, adaptation and vulnerability: regional aspects. Cambridge University Press, Cambridge
Frees EW (1995) Assessing cross-sectional correlation in panel data. J Econom 69:393–414
Friedman M (1937) The use of ranks to avoid the assumption of normality implicit in the analysis of variance. J Am Stat Assoc 32:675–701
Fung CC, Tang SC, Wong KP (2010). A proposed study on the use of ICT and smart meters to influence consumers' behavior and attitude towards Renewable Energy. In: IEEE PES general meeting. IEEE, pp 1–5
Gautier A, Jacqmin J, Poudou JC (2018) The prosumers and the grid. J Regul Econ 53(1):100–126
Geweke J (1982) Measurement of linear dependence and feedback between multiple time series. J Am Stat Assoc 77:304–313
Goebel C, Callaway DS (2012) Using ICT-controlled plug-in electric vehicles to supply grid regulation in California at different renewable integration levels. IEEE Trans Smart Grid 4(2):729–740
Granger CWJ (1969) Investigating causal relations by econometric models and cross-spectral methods. Econometrica 37:424–438
Harris RD, Tzavalis E (1999) Inference for unit roots in dynamic panels where the time dimension is fixed. J Econom 91(2):201–226
Haseeb A, Xia E, Saud S, Ahmad A, Khurshid H (2019) Does information and communication technologies improve environmental quality in the era of globalization? An empirical analysis. Environ Sci Pollut Res 26(9):8594–8608
He J, Wang Y, Chen W (2020) Energy transition driven by the energy internet. In: Annual report on China's response to climate change (2017). Springer, Singapore, pp 77–89
Higón DA, Gholami R, Shirazi F (2017) ICT and environmental sustainability: a global perspective. Telemat Inform 34(4):85–95
Hoel M, Kverndokk S (1996) Depletion of fossil fuels and the impacts of global warming. Resour Energy Econ 18(2):115–136
Inglesi-Lotz R, Dogan E (2018) The role of renewable versus non-renewable energy to the level of CO_2 emissions a panel analysis of sub-Saharan Africa's Big 10 electricity generators. Renew Energy 123:36–43
IPCC (2014) Climate change 2014: synthesis report. In: Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change. IPCC, Geneva, Switzerland. https://www.ipcc.ch/site/assets/uploads/2018/02/SYR_AR5_FINAL_full.pdf
Jindal A, Schaeffer-Filho A, Marnerides AK, Smith P, Mauthe A, Granville L (2020). Tackling energy theft in smart grids through data-driven analysis. In: 2020 international conference on computing, networking and communications (ICNC). IEEE, pp 410–414
Kao C (1999) Spurious regression and residual-based tests for cointegration in panel data. J Econ 90:1–44
Kasayanond A, Umam R, Jermsittiparsert K (2019) Environmental sustainability and its growth in Malaysia by elaborating the green economy and environmental efficiency. Int J Energy Econ Policy 9(5):465
Khan N, Baloch MA, Saud S, Fatima T (2018) The effect of ICT on CO 2 emissions in emerging economies: does the level of income matters? Environ Sci Pollut Res 25(23):22850–22860
Kramers A, Höjer M, Lövehagen N, Wangel J (2014) Smart sustainable cities–Exploring ICT solutions for reduced energy use in cities. Environ Model Softw 56:52–62
Lee JW, Brahmasrene T (2014) ICT, CO_2 emissions and economic growth: evidence from a panel of ASEAN. Glob Econ Rev 43(2):93–109
Lin B, Omoju OE, Okonkwo JU (2016) Factors influencing renewable electricity consumption in China. Renew Sustain Energy Rev 55:687–696
Long X, Naminse EY, Du J, Zhuang J (2015a) Nonrenewable energy, renewable energy, carbon dioxide emissions and economic growth in China from 1952 to 2012. Renew Sustain Energy Rev 52:680–688
Long X, Zhao X, Cheng F (2015b) The comparison analysis of total factor productivity and eco-efficiency in China's cement manufactures. Energy Policy 81:61–66

Luderer G, Bosetti V, Jakob M, Leimbach M, Steckel JC, Waisman H, Edenhofer O (2012) The economics of decarbonizing the energy system—results and insights from the RECIPE model intercomparison. Clim Change 114(1):9–37

Mekonnen Y, Sarwat AI (2017) Renewable energy supported microgrid in rural electrification of Sub-Saharan Africa. In: 2017 IEEE PES power Africa. IEEE, pp 595–599

Mensah CN, Long X, Dauda L, Boamah KB, Salman M, Appiah-Twum F, Tachie AK (2019) Technological innovation and green growth in the Organization for Economic Cooperation and Development economies. J Clean Prod 240:118204

Mirza UK, Ahmad N, Harijan K, Majeed T (2009) Identifying and addressing barriers to renewable energy development in Pakistan. Renew Sustain Energy Rev 13(4):927–931

Molla T, Khan B, Moges B, Alhelou HH, Zamani R, Siano P (2019) Integrated optimization of smart home appliances with cost-effective energy management system. CSEE J Power Energy Syst 5(2):249–258

Muhammad S, Long X, Salman M, Dauda L (2020) Effect of urbanization and international trade on CO_2 emissions across 65 belt and road initiative countries. Energy 196:117102

Murshed M (2018) Does improvement in trade openness facilitate renewable energy transition? Evidence from selected South Asian economies. South Asia Econ J 19(2):151–170

Murshed M (2019a) A review of the prospects and benefits of smart gridding technology adoption in Bangladesh's power sector. Nat Gas Electr 36(3):19–28

Murshed M (2019b) An empirical investigation of foreign financial assistance inflows and its fungibility analyses: evidence from Bangladesh. Economies 7(3):95

Murshed M (2020a) Electricity conservation opportunities within private university campuses in Bangladesh. Energy Environ 31(2):256–274. https://doi.org/10.1177/0958305X19857209

Murshed M (2020b) Are trade liberalization policies aligned with renewable energy transition in low and middle income countries? An instrumental variable approach. Renew Energy 151:1110–1123. https://doi.org/10.1016/j.renene.2019.11.106

Murshed M (2020c) Revisiting the deforestation-induced EKC hypothesis: the role of Democracy in Bangladesh. GeoJournal. https://doi.org/10.1007/s10708-020-10234-z

Murshed M (2020d) An empirical analysis of the non-linear impacts of ICT-trade openness on renewable energy transition, energy efficiency, clean cooking fuel access and environmental sustainability in South Asia. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-020-09497-3

Murshed M (2020e) LPG consumption and environmental Kuznets Curve hypothesis in South Asia: a time-series ARDL analysis with multiple structural breaks. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-020-10701-7

Murshed M, Dao NTT (2020) Revisiting the CO_2 emission-induced EKC hypothesis in South Asia: the role of export quality improvement. GeoJournal. https://doi.org/10.1007/s10708-020-10234-z

Murshed M, Tanha MM (2020) Oil price shocks and renewable energy transition: Empirical evidence from net oil-importing South Asian economies. Energy Ecol Environ. https://doi.org/10.1007/s40974-020-00168-0

Murshed M, Abbass K, Rashid S (2020a) Modeling renewable energy adoption across south Asian economies: empirical evidence from Bangladesh, India, Pakistan and Sri Lanka. Int J Finance Econ. https://doi.org/10.1002/ijfe.2073

Murshed M, Ali SR, Banerjee S (2020b) Consumption of liquefied petroleum gas and the EKC hypothesis in South Asia: evidence from cross-sectionally dependent heterogeneous panel data with structural breaks. Energy Ecol Environ. https://doi.org/10.1007/s40974-020-00185-z

Murshed M, Nurmakhanova M, Elheddad M, Ahmed R (2020c) Value addition in the services sector and its heterogeneous impacts on CO 2 emissions: revisiting the EKC hypothesis for the OPEC using panel spatial estimation techniques. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-020-09593-4

Murshed M, Ferdaus J, Rashid S, Tanha MM, Islam J (2020d) The environmental Kuznets Curve hypothesis for deforestation in Bangladesh: an ARDL analysis with multiple structural breaks. Energy Ecol Environ. https://doi.org/10.1007/s40974-020-00188-w

Nurulin YR, Skvortsova IV, Kalchenko OA (2019) Energy planning and energy efficiency in smart city areas. In: SHS web of conferences, vol 61. EDP Sciences, p 01017

Omer AM (2008) Energy, environment and sustainable development. Renew Sustain Energy Rev 12(9):2265–2300

Ożadowicz A (2017) A new concept of active demand side management for energy efficient prosumer microgrids with smart building technologies. Energies 10(11):1771

Palit D, Bandyopadhyay KR (2016) Rural electricity access in South Asia: is grid extension the remedy? A critical review. Renew Sustain Energy Rev 60:1505–1515

Panajotovic B, Jankovic M, Odadzic B (2011) ICT and smart grid. In: Proceedings for the 10th international conference on telecommunication in modern satellite cable and broadcasting services, pp 118–121

Park Y, Meng F, Baloch MA (2018) The effect of ICT, financial development, growth, and trade openness on CO_2 emissions: an empirical analysis. Environ Sci Pollut Res 25(30):30708–30719

Pata UK (2018) Renewable energy consumption, urbanization, financial development, income and CO_2 emissions in Turkey: testing EKC hypothesis with structural breaks. J Clean Prod 187:770–779

Pesaran MH (2004) General diagnostic tests for cross section dependence in panels. Cambridge working paper in economics no. 0435

Pesaran MH (2007) A simple panel unit root test in the presence of cross-section dependence. J Appl Econom 22(2):265–312

Petroleum British (2018) Statistical review of world energy. British Petroleum, London

Rajbongshi R, Borgohain D, Mahapatra S (2017) Optimization of PV-biomass-diesel and grid base hybrid energy systems for rural electrification by using HOMER. Energy 126:461–474

Roche OM, Blanchard RE (2018) Design of a solar energy centre for providing lighting and income-generating activities for off-grid rural communities in Kenya. Renew Energy 118:685–694

Rockström J, Gaffney O, Rogelj J, Meinshausen M, Nakicenovic N, Schellnhuber HJ (2017) A roadmap for rapid decarbonization. Science 355(6331):1269–1271

Rodríguez Casal C, Van Wunnik C, Delgado Sancho L, Claude Burgelman J, Desruelle P (2005) How will ICTs affect our environment in 2020? Foresight 7(1):77–87. https://doi.org/10.1108/14636680510581330

Saboori B, Sulaiman J (2013) Environmental degradation, economic growth and energy consumption: evidence of the environmental Kuznets curve in Malaysia. Energy Policy 60:892–905

Salman M, Long X, Dauda L, Mensah CN (2019) The impact of institutional quality on economic growth and carbon emissions: evidence from Indonesia, South Korea and Thailand. J Clean Prod 241:118331

Sharif A, Raza SA, Ozturk I, Afshan S (2019) The dynamic relationship of renewable and nonrenewable energy consumption with carbon emission: a global study with the application of heterogeneous panel estimations. Renewable Energy 133:685–691

Shawon MH, Muyeen SM, Ghosh A, Islam SM, Baptista MS (2019) Multi-agent systems in ICT enabled smart grid: a status update

on technology framework and applications. IEEE Access 7:97959–97973
Skea J, Van Diemen R, Hannon M, Gazis E, Rhodes A (2019) Energy innovation for the twenty-first century. Edward Elgar Publishing, Cheltenham
Smil V, Knowland WE (1980) Energy in the developing world: the real energy crisis
Smith LV, Leybourne S, Kim T-H, Newbold P (2004) More powerful panel data unit root tests with an application to mean reversion in real exchange rates. J Appl Econ 19:147–170
Sousa T, Soares T, Pinson P, Moret F, Baroche T, Sorin E (2019) Peer-to-peer and community-based markets: a comprehensive review. Renew Sustain Energy Rev 104:367–378
Stallo C, De Sanctis M, Ruggieri M, Bisio I, Marchese M (2010) ICT applications in green and renewable energy sector. In: 2010 19th IEEE international workshops on enabling technologies: infrastructures for collaborative enterprises. IEEE, pp 175–179
Urmee T, Harries D, Schlapfer A (2009) Issues related to rural electrification using renewable energy in developing countries of Asia and Pacific. Renew Energy 34(2):354–357
Valentine SV (2011) Emerging symbiosis: renewable energy and energy security. Renew Sustain Energy Rev 15(9):4572–4578
van Alphen K, van Sark WG, Hekkert MP (2007) Renewable energy technologies in the Maldives—determining the potential. Renew Sustain Energy Rev 11(8):1650–1674
Vanek J (1968) The factor proportions theory: the n-factor case. Kyklos 21(4):749–756
Vivoda V (2010) Evaluating energy security in the Asia-Pacific region: a novel methodological approach. Energy Policy 38(9):5258–5263
Wang Y, Sanchez Rodrigues V, Evans L (2015) The use of ICT in road freight transport for CO_2 reduction–an exploratory study of UK's grocery retail industry. Int J Logist Manag 26(1):2–29
Weiller C, Neely A (2014) Using electric vehicles for energy services: industry perspectives. Energy 77:194–200
Westerlund J (2007) Testing for error correction in panel data. Oxford Bull Econ Stat 69(6):709–748
Westerlund J (2008) Panel cointegration tests of the fisher effects. J Appl Econ 23:193–233
Worighi I, Maach A, Hafid A, Hegazy O, Van Mierlo J (2019) Integrating renewable energy in smart grid system: architecture, virtualization and analysis. Sustain Energy Grids Netw 18:100226
World Bank (2020) World development indicators database. The World Bank
World Energy Council (2018) The role of ICT in energy efficiency management: household sector. https://www.worldenergy.org/wp-content/uploads/2018/06/20180420_TF_paper_final.pdf
Xue Y, Cai B, James G, Dong Z, Wen F, Xue F (2014) Primary energy congestion of power systems. J Modern Power Syst Clean Energy 2(1):39–49
Yang M, Yu X (2015) Energy efficiency: benefits for environment and society. Springer, Berlin
Yasmin N, Grundmann P (2019) Adoption and diffusion of renewable energy—the case of biogas as alternative fuel for cooking in Pakistan. Renew Sustain Energy Rev 101:255–264
Zafar R, Mahmood A, Razzaq S, Ali W, Naeem U, Shehzad K (2018) Prosumer based energy management and sharing in smart grid. Renew Sustain Energy Rev 82:1675–1684
Zafar MW, Shahbaz M, Hou F, Sinha A (2019) From nonrenewable to renewable energy and its impact on economic growth: the role of research & development expenditures in Asia-Pacific Economic Cooperation countries. J Clean Prod 212:1166–1178
Zhang C, Wu J, Zhou Y, Cheng M, Long C (2018) Peer-to-Peer energy trading in a Microgrid. Appl Energy 220:1–12
Zhang J, Wang B, Latif Z (2019) Towards cross-regional sustainable development: the nexus between information and communication technology, energy consumption, and CO_2 emissions. Sustain Dev 27(5):990–1000