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Coal efficiency, carbon reduction, and future policy perspective in Pakistan's economic growth: a decomposition and decoupling approach

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Pakistan is moving toward the large-scale use of coal. Coal plays a dominant role in Pakistan's energy mix and is estimated to reach 30% by 2030. The purpose of this study is to analyze coal imports and indigenous reserves in relation to CO_2 emissions. In particular, this study constructs the logarithmic mean Divisia index (LMDI) method to see the impact of the factors, decoupling index for the economic relationship, and pollution from coal-fired power plants from 1986 to 2019. The empirical results show that 1) coal consumption and imports are interrelated, while coal production has had the lowest production level since 1986; 2) the energy intensity impact plays a medium role in decreasing coal utilization, followed by the coal share effect; however, the aggregated impact accounts for 0.023% of the total coal use; 3) the economic and population activity effects progressively increase with coal consumption by 0.25% and 0.35%, respectively, with the annual average growth; 4) only "three" decoupling states were observed: expansive coupling, expansive negative decoupling, and weak decoupling. Expansive negative decoupling occurred due to high energy share and energy intensity. Expansive coupling occurred only in 2001 due to rapid growth in coal proportion and a sluggish decrease in energy intensity, and weak decoupling showed a decoupling association between economic growth and coal utilization; and 5) the various coal compositions, such as moisture, volatile matter, fixed carbon, ash, and sulfur, can be evaded by 1.82, 4.83, 5.16, 1.43, and 0.39 Mt currently. Finally, environmental analysis recognized that implementing clean coal technologies significantly saves fuel and, consequently, reduces emissions. This study also discusses further policies.

KEYWORDS

coal consumption, LMDI, decoupling index, fuel efficiency, CO_2 emission, Pakistan

1 Introduction

Energy consumption has become one of the important influences on an individual country's economic development, environment, climate change, food security, health, employment, and social factors (Zheng and Walsh, 2019). For huge production, the world protected and applied multiple huge fuels, particularly for emerging nations,

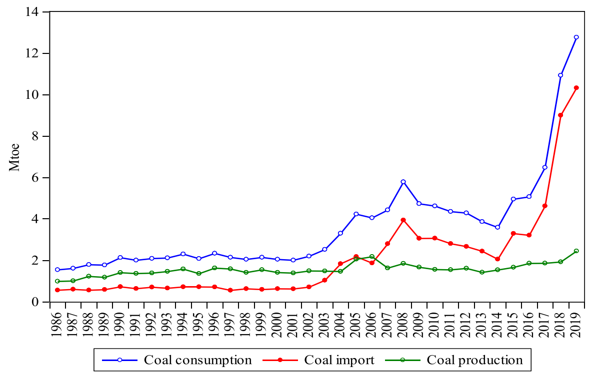

FIGURE 1
Pakistan's coal consumption, production, and import from 1986 to 2019.

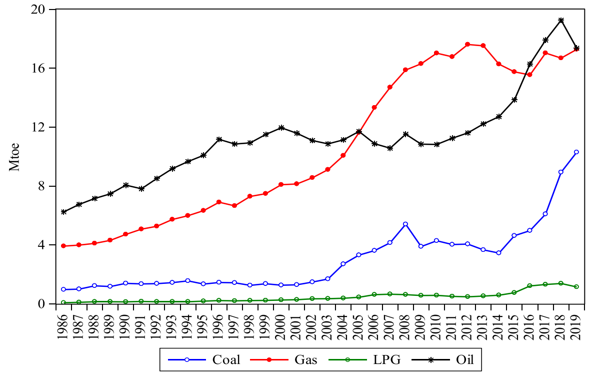

FIGURE 2
Pakistan's energy mix from 1986 to 2019.

which will influence localities, people, living standards, and natural resources (Lin and Raza, 2019). Being the second largest populated nation in South Asia, Pakistan has stayed on the rising focused agenda, lined with vast investments from established countries such as the United States (US), China, and Russia.

Pakistan has the world's seventh largest coal reserves, with a heating value of approximately 9,000 British thermal units (Btu/lb) and reserves of 185.175 billion tons (Pakistan Energy Vision, 2016; Vision, 2035, 2014). This was discovered in 1991 by Pakistan's Geological Survey and the US agency for international development. This will maximize coal consumption (CC) in the energy sector before 2025 in terms of coal efficiency, electricity supply, electricity demand, and energy production. Currently, coal fulfills the commercial energy needs of Pakistan by 15.4%. The domestic production of coal was 5.46 million tons of oil equivalents (Mtoe) in 2019, which showed an increase of 34.3% over the previous year, while coal production started flowing from the Thar coal field (HDIP, 2019), in which coal imports increased by 14.6% during 2019. As shown in Figure 1, the overall coal consumption increased significantly by 19.7% compared to the previous year.

Regarding the energy mix, Pakistan is attempting to encourage coal consumption and increase its share in the energy mix because of energy security. The energy mix of oil, coal, gas, and LPG was counted at 31.58%, 18.72%, 31.4%, and 2.1% in 2019, respectively (HDIP, 2019), as shown in Figure 2. It is obvious that coal consumption is the third highest fuel in the energy mix and shows a positive trend over the period. Coal is the main energy source in Pakistan and plays a strategic role in the country's economic development. Due to its abundance in proven reserves and its constancy in supply, coal will continue to be an imperative component of the primary energy mix in the country, at least over the next few decades. Although it adds to a large share of greenhouse gas (GHG) emissions, reducing this carbon-constrained worldwide environment is unavoidable, and the Pakistan coal industry might be significantly influenced by GHG emission reduction policies. As a developing country in Asia, Pakistan's growing population and industrialization influenced huge energy utilization in various sectors, which rely heavily on fossil fuels (i.e., oil, coal, and gas) (Lin, B., & Raza, 2020a). Currently, domestic energy resources cannot meet the increasing energy demand; thus, the government should utilize clean technologies to reduce the pollution and energy crisis in the country. This study, therefore, measures the population,

TABLE 1 Evaluation criteria of the decoupling indicator.

	$\sum(\Delta CC_{ES}^t, \Delta CC_{EI}^t)$	$\sum(\Delta CC_{PG}^t, \Delta CC_{P}^t)$	D^t	Decoupling state
1	>0	>0	$D^t \geq 0$	END
2	<0	>0	$0 > D^t \geq -0.4$	EC
3	<0	>0	$-0.4 > D^t \geq -1$	WD
4	>0	>0	$-1 > D^t$	SD
5	>0	<0	$D^t \leq 0$	SND
6	<0	<0	$0.4 \geq D^t > -1$	WND
7	<0	<0	$1 \geq D^t > 0.4$	RC
8	<0	<0	$D^t > 1$	RD

Note: END, expansive negative decoupling; EC, expansive coupling; WD, weak decoupling; SD, strong decoupling; SND, strong negative decoupling; WND, weak negative decoupling; RC, recessive coupling; RD, recessive decoupling.

TABLE 2 Allocation of the efficiency range set for individual estimated technology[a].

Technology	Coal-fired power plant efficiency (η)
Subcritical	39%
Supercritical	41%–43%
Ultra-supercritical	44%

[a]The allocation of the efficiency range for individual coal-fired power plants has been analyzed based on the plant information. We could not estimate the individual sector's allocated efficiency because of the unavailability of accurate information in the energy statistics of Pakistan. This is also our limitation.

economic activities, energy intensity, and coal share for 34 years, which are the key factors in increasing the economy. Given the availability of current information about coal emissions in 2019, we estimated plant efficiency.

Pakistan is still in the initial development phase compared to advanced and developing countries. It is unavoidable that Pakistan needs additional energy to fulfill its domestic demands. However, the coal-related energy framework has led to grave ecological pollution. Confronted with the huge pressure of national environmental safety and worldwide climate variation, regulating fast-growing coal consumption has become a key concern for the government of Pakistan. Thus, investigating the decoupling association between coal utilization and economic growth (EG) may benefit from distinguishing energy policy and energy security strategy.

As per Kraft and Kraft (1978), many researchers have broadly reviewed the association between EG and energy consumption (EC). However, such research did not reach a definite decision regarding the causative direction between EG and EC. Few studies found directional causalities using extended datasets. For example, Abosedra and Baghestani (1989) for the US from 1947 to 1987; Narayan and Smyth (2005) for Australia; Ho and Siu (2007) for Hong Kong; Hu and Lin (2008) for Taiwan; Zhang and Cheng (2009) for China; Acaravci (2010) for Turkey; and Payne and Taylor (2010) found unidirectional causality. Several studies also investigated the bidirectional causality between EC and EG; for example, by investigating facts for G-7 and G-10 developing countries besides Pakistan, Soytas and Sari (2003) found bidirectional causality between energy use and economy in Argentina from 1950 to 1990.

Moreover, research on the existing topic has concentrated on emerging nations; for example, Yuan et al. (2007) for China using the cointegration method between electricity and EG; Chiou-Wei et al. (2008) for the US and Asian emerging countries using linear and nonlinear Granger causality tests; Ruhul et al. (2008) for six non-Organization of Economic and Cooperation Development (OECD) Asian emerging nations using Granger causality; Bowden and Payne (2009) for the US using Granger causality; Yoo and Ku (2009) for 20 European and Asian countries using cointegration; and Ozcan and Ari (2015) for 15 OECD countries using bootstrap causality tests. However, they found unidirectional and bidirectional causalities among the variables.

In various countries, numerous researchers have investigated coal ingestion and its significance for EG using new and longer time-series statistics. Jinke et al. (2008) reviewed the causative association between coal utilization and EG in the main OECD and non-OECD countries. Yang et al. (2020) analyzed the structural path for China's coal consumption using input–output methods and found that investment, exports, and households are the main factors in coal consumption. Asghar (2008), for five South Asian countries using causality analysis from 1971 to 2003, found that there is a unidirectional causality running from coal to economic growth in Sri Lanka, Bangladesh, and Pakistan. Wolde-Rufael (2010) used the causality analysis between coal consumption and EG for "six" key coal-consuming nations, covering the period of 1965–2005, and found that there is a unidirectional causality running from coal to economic development in India and Japan; however, an opposite causality was estimated in China and Korea. Li and Leung (2012) investigated the association between China's coal consumption and real GDP using panel data and revealed that there is a bidirectional causality in the coastal and central regions and a unidirectional causality in the Western region. Bloch et al. (2012) analyzed a similar factor's association in China. Bildirici and Bakirtas (2014) analyzed

TABLE 3 Present Thar coal reserves on 30 June 2019 (million tons).

Block or field	Area (sq. km)	Drill holes	Measured reserves	Indicated reserves	Inferred reserves	Hypothetical resources	Total
Sinhar Vikian-Varvia	122	41	620	1,918	1,028	0	3,566
Singharo Bhitro	55	43	640	944	0	0	1,584
Saleh Jo Tar	99.5	41	411	1,337	258	0	2,006
Sonal Ba	80	42	637	1,640	282	0	2,559
Total field	365.5	167	2,308	5,839	1,568	0	9,715
The rest of Thar coal field	8,643.5	335	4,717	11,291	37,082	112,700	165,790
Total Thar coal field	9,000	502	7,025	17,130	38,650	112,700	175,505

Note: Mineral assets: 60% of measured reserves.

Measured reserves: including the maximum degree of geological assurance. Coal lies in a radius of 0.4 km (km) from the point of the coal dimension.

Indicated reserves: containing a moderate degree of geological assurance in which coal comes up with a radius of 0.4–1.2 km from the estimation point.

Inferred measurement: Taking a small degree of geological assurance, coal exists in a radius of 1.2–4.8 km estimation point.

Hypothetical resources: unexplored coal reserves, usually the addition of inferred assets in which coal comes in 4.8 km from the point of coal estimation.

Source: HDIP [6].

TABLE 4 Decomposition analysis with various factor variations from 1986 to 2019 (unit: %).

Period	ΔCC^t_{EG}	ΔCC^t_{EI}	ΔCC^t_{PG}	ΔCC^t_{P}	ΔCC^t_{total}
1986–87	−1.073224	−0.034274	1.037771	1.069726	100.000
1987–88	0.623484	0.002823	0.215584	0.158108	100.000
1988–89	2.046021	0.201660	−0.465678	−0.782003	100.000
1989–90	0.485267	0.254150	0.084022	0.176561	100.000
1990–91	1.766090	1.283902	−0.859757	−1.190235	100.000
1991–92	−5.353675	−1.201365	4.717148	2.837892	100.000
1992–93	−0.470328	1.129870	−0.196779	0.537238	100.000
1993–94	0.421543	0.123436	0.112811	0.342210	100.000
1994–95	1.247671	0.073812	−0.135830	−0.185653	100.000
1995–96	−0.181283	0.557831	0.248635	0.374816	100.000
1996–97	−0.933010	2.790062	1.580228	−2.437280	100.000
1997–98	1.234672	−0.040221	0.025440	−0.219892	100.000
1998–99	0.595104	−0.044958	0.103750	0.346104	100.000
1999–2000	1.615058	−0.074620	−0.197483	−0.342955	100.000
2000–01	1.047363	−1.490704	0.401347	1.041995	100.000
2001–02	0.901293	−0.079718	0.004349	0.174076	100.000
2002–03	0.790018	−0.221806	0.251739	0.180049	100.000
2003–04	0.793907	0.051033	0.105914	0.049145	100.000
2004–05	0.494040	0.193957	0.198546	0.113457	100.000
2005–06	0.358944	−0.017609	0.395128	0.263536	100.000
2006–07	0.575494	0.084366	0.175703	0.164437	100.000
2007–08	0.657964	0.278226	−0.021784	0.085594	100.000
2008–09	0.835684	0.249424	−0.017037	−0.068070	100.000
2009–10	24.782531	−23.949864	−0.063317	0.230650	100.000
2010–11	38.283639	−36.845022	−0.089345	−0.349272	100.000
2011–12	284.634569	−287.947785	1.652023	2.661193	100.000
2012–13	23.375398	−21.956950	−0.213858	−0.204590	100.000
2013–14	0.849139	0.905563	−0.409082	−0.345620	100.000
2014–15	0.820959	0.022689	0.085742	0.070610	100.000
2015–16	−0.087673	0.336484	0.460131	0.291057	100.000
2016–17	0.511904	0.222352	0.163734	0.102010	100.000
2017–18	0.757649	0.094113	0.094512	0.053726	100.000
2018–19	0.999613	−0.069473	−0.074210	0.144069	100.000
1986–2019	0.382253	0.023054	0.246233	0.348459	100.000

the causality for six Asian and European countries from 1980 to 2011 using long-run causality analysis found between coal and economic growth with a bidirectional causality for India and China, and Lei et al. (2014) used the causality investigation between coal utilization and economic development for the US, and European and Asian countries over 2000–2010. They estimated a bidirectional causality association between coal use and economic development in Russia, Japan, and Germany; however, a unidirectional causality exists only in China. Govindaraju and Tang (2013) used the robust technique of cointegration to obtain conclusive outcomes between EG and coal consumption in China and India. They revealed that there is a bidirectional causal relationship between coal and economic growth, both in the short and long-run periods. Raza and Shah (2019) used causality analysis among domestic factors in Pakistan from 1981 to 2017 and found that there is bidirectional causality between coal consumption and economic growth both in the long and short run. Lin and Raza (2020b) employed input–output analysis for coal consumption of various sectors in Pakistan from 1999 to 2018. They estimated that the economic scale is the factor that drives the growing coal use in Pakistan. Khan et al. (2020) investigated the overall energy and carbon emissions of various sectors using the quantile regression method but could not differentiate which fuel is more efficient in a rising economy. With the positive results of past studies, the coal and

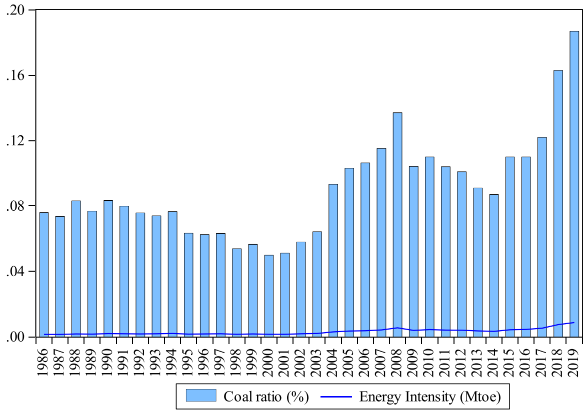

FIGURE 3
Trend in Pakistan's energy intensity and coal ratio from 1986 to 2019. Source: author's calculation.

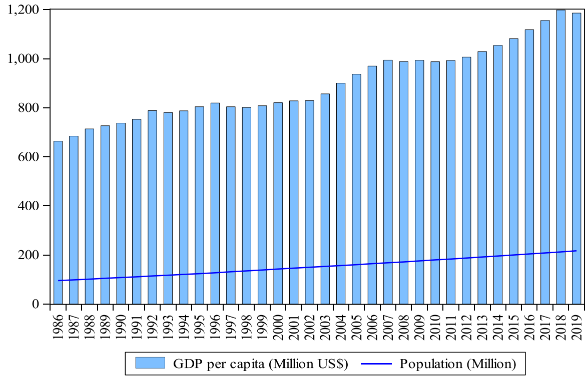

FIGURE 4
Trend in Pakistan's GDP *per capita* and population from 1986 to 2019 (Pakistan Economic Survey, 2019-2020; WDI, 2020).

TABLE 5 Estimation of decoupling states between coal consumption and economic growth in Pakistan from 1986 to 2019.

Period	$\sum(\Delta CC_{ES}^t, \Delta CC_{EI}^t)$	$\sum(\Delta CC_{PG}^t, \Delta CC_P^t)$	D^t	Decoupling state
1986–87	−3.335057	6.346402	−0.525504	WD
1987–88	14.020376	8.365400	1.675996	END
1988–89	−10.725776	5.953847	−1.801487	WD
1989–90	16.252780	5.727765	2.837543	END
1990–91	−10.351011	6.957228	−1.487807	WD
1991–92	−9.010612	10.385220	−0.867638	WD
1992–93	4.869120	2.513461	1.937217	END
1993–94	6.772142	5.654299	1.197698	END
1994–95	−29.644356	7.211712	−4.110585	WD
1995–96	4.097200	6.783734	0.603974	END
1996–97	−3.235991	1.493449	−2.166790	WD
1997–98	−21.343028	3.474549	−6.142675	WD
1998–99	5.914443	4.836242	1.222942	END
1999–2000	−16.019495	5.620182	−2.850351	WD
2000–01	−1.407178	4.581203	−0.307163	EC
2001–02	16.246002	3.528223	4.604585	END
2002–03	12.039384	9.148822	1.315949	END
2003–04	87.885060	16.128303	5.449120	END
2004–05	42.867734	19.440298	2.205097	END
2005–06	10.552474	20.362788	0.518223	END
2006–07	36.434149	18.780813	1.939967	END
2007–08	120.747691	8.230026	14.671605	END
2008–09	−168.492279	13.215260	−12.749827	WD
2009–10	33.275540	6.687078	4.976096	END
2010–11	−37.929438	11.564226	−3.279894	WD
2011–12	−10.991652	14.309169	−0.768154	WD
2012–13	−57.766705	17.041403	−3.389786	WD
2013–14	−38.761866	16.671585	−2.325026	WD
2014–15	102.730401	19.038851	5.395830	END
2015–16	8.787598	26.530740	0.331223	END
2016–17	84.646890	30.635649	2.763019	END
2017–18	248.702925	43.283470	5.745910	END
2018–19	129.195337	9.703430	13.314399	END

Note: END, expansive negative decoupling; EC, expansive coupling; WD, weak decoupling; SD, strong decoupling; SND, strong negative decoupling; WND, weak negative decoupling; RC, recessive coupling; RD, recessive decoupling.

economic factors in the current era's decoupling are yet to be analyzed, especially for Pakistan.

However, whether economies are becoming less reliant on sources of energy assets has become another imperative issue. The decoupling investigation has become an imperative technique to examine these issues; decoupling is a strand of research on the dilemma between EG and carbon pollution, the concept of which was originally taken from the field of physics. Zhang (2000) initially used the decoupling analysis definition to investigate the association between CO_2 emissions and EG in China at the start of the 2000s. OECD defines decoupling as dissociating economic growth from environmental degradation, such as by

TABLE 6 Saving coal consumption based on different efficiencies and subcritical, supercritical, and ultra-supercritical technologies.

No.	Technology	η (%)	$e_{fuel} = PC/_{LHV_{fuel}} .\eta \, (Mt/Bt)$
1	Subcritical	39	0.4160
2	Supercritical	41	0.4374
3	Ultra-supercritical	44	0.4694
			$e_{fuel} = PC/_{HHV_{fuel}} .\eta \, (Mt/Bt)$
1	Subcritical	39	0.3023
2	Supercritical	43	0.3333
3	Ultra-supercritical	44	0.3411

TABLE 7 Avoidance of the CO_2 emission rate and the emission factors concerning various coal compositions.

No.	Coal composition component (%)		$S_{CO_2} \, (Mt)$
1	Moisture	145.6	1.820134
2	Volatile matter	386.7	4.834106
3	Fixed carbon	413.3	5.166630
4	Ash	114.7	1.433856
5	Total sulfur	31.7	0.396279

breaking the relationship between them (OECD-2010, 2002). In 2002, this analysis was generally applied and formally defined by the OECD. This analysis is generally applied in the carbon emission-related literature at the country, sector, and regional levels (Grand, 2016; Raza and Lin, 2020). Presently, there are two methods of determining the decoupling association among energy, energy-related emissions, and EG.

First, as per Juknys (2003), there are three types of decoupling (i.e., primary, secondary, and double decoupling). However, primary decoupling is the decoupling relationship between natural resource utilization and EG. Secondary decoupling is the decoupling of ecological pollution from utilizing natural resources. Double decoupling occurs if both primary and secondary decoupling occur meanwhile. Thus, following Juknys' decoupling thought, Tapio (2005) re-defined the Tapio decoupling indicator and found "three" decoupling states, i.e., decoupling, coupling, and negative decoupling. This showed the decoupling of states in the transport sector of Europe. For a better understanding, Tapio divided "three" decoupling states into "eight" logical possibilities (i.e., weak negative decoupling, weak decoupling, expansive decoupling, strong decoupling, expansive negative decoupling, recessive coupling, expansive coupling, and strong negative decoupling), which are presented in the following section. After that, the decoupling index proposed by Tapio was broadly applied to investigate the impact of energy, the economy, and the environment. For example, De Freitas and Kaneko (2011) applied the Tapio index for Brazil's CO_2 emissions and EG over 2004–2009; Zhang et al. (2018) employed Tapio decoupling to estimate the association between coal ingestion and EG in China; Raza and Lin (2020) used this technique to estimate EC and EG for Pakistan's transport sector over 1984–2018; and Lin and Raza (2021) employed a similar method to estimate electricity utilization and EG in Pakistan from 1989 to 2018.

Following the logarithmic mean Divisia index (LMDI) technique, Zhang et al. (2015) discussed the major motivations for the decoupling process, while Diakoulaki and Mandaraka (2007) stated a decoupling indicator that was applied to evaluate the actual struggles assumed in the individual region and their impact on decoupling the environmental dimensions and EG. For this, Zhang et al. (2013) measured the decoupling relationship between electricity uses from EG in China. This technique was also employed by Zhang and Guo (2013) and Zhang et al. (2018) for Chin's EC and *per capita* income. Furthermore, clean coal technologies (CCTs) aim to lessen the ecological influence of coal consumption and include technologies for organizing coal, coal gasifying, and enhancing efficiency in power plants, eliminating contaminants for CO_2 emission and storage. For this reason, investments in CCTs are costly and employed only if they are maintained by technical, ecological, and economic viability (Mishra et al., 2015). To be considered a CCT, coal-fired power plants should fulfill a minimum of one of the given standards: a) high production compared to the traditional power plants because of their operation at maximum pressures and temperatures; b) based on the carbon storage system; and c) minimize nearby pollutants (i.e., heavy metals, particular matter, NOx, and SOx). This system, together with other machines that permit lessening emissions, could drive each plant's discharges to near "0" (Rocha et al., 2021). Thus, the applicability of CCTs in various coal power plants considerably influences overall efficiency and pollution reduction. Moreover, subcritical, supercritical, and ultra-supercritical coal-fired plants are samples of CCTs since they permit clean and highly proficient coal use, making it feasible to produce energy with minimum environmental pollution (Oboirien et al., 2018). The statement of supercritical originates from the thermodynamic concept of the critical point, which, for water, mentions the condition with a pressure of 22 MPa and a temperature of 374°C; in a process where steam situations are higher than that, this point is named supercritical. On the other hand, ultra-supercritical is more advanced than supercritical, which is usually stated for systems including a pressure of steam higher than 25 MPa and a temperature of more than 580°C, but it varies from country to country (Fan et al., 2018). Therefore, this research measures the various coal compositions that influence the environment at lower heating values (LHVs); however, they also carry a greater carbon emission of produced energy at that time. Thus, the objective of the environmental excellence index is to examine the extensive variability of coal compositions, which might support future decisions. Thus, this study adds to the literature on aspects of CCTs, fired-power plant efficiency, and integrating economic and ecological aspects, particularly for Pakistan.

To date, numerous scholars have concentrated on the relationship between EC and EG in Pakistan using causality and simple regression methods. Furthermore, there is a strong association between EG and EC in Pakistan (Lin and Raza, 2020a). Thus, using these factors for Pakistan's productivity, a study that impacts coal consumption, coal efficiency, and CCT is not yet analyzed. This research aims to answer the current issue.

Currently, the decoupling indicator is based on the decomposition outcome status, of which the state lies in coal consumption and Pakistan's EG, such as the strong, weak, or no decoupling state. Moreover, the description of the decoupling indicator is controlled by whether the economic activity impact is negative or positive. Ang (2004) decided that the LMDI technique was ideal compared with different decomposition approaches. In order to reduce this issue, the existing study again applies a decoupling indicator based on the decomposition outcomes of the LMDI process.

This study has the following motivations: first, the position of indigenous coal production, coal consumption, and coal imports is investigated. Second, the LMDI technique is employed to discover the influence of the factors that affected coal consumption in Pakistan from 1986 to 2019. Third, a decoupling index is established based on decomposition outcomes, which are applied to estimate the decoupling association between coal consumption and EG in Pakistan. Fourth, the research analyzes the efficiency range of highly effectual coal (i.e., supercritical and ultra-supercritical) compared to subcritical power plants at lower and higher heating values (HHVs). Importantly, it quantifies i) environmental impacts using coal-fired power plants; ii) subcritical, supercritical, and ultra-supercritical technologies at lower and higher heating values; iii) carbon emissions avoided under various coal composition components; and iv) the country's economic valuation using up-to-date data to describe the systematic, influential, and realistic picture of the coal power system. Thus, this study first attempted to analyze the factor's decomposition and decoupling progress with coal technology installed in Pakistan. Finally, the study provides energy security, CCT efficiency, and import reduction policies for Pakistan under the umbrella of the Intended Nationally Determined Contribution (INDC) (Vision 2025–2035, 2014) and coal plans linked to the China–Pakistan Economic Corridor (CPEC). In addition, few studies have been conducted nationally or internationally; for instance, Yin and Zhao (2023) conducted a descriptive analysis to analyze a clean, low-carbon, and diversified modern rural new energy system for China. Yu and Yin (2023) used a quantum evolutionary game model for new energy enterprises and village collectives. Raza and Dongsheng (2023) employed the decomposition method to investigate the carbon damage and carbon sources in Pakistan. Zhao et al. (2023) used the evolutionary game method to develop a green novel environment in photovoltaic building materials for manufacturing mechanisms. Raza and Lin (2023) used decomposition analysis for Bangladesh's natural gas consumption. They analyzed the energy, economy, and pollution effects based on energy aggregates or an individual source using limited factors without discussing the current measures. With the intention of enhancing past research, the novelty of the present research is to apply more accurate measures of energy efficiency. Due to different factors employed in various countries, sectors and individual countries have developed their own models using economic growth, energy consumption, fossil fuels, renewable energy, etc., at different time intervals (e.g., Ang, 2004; Ang and Liu, 2007; Diakoulaki and Mandaraka, 2007; Lin and Raza, 2020a; Zhao et al., 2023) in the literature due to their desirable properties. Few of the past studies have analyzed countries' energy efficiency based on decomposition models (Goh and Ang, 2019); however, they missed individual fuel consumption and their efficiency in the process of energy–economic growth. For forecasts and policy estimations, only a few studies have analyzed industrialized countries or regions without using the current factors of this study. On this basis, the present study fills the gap in previous work, observing current progress in the decomposition analysis and reporting the results of the main economic factors and their efficiency. Based on study objectives and motivations, our study answers the following questions: what are the key impacting factors that actually lead to energy and economic activity? What are the factors that decouple coal from economic growth? What has been the relationship between coal production, imports, and consumption since 1986? What are the effects of LHVs and HHVs of fuel in the current period? Which policies are imperative to distinguish fuel and economic sustainability in Pakistan? Thus, the current study will bridge the gaps in the coal sector and encourage evidence-based scientific models that are significantly useful for academics and policymakers, particularly in emerging countries, toward sustainability.

The remaining portion of the study is structured as follows: Section 2 provides the methodologies employed in this study; Section 3 describes data collection and its sources; Section 4 presents the major results; and Section 5 concludes the results and policy implications.

2 Research and data methodology

2.1 Logarithmic mean Divisia index

The LMDI technique can be shown as an extended Kaya identity, which was first established by Kaya (1989). This technique is generally employed to analyze the impacting factors, including energy consumption and pollution emissions (Lin and Raza, 2019). The selected variables (i.e., coal consumption, economic progress, population, and total energy consumption) are significant and define the strength and effects. Thus, the LMDI technique is employed to estimate the variations in various sectors and coal utilization in Pakistan and can be applied to test the economic situation. Therefore, the existing variables are imperative to analyze their relationship because Pakistan's small economy depends on coal (Lin and Raza, 2020b). Currently, the decomposition can be estimated in two ways: a) structural decomposition analysis (SDA) and b) index decomposition analysis (IDA). IDA has been broadly employed to better analyze trends of influencing factors in energy and emissions, which are consistent with the studies by Wang et al. (2017), Raza and Lin (2019), and Wei et al. (2020), considering time-series statistics is the key benefit of IDA. Furthermore, the IDA method has "two" approaches: a) the LMDI technique and b) the complete decomposition technique. By matching different IDA approaches, Ang (2004) found that LMDI was the best technique. The major advantage of the LMDI method is that it deals with zero-value problems and is also commonly used in energy analysis and its impact on other influencing factors (i.e., CO_2, population, energy intensity, etc.). To handle "0" values in the LMDI technique, Ang and Liu (2007) described eight strategies. However, the decomposition model for coal consumption could not include important factors, e.g., the efficiency of coal-fired power generation and share in total electricity, due to the unavailability of information. Thus, we estimated fuel and environmental efficiency for the current period, which could be further analyzed using the decomposition method based on information availability. In the existing research, the LMDI technique is applied to decompose coal utilization into some impacting factors. Regarding the modeling process, coal consumption is an energy-related aggregate, four major factors contribute to variations in coal consumption over time, and an individual factor is linked to a quantifiable variable, whereby there are different variables (i.e., coal, total energy, economic growth, and population). The general IDA identity is given in Eq. 1.

$$CC^t = \sum CC^t = \sum_i \frac{CC^t}{TEC^t} \times \frac{TEC^t}{GDP^t} \times \frac{GDP^t}{POP^t} \times POP^t, \tag{1}$$

$$CC^t = \sum ES^t.EI^t.PG^t.P^t, \tag{2}$$

where CC, TEC, GDP, POP, and t indicate the coal consumption, total energy consumption, gross domestic product, population, and time in years, respectively. $ES^t = \frac{CC^t}{TEC^t}$ is the proportion of coal use to overall energy utilization in year t, EI^t is the energy intensity in time t, PG^t is the GDP *per capita* in year t, and P^t is the population in year t.

The variation in coal utilization in Pakistan between 0 and t year (base year to the current year), represented by ΔCC_0^t, could be decomposed into “4” effects:

ΔCC_{ES}^t presents the changes/variations in the coal share effect.
ΔCC_{EI}^t presents the variations in the energy intensity effect.
ΔCC_{PG}^t presents the variations in the economic activity effect, and
ΔCC_P^t presents the variations in the energy population effect, as shown in Eq. 3.

$$\Delta CC^t = CC^t - CC^0 = \Delta CC^t = \Delta CC_{ES}^t + \Delta CC_{EI}^t + \Delta CC_{PG}^t + \Delta CC_P^t, \tag{3}$$

where Δ is the change. To analyze each factor’s individual influence, Eq. 3 can be stated in such a way.

$$\Delta CC_{ES}^t = \frac{CC^t}{\ln(CC^t - CC^0)} \times \ln\left(\frac{ES^t}{ES^0}\right), \tag{4}$$

$$\Delta CC_{EI}^t = \frac{CC^t}{\ln(CC^t - CC^0)} \times \ln\left(\frac{EI^t}{EI^0}\right), \tag{5}$$

$$\Delta CC_{PG}^t = \frac{CC^t}{\ln(CC^t - CC^0)} \times \ln\left(\frac{PG^t}{PG^0}\right), \tag{6}$$

$$\Delta CC_P^t = \frac{CC^t}{\ln(CC^t - CC^0)} \times \ln\left(\frac{P^t}{P^0}\right). \tag{7}$$

The index number form could be as follows:

$$\frac{\Delta CC_{ES}^t}{\Delta CC_{total}^t} \times 100\% + \frac{\Delta CC_{EI}^t}{\Delta CC_{total}^t} \times 100\% + \frac{\Delta CC_{PG}^t}{\Delta CC_{total}^t} \times 100\% + \frac{\Delta CC_P^t}{\Delta CC_{total}^t} \times 100\% = 100\%. \tag{8}$$

2.2 Decoupling analysis

The decoupling method confirms the relationship between the associated variables. As per the statement of various factors shown in Section 2.1, ΔCC_{PG}^t and ΔCC_P^t are the major key drivers driving coal consumption (CC), although ΔCC_{ES}^t and ΔCC_{EI}^t are general efforts mentioning all activities directly or indirectly persuading a reduction in coal utilization. Compared with the model by the OECD, Tapio processes the benefits of small data supplies, correct outcomes, and small calculations (Wei et al., 2020). Therefore, this method has been broadly employed to estimate the association between fuel, environmental factors, and economic progress (Qian et al., 2020). Thus, to evaluate the degree to which existing endeavors are effective regarding the dissociation between CC and GDP, the decoupling index from the 0–t year, D^t, is defined as follows:

$$D^t = \frac{\Delta CC_{ES}^t + \Delta CC_{EI}^t}{\Delta CC_{PG}^t + \Delta CC_P^t}. \tag{9}$$

As per the proportion of efforts lessening coal consumption and its leading influences that drive CC and the decoupling standards given by Tapio (2005), eight types of decoupling states are stated in the present study, as shown in Table 1. The annual growth rate of coal consumption is less than or equal to zero, showing that coal use is absolutely decoupled from economic growth.

2.3 Fuel efficiency and CO_2 emissions

The estimation was conducted by observing the current installed capacity based on its efficiency as per the operation technology. In this way, the analysis is linked with a study by Rocha et al. (2021). The method established is a mechanism to analyze various substitutes from fuel efficiency and environmental viewpoints, showing how coal composition can influence decision-making. The scope for enhancement of the investigation was established with an installed capacity of 186,700 million tons of coal reserved and an LHV and HHV of 174,346 and 239,910 Btu/lb, respectively, as shown in Table 2. Table 2 shows an efficiency range for supercritical and ultra-critical technologies since there is an efficiency range for similar technologies because of additional factors independent of the technology used. However, as per HDIP (2019), investigating the coal-fired plants as a whole, the average value is 0.4, while novel plants might have a maximum capacity factor greater than 0.5; therefore, standardizing the boundary conditions of the research that accepts current units will function on the basis of the country’s structure.

Thus, to calculate the fuel efficiency of the individual set, situations for the enhancement of environmental investigations can be taken as by Eq. 10:

$$e_{fuel} = PC \big/ LHV, HHV_{fuel}.\eta, \tag{10}$$

where e_{fuel} is the efficiency fuel, PC is the installed power capacity (million tons), LHV_{fuel} is the lower heating value (Btu/Ib), HHV_{fuel} is the higher heating value (Btu/Ib), and η is the coal-fired power plant efficiency (%). The current work does not estimate the influence of environmental conditions on the loss of efficiency over the lifespan.

Furthermore, the environmental estimation was conducted by estimating the CO_2 emissions using the various coal compositions and computing how the plant productivity can support encouraging an energy matrix with a lower intensity of CO_2 releases. Thus, the CO_2 emissions rate and the emission factors regarding various coal compositions can be calculated by Eq. 11. Eq. 11 makes it probable to obtain the carbon emission rate and the emission factor in million tons. The CO_2 releases avoided by the process with maximum efficiency are considered. Further outcomes are discussed in the following section.

$$S_{CO_2} = \frac{X_c.e_{fuel}.M_{CO_2}}{100.M_c}, \tag{11}$$

where S_{CO_2} is the specific CO_2 emissions in million tons, X_c is the % by weight of carbon existing in the elemental chemical composition (i.e., moisture, volatile matter, fixed carbon, ash, and total sulfur), M_{CO_2} is the molecular weight of CO_2 emission, and M_c is the molecular weight of carbon.

2.4 The data

The study period in the current study is from 1986 to 2019. The present study used yearly time-series data bounding a period of 34 years on the maximum availability of data. Furthermore, the various industries (i.e., cement, brick kilns, Pak steel, power, and domestic sectors) played an active role and mostly motivated the country's economy. Due to the intensive usage of coal in the cement, brick kilns, and power sectors in Pakistan, the development in these sectors is naturally linked with an increase in coal consumption. As per HDIP (2019), the cement/other sectors consumed the maximum coal by 47.5%, the power sector by 27.4%, and brick kilns by 25% in 2019. All the energy-related data in the existing research are collected from different annual books of HDIP (2019). The measurement unit of energy data is taken as Mtoe. Because of the lack of data on Pakistan's provinces, i.e., Punjab, Sindh, Baluchistan, Khyber Pakhtunkhwa, Gilgit-Baltistan, and Azad Jammu and Kashmir, this study does not include these six provinces and states. The GDP data are composed of WDI (2020). The unit of GDP is a million USD at a constant 2010 price. Population data are obtained from the World Development Indicators and the Pakistan Economic Survey (2020). All the population data have been arranged in millions. Data related to aggregate coal-fired power plants' LHV, HHV, coal-installed power capacity, and coal composition are collected from HDIP (2019). The measurement units of LHV and HHV are considered to be Btu/lb, coal power capacity as million tons, and the overall estimated coal-fired plant efficiency and coal composition data as a percent.

3 Empirical outcomes and discussion

3.1 Description of Pakistan's coal reserves/resources

Pakistan's coal production, coal consumption, and import trends are shown in Figure 1. It can be seen that coal utilization and coal imports in Pakistan increased by a record after 2014. Coal consumption and imports reached 12.76 Mtoe and 10.32 Mtoe from 1.54 Mtoe and 0.56 Mtoe from 1986 to 2019, with an average rate of 9.6% and 17.4%, respectively. During the period, the increase in coal production did not cause significant fluctuations. In 2019, the indigenous coal production was 2.44 Mtoe, which increased at an average rate of 1.48% from 1986 to 2019. The reason is that since 2014, Pakistan has become a net coal importer, which has stopped indigenous coal production at the demand level. Although coal accounted for exceeding 24.5% of the overall primary energy consumption in 2019, in 1986, 6.15% of coal was consumed by various industrial sectors (HDIP, 2019).

Table 3 shows the available coal reserves in Pakistan during the current period. However, the trend in Figure 1 shows that Pakistan's coal energy consumption statistics are becoming more and more accurate. Various coalfields have not changed from 2014 to 2019, as per available information because of Pakistan's high energy crisis; the energy shortfall surpasses 6,000 megawatts (Lin and Raza, 2019). The rapid demand for energy from increasing demographic burdens and extreme industrial development has added to the crisis. Currently, domestic coal plays a small role in the energy mix; notwithstanding, the Thar Desert is one of the biggest underdeveloped coal assets in the world. The annual demand of Pakistan for coal exceeds the supply; therefore, Pakistan depends on foreign coal to satisfy its needs, especially for industrial consumption. Based on the availability of huge coal resources (see Table 3), the aim of emerging Thar coal deposits is to produce energy from Pakistan's coal assets, to lessen the imported coal dependency, and to add toward bridging the gap between energy demand and supply.

Thar, with 175 billion tons of coal, is home to the seventh biggest coal mine in the world and is predictable as a merely feasible and supportable outcome of Pakistan's shortfall. Based on huge field assets linked in energy terms to the collective oil reserves of Saudi Arabia and Iran, they are proficient in generating 100,000 megawatts of electricity for the next 200 years. Based on various blocks/fields, coal drilling, and different reserves, the current situation suggests that a cheap and sustainable energy roadmap for Pakistan is necessary to exploit the utilization of domestic resources in mixed energy. To reduce the energy crisis and increase energy security, the government is also determined to improve coal capacity to approximately 38,000 megawatts by 2047 using the Indicative Generation Capacity Expansion Plan (IGCEP). Moreover, CPEC, worth $46 billion, frequently focuses on energy projects, of which $6.4 billion is bound for coal energy employing clean coal technologies.

Overall, during the study period, the cement sector was the highest coal user (54.3%) amongst all the other subdivisions, i.e., power (27.4%), brick kilns (25%), and coke use (1.7%) in 2019 (HDIP, 2019). In 2019, coal consumption by the power sector increased by 105.6%, the industrial sector by 23.5%, and brick kilns by 14.6% compared to the previous year, 2018. However, the domestic sector stopped coal consumption after 2007, which was 2.33% of the total coal consumption; therefore, the industrial sector is the most nominated end user of coal in the current study. Thus, the share of the remaining sectors remains relatively consistent during the study period and is forthcoming.

3.2 Decomposition analysis

Decomposition outcomes based on the LMDI approach are shown in Table 4. The energy intensity effect (ΔCC_{EI}^{t}) plays a medium role in decreasing coal ingestion except in 1988, 1990, 1993–94, 1998, 2000, 2004–05, 2007–08, 2011, 2013, and 2015–18. The aggregated influence is an upsurge of 22.067 Mtoe, which accounts for 0.023% of the overall coal utilization variation in the total value. Figure 3 shows the trend of Pakistan's energy intensity (EI) from 1986 to 2019, which presents an overall increase/decrease in EI during the period. The trend of EI can be separated into "four" phases: a stable phase from 1986 to 2001, an increasing phase between 2002 and 2008, a quick decrease phase between 2009 and 2014, and a quick increase phase between 2015 and 2019. The fluctuation in EI can describe why the EI impact plays a positive or negative role during the period. During 2009–2014, the rapid decrease in EI can be credited to the impact of numerous productions and imports from different countries, consistent with the results obtained by Lin and Raza (2021). During the increasing trend from 2015 to 2019, EI may be changed due to the development of urbanization and industrialization (Lei et al., 2014), which needed higher energy-intensive products, i.e., bricks, cement, Pak steel, and power. Moreover, Pakistan's resource-extensive EG design has not transferred significantly.

As shadowed by ΔCC_{EI}^{t}, the coal share effect (ΔCC_{ES}^{t}) is another factor that increased coal utilization during the maximum period, as shown in Table 4. The aggregated impact is an increase of 365.90 Mtoe, which accounts for 0.38% of the overall coal utilization variation in the entire value. The trend of the coal proportion from 1986 to 2019 is also shown in Figure 3. The trend curve of the coal ratio can be distributed into five phases: a slow and stable phase from 1986 to 1994, a decreasing phase from 1995 to 2000, a rapid growth phase from 2001 to 2008, a fast decreasing trend from 2009 to 2014, and a fast growth phase from 2014 to 2019. As per IEA (2017), the global energy intensity decreased by 12.6% between 2010 and 2016, showing efforts to follow sustainable EG and the environment. From Pakistan's perspective, as shown in Figures 1, 3, coal consumption, imports, and production decreased substantially during 2009–2014 (HDIP, 2019). Furthermore, in line with IEA (2017), carbon emissions have remained stable at approximately 30–32 billion tons annually since 2010. However, productivity enhancements have decreased energy imports (Lin and Raza, 2020a). The variation in the coal share is the major reason that the proportion of coal plays a major role in increasing coal utilization in Pakistan.

The economic activity effect (ΔCC_{PG}^{t}) presents an incessant growth in coal consumption in Pakistan except for the following years: 1993, 1997–98, 2008, 2010, and 2019. The aggregated effect is an increase of 235.79 million, which accounts for 0.25% of the overall change during the period. Since economic reforms in the 1960s were initiated in agriculture, education, legal, other trade, and taxation simultaneously, Pakistan has faced spectacular economic growth (Pakistan Bureau of Statistics, 2019). The *per capita* GDP of Pakistan reached 1,185.45 million USD in 2019 from 663.29 million USD in 1986, with an average yearly growth rate of 0.79%, as shown in Figure 4. The rising *per capita* GDP is the major driving force for coal consumption during this time (Zhang et al., 2018). Following ΔCC_{PG}^{t}, the population effect (ΔCC_{P}^{t}) is another factor leading to the increased coal consumption. The analysis presents that ΔCC_{P}^{t} led to a progressively increased 216.56 million in 2019 from 95.21 million in 1986, with a yearly average growth of 0.35%, as shown in Figure 4, which could comprehend that the impact of people's growth also increases coal consumption in Pakistan.

3.3 The decoupling estimations

As per the decoupling index (DI) definition in Section 2.2, DI is stated as the proportion of the total of coal share influence and energy intensity effect ($\sum(\Delta CC_{ES}^{t}, \Delta CC_{EI}^{t})$) to the sum of economic activity influence and population effect ($\sum(\Delta CC_{PG}^{t}, \Delta CC_{P}^{t})$). As shown in Table 4, the maximum values of ΔCC_{PG}^{t} and ΔCC_{P}^{t} are positive and show an increasing trend during the selected period. We found only "three" decoupling states during 1986–2019, namely, weak decoupling, expansive negative decoupling, and expansive coupling, as shown in Table 5.

Expansive coupling only appeared in 2001, and the decoupling indicator was −0.31. Expansive negative decoupling occurred in 19 years, 1988, 1990, 1993–94, 1996, 1999, 2002–08, 2010, and 2015–19, and the decoupling indicators were 1.67, 2.83, 1.93, 1.19, 0.60, 1.22, 4.60, 1.31, 5.44, 2.20, 0.51, 1.93, 14.67, 4.97, 5.39, 0.33, 2.76, 5.74, and 13.31, respectively. The coal utilization provided weak decoupling in 13 years, 1988, 1990, 1993–94, 1996, 1999, 2002–08, 2010, and 2015–19, and decoupling indicators were −0.52, −1.80, −1.48, −0.86, −4.11, −2.16, −6.14, −2.85, −12.74, −3.27, −0.76, −3.38, and −2.32, respectively (see Table 5). These results are consistent with the results obtained by Lin and Raza (2020b) and Wang et al. (2017).

The appearance of expansive negative decoupling in 1988, 1990, 1993–94, 1996, 1999, 2002–08, and 2010 can be discussed by the variation in the energy intensity impact and coal share impact, as shown in Table 4. As shown in Figure 3, EI slowly increased to 0.00021 Mtoe/million in 1989–1990 from 0.00020 Mtoe/million. Figure 3shows that the coal ratio also increased during 1989–1990, 1993–1994, 1996, 1999, 2002–08, and 2010 because of fluctuations in energy intensity.

The advancement in 2001 showed expansive coupling, which is also referred to as the variation in ΔCC_{PG}^{t} and ΔCC_{ES}^{t}. During 2001, the yearly growth share of *per capita* GDP touched 145.97 million USD, correspondingly. The proportion of coal use to the overall energy utilization increased to 25.25 Mtoe in this period (HDIP, 2019). Overall, it is observed that the occurrence of expansive coupling in 2001 might be due to the rapid growth in the coal ratio and sluggish decrease in EI, as shown in Figure 3. Moreover, expansive coupling in 2001 led to a sluggish reduction in the coal ratio.

As per Table 4, ΔCC_{PG}^{t} and ΔCC_{P}^{t} play an imperative role in the re-coupling procedure. Weak decoupling appeared in 9 various years, as shown in Table 5. However, ΔCC_{EI}^{t} influence has decreased sufficiently for decoupling the association between coal consumption and GDP in Pakistan except in 1988, 1990, 1993–94, 1996, 1999, 2002–08, 2010, and 2015–19 during the research period. Finally, the coal share effect is the factor that played an essential role in the "13" years of weak decoupling processes, while expansive negative decoupling outcomes are found in the "19" years. Currently, because of high energy demand and reliance on indigenous energy resources, Pakistan should convert raw coal into clean coal technologies and substitute oil with coal, gas, and renewable energy resources. This decoupling is evident in the latest study by Lin and Raza (2021), who estimated the electricity consumption in Pakistan.

3.4 Environmental analysis

According to Eq. 10 and outcomes shown in Table 6, coal savings are almost linear in their relationship with efficiency at both LHV and HHV coal-fired levels, including subcritical, supercritical, and ultra-supercritical. Thus, fuel conservation can be extrapolated to efficiencies outside the examined range based on a linear regression of the statistics, which is in accordance with the research by Rocha et al. (2021). Moreover, as proved, because of numerous various coal compositions, a calculation on the basis of data estimation would need curve construction and data linearity for every composition under investigation, which makes the specificity of individual coal kinds obvious. Therefore, this piece of evidence should be taken into consideration when deliberating the ecofriendly benefits of employing novel CCTs and technologies for coal production.

Currently, CO_2 emissions signify the largest concern about coal-fired power plants because of their characteristics as gases (Yue et al., 2021). The carbon emissions rate and emission factors relating to different coal compositions (i.e., moisture, volatile matter, fixed carbon, ash, and total sulfur) in Pakistan, which are also released, have advanced technologies that are broadly employed to eliminate these contaminants from the exhaust gas with maximum productivity. However, technologies concerned with CO_2 capture machinery are on the way to becoming feasible for implication on a huge scale. As Pakistan's energy sector has already been going through a transition over the last few years, oil consumption for power production has been substituted by coal (HDIP, 2019). However, it would be wise to widely measure and recognize this evolution in Pakistan, which will influence efforts for environmental degradation, economy, and climate change burdens now and for the coming generations. The cost linked to these advanced systems shows that the way to economic viability also includes plant application and advancement, for instance, ultra-supercritical technology to lessen the condition of the system in a way that the prices linked with the carbon capture could punish economic indicators less intensely (Hammond and Spargo, 2014). Therefore, there are ways to avoid emissions, i.e., the establishment of high-efficiency plants, which are of necessary application in coal-fired plants in reducing emissions and commercial energy needs.

As per Eq. 11, carbon emissions rates based on different coal compositions are given in Table 7. Table 7 shows a significant amount of CO_2 emissions for 186,007 million tons of installed coal capacity. It is likely to prove the evaded discharges from various coal compositions under particular conditions of higher efficiency. It is obvious that each composition, e.g., moisture, volatile matter, fixed carbon, ash, and total sulfur, avoids emissions by 1.82, 4.83, 5.16, 1.43, and 0.39 Mt, respectively. Odeh and Cockerill (2008) estimated emissions from coal-fired power plants in the UK using sensitivity analysis at LHV, and Rocha et al. (2021) quantified coal-fired power plant emissions for Brazil using hypothetical analysis of various plants at LHV. The previous estimations are completely different and focused on coal-fired plants, but the various economic factors, coal efficiency, coal composition, and CO_2 emissions reduction for Pakistan were not considered; therefore, the wide range recognized for estimation made it conceivable to assume imperative issues. It can be noted that the emission from each composition might be evaded under the condition of 34% efficiency (HHV). Overall, the fuel efficiency and CCTs are highly expressive for embedding power production units and decision-making.

4 Conclusion and policy recommendations

4.1 Conclusion

Using the yearly data from 1986 to 2019, this study syndicates the logarithmic mean Divisia index with the Tapio index model to measure coal consumption into four influencing factors: coal share, energy intensity, economic activity, and population effects. Moreover, it also assessed the decoupling index and the coal consumption in Pakistan associated with economic development. Thus, based on the aforementioned findings, the major conclusions are as follows.

First, the results exhibited a significant (1.34%) reduction in total coal consumption. However, ups and downs existed during the period, but the overall impact was negative, followed by the coal share effect. The population and economic effects slightly increased throughout the entire period, particularly in the current years. The economic share and population effects progressively increased coal consumption by 0.84% and 1.18% over the study period, respectively. Concerning economic development, minimum production adjustments naturally add to decreasing the CO_2 emission level; however, the consumption of coal will contribute to enhancing economic development.

Second, expansive negative decoupling is observed in the majority of subperiods, involving 1987–88, 1989–90, 1992–94, 1995–96, 1998–99, 2001–08, 2009–10, and 2014–19. This seemed to be because economic growth rates have slowed down with increased coal consumption. Growth in energy substitution and numerous other government policies likely impacted the huge consumption rate. The expansive coupling occurred only in 2001 because of the rapid growth in coal proportion and sluggish decrease in energy intensity (1.4%), while weak decoupling showed a decoupling association between coal consumption and the economy during 1986–87, 1988–89, 1990–92, 1996–98, 1999–2000, 2008–09, and 2010–14 with a decreasing trend in coal and intensity. This presents that coal share is the only factor that played an imperative role in the weak decoupling process.

Third, the implications of supercritical and ultra-supercritical technologies would provide significant fuel savings and, subsequently, could evade huge CO_2 emission releases. It was estimated that the emissions from various coal compositions (i.e., moisture, volatile matter, fixed carbon, ash, and sulfur) could be avoided by 1.82, 4.83, 5.16, 1.43, and 0.39 Mt during the current time. Thus, on the basis of our results, subsequent policy recommendations should be given greater attention.

Finally, many questions remain unanswered, for instance, we use the decomposition and decoupling approaches and compare the different efficiency technologies for saving coal consumption for the current period. The objective is to discuss the coal situation regarding economic and population growth. Thus, in our future work, our research direction is to comprise further factors for long intervals under clean coal technologies and extend the model to a case in which the market demand is impacted by a domestic price on the availability of data on the basis of sector-wise economic efficiency and pollution factors that will check energy substitution and technical change (i.e., clean coal technologies).

4.2 Policy recommendations and discussion

For Pakistan, its growing population and industrialization caused huge energy consumption. Coal is Pakistan's third primary energy source, having the world's seventh largest coal reserves in Thar. However, Pakistan is still in the early stages of growing energy security, economy, and urbanization, leading to more coal consumption. Currently, domestic energy resources cannot meet the increasing energy demand due to a lack of technology and infrastructure. To check the energy security and economic situation, we analyzed the association between coal consumption and EG because of an imperative issue. Under the energy-related policies for Pakistan, INDC, Vision-2025 and Pakistan 2025, 2014, Vision-2035, 2014, and coal projects linked to the China–Pakistan Economic Corridor (CPEC) are imperative from energy and economic perspectives. Pakistan, the net coal importer, has directly impacted current reserves (185.175 billion tons) and indigenous coal production (5.8 million tons) to fulfill its industrial needs (HDIP, 2019). Furthermore, the Thar Desert has one of the largest underdeveloped coal reserves in the world, with 175 billion tons. Therefore, for long-run energy security, domestic resources could be utilized. Furthermore, due to its acute energy crisis, the enormous reserves of coal could be utilized to maintain its energy security and industrial needs. Therefore, the following policies might support economic development and environmental protection in the future.

a) Based on the consumption, production, and coal import situation, Pakistan should promote scientific and technological innovation capacity. Currently, the energy crisis in Pakistan is a serious issue, which could be fulfilled by utilizing national energy resources (i.e., oil, gas, coal, and renewable resources). Moreover, Pakistan is not well-developed in modeling the mining sector, which involves designing, planning, exploration, mine growth, and technical equipment. To meet the huge energy demand, Pakistan should use its indigenous energy resources. With huge coal reserves, the coal import reached 10.32 Mtoe, which is 24% higher than its production (HDIP, 2019). The maximum import is because of the huge demand for different industries in different sectors. Therefore, Pakistan should concentrate on developing clean coal technologies and clean energy sources (i.e., solar, wind, bagasse, and biogas), which will not only enhance the efficiency of firms and energy security but also control pollution and, thus, enhance the economy.
b) Because EG leads to huge coal consumption, if the Pakistani economy keeps increasing at a maximum ratio over the future, GHG emissions will follow, and the country's management will continue to encounter the EG–emission dilemma. As coal is the key contributor to GHG emissions, controlling the utilization of coal looks like an effective way to control GHG emissions. To evade the possible interface with EG, GHG emissions reduction might be attained by further promoting the effectual use of coal and implementing advanced carbon capture technologies. The estimations add the renewal of current machinery and foreign technologies, which drive an upsurge in the coal consumption price and, finally, a decrease in pollution. Furthermore, e.g., Pakistan's decision to diminish its dependence on imported fuel and interchange it with lower-emitting equipment might lead to technical and energy security problems, so this decision might not be feasible in the short term. However, the slow diversification of energy resources might actually improve the energy supply in the long run. In major energy projects based on CPEC, GHG emissions could be controlled by accelerating the expansion of new energy technologies and industries. Furthermore, for energy efficiency, industrialists should be guided about energy conservation.
c) Scientifically, the ultra-supercritical technology applied by developed nations (i.e., the United Kingdom, China, and Canada) can support the reduction of CO_2 emissions and other greenhouse gases (Thitakamol et al., 2007; Raza and Tang, 2022). The implications of pollution control technologies, such as pressurized fluidized bed combustion, electrostatic separators, and zero CO_2 emissions technologies, should become common in the future.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding authors.

Author contributions

MR: conceptualization, data curation, formal analysis, methodology, software, validation, writing–original draft, and writing–review and editing. BL: conceptualization, data curation, formal analysis, investigation, methodology, supervision, validation, writing–original draft, and writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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