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Research paper

Techno-economic assessment and sustainability impact of hybrid energy systems in Gilgit-Baltistan, Pakistan

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ABSTRACT

Remote electrification remains a critical issue for the Gilgit Batistan region of Pakistan, where most of the population lives without access to the national grid and mostly relies on traditional energy resources, which undermines the huge potential of renewable energy in the region. This paper addresses the energy access issue of 1.8 million people of Gilgit-Baltistan (GB), of which 86% reside in the rural areas. To resolve the problem of energy access in the region, this paper analyzes cost-effective solutions based on renewable energy resources and proposes suitable hybrid systems for 14 independent sites. For this purpose, available energy resources and regional demands have been assessed to present the optimized hybrid energy systems for the identified sites. Hybrid optimization model for multiple energy resources is designed to carry out the techno-economic feasibility analysis. Moreover, equivalent forest absorbing CO_2, glacier mass loss, and social cost have been evaluated. Results show that the combination of wind and hydro with battery backup gives the most optimum cost of energy (COE) ranging between 0.0470–0.0968 \$/kWh. Similarly, 8349 acres of forest are needed to absorb the annual CO_2 emissions. As 0.58 million tons of glacier, and 0.882 million \$/year social cost of carbon (SCC) can be lost due to emissions of fossil fuel-based generation. To ameliorate from such adverse effects, a community-based hybrid system may provide clean and green energy to increase energy access across Gilgit-Baltistan.

1. Introduction

The dominance of conventional energy sources in South Asian countries like Pakistan has contributed to raising the temperature of Himalayas, Hindukush, and Karakorum ranges (Ren et al., 2017). The current energy mix of Pakistan depicts that the ratio between fossil fuel and renewable energy is about 3:1, with an installed capacity of 17,038 MW thermal energy (Uddin et al., 2019; Bhatti, 2016). This fossil fuel-based energy generations may grow further due to China–Pakistan Economic Corridor (CPEC) investment in the coal-based power projects (Muzammil Zia et al., 2018). The rise in CPEC activities will bolster the environmental changes in the mountainous area of the country which has already experienced unusual events in recent years. For instance, many incidents of glacier lake outburst flood have happened in northern Pakistan and massive floods have been observed over the last two decades (Amin et al., 2020). Scientists have emphasized the need of developing renewable energy resources for reducing the carbon footprint which will eventually slow down the pace of climate change in more endangered parts of the world, such as Pakistan (Ur Rehman et al., 2019; Hutfilter and others, 2019).

Gilgit-Baltistan in the north, faces severe electricity shortfalls despite having a good potential of untapped photovoltaic (PV), wind, and hydro resources due to lack of proper energy policy, infrastructural development issues, and investment barriers for private sector. Sustainable energy access is a major issue of the region, with 15 to 18 h daily power outages that have critically hampered the commercial activities (Ayman, 2016). Across Gilgit Baltistan, energy sources used in household and commercial enterprises are firewood, kerosene oil, candles, hydropower, thermal power, dung cakes, diesel oil, batteries, liquefied petroleum gas (LPG), and coal. The current energy mix of the GB region is 45% firewood, 30% LPG, 19% electricity (distributed hydro plants), and 6% kerosene oil (Wali, 2018).

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Grid extension to low load-factor areas is an expensive undertaking, while the micro-grid concept and rural electrification based on the indigenous resources are giving eminent solutions in developing countries (Rehman et al., 2019). Mohamed, Mohamed A, et al. proposed particle swarm optimization (PSO) algorithm to optimize the cost and size of grid tight PV/wind hybrid system for a case study of Riyadh, Saudi Arabia (Mohamed et al., 2017). The result shows that about $ 48.2 million can be saved through renewable energy integration for the period of 25 years. Similarly, Eltamaly, Ali M., et al. have implemented PSO to analyze the impact of high priority and low priority loads for optimal configuration of PV/wind/fuel-cell/diesel generator (DG) system (Eltamaly et al., 2017). They also used load shifting strategies in a comparative analysis of parallel and series implemented PSO to minimize the system size and cost with most reliable renewable energy combinations (Mohamed et al., 2016). Demand management concept of smart grids (SG) provides a reliable energy solution with decline in the load factor of the power system. Azaza, Maher and Wallin, Fredrik carried out a feasibility study of hybrid microgrids system across different zones of Sweden with tradeoff between three optimization objectives (reliability, economic and clean production) through meta heuristic PSO method (Azaza and Wallin, 2017). Sensitivity analysis on number of consumers shows that probability of loss of power supply increases linearly with demand and variation in energy cost decreases inversely, while the renewable fraction remain unchanged.

Fathy, Ahmed performed different meta-heuristic techniques such as mine blast algorithm (MBA), cuckoo search (CS), artificial bee colony (ABC) and PSO on the MATLAB/Simulink model of hybrid PV/wind/fuel-cell system (Fathy, 2016). MBA gives most economical energy cost with least running time followed by CS algorithm, ABC algorithm and PSO algorithm without affecting the reliability issue of the respective hybrid system. Similarly, Zahboune, Hassan, et al. have also developed a MATLAB/Simulink model based on Modified Electric System Cascade Analysis (MESCA) optimization techniques to comparatively analyze the MESCA and Hybrid Optimization of Multiple Energy Resources (HOMER Pro) results (Zahboune et al., 2016). HOMER gives a better configuration of hybrid PV/wind/battery system to satisfy the demand as its loss of power supply probability (LPSP) is 1.79%, while for MESCA it is 1.97%. The comparative analysis of HOMER Pro and MESCA concluded that there is negligible difference in energy production and COE, making HOMER suitable for feasibility studies of hybrid systems.

Energy provision to 1.2 billion un-electrified population of developing countries can be fulfilled by harnessing the indigenous renewable resources available in the respective area (Ahmad et al., 2018). Government of Pakistan is focusing on renewable energy sources to tackle water scarcity and energy crisis in the rural areas, where 50% population have no electricity access (Saghir et al., 2019). Lal, Deepak Kumar, et al. have studied the feasibility of wind/hydro/PV/diesel hybrid system using HOMER for an unelectrified rural area of Orissa State, India (Lal et al., 2011). They concluded that the grid tariff will be economical for an area within 128 km radius from the existing grid. Beyond 128 km, the standalone hybrid system provides the least COE 0.207 $/kWh. Furthermore, Baneshi, Mehdi, et al. proposed a solution of photovoltaic, wind, diesel generator and battery system with least COE 0.057 $/kWh for bulk demand of Shiraz, Iran, while for grid it was about 0.0837 $/kWh (Baneshi and Hadianfard, 2016). Some of the techno-economic studies based on HOMER are given in Table 1 and to the best of our knowledge, no such study has been done for the hilly terrain of the GB region. Moreover, literature offers little evidence of studies that interlink energy, environment, and climate change mitigations for such a large and remote area of Pakistan.

Previous studies lack real-time data of load for a large geographical region and mostly use idealistic load based on their assumptions. Moreover, in studies involving hydroelectric hybrid system, the flow rate of hydropower is considered as constant throughout the year. Similarly, impact of clean hybrid system on the environment and financial savings by eradicating harmful emissions, with comprehensive results of component sizes lacks in the literature. Studies involving environmental analysis only consider impact of emissions from conventional grid (i.e., electricity generation), whereas emissions directly from end use energy source such as liquified natural gas, firewood, and kerosene oil are mostly in literature. This study is going to answer how intermittent renewable sources integrated with variable hydroelectric power give an optimal solution in standalone mode. This paper also explores how the current energy mix practices across Gilgit Baltistan spoil the environment and elevate melting of glaciers. Moreover, we discuss how an economically suppressed region can be relieved from extra burden of invisible social cost of carbon emissions.

In this study, we have assessed the demand at each site with respect to their population and commensurate respective demand with the realistic grid profile of Skardu City. Similarly, the renewable energy resources have been examined and suitable hybrid systems at different sites across GB are suggested. HOMER Pro is used for techno-economic analysis, while RETScreen Expert has measured the greenhouse gas (GHG) emissions and the equivalent forest required to absorb these emissions. These findings are also helpful to analyze the impact of renewable energy adaptation in GB on glacier melting. The hybrid energy system proposed for the respective site may reduce the energy security problem and provide reliable clean electricity closer to the load. Moreover, the social cost of carbon emissions has also been presented for every selected site, based on energy economics literature.

2. Energy-economics of Gilgit-Baltistan

Gilgit-Baltistan has a mountainous terrain in the north of Pakistan. GB borders Azad Kashmir to the south, Khyber Pakhtunkhwa province to the west, the Wakhan Corridor of Afghanistan to the north, China to the northeast, and the Indian-held Kashmir to the southeast (Khan et al., 2003). GB contributes minutely in the economy of Pakistan despite having immense economic potential in the form of tourist attractions, massive resources of renewable energy, deposits of minerals and precious stones as well as its geopolitical location that facilitates the only road crossing trade link between Pakistan and China — the linchpin of CPEC. Firewood, LPG, and kerosene oil are the main sources of domestic energy, which are intensely used for cooking and heating purposes (Ali et al., 2018). These carbon-intensive energy resources are the major contributors to air pollution and environmental changes.

Electricity is generated by small hydropower stations with capacities ranging from 50 kW to 4000 kW. Currently, 119 hydropower stations are in operation with a total installed capacity of 148.69 MW (Hussain and Akhter, 2018). During winter, the supply of electricity reduces due to low water flows in rivers, however, demand remains high because of harsh weather. The seasonal shifting of the population from higher altitudes to lower valleys also affects the overall demand for energy in winter. During summer, a substantial influx of tourists is another factor in the increased energy demand across GB. However, the region is significantly affected in winter, as river flows decrease to drastic low levels, while harsh weather increases energy demand. Seasonal variation in electricity generation, demand, and shortfall of the ten districts of GB are clearly illustrated in Fig. 1. Gilgit region has 6 districts namely Gilgit, Nagar, Hunza, Ghizer, Diamer

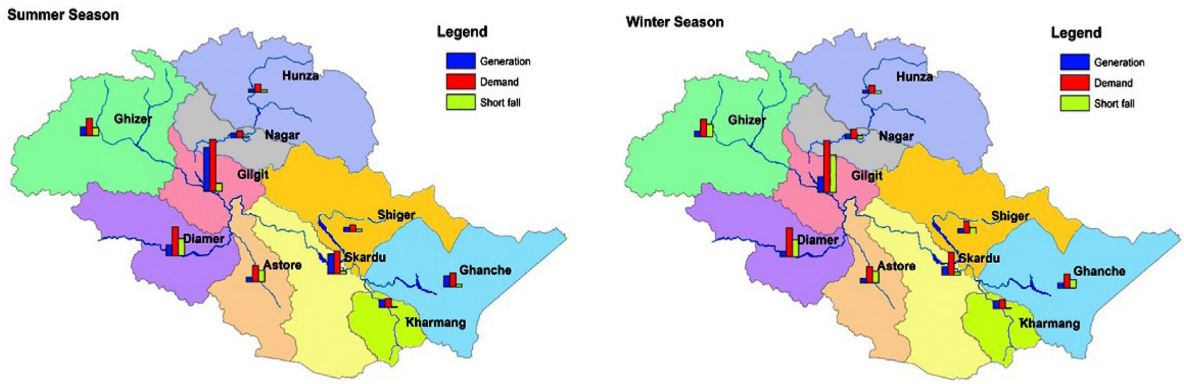
Table 1
Overview of different articles related to rural electrification and hybrid system.

Sr.	Study site	Load types	Resources	Findings
1	Chunian, Punjab (Kamran et al., 2018)	Residential, stores and schools	Hydro, wind, solar, DG and battery	Analyzed three strategies i.e. (a) available resources, (b) replacing hydro with DG and (c) load/demand management. Optimum solution is given by micro-hydro and solar with COE 0.0437 \$/kWh and net present cost (NPC) \$ 284,877.10% capacity shortage on the load.
2	Nooriabad, Sindh (Rehman et al., 2016)	Residential, commercial and community sectors	Wind, solar, DG and battery	Consider a hypothetical village of 100 households having 205 kWh daily energy consumption. Environmental analysis has manifested that PV/wind/DG/battery system would avoid 1060-tons carbon emissions than standalone DG system
3	Chaghi and Ornach, Baluchistan (Ismail et al., 2015)	Residential and community	Solar, wind, DG and battery	Carried out carbon emission analysis for two distant areas. Optimum result showed that 75 kW PV, 150 kW wind turbine, 130 kW DG and 96 batteries (6 V each) gives least cost of energy. The system contributes 18% excess electricity and 51% reduction in greenhouse gas emissions than DG system.
4	Murshakhel KPK, Pakistan (Younas et al., 2019)	Community and commercial	Hydro, solar and biomass	Three different combinations of the resources have been comparatively analyzed. Results showed PV/hydro has most economical i.e. COE 0.088 \$/kWh, while hydro/biogas was also compatible with 0.093 \$/kWh.
5	Cape town, South Africa (Luta and Raji, 2019)	Residential and commercial	Solar, super conductor, and fuel cell.	Used HOMER Pro for optimal sizing of hydrogen fuel storage and super conductor for reliable electricity. Result showed 400 kW electrolyzer with 80 kg H_2 storage and 16 strings of 32,768 number of super conductors required for 98.2% PV production.
6	Kavaratti, India (Singh et al., 2017)	Metropolis	Solar, wind, DG and battery	Analyzed load profile of a remote island through Dig SILENT Power Factory 6 and used HOMER Pro to model a hybrid system. Levelized cost of energy found to be 0.110 \$/kWh and \$ 15,039,701 NPC for a lifetime of 25 years.
7	Makkah, Saudi Arabia (Al Garni et al., 2018)	Metropolis	Solar and grid	Comparatively analyzed different tracking system of grid connected PV. Fixed system was economical while vertical axis has 34% more energy. Vertical tracking PV system can purchase minimum energy from grid and gives an optimized result at 0.04475 \$/kWh COE.
8	Mahishpur Dhaka Bangladesh (Bhattacharyya, 2015)	Community and small industry	Solar, wind and battery	Presented a business model to replace solar home system (SHS) project by mini grid. A case study of an un-electrified village has been analyzed and result shows that mini-grid system can give reliable energy at half of the capital cost of SHS.

(Chilas) and Astore, while Skardu, Ghanche, Kharmang and Shiger are the district of Baltistan region. Gilgit is the capital of the GB region and due to trade activities, it has highest gap of 54.8 MW in winter, while the total shortfall of the whole GB is about 242 MW.

Gilgit-Baltistan has a rugged terrain that makes an extension of the national grid very costly. Therefore, GB remains electrically isolated from the country and consequently faces severe shortfalls. In near future, a mega hydro project like Diamer-Basha will enable the construction of a 765 kV double-circuit transmission line to connect the region with the national grid (National Transmission & Dispatch Company , NTDC). Though a small region of GB in south-east will be connected to national grid, interconnection of all the dispersedly populated areas through the mountainous terrain is a daunting task for provisional government. SG technologies made it favorable to share energy among distributed region with a robust centralized and distributed energy management system coupled with smart energy hubs and storages, which provide reliable, secure and resilient clean energy with minimum transmission congestions (Gong et al., 2020; Mohamed et al., 2020). Therefore, micro grid technologies will remain most suitable for provision of electricity to these off-grid areas. Moreover, micro grids are crucial building blocks of future national grids with in-built resilience.

Across GB, power is generally distributed over short distances through 11 kV distribution lines for domestic, commercial, and industrial usage. In only a few areas of Gilgit and Skardu, the power supply network has been augmented with 66 kV transmission lines, while a majority of the GB region relies on 11 kV feeders, where each feeder is independently supplied by a group of hydel and thermal power plants. This transmission and distribution system experiences tremendous operational difficulties in terms of selective tripping and load management. Faults are cleared by tripping an entire feeder because of limited switchgear deployment along the length of the feeder. Moreover, load shedding by intentional simultaneous tripping of multiple feeders is practiced throughout GB to manage severe power shortages.



District	Generation	Demand	Short fall
Gilgit	37.95	45	7.05
Diamer	9.39	25	14.81
Skardu	17.5	20	2.5
Ghizer	7.79	15	7.21
Ghanche	9.7	12	2.3
Astore	3.9	14	10.1
Nagar	4.1	6	1.4
Hunza	2.9	7	2.1
Shigar	3.64	6	2.36
Kharmang	7.09	8	0.91

District	Generation	Demand	Short fall
Gilgit	25.2	80	54.8
Diamer	7.91	25	17.09
Skardu	13.55	30	14.45
Ghizer	4.99	25	19.43
Ghanche	6.79	20	13.05
Astore	3.74	22	18.26
Nagar	3	9	5.5
Hunza	2.5	9	4.5
Shigar	1.87	10	8.13
Kharmang	5.92	12	6.08

Fig. 1. Electricity demand and supply of Gilgit Baltistan in summer & winter season (Hussain and Akhter, 2018).

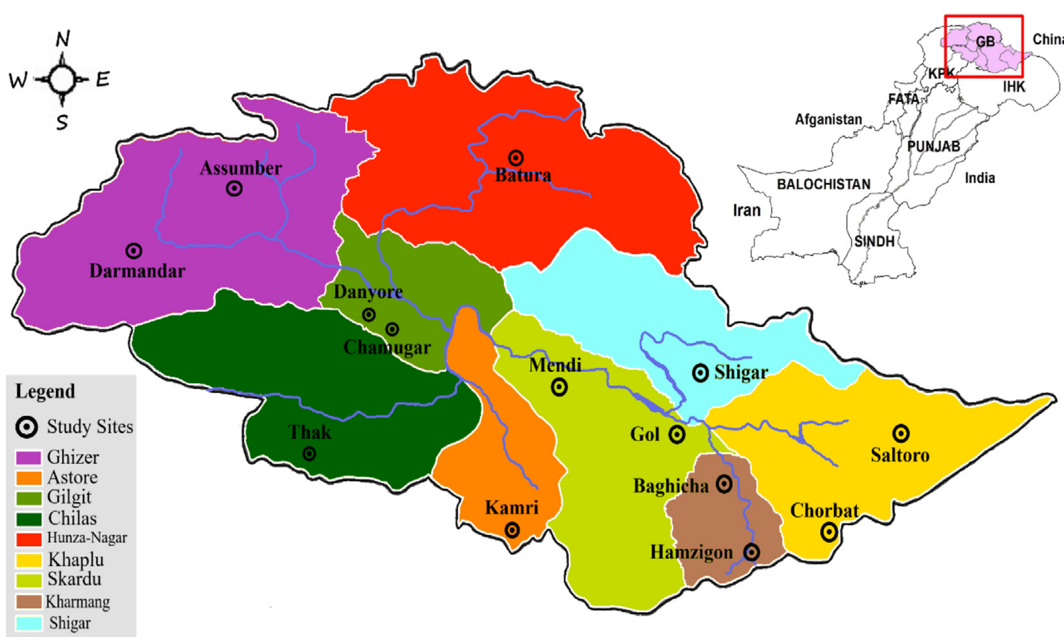


Fig. 2. Solar, wind and hydro hybrid energy system study sites of Gilgit-Baltistan.

The hydroelectric power supply is unable to meet full load demand, therefore population across Gilgit-Baltistan has to rely on other energy sources to fulfill their needs. Several environmental complications are associated with this pattern of energy usage. For example, continuous felling of trees and bushes for firewood is contributing to deforestation in many parts of the region. Furthermore, melting glaciers are a big threat for the future dwellings in GB. Domestic and regional practices of harmful industrial emissions will further elevate the glacier melting rate over the next decade. The usage of fossil fuel-based energy resources for household and commercial purposes is one of the major factors in melting glacier across the region.

A recent study about the Himalayas, Karakorum, and Hindukush mountain ranges provides evidence that temperature change of this region may exceed 2 °C, i.e., between 3-5 °C (Krishnan et al., 2019). The rising temperature will further increase the melting of precious glaciers in the region. A study into tapping the indigenous renewable resources across Himalayas and Karakorum was desperately needed to counter the alarming situation by attaining positive effects of renewable resources on the climate. This study focuses on the assessment and adaptation of a hybrid energy system for 14 sites across GB, marked in Fig. 2, as proposed hybrid renewable system can relieve the region from drastic climate change and environmental complications. These sites are selected based on available demand, population, and energy resources data.

3. Methods

The off-grid hybrid energy system is gaining attention for rural electrifications across the world. Techno-economic studies through HOMER software have been conducted since its development by National Renewable Energy Laboratory (NREL), the USA in 1993. HOMER Pro is the latest version, and it has powerful optimization tools that consider several energy resources running at the same time (Francklyn, 2017; Sinha and Chandel, 2014). HOMER Pro is preferred for its robustness and hourly simulation with sensitivity analysis. It is pertinent to note that other energy software like RETScreen, iHOGA, HYBRID2, and System Advisor Model (SAM) lack these features (Sharma et al., 2014; Freeman et al., 2018). Moreover, it facilitates a detailed configuration of various energy resources that can be coupled with different storage and heating systems. Besides, atmospheric parameters like wind speed, temperature, solar irradiance, and clearness index of any location can be directly extracted from its online database.

Hybrid energy system model is designed by using the inbuilt modules of different components of generation, storage, and load sources. The hybrid system composed of built-in energy generating sources such as hydroelectric turbine, wind turbine, solar module, and diesel generators, batteries array for backup storage and the hourly demand is inserted in the load module of HOMER Pro software. HOMER optimizer is used for optimal balance of energy at each hourly step of simulation time. This software simulates on proprietary derivative-free algorithm and optimizes a hybrid system based on net present cost as an objective function, which is given as (Afridi et al., 2018).

$$Objective\ Function\ (OF) = min(NPC_{total}) \tag{1}$$

$$NPC_{total} = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_o \tag{2}$$

Similarly, the COE is calculated as,

$$COE = \frac{LCC}{\sum_{t=1}^{T} E_{total}} \tag{3}$$

$$LCC = C_{\mathrm{cap}} + C_{\mathrm{rep}} + C_{\mathrm{OM}} + C_{fuel} - C_{salvage} \tag{4}$$

Total net present cost ($\mathrm{NPC_{total}}$) depends upon C_{t} - total cash inflow during the time period ‘t’, C_{o}- the total initial investment cost, and the discounted rate is ‘r’. COE is linked to the total annual energy production (E_{total}) and life cycle cost (LCC), which includes parameters such as capital cost (C_{cap}), replacement cost (C_{rep}), operation and maintenance cost (C_{OM}), fuel cost (C_{fuel}) in case of diesel generators, and salvage cost (C_{salvage}) associated with the respective components.

The study starts with the identification of sites available for hydroelectric power generation across GB. The population near the hydro sites are used for assessing the energy demand at the respective site. Primary data of renewable energy resource characteristics such as water flow rate, wind speed, and solar irradiance at each site is used to analyze different combinations of a hybrid system. Techno-economic analysis at each site has been carried out for multiple resource combinations with or without battery or DG backup. Different combinations of solar, wind, hydro, and battery hybrid energy systems have been recommended for each site, based on net present cost, and cost of energy. Furthermore, emissions from each combination involving DG are helpful in environmental analysis. HOMER Pro software is used for detailed comparative analysis of the following combinations:

i. Hydro/Wind with DG or Battery Storage.
ii. Hydro/PV with DG or Battery Storage.
iii. PV/Wind with DG or Battery Storage.
iv. Hydro/Wind/PV with DG or Battery Storage.

In major parts of GB, hydroelectricity is coupled with electric power from diesel generators to minimize load shedding periods, especially in winters. Moreover, the energy mix of GB demonstrates that only one-fourth of energy is provided by electricity i.e., mainly hydropower. RETScreen Expert is used for analyzing the impact of current energy mix and energy from the hydro/DG hybrid system on forests absorbing emissions and glaciers. The social cost of carbon emission is a key element in developing a policy related to climate change and energy. Therefore, using the past literature SCC is also calculated for the current energy mix of GB and the hydro/DG system scenarios.

3.1. Load assessment

Since about 75% population of Gilgit-Baltistan is connected to unreliable and inefficient generating plants, it faces severe shortfalls both in summer and winter season (UNICEF, 2017). Data for load assessment and conservative demand at the selected sites are provided by Gilgit-Baltistan Water & Power (GBW&P) department. Furthermore, the number of households and electricity demand for lighting, cooling, heating, cooking, and economic activities are given by local community-based organizations. Per capita electricity consumption of Pakistan has been about 970 kWh/year in 2016 (NEPRA, 2018). In Gilgit Baltistan, on average a household occupies 8 persons, thus a ratio of 21.26 kWh/day per household is used to find the net energy demand at each site (Cerny and Havrankova, 2013). By comparative analysis of this data, adequate energy demand for the population at each site has been assessed, as given in Table 2.

HOMER Pro software user has an option to insert its hourly load profile in the load module. Hybrid modeling of an unelectrified area requires an implicit profile or use of the built-in community, residential and industrial scheme of the software. In this study, a one-year load profile of the Skardu grid is used in the hourly load module and the data is provided by the GBW&P department, Skardu. Since temperature variations and climate conditions are the same across the region, similar consumption patterns are assumed for each site. Moreover, load profile data of the Skardu grid is used in each case because the economic and trading activities are similar throughout GB. Blue colored graph in the upper part of Fig. 3 shows the real data of Skardu grid that includes multiple blackouts. The blackouts are represented by points in the graph when it touches or approaches 0 MW. The blackouts account for nearly half of the year, rendering this data unsuitable for analysis. Therefore, a base to peak ratio of 0.375 is used to find the base load of the given grid in Skardu (Sen and Bhattacharyya, 2014). Baseload determined by the peak ratio is illustrated in reddish yellow color in the upper part of Fig. 3. The modified profile is a realistic grid profile, and this hourly load data is used as a reference for simulation at each site. The modified hourly load profile of Skardu grid is then scaled up or down, in the HOMER Pro load profile, according to the daily demands of respective sites listed in Table 1. The boxed region in the upper part of Fig. 3 is data of the first half of March that is presented in greater resolution in the lower part of Fig. 3, to clearly illustrate daily peak and non-peak hours.

3.2. Solar irradiance

Real-time hourly data of irradiance are required for accurately modeling a hybrid system utilizing the solar energy module. The on-ground data for solar is not available for the selected site. Therefore, the hourly profile generated by the built-in data sets of National Aeronautics and Space Administration (NASA)

Table 2
Electricity Demand at the respective sites under study.

Project area	Location Coordinates	Households No.	Energy demand kWh/day	Peak load kW	Average load kW
Assumber	36°24.6′N, 73°49.9′E	218	4635	580	167
Darmandar	36°15.2′N, 73°24.2′E	942	20027	2500	834
Chamugar	35°50.8′N, 74°32.3′E	435	9250	1150	384
Danyore	35°55.6′N, 74°23.3′E	980	20835	2600	834
Batura	36°27.6′N, 74°53.3′E	865	18390	2300	834
Thak	35°17.4′N, 74°06.5′E	2450	52087	6510	2169
Kamri	34°47.5′N, 75°04.7′E	190	4039	500	158
Chorbat	34°55.1′N, 76°42.0′E	430	9142	1150	384
Saltoro	35°12.3′N, 76°28.6′E	1525	32422	4050	1350
Baghicha	35°01.5′N, 76°05.6′E	830	17646	2200	735
Hamzigon	34°44.3′N, 76°10.4′E	790	16796	2100	700
Gol	35°10.5′N, 75°54.0′E	935	19878	2480	835
Mendi	35°35.5′N, 75°12.6′E	1320	28064	3500	1167
Shigar	35°28.6′N, 75°41.8′E	1395	29658	3700	1235

Fig. 3. Real time hourly load profile of Skardu grid used in HOMER Pro simulations.

is used in the study. The monthly average clearness index and solar irradiance will be synthesized to hourly data by using the built-in algorithm of V.A. Graham in HOMER Pro (Kumar et al., 2016). The average daily solar irradiations in the districts of Gilgit-Baltistan are given in Table 3 for each month. Chilas has a good solar profile with maximum irradiance 7.981 kWh/m^2/day in July and an annual average of 5.624 kWh/m^2/day. Furthermore, Khaplu district has the least radiation in December i.e., 1.783 kWh/m^2/day, while the annual average is 4.864 kWh/m^2/day. Across GB, low solar radiation is experienced in winter months, whereas good solar radiation in summers. The intensity of solar radiation is remarkable due to the high clearness index owing to a clear and particle-free atmosphere. Furthermore, one of the most interesting facts about the PV module is that solar cells operate efficiently at low temperatures. Therefore, it is believed that the adaptation of the PV system will provide efficient energy to the cold region of GB.

3.3. Wind speed

Wind resource mapping by NREL, in collaboration with the United States Agency for International Development (USAID), illustrates that there are many small wind resource patches across Gilgit-Baltistan. Furthermore, the global wind atlas by Energy Sector Management Assistance Program (ESMAP) and World Bank shows many isolated wind corridors in the north of Pakistan; most of them exist in Gilgit-Baltistan and Azad Jammu Kashmir (Baloch et al., 2017; Badger et al., 2019). Due to a lack of availability of on-ground monthly and hourly wind speed data, the online available data sets of NASA are directly incorporated in HOMER Pro software. Baseline wind speed data available in

Table 3
Mean daily solar irradiance in kWh/m^2/day of the districts of Gilgit-Baltistan.

Month	Baltistan Region				Gilgit Region				
	Khaplu	*Kharmang*	*Shigar*	*Skardu*	*Ghizer*	*Chilas*	*Astore*	*Hunza-Nagar*	*Gilgit*
Jan	2.197	3.010	2.786	3.530	3.002	3.201	2.985	3.013	3.074
Feb	3.086	3.369	3.522	3.963	3.890	4.128	3.835	3.752	3.938
Mar	4.278	4.913	5.192	5.539	5.067	5.319	4.989	4.982	5.093
April	6.582	6.224	6.487	6.442	6.109	6.712	6.098	6.336	6.247
May	7.515	7.125	7.404	7.259	6.958	7.259	6.843	7.306	7.095
June	7.682	7.284	7.600	7.748	7.338	7.834	7.156	7.563	7.443
July	7.132	6.867	7.149	7.367	7.124	7.981	6.974	7.112	7.189
Aug	6.346	6.168	6.260	6.486	6.191	6.734	6.032	6.273	6.343
Sept	4.950	5.278	5.941	6.087	5.807	6.087	5.586	5.793	5.758
Oct	4.006	4.381	4.905	5.113	4.594	5.106	4.432	4.683	4.649
Nov	2.818	3.465	3.702	3.975	3.536	3.952	3.437	3.506	3.529
Dec	1.783	2.258	2.688	3.582	2.461	3.173	2.390	2.475	2.508

the software are measured at an anemometer height of 50 m. For different hub heights of a wind turbine, HOMER Pro adjusts the baseline data to the scaled value. For all selected sites, wind resource data includes the values of four advanced parameters: (i) Weibull distribution; (ii) hourly autocorrelation factor; (iii) diurnal pattern strength; and (iv) hour of peak wind speed (Waewsak et al., 2011). In the study, hub height ranges from 40–80 meters depending upon energy demand as well as the topography of the site and surrounding area.

Wind through the deep valleys will be effective in improving the energy access in Gilgit-Baltistan. Fig. 4 shows the average monthly wind speed in various districts of the Baltistan and Gilgit region. The hourly wind speed varies abruptly than that of given monthly average, the figure gives variation of wind speed of the study sites of the two regions. Khaplu has the highest wind speed of 7.79 m/s in December, while an annual average of 7.11 m/s throughout the year. Chilas experiences the lowest wind speed of 5.2 m/s in April and an annual average of 6.05 m/s. However, the overall wind speed across GB places the region in "very good" wind energy resource potential area (Bruck et al., 2018).

3.4. Hydro flow

Gilgit-Baltistan is known as a water bank of the country. Many micro and mini hydroelectric plants are used to provide electricity to suburban centers and small rural communities. The operating cost of small hydropower plant is very little compared to other conventional and renewable sources. Therefore, local government and international organizations have consistently shown interest in financing community-based micro-hydro stations in GB. Plenty of mini and micro-hydro sites have been discovered across GB which could not be developed due to lack of resources and investment. Moreover, the provision of electricity by a single resource leads to a reliability issue because low water flow in winter cannot cater to the high demand. As a result, a back-up system must be incorporated to ensure a reliable supply of electricity for heating, lighting, and cooking purpose.

The dispersed population of GB is mostly provided electricity through 11 kV distribution network directly from a local hydropower plant. The water flow data for different streams and perennials of GB are collected from the GBW&P department. Fig. 5 show the average monthly water flow rate (m^3/s) at different hydro sites of Baltistan and Gilgit areas, respectively. An exceptionally high flow rate of 15.87 m^3/s occurs in Saltoro Lungma (river) of Khaplu district. In contrast, Chamugar Nullah (stream) experiences the least average annual flow of 1.69 m^3/s. The average annual flow of all the sites indicates the availability of adequate hydropower for electrification, but there is a large difference in the summer and winter flows.

The average stream flows between November and February lie in a range of 0.16–1.63 m^3/s for all the hydro sites except Batura (3.39 m^3/s), Chorbat (4.34 m^3/s), and Saltoro (6.67 m^3/s). Furthermore, summer flows between June and September increase more than ten times the streamflow in a winter month, for many sites. The monthly mean water flow of one year is used as an input in the HOMER Pro hydro resource module, while the design flow rate of hydroelectric turbines can be calibrated by the user. In this study, the design flow rate of the turbine at each site is two times the minimum available water flow at the respective hydro site. This study mainly focus on peak winter demand, thus the least hydro flow rate data of each site has been as reference for designing the flow rate of turbine at respective sites.

Similarly, an average flow of each month has been given to HOMER Pro, which builds a set of 8760 values, or one streamflow value for each hour of the year. It creates hourly values by assuming that the streamflow remains steady at the average value throughout the month; the HOMER Pro assigns the monthly average value to each hour of that month and uses this data to calculate the output of the hydro turbine in each time step.

3.5. Components used in hybrid system

To model a hybrid system based upon net present cost and cost of energy, different cost involves the components, that convert diverse energy sources into end-use electrical energy. These costs include capital cost for installation, replacement cost, and annual operation & maintenance (O&M) cost. The technical specification and the costing of all the items have been discussed one by one.

3.5.1. Solar PV

Generic flat-plate PV modules of 1 kW capacity are used in this study. Capital cost per kW in the local market is nearly 700 $/kW, whereas replacements cost is taken as 500 $/kW (Shahzad et al., 2017). In this study, the lifetime of a PV panel is 25 years and the de-rating factor is 80%. The HOMER Pro optimized the size of the PV module required by analyzing the available hourly irradiation and varying load at the respective sites. Though ground reflectance increases in winters due to snowfall, the default value of 20% is used in the study (See Table 4).

3.5.2. Wind turbine

Wind turbines will convert the kinetic energy of wind into electrical energy through mechanical means. They have different shapes and sizes that can be installed at the sites according to the wind speed and location. The wind blows irregularly and makes the power output of the wind energy system variable and fluctuating. Therefore, the system must be coupled with other energy sources for reliable provision of electricity. The HOMER Pro has a built-in library of different wind turbines that contains their specifications provided by manufacturers.

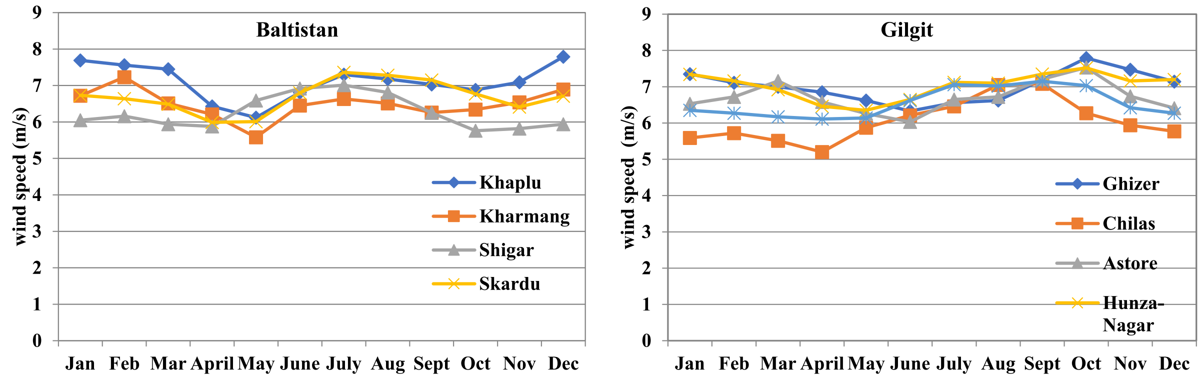


Fig. 4. Monthly average wind speed (m/s) of the districts of the Baltistan and Gilgit region.

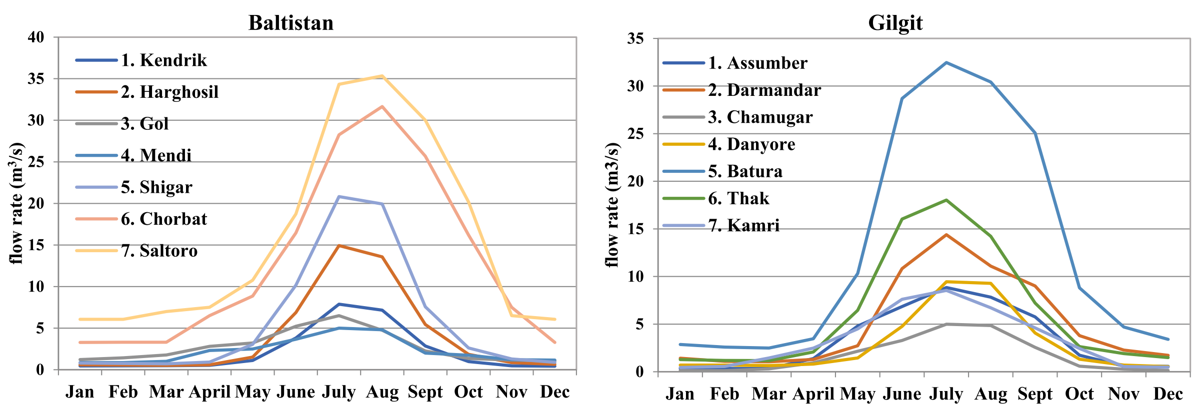


Fig. 5. Monthly average water flow rate (m3/s) at study sites of Baltistan and Gilgit region.

Table 4
Cost per kW and technical parameters of PV Panels (Shahzad et al., 2017).

Capital cost ($/kW)	Replacement cost ($/kW)	O&M cost ($/kW/year)	Lifetime (year)	Derating factor (%)
700	500	10	25	80

For this study, Leitwind turbines of rated capacity ranging between 800 kW to 2000 kW are used for peak demand greater than 800 kW. EWT Directwind turbine of rated capacity 250 kW and 100 kW Norvento nED are used for peak demand less than or equal to 500 kW. These turbines are chosen due to their low cut-in speed nearly 3 m/s and high cut-out speed of 25 m/s. These turbines give optimal ratio of rated capacity between 5.5–10.5 m/s wind speed, which means they generate greater energy at the respective wind speed as compared to other turbines in the library. Moreover, at rated wind speeds 12–20 m/s, these turbines are very effective and give maximum output before applying mechanical brakes at cut-out speed. The per kW costs of wind turbine are given in Table 5.

3.5.3. Power converter

Intermittent renewable sources need a storage system to provide reliable electricity to the end-users. Solar cells generate electricity as direct current (DC) power, while most of the household load operates on alternating current (AC) power. Similarly, the battery energy system can store only DC power. Thus, a power converter provides a bridge to transfer power between AC and DC systems. A generic power converter is used in the hybrid system and the technical specification with costs is given in Table 6.

3.5.4. Battery storage

As we know that solar and wind energy production depends upon the continuously varying solar irradiance and wind speed. One of the significant barriers to adopting such renewable sources is their fluctuating nature, which results in non-reliable electricity provision to the consumers. Battery storage tries its best to cater to such adverse situations, as it will provide the stored energy during low wind speed and bad weather or at night. In this study, lithium-ion battery is used for analysis, as it is easily available in the local market and better than lead–acid battery. Table 7 gives the economic and technical parameter of 1 kWh Li-ion battery used in hybrid modeling.

3.5.5. Diesel generator

Diesel generator gives a promising solution in a hybrid system with wind and solar energy sources. The quick ON–OFF property ease to use diesel generators with intermittent energy sources. In the grid-connected urban areas of developing countries, DGs are also used as backup resources in case of power shut down. Currently, many suburban areas of GB have been powered with DGs in winter, while the government provides fuel in all the places and it takes little hassle and cost to transport the fuel to the site. The capital cost of DG is marginal and comparable to the components of renewable energy sources, but O&M cost is much higher than the others due to the high price of diesel fuel. DG set has been used in the study to analyze the impact of current hydro/diesel practice on the environment. Table 8 gives the technical parameter and economic cost per kW DG used in different hybrid systems.

Table 5
Cost per kW and other technical parameters of Wind Turbine (Jahid and Hossain, 2018).

Capital cost ($/kW)	Replacement cost ($/kW)	O & M cost ($/kW/year)	Lifetime (year)	Cut-in speed (m/s)
1500	1250	10	25	3

Table 6
Cost and other technical parameters of power converter (Shahzad et al., 2017).

Capital cost ($/kW)	Replacement cost ($/kW)	Lifetime (year)	Efficiency (%)	Relative capacity (%)
150	150	15	90	100

Table 7
Cost and other technical parameters of Li-ion battery (Shahzad et al., 2017).

Capital cost ($/kW)	Replacement cost ($/kW)	O&M cost ($/kW/year)	Lifetime (year)	Round-trip efficiency (%)	Max. capacity (Ah)
200	200	10	15	80	276

Table 8
Cost per kW and other parameters of Diesel Generator (Jahid and Hossain, 2018).

Capital cost ($/kW)	Replacement cost ($/kW)	Lifetime (hours)	Efficiency (%)	O&M cost ($/hour)
500	450	15000	45	0.03

3.5.6. Hydroelectric power

In most of the country, hydropower remains one of the most important renewable sources due to its least variability and smooth power generation. Rural electrification in many isolated villages of northern Pakistan has been done through micro/mini-hydropower plants. The ease of construction and operation make micro/mini hydroelectric station to be monitored by local community through capacity development programs. Capital cost of these plants are somehow noticeable than other sources, but its invariable hourly provision of electricity and high efficiency make it unique in the hybrid system. Technical and financial cost for 14 hydro sites of Gilgit-Baltistan is given in Table 9. These costs are provided by the GBW&P department and local organization working on hydropower plants. Capital costs involve purchase of turbine and auxiliary equipment, transportation cost and land acquisition cost. The O&M cost involve the payment to the engineers, sub engineers and workers that are supervising the respective hydro plant (See Table 9).

4. Results & discussion

The following analysis has been carried out based on the HOMER Pro simulation results, and emission findings from RET Screen Expert.

4.1. Comparative analysis of COE

The optimal combination of different resources in the hybrid energy system depends upon the hourly electricity demand and profile of available resources at the respective site. Simulations have been performed by the HOMER Pro optimizer on 14 different sites of the Gilgit and Baltistan region. The proposed systems at each site have been optimized on the basis of net present cost and cost of energy. All the five possible combinations have been analyzed to check the availability of adequate alternate energy resources in the form of wind and solar at the respective site. Fig. 6 shows the possible combination of different renewable sources with and without DG/battery backup for all the sites of Gilgit region based on COE. Furthermore, in Fig. 7, the COE of all the sites of Baltistan region is given for comparative analysis.

In these (Figs. 6 & 7), black line is the cost of hydro energy i.e. 10.9 ¢/kWh; the tariff of 1.5 MW plant installed on the Jhang Branch Canal in Punjab, set by National Electric Power Regulatory Authority (NEPRA) (Hussain, 2016). While the red line is the cost of energy from the national grid in the capital of Pakistan; the tariff of IESCO 17.5 ¢/kWh, set by NEPRA (Yasir et al., 2018). These two references are used for comparative analysis of different renewable combinations and comparison between the study sites. The figures are labeled by COE on *y*-axis while *x*-axis is labeled by different combinations of hybrid systems with subcategory of study areas of the respective region. Results show that in absence of back-up battery storage or DG the hydro/PV hybrid system is not feasible for any site, due to following reasons. The annual peak of every site occurs in the night hours of the winter season, so the low hydro flow during winter cannot solely cater to the peak value and solar energy is only available during daytime as there is no battery storage.

4.1.1. Gilgit region

The profile of wind across the Gilgit region is astonishing and capable of catering to the peak demand of winter at the least cost of energy with no backup system. All the combinations with hydro sources give a suitable cost of energy, which is less than hydro tariff except hydro/PV/DG and hydro/DG of Chamugar and Danyore sites. Hydro/wind/battery hybrid system at Assumber gives the least cost of energy i.e., 4.72 ¢/kWh, while Kamri has the maximum COE 9.68 ¢/kWh for the same hybrid combination. The Fig. 6 shows that combinations of renewable energy sources such as wind/hydro, solar/wind/hydro, wind/hydro/battery, solar/wind/hydro/battery are feasible to provided clean energy at all the respective sites of Gilgit region. Wind and solar combination with DG or battery are only recommended if other cheap hybrid possibilities do not exist. Wind/solar/battery at Kamri gives the least COE 12.61 ¢/kWh with battery, while wind/solar/DG at Thak has the maximum cost of energy i.e., 26.53 ¢/kWh. At Assumber sites, hydro with DG or battery gives promising solution with minimum COE up to 5.1 ¢/kWh.

4.1.2. Baltistan region

Baltistan region lies in the Karakorum range with famous glaciers such as Baltoro, Biafo, Braldu, Siachen, Bilafond, and Gondokoro etc. These freshwater banks provide enough hydroelectric power in summer, but alternate energy source must be incorporated for higher winter demand. Fig. 7 illustrates the cost

Table 9
Cost per kW of different micro, mini, and small hydropower plant of GB.

Sr. no	Sites under study	Capital ($/kW)	Replacement ($/kW)	O&M ($/kW/year)	Design flow rate (m^3/s)	Net head (m)
1	Assumber	1380	1000	37.4	0.67	92
2	Darmandar	1720	1500	41.2	2.1	145
3	Chamugar	1980	1600	43.4	0.22	385
4	Danyore	1500	1200	45	1.3	93
5	Batura	1425	1075	39.9	4.98	72
6	Thak	1650	1250	44.5	2.34	300
7	Kamri	1580	1200	47.4	0.9	76
8	Chorbat	2006	1360	44	6.56	210
9	Saltoro	1680	1180	41	12.12	35
10	Baghicha	1800	1600	62	0.84	270
11	Hamzigon	1460	1200	52	1.04	152
12	Gol	1550	1250	46	1.3	98
13	Mendi	2050	1750	61	1.7	245
14	Shigar	1965	1500	49	1.42	236

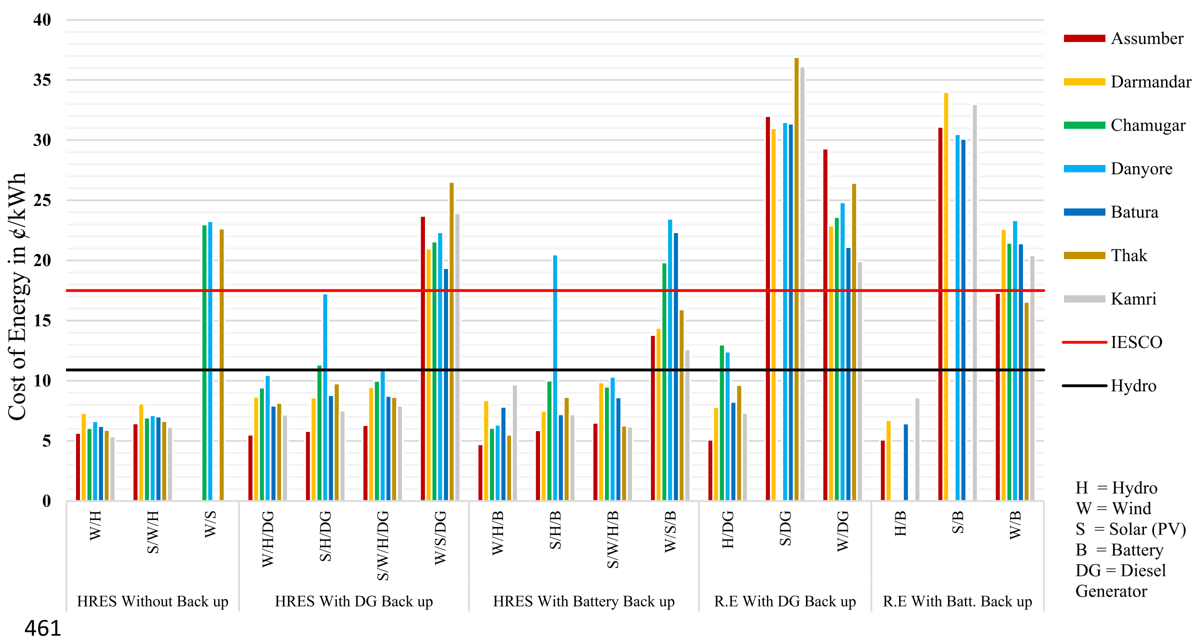


Fig. 6. Cost of Energy for all the possible hybrid system combinations of Gilgit Region.

of energy for different hybrid systems in Baltistan region. Most of the sites are feasible for deployment of renewable energy and show least cost of energy, especially for hydro coupled hybrid system.

The simulation results from the HOMER Pro optimizer show that solar and wind energy sources with hydropower will give a viable solution for all the sites. Hydro remarkably decreases the COE from 25.63 ¢/kWh for wind/solar/battery system to 5.34 ¢/kWh for hydro/wind/solar/battery of the Gol site. The same decrement trends can be seen in other hydro combinations for all the sites of the Baltistan region. Saltoro, Chorbat, and Gol rivers have multiple sub-tributaries supported by different glaciers, which facilitate adequate water flow in winter. That is why the least COE is given by hydro/battery system for these sites i.e. up to 4.74 ¢/kWh Saltoro, 4.86 ¢/kWh Chorbat and 5.57 ¢/kWh Gol. But hydro/battery is not feasible for all the other remaining sites due to significant capacity shortage.

Wind/hydro and solar/wind/hydro hybrid combinations, with or without battery, give a feasible solution for all the sites, with the minimum COE 4.84 ¢/kWh in case of wind/hydro system of Shigar and the highest COE 8.24 ¢/kWh for solar/wind/hydro/battery system at Chorbat. Solar/DG hybrid system has maximum COE 39.6 ¢/kWh at the Shigar site, which is the highest cost of energy among all the possible combinations for the Baltistan region.

4.2. *Techno-economic analysis*

As mentioned in the methodology, different renewable combinations with battery or DG will be analyzed for reliable provision of electricity from highly intermittent wind and solar resources. Techno-economic results with net present cost, cost of energy, payback period and component sizes of these cases are given in Appendix (Tables A.1–A.8) of the paper. These hybrid systems will be comparatively analyzed and discussed with reference to a backup system (DG/battery storage) as following.

i. *Hydro/Wind with DG or Battery Storage:*

Hydro/wind/battery system costs less than the hydro/wind/DG system at most of the sites of Gilgit-Baltistan. Assumber and Kamri have almost equal installed capacity of hydropower. Assumber gives the least COE i.e., 4.7 ¢/kWh, while Kamri has higher COE 9.68 ¢/kWh among the hydro/wind/battery system of all the study sites. This is because hydro flow rate at Assumber river can provide a good share of electricity from hydropower even in the winter season. In consequence, only 100 kW wind turbine with 157 kWh battery bank is enough to provide reliable electricity during peak demand. For the reliable provision of electricity at Kamri, the sizes of wind turbines and battery banks need to be increased to 250 kW and 300 kWh, respectively. Besides, most of the sites have more than 50% excess energy in both

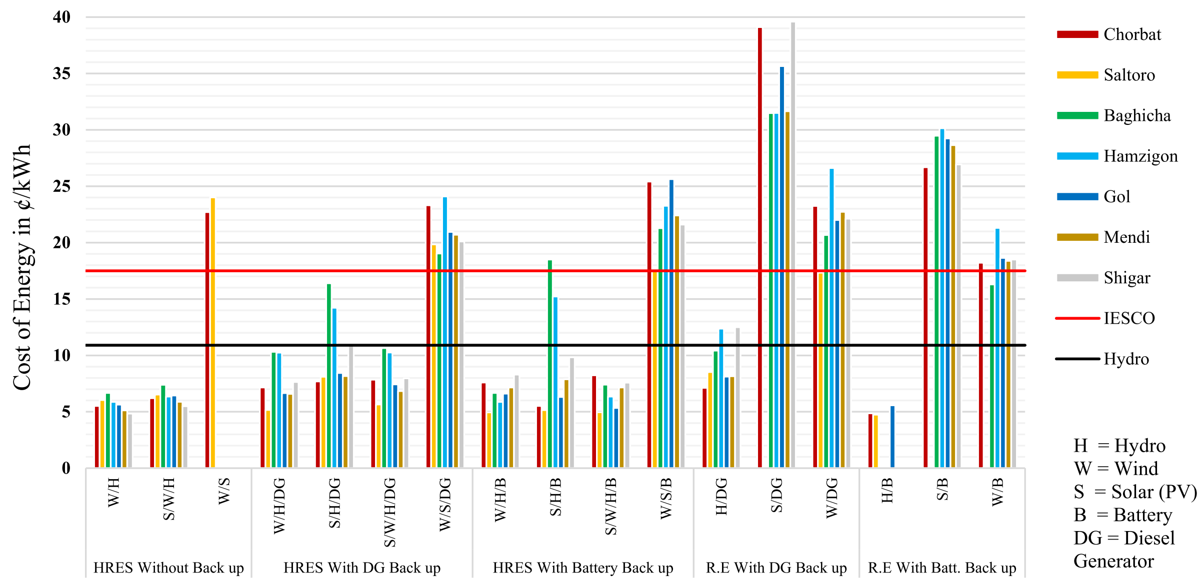


Fig. 7. Cost of Energy for all the possible hybrid system combinations of Baltistan Region.

Hydro/wind/DG and Hydro/wind/battery system. Shigar, Chorbat, and Kamri are the sites where the DG back up system incurs less COE than the battery storage system.

ii. *Hydro/PV with DG or Battery Storage:*

The sunshine hours in winter will probably be lesser than the summer season. In the study, the peak demand occurs after the sunsets i.e., after 5.30 p.m. in winter months. Therefore, DGs will be used at the respective sites for uninterrupted provision of electricity to cater the high demand at nighttime. Moreover, due to bad weather and low water flow in winter, DGs may also need to be incorporated for the daytime demand. Therefore, for all sites, the COE for hydro/PV/DG system is higher than that of hydro/wind system. It is interesting to note that Danyore, Baghicha and Hamzigon have higher COE for hydro/PV/battery system than DG backup i.e., 20.5 ¢/kWh, 18.5 ¢/kWh and 15.22 ¢/kWh, respectively. While for all the other sites, battery provides lower cost of energy than DG. For the above referred three sites, the installed capacities of solar energy systems are much greater than hydropower plants. Consequently, there is a good share of PV in overall energy production in the hydro/PV/battery system, for example, the highest share of 54.2% for Danyore.

iii. *PV/Wind with DG and Battery Storage:*

Across Gilgit-Baltistan, hydropower is known as the main source of electricity. However, the study reveals that wind and solar energy will also provide enough electricity for the population of Gilgit-Baltistan. The cost of energy for the PV/wind/DG system varies between 17.8–26.5 ¢/kWh. Up to 66% additional energy can be provided by PV/wind/DG system, which shows that available wind and solar profiles can provide adequate energy across Gilgit-Baltistan. The levelized cost of energy for PV/wind/battery system is least for Assumber i.e., 13.8 ¢/kWh. The 3600 kW PV system at Shigar has the highest percentage share of 52.5% in the overall energy production of PV/wind/battery system. For clean energy provision, Danyore needs 36540 kWh battery storage system to replace 2000 kW DG system of PV/Wind/DG.

iv. *Hydro/Wind/PV with DG or Battery Storage:*

Hydro, wind, solar, and battery combination is the most suitable since multiple renewable energy sources provide more reliable green electricity. Furthermore, the intermittency and variability of wind and solar energy can be catered by battery storage. For the hydro/wind/PV/battery system of all the sites, COE is less than the tariff (10.9 ¢/kWh) approved for hydropower plants by NEPRA. Saltoro site experiences the least cost of energy 4.96 ¢/kWh among all the sites, while Danyore has the highest COE 10.32 ¢/kWh. DG share in hydro/wind/PV/DG varies between 0.7–3.8% and DG mainly operates in winters to provide electricity during a shortage of renewable energy. Hydro/wind/PV/DG system also provides an economical cost of energy, but due to environmental concerns, this system will not be recommended for the respective sites.

The overall results, in terms of average NPC and COE, for the above discussed scenarios are summarized in Table 10. It is evident that hydro/wind/battery system is the most suitable across GB with the least overall COE value of 6.8 ¢/kWh and the least NPC of $6,322,356. Moreover, hydro/wind/PV/battery system is the second most promising hybrid system because despite a higher overall COE value of 7.7 ¢/kWh and higher NPC of $7,130,861 it offers greater diversity of renewable resources. It is pertinent to note that due to more steady hydro flows than intermittent wind and solar options, most of the favorable combinations of hybrid energy systems for GB included abundant hydro resources. The worst combination is PV/Wind/DG hybrid system because it gives energy at very high average rate of 21.7 ¢/kWh with 15% net diesel generation across the region that causes higher environmental degradation than other scenarios.

4.3. Environmental & social aspects

The current energy mix of Gilgit-Baltistan highly depends on fossil fuels with a 75% share in overall end-use energy consumption in both rural and suburban areas. RETScreen Expert has an energy module for LPG, biomass, DG, and kerosene oil that can be analyzed in terms of domestic energy usage. Moreover, it gives an equivalent forest area to absorb carbon emissions from such energy sources. The current energy mix of GB contains 40% LPG, 30% firewood (biomass), 6% kerosene oil, and 24% hydroelectric power. In various suburban areas of GB, diesel generators coupled with hydropower have been used to provide electricity in winters. Thus, a hydro/DG hybrid system is also analyzed to provide energy for lighting, cooking, cooling/heating, and economic activities. For such analysis, the percentage share of DG or the total annual generation of DG in the hydro/DG system is used to find the carbon emissions and equivalent forest required to absorb it at each site. The energy mix is used as a reference to

Table 10
Overall average costs of different hybrid combinations for all the study sites of GB.

System	Net present Cost (NPC) $	Cost of energy (COE) ¢/kWh
Hydro/Wind/DG	7,660,947	7.9
Hydro/Wind/Battery	6,322,356	6.8
Hydro/PV/DG	9,894,752	10.2
Hydro/PV/Battery	8,294,782	9.7
PV/Wind/DG	19,696,792	21.7
PV/Wind/Battery	23,352,355	19.9
Hydro/Wind/PV/DG	8,033,786	8.6
Hydro/Wind/PV/Battery	7,130,861	7.7

find the emissions from the energy generation requirements at the respective site.

Furthermore, glacier mass loss from per kg emission of carbon is nearly 15.6 kg, while the loss in the density of glacier ice is about 900 kg/m^3 (Huss, 2013; Marzeion et al., 2018). These two reference values are used to find the glacier mass loss as well as glacier volume loss at each site. Moreover, the social cost of marginal GHG emissions will also be faced in near future because the region is vulnerable to climate change. Therefore, the global social cost of carbon (SCC) at each site is calculated using a reference value of 24.02 $/tC and this SCC is considered an essential factor in making policies related to energy and climate change of the GB region (Tol, 2019). Table 11 shows the environmental results of the current energy mix and its impacts on the surroundings of study sites in the form of equivalent forest required to absorb emissions due to fossil fuel-based energy usage, glacier melting, and SCC. Methane, nitrogen oxide and CO_2 are gases emitted during energy production by fossil fuels. RETScreen follows the GHG emission reduction analysis model to covert the methane and nitrogen oxide into their equivalent CO_2 emissions and forest need to absorb these gases (Palma et al., 2020). 36,742 tons/year CO_2 will be emitted from the current energy mix and about 8349-acres forests are required to absorb the emissions from the 14 sites. Furthermore, about 0.58 million tons of glacier/snow and $ 882,545 will be lost every year due to these emissions and consequently, the sustainability and welfare of the population of GB will be in perils.

5. Conclusions and policy recommendations

Pakistan is a country with diverse renewable energy sources across its territories and has initiated programs to utilize these disperse resources under CPEC activities. Gilgit-Baltistan is proving to be a crucial link in CPEC activities, as this region holds the only ground connection between China and Pakistan. Rapidly changing climate and incessant pollution from current energy mix of the region is an alarming situation for GB. The study has focused on techno-economic and feasibility studies of renewable energy sources in which we have also covered the social and environmental aspects of using carbon graded domestic resources in underprivileged rural areas of Pakistan.

Comparative analysis of COE has shown that wind and hydro coupled with a battery backup, are the most suitable energy resources across GB among all the above discussed combinations, at an average rate of 0.068 $/kWh. PV integration in this hydro/wind/battery system can be more reliable with 60% excess energy in both scenarios, but it elevates the cost to 0.077 $/kWh. The study has shown that such economical hybrid systems will provide clean energy to conserve atmosphere and glaciers from degradation due to drastic toxic gases emissions from end-use energy sources. These hybrid renewable energy systems will provide reliable energy, help in preserving the environment, and reduce the pollution of 36,742 tons/year CO_2 from current energy mix. Moreover, an adequate monetary incentive in the form of social cost of carbon can be saved by implementing hybrid renewable energy systems across the region. The study concludes that adaptation of community-based HRES is a desperate need for Gilgit-Baltistan in the current situation.

Tapping available wind and solar energy in the hydro rich region of the country will surely strengthen the 2030 renewable energy vision of the government and encourage the utilization of indigenous clean resources. To facilitate the private sector, the GB government should give incentives in the form of exemption in customs duty and the sales tax on the imported equipment of renewable energy sources. An independent organization like NEPRA or Alternative Energy Development Board (AEDB) should have jurisdiction over GB so that all stakeholders, including both federal and provincial governments as well as private investors, can effectively synergize their efforts, under a yet to be developed uniform energy and environment policy framework for GB.

Based on the data provided by the GBW&P department, this study has been conducted for the selected sites of GB and more feasible sites of HRES can be identified in the future to fully tap the renewable resource. To model and optimize renewable energy system with different constraints, PSO, MILP, GA, BPSO and similar intelligent algorithm will surely give promising results (Eltamaly et al., 2016). ArcGIS or similar geographic information system (GIS) tools may be helpful in sketching the best points to installed solar and wind farms. Moreover, small metrological stations can be installed at different places in remote areas and HRES can be designed based on real data obtained from the sites. It is assumed that the whole region has the same energy practices, yet detailed comparative analysis can be based on rural/urban as well as district/region division.

CRediT authorship contribution statement

Mazhar Ali: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing - original draft, Visualization, Funding acquisition. **Rashid Wazir:** Conceptualization, Methodology, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Kashif Imran:** Conceptualization, Methodology, Software, Validation, Resources, Writing - original draft, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Kafait Ullah:** Resources, Writing - original draft, Writing - review & editing. **Abdul Kashif Janjua:** Writing - review & editing. **Abasin Ulasyar:** Writing - review & editing. **Abraiz Khattak:** Writing - review & editing. **Joseph M. Guerrero:** Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Table 11
Carbon emission, forest absorbing CO_2, glacier losses, and SCC from current energy mix of GB.

Project area	Current energy mix scenario									
	LPG	Biomass	Kerosene	Hydro	DG	Gross GHG emissions	Forest absorbing CO_2	Glacier mass loss	Glacier volume loss	SCC
	Therms (US)	Therms (US)	Therms (US)	kWh	kWh	tons/year	Acre	tons/year	m3/year	$/year
Gilgit Region										
Assumber	19,978	14,983	2,997	1,447,262	16,097	414	94	6,546	7,140	9,951
Darmandar	99,781	74,836	14,967	7,155,488	153,489	2,134	485	33,719	36,783	51,266
Chamugar	45,891	34,418	6,884	2,998,494	363,046	1,241	282	19,609	21,391	29,816
Danyore	99,605	74,703	14,941	5,552,287	1,743,754	3,542	805	55,963	61,049	85,079
Batura	99,724	74,793	14,959	7,049,087	255,666	2,224	506	35,135	38,328	53,420
Thak	259,387	194,540	38,908	17,651,070	1,349,005	6,392	1,452	100,981	110,157	153,529
Kamri	19,966	14,974	2,995	1,417,140	45,337	440	100	6,952	7,584	10,574
Baltistan Region										
Chorbat	45,127	33,845	6,769	3,150,180	155,360	1042	236	16,455	17,951	25,029
Saltoro	161,560	121,170	24,234	10,887,508	946,740	4,076	926	64,391	70,242	97,896
Baghicha	87,774	65,830	13,166	5,207,838	1,221,592	2,842	646	44,904	48,984	68,255
Hamzigon	83,717	62,788	12,558	5,120,473	1,011,830	2,574	585	40,679	44,376	61,837
Gol	103,753	77,815	15,563	7,174,337	425,596	2,455	558	38,794	42,319	58,967
Mendi	139,524	104,643	20,929	9,606,902	613,206	3,338	759	52,741	57,533	80,188
Shigar	147,494	110,620	22,124	9,593,864	1,210,037	4,027	915	63,637	69,419	96,738
Total	**1,413,281**	**1,059,958**	**211,994**	**94,011,930**	**9,510,755**	**36,742**	**8,349**	**580,506**	**633,256**	**882,545**

Table A.1
Techno economic results of wind/hydro/DG system of Gilgit and Baltistan Regions.

Project area	Wind/Hydro/DG									
	Total NPC	Levelized COE	Payback period	Hydro		Wind		DG		Excess
	($)	¢/kWh	year	kW	%age	kW	%age	kW	%age	%age
Gilgit Region										
Assumber	1,044,605	5.52	8.7	500	91.4	100	7.9	250	0.7	68
Darmandar	8,196,319	8.67	11.0	2560	74.27	1500	25.2	1250	0.5	71
Chamugar	4,099,992	9.43	8.6	580	56.97	800	40.9	750	2.1	61
Danyore	11,714,800	10.47	7.8	1050	48.4	2000	46.7	1500	4.9	56
Batura	7,493,793	7.93	11.7	1600	67.6	1500	31.6	1500	0.8	63
Thak	20,030,310	8.16	8.3	4000	71.4	3000	26.1	3500	2.5	56
Kamri	1,357,505	7.18	9.8	410	74.6	250	24.4	250	1.0	68
Baltistan Region										
Chorbat	3,108,960	7.15	10.5	730	60.2	800	39	600	0.8	63
Saltoro	7,889,409	5.16	8.2	2000	76.3	1000	21.7	2000	2	47
Baghicha	8,567,069	10.31	7.6	1050	49.5	1600	48	1250	2.5	60
Hamzigon	8,119,904	10.24	6.9	1000	55.4	1500	41.3	1250	3.3	57
Gol	6,282,646	6.66	8.3	1500	76.5	800	22	1500	1.5	56
Mendi	8,686,987	6.58	6.6	2000	80.1	800	17.2	2000	2.7	52
Shigar	10,660,960	7.64	9.8	2000	66.3	1600	30.7	2000	3	54

Table A.2
Techno economic results of wind/hydro/battery system of Gilgit and Baltistan Regions.

Project area	Wind/Hydro/Battery									
	Total NPC	Levelized COE	Payback period	Hydro		Wind		Excess	Battery	Converter
	($)	¢/kWh	year	kW	%age	kW	%age	%age	kWh	kW
Gilgit Region										
Assumber	891,727	4.7	9.3	500	92	100	8	68.50	157	110
Darmandar	7,917,508	8.38	10.8	2560	74	800	26	70.72	1025	970
Chamugar	2,642,516	6.1	10.7	580	53.7	800	46.3	63.28	1000	300
Danyore	5,982,401	6.34	10.3	1050	48.7	1000	51.3	55.78	600	840
Batura	7,386,050	7.82	11.7	1600	67.4	1500	32.6	63.49	1250	750
Thak	13,529,300	5.51	10.8	4000	71.9	3000	28.1	56.10	1370	635
Kamri	1,831,373	9.68	10.7	410	46.8	250	53.2	79.96	300	250
Baltistan Region										
Chorbat	3,295,906	7.59	10.8	730	60.6	500	39.4	62.50	2060	390
Saltoro	7,578,360	4.95	10.8	2000	77.8	1500	22.2	45.47	3330	2865
Baghicha	5,545,379	6.7	10.7	1050	48.2	1600	51.8	61.46	600	540
Hamzigon	4,656,592	5.87	10.8	1000	55.6	1500	44.4	57.02	200	100
Gol	6,233,076	6.6	10.8	1500	77.7	800	22.3	55.04	2265	2044
Mendi	9,437,610	6.8	11.3	2000	82.3	800	17.7	50.18	5515	1912
Shigar	11,585,190	8.3	10.7	2000	68.4	1600	31.6	52.87	7135	2231

Table A.3
Techno economic results of PV/hydro/DG system of Gilgit and Baltistan Regions.

Project area	PV/Hydro/DG										
	Total NPC	Levelized COE	Payback period	Hydro		PV		DG		Excess	Converter
	($)	¢/kWh	year	kW	%age	kW	%age	kW	%age	%age	kW
Gilgit Region											
Assumber	1,100,382	5.82	9.3	500	92.3	100	6.7	250	1	68	50
Darmandar	7,851,390	8.61	10.4	2560	90.5	500	7.8	1250	1.7	64	281
Chamugar	4,921,836	11.33	10.7	580	79.7	250	13	750	7.3	45	259
Danyore	16,280,650	17.25	10.3	1050	62.2	1000	24.5	2000	13.3	44	801
Batura	8,313,231	8.8	11.7	1600	86.5	500	10.5	1500	3	53	234
Thak	24,011,990	9.78	10.8	4000	90	1200	3.7	3500	6.3	45	260
Kamri	1,419,928	7.51	10.7	410	91.5	100	6	250	2.5	61	53
Baltistan Region											
Chorbat	3,342,726	7.69	10.9	730	89.1	200	6.6	600	4.3	45	32.4
Saltoro	12,407,400	8.11	10.8	2000	84.9	500	6.5	2000	8.6	41	361
Baghicha	13,642,010	16.4	10.8	1050	64	1000	25.8	1800	10.2	49	636
Hamzigon	11,281,560	14.22	10.8	1000	68.2	800	22.3	1600	9.5	47	640
Gol	7,970,053	8.44	10.8	1500	87	500	9	1500	4	50	150
Mendi	10,787,330	8.17	10.7	2000	85	600	10	2000	5	48	525
Shigar	15,196,030	10.88	10.8	2000	81.4	600	10.4	2500	8.2	44	595

Table A.4
Techno economic results of PV/hydro/battery system of Gilgit and Baltistan Regions.

Project area	PV/Hydro/Battery									
	Total NPC	Levelized COE	Payback period	Hydro		PV		Excess	Battery	Converter
	($)	¢/kWh	year	kW	%age	kW	%age	%age	kWh	kW
Gilgit Region										
Assumber	1,114,256	5.9	9.3	500	93.2	100	6.8	68	874	168
Darmandar	7,075,833	7.5	10.8	2560	92.1	500	7.9	64	4172	990
Chamugar	4,344,502	10	10.7	580	65.9	800	34.1	55	8312	723
Danyore	19,354,510	20.5	10.3	1050	45.8	3000	54.2	58	29434	1921
Batura	6,811,198	7.21	11.7	1600	89.2	500	10.8	52	4836	943
Thak	21,140,175	8.64	N/P	4000	78.6	1200	21.4	50	9853	845
Kamri	1,359,345	7.2	10.7	410	93.8	100	6.2	60	1390	240
Baltistan Region										
Chorbat	2,398,535	5.52	10.9	730	93	200	7	42	4590	445
Saltoro	7,869,984	5.2	10.7	2000	90.8	500	9.2	36	10130	1790
Baghicha	15,377,550	18.5	10.8	1050	55.3	2000	44.7	56	22830	1660
Hamzigon	12,062,390	15.22	10.8	1000	55	1800	45	57	16400	1477
Gol	5,945,120	6.3	10.8	1500	90.7	500	9.3	48	5660	1100
Mendi	10,398,720	7.9	10.7	2000	77.5	1500	22.5	53	11820	2370
Shigar	13,720,220	9.83	10.7	2000	61	3000	39	58	14100	3620

Table A.5
Techno economic results of PV/wind/hydro/DG system of Gilgit and Baltistan Regions.

Project area	PV/Wind/Hydro/DG												
	Total NPC	Levelized COE	Payback period	Hydro		Wind		PV		DG		Excess	Converter
	($)	¢/kWh	year	kW	%age	kW	%age	kW	%age	kW	%age	%age	kW
Gilgit Region													
Assumber	1194698	6.31	9.3	500	85.7	100	7.5	100	6.2	250	0.6	71	46
Darmandar	8,955,644	9.5	10.7	2560	69.9	1500	23.6	500	6	1250	0.5	72	250
Chamugar	4,339,220	10	10.7	580	52.3	800	37.5	250	8.5	750	1.7	64	156
Danyore	11,556,380	11.03	10.3	1050	44.4	2000	43	500	8.8	1500	3.8	60	378
Batura	8,245,249	8.73	11.7	1600	62.6	1500	29.2	500	7.5	1500	0.7	66	225
Thak	21,226,850	8.64	10.8	4000	78.9	1500	14.4	1200	3.2	3500	3.5	52	300
Kamri	1,499,580	7.93	10.7	410	71.2	250	23.3	100	4.7	250	0.8	70	31.3
Baltistan Region													
Chorbat	3,412,890	7.8	10.9	730	57.5	800	37.4	200	4.3	600	0.8	64	21.6
Saltoro	7,591,563	5.72	9.4	2000	70.8	1000	20.2	500	7.2	2000	1.8	50	245
Baghicha	8,847,525	10.65	10.9	1050	46.1	1600	44.4	400	7.4	1250	2.1	63	381
Hamzigon	8,130,317	10.25	10.8	1000	52.6	1500	39.2	250	5.4	1250	2.8	59	148
Gol	7,011,115	7.43	10.8	1500	70.9	800	20.4	500	7.3	1500	1.4	59	196
Mendi	9,353,120	6.84	10.7	2000	73.5	800	15.7	600	8.5	2000	2.3	56	387
Shigar	11,108,850	7.96	10.7	2000	61.3	1600	28.4	600	7.8	2000	2.5	58	378

Table A.6
Techno economic results of PV/wind/hydro/battery system of Gilgit and Baltistan Regions.

Project area	PV/Wind/Hydro/Battery											
	Total NPC	Levelized COE	Payback period	Hydro		PV		Wind		Excess	Battery	Converter
	($)	¢/kWh	year	kW	%age	kW	%age	kW	%age	%age	kWh	kW
Gilgit region												
Assumber	1,228,744	6.5	9.3	500	86.2	100	6.3	100	7.5	70	736	200
Darmandar	9,325,988	9.87	10.8	2560	70.1	500	6.1	800	23.8	72	3680	580
Chamugar	4,563,163	9.51	11.3	580	53.2	250	8.6	800	38.2	64	1800	940
Danyore	12,556,620	10.32	10.3	1050	53.3	1000	21	1000	25.7	52	15850	1910
Batura	8,140,687	8.62	11.7	1600	62.4	500	7.5	1500	30.1	66	2500	500
Thak	15,383,190	6.27	10.8	4000	69.8	1200	2.9	3000	27.3	57	2760	785
Kamri	1,169,623	6.19	10.7	410	69.2	100	4.6	250	26.2	70	80	48
Baltistan Region												
Chorbat	3,580,625	8.24	10.9	730	58	200	4.3	800	37.7	64	4080	340
Saltoro	7,591,563	4.96	10.7	2000	72.3	500	7.3	1000	20.4	50	2220	956
Baghicha	6,153,887	7.4	10.8	1050	44.7	400	7.2	800	48.1	64	3100	312
Hamzigon	5,033,695	6.35	10.8	1000	52.6	250	5.4	1000	42	59	2050	533
Gol	5,090,315	5.34	11.0	1500	69.7	500	7.2	800	23.1	60	460	670
Mendi	9,437,610	7.15	10.7	2000	75.2	600	8.8	800	16	54	9860	1760
Shigar	10,576,340	7.58	10.7	2000	73.6	600	9.4	800	17	49	12720	2270

Table A.7
Techno economic results of PV/wind/DG system of Gilgit and Baltistan Regions.

Project area	PV/Wind/DG										
	Total NPC	Levelized COE	Payback period	Wind		PV		DG		Excess	Converter
	($)	¢/kWh	year	kW	%age	kW	%age	kW	%age	%age	kW
Gilgit Region											
Assumber	4487610	23.7	10.4	800	70.4	300	22	500	7.6	66	258
Darmandar	19,769,890	21	10.4	3000	65.8	1500	25	2000	9.2	62	1285
Chamugar	9,369,909	21.6	12.4	1600	68.1	800	24.6	1000	7.3	68	590
Danyore	22,006,010	22.3	8.6	6000	83.3	1000	11.4	2000	5.3	74	1050
Batura	18,277,110	19.4	11.9	4500	78	1200	16	2000	6	70	1153
Thak	65,144,690	26.5	12.3	13500	88.3	1200	2.2	6000	9.5	67	305
Kamri	4,528,588	23.9	10.4	750	78.1	250	13.1	500	8.8	66	210
Baltistan Region											
Chorbat	10,119,960	23.3	10.8	3200	93.1	200	2.7	900	4.2	78	198
Saltoro	11,999,440	17.8	14.7	5000	92.1	500	6.6	2000	1.3	55	347
Baghicha	15,815,890	19	10.8	2400	71.3	1000	20	1800	8.7	60	1000
Hamzigon	19,127,840	24.1	10.8	3000	64.9	1500	26.6	2100	8.5	66	1080
Gol	19,756,870	21	10.8	4000	81.2	1000	11.6	2000	7.2	67	1050
Mendi	27,333,360	20.7	10.7	4800	75	1500	17	3000	8	65	1600
Shigar	28,017,920	20.1	10.7	4800	72	1800	20	3000	8	64	1900

Table A.8
Techno economic results of PV/wind/battery system of Gilgit and Baltistan Regions.

Project area	PV/Wind/Battery									
	Total NPC	Levelized COE	Payback period	PV		Wind		Excess	Battery	Converter
	($)	¢/kWh	year	kW	%age	kW	%age	%age	kWh	kW
Gilgit Region										
Assumber	2,600,087	13.8	9.3	300	29.3	600	70.7	54	2668	530
Darmandar	13,609,740	14.4	10.8	1000	19.7	3000	80.3	55	16800	2580
Chamugar	9,909,340	19.9	12.3	1200	52	800	48	54	32440	1670
Danyore	22,124,140	23.5	10.3	2500	50.5	2000	49.5	53	36540	2690
Batura	21,088,120	22.3	11.7	2600	40.2	3000	59.8	65	31820	3000
Thak	112,709,300	15.9	13.1	1200	11.3	8000	88.7	81	13800	6450
Kamri	2,383,194	12.6	10.7	250	18	500	82	53	2700	590
Baltistan Region										
Chorbat	11,034,790	25.4	10.8	600	14.7	2400	85.3	59	18270	1230
Saltoro	11,500,270	17.5	14.6	800	5.6	6000	94.4	61	2100	650
Baghicha	17,667,020	21.3	10.7	1500	38.6	2400	61.4	49	15510	2185
Hamzigon	18,429,280	23.3	10.8	2000	52.3	2000	47.7	50	15525	3000
Gol	24,161,780	25.6	10.8	2000	26.3	3200	73.7	63	19360	2530
Mendi	29,581,580	22.4	10.7	2800	38.8	3200	61.2	57	24410	3490
Shigar	30,134,330	21.6	10.7	3600	52.5	2400	47.5	53	29935	4640

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Appendix

See Tables A.1–A.8.

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