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Levelized Cost of Electricity Generation by Small Hydropower Projects under Clean Development Mechanism in India

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Abstract: Contrary to conventional fossil fuel-based electricity generation technologies, renewable energy centered technologies, specifically small hydropower, release a lesser amount of anthropogenic greenhouse gases but are normally more expensive. A major segment of the capital investment in the current small hydropower scenario accounts for equipment and construction process costs. The construction and cost administration process are generally limited to analysis of the capital cost of civil constructions, electro-mechanical equipment works, neglecting the costs related to operating and maintaining the plant, replacement or refurbishment, certified emission reductions, among others. Contemporary studies indicate that these costs form a substantial fraction of the total capital investment. Consequently, for cost management and investment decision making, small hydropower plant developers are drawing increased attention in recent years towards conducting life cycle costing studies that take into account the ignored costs. In addition, small hydropower plants in developing nations can become more competitive by trading the emission reductions achieved under the provision of the Clean Development Mechanism, an outcome of the Kyoto Protocol proposed at the United Nations Framework Convention on Climate Change. In this paper, a modest attempt has been made to determine the Levelized cost of electricity generation using life cycle costing methodology, which accounts for all the costs over operating lifetime on a range of small hydropower plants and the results are analyzed.

Keywords: small hydropower plant; cost components; life cycle costing; levelized cost of electricity; clean development mechanism

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Citation: Patro, E.R.; Kishore, T.S.; Haghighi, A.T. Levelized Cost of Electricity Generation by Small Hydropower Projects under Clean Development Mechanism in India. *Energies* **2022**, *15*, 1473. https://doi.org/10.3390/en15041473

Academic Editors: Carlo De Michele and Chirag Trivedi

Received: 20 January 2022
Accepted: 14 February 2022
Published: 17 February 2022

1. Introduction

Renewable energy-based electricity generation emits less anthropogenic greenhouse gases (GHG) than conventional fossil fuel-centered electricity generation technologies but is usually expensive. The Clean Development Mechanism (CDM) of the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) offers a prospect for renewable energy-based electricity generation systems in emerging nations to become more competitive by leveraging monetary benefits extended by the reduction in emissions possible from a renewable energy project. The prime focus of CDM continues to be on the energy industry because of the huge amount of registered renewable energy projects and their probable effect on the electricity generating cost [1]. A project under CDM receives Certified Emission Reductions (CER), which is equal to abating one ton of CO_2 equivalent and is even verifiable and measurable. The project titleholder can trade the CERs to developed countries, companies, or governments. The latter can use them to support their emission reduction goals committed under the Kyoto Protocol [2]. Consequently, CDM can be an additional revenue source for renewable energy projects. The net revenue from CER trades makes projects based on renewable energy sources more competitive until the average cost of issuing a CER (i.e., UNFCCC charges to monitor and verify emission reductions) is less than the CER tradable price.

This study's main aim is to estimate the electricity generation costs by Small Hydropower (SHP) projects located in India. The Levelized cost of electricity (LCOE) is regularly used for assessing the cost-effectiveness of various electricity generation technologies on a dependable basis [3]. Cost appraisals of various alternate energy generation technologies regularly use LCOE and suggest the least cost investment alternative among available alternatives [4,5]. In general, LCOE computations involve the production cost estimations for each technology type related to project's geography, capacity, operating mode, time and assumptions regarding economic parameters [6]. This study determines the LCOE generation for low and high head SHP plants by using cost correlations existing in the literature developed by considering various existing SHP projects in India. The process of developing correlations involves collecting data from existing power plants for performing cost analysis, i.e., feasibility studies regarding technical, economic and financial factors influencing the establishment and operation of the SHP plant [7]. Decisions related to investments in SHP projects are generally based on thorough and precise techno-economic and cost–benefit analysis with the prevailing market conditions [8]. Financial feasibility is concerned mostly with the profitability of the SHP projects, while economic analysis is concerned with both monetary and societal benefits [9]. The most straightforward approach to evaluate the economic feasibility of the SHP project is using the payback period and the net present value for the investments. For SHP projects, the payback period is highly dependent on the current financial markets [10–12]. The prevailing state of the market is determined by nation's borrowed capital and its interest, tariffs, taxes, inflation, subsidies and other economic factors [13]. Most of the works in the literature focused on developing correlations for cost components influencing total cost of the project and establishing methodologies to determine financial feasibility of a project, but very few in the literature mentioned about environmental costs and how to include them [14–16].

Computation and comparison of LCOEs for different SHP plants classified based on head and capacity were done. The calculations consider the Net Present Value (NPV) of initial capital costs, operation and maintenance costs, replacement costs and the projected net revenue of the emission reductions (i.e., the difference of CER income and issuance costs). Using the data, the first Life Cycle Cost (LCC) for each SHP configuration considered was calculated. Further using annualized electricity production cost function, the LOCE of a particular SHP configuration has been calculated considering the returns associated without and with the expected returns from CERs. The proposed methodology helps in investment decision making for SHP developers and also aids as a significant tool to measure the deployment and progress of CDM for SHP projects.

1.1. Small Hydropower and Clean Development Mechanism Technology

SHP technologies are exceptionally robust with an average operating life spanning over 50 years and entail less maintenance, despite being the most environmentally benign clean energy alternatives available. SHP is characterized as a maximum density resource of all the existing clean energy generation sources. SHP is the leading renewable energy generating resource globally [17]. Major advantages exhibited by SHP plants are reduced gestation times, devoid of submergence, resettlement and other complications associated with the environment and ecosystem [9,18]. Hydraulic turbines convert water pressure into mechanical power of shaft, which is further used to run an alternator or other electricity-generating machines. The power thus obtained is proportional to the hydraulic pressure, volume flow rate and net water head. The universal formula for power generated by a hydro system is given by Equation (1).

$$P = \eta \rho g Q H \quad (1)$$

where P is the electrical power generated (kW), η is the total efficiency, ρ is the water density (kg/m^3), g is the acceleration due to gravity (m/s^2), Q is the discharge passing through the turbine (m^3/s), and H is the net head of water across the turbine (m). Table 1 gives information about the various components of low and high head SHP schemes [19]. Based on the head availability, SHP plants are broadly classified as high, medium and low head plants. Further, SHP plants can be dam toe, run-of-the-river, and canal-based plants.

Table 1. Various components of SHP plants.

SHP Type → Components ↓	Run of River SHP	Dam Toe SHP	Canal-Based SHP
Civil Works Components	Powerhouse building, diversion weir, power channel, desilting chamber, intake channel, forebay, penstock, spillway, tail race	Power house building, intake, penstock, tail race	Power house building, spillway, diversion weir
Electro-mechanical Components	Turbine with governing system; switch gear, generator with excitation system, control and protection equipment; mechanical and electrical auxiliaries; switchyard and main transformer equipment.		

The Kyoto Protocol is a protocol to the United Nations Framework Convention on Climate Change (UNFCCC or FCCC) to fight global warming. Under this, developed nations (Annex-1 of Kyoto Protocol) and developing nations (Non-Annex-1 of Kyoto Protocol) will reduce combined Greenhouse gas (GHG) emissions by at least 5% below their 1990 levels by first commitment 2008 to 2012 [20]. Kyoto Protocol aims to bind constraints on GHG emissions, cut the costs of reducing emissions, and establish global markets for GHG emission permits. Kyoto Mechanisms involve emissions trading, which allows the country to sell its spare emission units to nations that have surpassed their targets, joint implementation which allows developed countries to get emission reduction units from projects developed in other developed countries for emission reduction. While Clean Development Mechanism (CDM) allows developed nations to earn emission reduction units from emission reduction projects in developing nations. CDM is one of the flexibility mechanisms defined in Article 12 of the Kyoto Protocol and is intended to meet two objectives viz. to assist parties not included in Annex I in achieving sustainable development and in contributing to the ultimate objective of the UNFCCC, which is to avert treacherous climate change and to support parties involved in Annex I in attaining compliance with their enumerated emission limitation and reduction obligations (GHG emission caps) [20].

The Indian market is extremely receptive to CDM. Up until December 2014, India had completed around 3000 projects, nearly 40% of which had been registered with the UNFCCC. The CDM and additional market instruments have reinforced the improvement and execution of these projects and created over 170 million Certified Emission Reductions (CERs), which industrialized countries utilized to meet their Kyoto Protocol compliance obligations [21]. Renewable energy projects have subjugated the number of registered CDM projects, while industrial gas projects have consistently made up the majority of CERs [21]. The volume of CO_2 releases saved by a renewable power scheme would fundamentally be governed by the quantity of fuel avoided by its use, which, in sequence, depends upon the electricity generated from the renewable power scheme annually. Electricity produced annually depends on the plant capacity and plant load factor (PLF) of the renewable power scheme. Hence, the Gross Annual CO_2 Emissions (GCE) reduced by a renewable power project, $GCE_{Project}$, can be estimated as

$$GCE_{Project} = (8760 \times PLF_{Project} \times P_{Project})CEF_e, \quad (2)$$

where CEF_e is the CO_2 emission factor for electricity. The CO_2 emissions alleviation through renewable power schemes in India is projected based on the provincial standard [22,23].

1.2. CDM Potential of SHP

The total SHP potential in the country is evaluated at about 21.13 GW from 7133 project sites corresponding to 12.68 GW at a 60% load factor. The total installed capacity of SHP projects (<25 MW) is 4.683 GW. The potential of SHP has been augmented from 20 GW in 2013 to 21.13 GW in 2019, while the installed capacity augmented from 3.4 GW in 2013 to 4.68 GW in 2019 [24]. This growth in SHP is accounted for by technical advancement and the constructive steps taken by the government. The gross annual CO_2 releases reduced by an SHP scheme, GCE_{SHP}, can be determined using Equation (2). The amount of CER generated and available for sale corresponding to annual energy production (AEP) is presented in Table 2.

Table 2. CDM potential of SHP projects in India.

S.No.	States/UTs	Small Hydro Power	Installed (MW)	To Be Exploited (MW)	CEF	AEP (TWh)	Estimated CDM Potential (Million CER/Year)	Estimated Revenue (Million INR)
1	Andhra Pradesh	409.32	162.11	247.21	0.86	1.30	1.12	81.57
2	Arunachal Pradesh	2064.92	131.11	1933.81	0.42	10.16	4.27	311.63
3	Assam	201.99	34.11	167.88	0.42	0.88	0.37	27.05
4	Bihar	526.98	70.70	456.28	1.05	2.40	2.52	183.82
5	Chhattisgarh	1098.20	76.00	1022.20	0.81	5.37	4.35	317.69
6	Goa	4.70	0.05	4.65	0.85	0.02	0.02	1.52
7	Gujarat	201.97	68.95	133.02	0.81	0.70	0.57	41.34
8	Haryana	107.40	73.50	33.90	0.80	0.18	0.14	10.41
9	Himachal Pradesh	3460.34	911.51	2548.83	0.80	13.40	10.72	782.36
10	Jammu and Kashmir	1707.45	180.48	1526.97	0.80	8.03	6.42	468.70
11	Jharkhand	227.96	4.05	223.91	1.05	1.18	1.24	90.21
12	Karnataka	3726.49	1280.73	2445.76	0.86	12.85	11.06	807.03
13	Kerala	647.15	222.02	425.13	0.86	2.23	1.92	140.28
14	Madhya Pradesh	820.44	95.91	724.53	0.81	3.81	3.08	225.17
15	Maharashtra	786.46	379.58	406.88	0.81	2.14	1.73	126.45
16	Manipur	99.95	5.45	94.50	0.42	0.50	0.21	15.23
17	Meghalaya	230.05	32.53	197.52	0.42	1.04	0.44	31.83
18	Mizoram	168.90	36.47	132.43	0.42	0.70	0.29	21.34
19	Nagaland	182.18	30.67	151.51	0.42	0.80	0.33	24.42
20	Odisha	286.22	64.63	221.59	1.05	1.16	1.22	89.27
21	Punjab	578.28	173.55	404.73	0.80	2.13	1.70	124.23
22	Rajasthan	51.67	23.85	27.82	0.80	0.15	0.12	8.54
23	Sikkim	266.64	52.11	214.53	0.42	1.13	0.47	34.57
24	Tamil Nadu	604.46	123.05	481.41	0.86	2.53	2.18	158.85
25	Telangana	102.25	90.87	11.38	0.86	0.06	0.05	3.76
26	Tripura	46.86	16.01	30.85	0.42	0.16	0.07	4.97
27	Uttar Pradesh	460.75	25.10	435.65	0.80	2.29	1.83	133.72
28	Uttarakhand	1664.31	214.32	1449.99	0.8.	7.62	0.00	0.00
29	West Bengal	392.06	98.50	293.56	1.05	1.54	1.62	118.27
30	Andaman and Nicobar	7.27	5.25	2.02	0.85	0.01	0.01	0.66
	Total	**21,133.62**	**4683.17**	**16,450.45**	**21.60**	**86.46**	**60.07**	**4384.90**

The above estimates are based on the assumption of 60% PLF. With 60% PLF the gross AEP potential has been estimated at 86.46 TWh. It can easily be understood that the AEP and corresponding CER and revenue generation are highly sensitive to PLF. The PLF is highly variable and can be impacted by various operating parameters such as instructions from operators in case of grid-connected projects, seasonal constraints, etc. A sensitivity analysis has been performed to study the effect of PLF on AEP and corresponding CER generation potential and the results of this sensitivity analysis are presented in Figure 1.

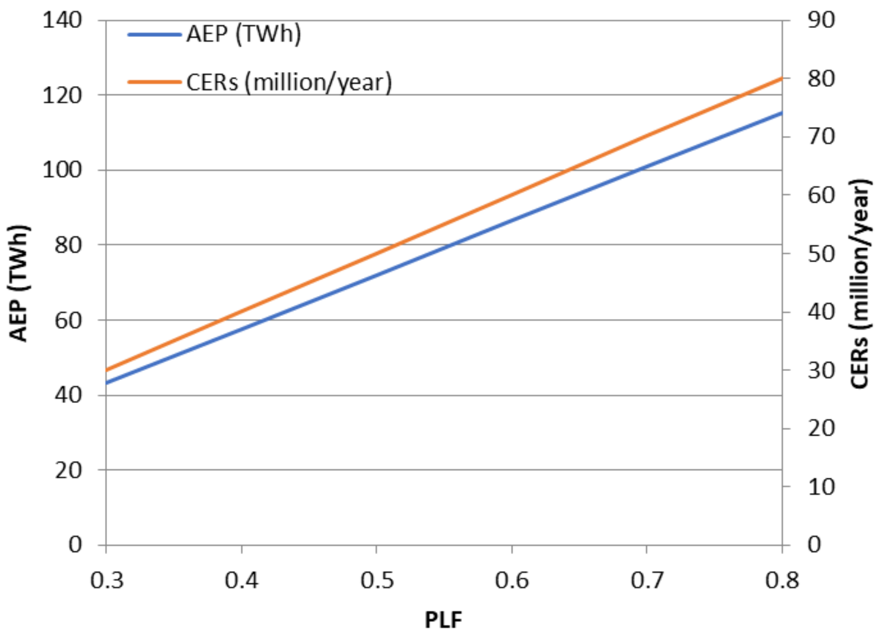

Figure 1. Variation of AEP and CER with PLF.

2. Methodology

At large, LCOE signifies the Net Present Value (NPV) of the per unit electricity generated cost over the SHP plant's expected economic lifetime. It can be computed as the percentage of the aggregate of discounted electricity generated cost and the discounted sum of electricity output over the SHP's operating life. The projected aggregate cost of delivering electricity at the point of interconnection to a load or grid usually comprises investment in terms of initial capital and a series of costs relating to fuel, operation and maintenance and others. Considering the plant's useful life, these costs and electricity output for each year are discounted by the time value of money. Thus, the computed LCOE is considered the least average price at which electricity can be traded to obtain a break even over the operating life of SHP [25]. The majority of SHP developers follow a typical cost management practice. The technical and economic viability of the SHP plant for carrying out the construction and getting operations underway is considered. This practice only reflects the investments up to a particular point, i.e., the SHP's design and construction. Although this period accounts for a significant portion of the total plant investments, other costs relating to SHP's generation losses, outage, maintenance, replacement and CERs must be considered in evaluating the plant's entire LCC, which is vital for evaluating the NPV [9].

SHP projects under CDM also produce a tradable derivative of electricity, CERs. However, CERs attract the costs of monitoring emission reductions, verified, and subsequent CER issuance. In this study, these extra incomes and expenditures were reflected while computing the LCOEs for SHP projects. The total value of an SHP project TV_O is influenced by the discounted cost of the expected profit from electricity sale and revenue from CER sale [25], represented by

$$TV_o = \sum_{t=0}^{T} \pi_t^X e^{-rt} + \sum_{t=0}^{T} \pi_t^Y e^{-rt}; t = 1, 2, \ldots.., T, \quad (3)$$

where X and Y represent the anticipated returns from electricity sales and CERs sales, and T is the project's operating life. Equation (3) can be rewritten to differentiate income and expenditures,

$$TV_o = \sum_{t=0}^{T} \rho_t^X X_t e^{-rt} + \sum_{t=0}^{T} \rho_t^Y Y_t e^{-rt} - NPV_0^j, \quad (4)$$

where, ρ^X and ρ^Y are the electricity and CER costs and NPV_0^j is the project's net present value. If both the cost of electricity and CER is combined to represent the total discounted cost, then

$$NPV_0^j = IC_0 + \sum_{t=0}^{T} OMC_t e^{-rt} + \sum_{t=0}^{T} RC_t e^{-rt} + \sum_{t=0}^{T} c_t^j Y_t e^{-rt}, \quad (5)$$

where IC_0 is the initial capital, OMC represents the annually varying maintenance and operation cost, RC represents the replacement cost and c represents the cost of issuing one CER, which is highly variable and includes the cost of emission reductions monetization under the CDM, comprising the issuance fee outstanding to the UNFCCC and outlays for monitoring and authentication. If the anticipated return from electricity and CER sale exceeds investment capital, the total value function can be represented as

$$TV(IC_0^*) = \rho_0^{-X} \sum_{t=0}^{T} X_t e^{-rt} + \rho_0^{-Y} \sum_{t=0}^{T} Y_t e^{-rt} - NPV^j(Y_0, X_0), \quad (6)$$

where the ρ_0^{-X} and the ρ_0^{-Y} denote the weighted average price of electricity and CER sales at the period the investment choice was realized. The envelope theorem can be used to recover total output levels that are constant with solution values, as

$$\frac{\partial IC^*}{\partial \rho_0^{-X}} = \sum_{t=0}^{T} X_t e^{-rt} = X_0 \text{ and } \frac{\partial IC^*}{\partial \rho_0^{-Y}} = \sum_{t=0}^{T} Y_t e^{-rt} = Y_0, \quad (7)$$

where X_0 and Y_0 represent the electricity and CER volumes that the SHP projects are expected to produce throughout the course of their life, weighted by the discount factors used to calculate the total value function. The accompanying combined cost functions can be articulated as $NPV_t^j(w_\tau, X_t, Y_t; S_\tau)$, where w_τ is the vector of anticipated input price and S_τ is the set of state variables that form the constraints of the LCOE problem. The problem can be streamlined when costs are not combined, i.e., when $NPV^j = NPV^X(X_o) + NPV^Y(Y_o)$ allows Equation (4) to be rewritten as

$$TV(IC_0^*) = \sum_{t=0}^{T} \rho_t^X X_t e^{-rt} + \rho_0^{-Y} \sum_{t=0}^{T} Y_t e^{-rt} - NPV^X(X_o) - NPV^Y(Y_o), \quad (8)$$

Using the above equation, the non-combined cost related to electricity production alone can be estimated as $NPV_t^X(w_\tau, X_t; S_t)$. Hence, the NPV of the total cost of electricity generated by the SHP project can be computed as

$$NPV_0^X = IC_0 + \sum_{t=0}^{T} OMC_t e^{-rt} + \sum_{t=0}^{T} RC_t e^{-rt} + \sum_{t=0}^{T} c_t Y_t e^{-rt} - \sum_{t=0}^{T} \rho_t^Y Y_t e^{-rt}, \quad (9)$$

The following equation can then estimate LCOE as

$$LCOE = NPV_0^X / \sum_{t=0}^{T} X_t e^{-rt}, \quad (10)$$

The above equation applies to all power projects producing electricity under CDM and is referred to as LCOE as per energy cost literature [3]. However, the above equation assumes that the SHP project operating life and CER issuance period is the same. Generally, SHP project life will be greater than the CER issuance period, and a much more generic way of representing Equation (10) to compute LCOE is as follows,

$$LCOE = \frac{IC_0 + \sum_{t=0}^{T} OMC_t e^{-rt} + \sum_{t=0}^{\tau} (c_t - \rho_t^Y) Y_t e^{-rt}}{\sum_{t=0}^{\tau} X_t e^{-rt}}, \quad (11)$$

where τ is the CER issuance period in years.

2.1. Cost Correlations of SHP

Correlation is a division of statistical relationships concerning dependence, although it most commonly refers to the degree to which two or more variables have a linear relationship. Correlations are helpful as they can indicate an analytical relationship that can be exploited for use in practical purposes. A lot of the literature is available pertaining to correlations developed for various cost components with respect to power (P) in kilowatt and head (H) in meters for SHP plants. The development of correlations was a progression of research efforts based on SHP plant data available across India. In general, depending on the SHP scheme type, civil work components differ but the electro-mechanical components are the same for all schemes. Table 3 gives information about the various correlations developed for low head SHP plants which were developed for run-of-river, dam toe and canal based SHP schemes [26–28]. The correlations for high head SHP plants involve various components and their combinations as every plant is site specific [9]. In this regard, the correlations have been developed based upon the work to be done for each civil work component. The work to be done consist of four sub-components majorly viz. excavation, concreting, reinforcement and structural steel required. However, the correlations pertaining to electromechanical components are directly dependent on head and capacity [29].

Table 3. Correlation for cost component of low-head SHPs.

Components → **SHP Type ↓**	**Civil Works Components**	**Electromechanical Components**
Run of River SHP	C_{PHB} = 92,615 $P^{-0.2351}$ $H^{-0.0585}$ $C_{DW\&I}$ = 12,415 $P^{-0.2368}$ $H^{-0.0597}$ C_{PC} = 85,383 $P^{-0.3811}$ $H^{-0.0307}$ C_{DC} = 20,700 $P^{-0.2385}$ $H^{-0.0611}$ $C_{F\&S}$ = 25,402 $P^{-0.2356}$ $H^{-0.0589}$ C_{P} = 7875 $P^{-0.3806}$ $H^{0.3804}$ C_{TR} = 28,164 $P^{-0.376}$ $H^{-0.624}$	C_{TG} = 63,346 $P^{-0.1913}$ $H^{-0.2171}$ C_{GE} = 78,661 $P^{-0.1855}$ $H^{-0.2083}$ C_{AUX} = 40,860 $P^{-0.1892}$ $H^{-0.2118}$ $C_{T\&SY}$ = 18,739 $P^{-0.1803}$ $H^{-0.2075}$
Dam Toe SHP	C_{I} = 17,940 $P^{-0.2366}$ $H^{-0.0596}$ C_{P} = 7875 $P^{-0.3806}$ $H^{0.3804}$ C_{PHB} = 85,717 $P^{-0.2355}$ $H^{-0.0588}$ C_{TR} = 28,164 $P^{-0.376}$ $H^{-0.624}$	C_{TG} = 66,282 $P^{-0.1866}$ $H^{-0.2094}$ C_{GE} = 79,927 $P^{-0.1854}$ $H^{-0.2097}$ C_{AUX} = 39,372 $P^{-0.1865}$ $H^{-0.2107}$ $C_{T\&SY}$ = 18,739 $P^{-0.1803}$ $H^{-0.2075}$
Canal-based SHP	C_{PHB} = 105,555 $P^{-0.238}$ $H^{-0.0602}$ C_{S} = 36,778 $P^{-0.2306}$ $H^{-0.0644}$ C_{DW} = 9909 $P^{-0.2295}$ $H^{-0.0623}$	C_{TG} = 63,346 $P^{-0.1913}$ $H^{-0.2171}$ C_{GE} = 78,661 $P^{-0.1855}$ $H^{-0.2083}$ C_{AUX} = 40,860 $P^{-0.1892}$ $H^{-0.2118}$ $C_{T\&SY}$ = 18,739 $P^{-0.1803}$ $H^{-0.2075}$

The following equations can compute the total cost of various SHP schemes based on the data obtained by correlations available in literature [26–29]. For run-off-river SHP scheme, the total civil cost is given by

$$C_{CIV} = C_{PHB} + C_{DW\&I} + C_{PC} + C_{DC} + C_{F\&S} + C_{P} + C_{TR}, \quad (12)$$

For dam toe SHP scheme, the total civil cost is given by

$$C_{CIV} = C_{PHB} + C_{I} + C_{P} + C_{TR}, \quad (13)$$

For canal-based SHP scheme, the total civil cost is given by

$$C_{CIV} = C_{PHB} + C_{S} + C_{DW}, \quad (14)$$

The components of electro-mechanical equipment cost are the same for all the SHP schemes, and hence, the total cost is given by

$$C_{EM} = C_{TG} + C_{GE} + C_{AUX} + C_{T\&SY}, \quad (15)$$

Based on the cost correlations of civil and electro-mechanical components, total SHP cost is given by

$$C_{SHP} = 1.13\ (C_{CIV} + C_{EM}), \tag{16}$$

where C_{CIV} is the cost of civil works, C_{PHB} is cost of powerhouse building, $C_{DW\&I}$ is cost of diversion weir and intake, C_{PC} is cost of power channel, C_{DC} is cost of desilting chamber, $C_{F\&S}$ is cost of forebay and spillway, C_{PST} is cost of the penstock, C_{TR} is cost of tailrace, C_I is cost of intake, C_S is cost of spillway, C_{DW} is cost of diversion weir, C_{TG} is cost of turbine governor system, C_{GE} is cost of generator exciter system, C_{AUX} is cost of mechanical and electrical auxiliaries, $C_{T\&SY}$ is cost of transformer and switchyard, C_{EM} is cost of electromechanical works and C_{SHP} is cost of SHP plant. The factor 1.13 corresponds to establishment related costs including survey and investigations, preliminary expenses on report preparation, design, audit and accounting, overheads, tools and facilities, communication costs and land costs have been included in indirect/ miscellaneous costs [6,19,20,30].

2.2. LCOE Calculations

This section deals with the LCOE computations for SHP schemes under consideration. All of these employ different civil work components and the same electro-mechanical components. As the variation of the head has a major impact on the capacity of the plant and cost, for high head SHP schemes, the characterization of LCOE has been carried out for different heads and the same power capacity. On the other hand, in low head SHP schemes, the cost is directly proportional to electro-mechanical equipment, which is dependent on the type of plant viz. Run off-river, dam toe and canal-based SHP. Hence, the characterization of LCOE has been done considering various combinations of type, capacity and head for low head SHP schemes. The functional life of the SHP plant for computation is considered to be 50 years with major restoration works being taken up after 25 years of plant operations, as it is consistent with the practice by the hydropower industry. ICs for the construction of SHP plants can be attributed more than a year before the plant was commissioned. This paper assumes that all ICs will occur in year zero. Table 4 shows the key technological and economic assumptions made in the calculations that reproduce the current state of the country's hydropower industry [31–33]. The reliability assessment in generation systems is very important [34,35], and since this study considers the overall life cycle cost of SHP, the reliability aspects are considered in the form of the annual plant load factor, rehabilitation times and replacement costs. Based on the correlations presented in Table 3, the civil works cost, and electro-mechanical components cost for different SHP schemes have been estimated using Equations (12)–(16). These estimates are then used for computing the LCOE using Equations (3)–(16) for SHP plants under consideration, and the data are presented in Tables 5 and 6. All costs are represented in INR/kW and LCOE is expressed as cost per unit, i.e., INR/kWh.

Table 4. Economic assumptions for LCC calculations.

Real Discount Rate	8%
Plant life	50 years
Annual O&M cost	1.5%
Turbine generator rehabilitation time	25 years
Generator exciter rehabilitation time	25 years
Auxiliary equipment rehabilitation time	10 years
Transformer rehabilitation time	30 years
Depreciation tax shield factor	0.35
Turbine efficiency	85%
Generator efficiency	90%
Annual plant load factor	36%
Average CER cost	2$
1 USD	75 INR
The benchmarked sale price of electricity	5 INR/kWh

Table 5. LCOE values for low head SHP plants with and without CER.

Plant	Capacity (kW)	Head (m)	C_{CIV}	C_{EM}	C_{SHP}	IC	OMC	RC	CER	LCC		LCOE	
										Without CER	With CER	Without CER	With CER
Run-off-River SHP	3000	3	26,891	35,599	70,613	494,293	706	4265	9228	499,264	490,036	4.14	4.06
	5000	10	22,288	25,074	53,519	374,631	535	3003	9228	378,170	368,942	3.14	3.06
	7000	20	19,911	20,330	45,472	318,306	455	2435	9228	321,195	311,968	2.66	2.59
Dam Toe SHP	3000	3	15,989	36,812	59,665	417,656	597	4263	9228	422,516	413,288	3.50	3.43
	5000	10	13,169	26,017	44,280	309,960	443	3011	9228	313,414	304,186	2.60	2.52
	7000	20	11,784	21,137	37,201	260,405	372	2446	9228	263,223	253,995	2.18	2.11
Canal-Based SHP	3000	3	19,131	32,348	58,171	407,199	582	3777	9228	411,558	402,330	3.41	3.34
	5000	10	17,021	24,231	46,615	326,305	466	2829	9228	329,600	320,372	2.73	2.66
	7000	20	16,312	20,926	42,079	294,553	421	2443	9228	297,417	288,189	2.47	2.39

Table 6. LCOE values of high head SHP Plants with and without CER.

Capacity (kW)	Head (m)	C_{CIV}	C_{EM}	C_{SHP}	IC	OMC	RC	CER	LCC		LCOE	
									Without CER	With CER	Without CER	With CER
2000	100	38,485	34,234	82,172	575,207	822	3115	10,253	579,144	568,891	4.8	4.72
2000	200	233,449	28,984	296,549	2,075,845	2965	2638	10,253	2,081,448	2,071,195	17.26	17.17
2000	300	119,545	22,205	160,178	1,121,243	1602	2021	10,253	1,124,865	1,114,612	9.33	9.24
2000	400	76,310	20,917	109,867	769,067	1099	1903	10,253	772,069	761,816	6.4	6.32
2000	500	54,774	20,107	84,616	592,313	846	1830	10,253	594,989	584,736	4.93	4.85
2000	600	42,283	19,576	69,902	489,311	699	1781	10,253	491,792	481,538	4.08	3.99
2000	700	34,291	19,225	60,474	423,319	605	1749	10,253	425,673	415,420	3.53	3.44
2000	800	28,816	19,001	54,033	378,234	540	1729	10,253	380,503	370,250	3.15	3.07
2000	900	24,868	18,866	49,419	345,936	494	1717	10,253	348,147	337,894	2.89	2.80
2000	1000	21,186	18,797	45,181	316,268	452	1711	10,253	318,430	308,177	2.64	2.55

3. Results and Discussion

From the calculations obtained in the previous section, it can be analysed that the LCOE reduces with an increase in capacity of the plant resulting in more significant savings which makes the projects profitable. This is further enhanced by taking into account the revenues generated by CDM in the form of tradable CERs. CDM enables SHP projects to be more economical even though the effectiveness remarkably depends on CER valuations in the international market and the duration of their earning period by the plant. SHP projects under CDM react to economies of scale in electrical energy production, i.e., the electricity produced by larger capacity plants will have lower per unit electricity costs and vice versa. The average per-unit cost of electrical energy produced is directly related to the project's duration (i.e., plants with more technical life will have less per unit cost). However, variances in electricity-generated timing will be considered for discounting for LCOE calculation purposes. The civil works govern the capital investment of medium, and high head SHP schemes cost as these schemes are site-specific. The cost of civil works and electro-mechanical equipment governs the cost of low head SHP schemes. Because machine sizes are relatively large, the size of powerhouse buildings and other civil works components is directly affected by the type and size of machines. The cost contribution to electro-mechanical equipment is higher in low head SHP schemes than in civil works. The following key illustrations demonstrate the effectiveness of the proposed methodology in evaluating various alternatives available for generating electricity from SHP plants.

(i) In all the three cases of low head SHP via dam toe, run-off-the-river, and canal-based schemes, the costs of electro-mechanical work were more than civil works, as illustrated in Figure 2. This is because, in low head SHP schemes, the machine sizes are relatively larger, the size of powerhouse building and other civil works components are directly affected by the type and size of machines and, hence, electro-mechanical equipment has a bigger cost contribution than civil works. However, for high head SHP plants, civil works costs are more than electro-mechanical components cost works as illustrated in Figure 3. This is because the capital investment of medium and high head SHP schemes are governed by the civil works cost as these schemes are site specific.

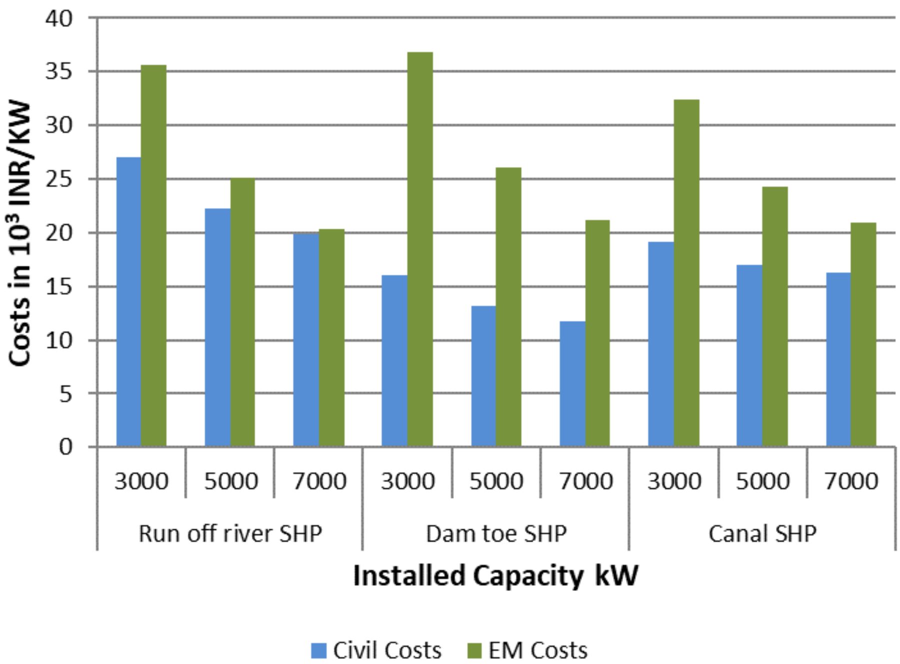

Figure 2. Cost of civil works vs. electro-mechanical components for low head SHP.

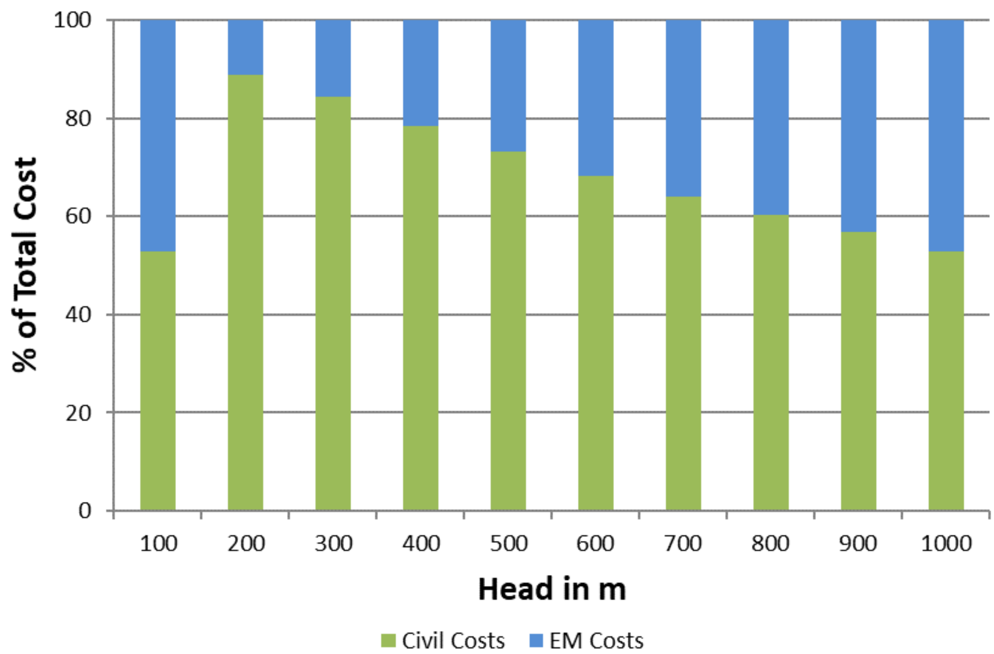

Figure 3. Cost of civil works vs. electro-mechanical components for 2000 kW plant.

(ii) IC, which is a combination of cost of civil works, electro-mechanical components and administrative, charges is more for SHP with low head and capacity. This decreases with an increase in head or capacity of the plant as illustrated in Figures 4 and 5 for low and high head SHP plants, respectively.

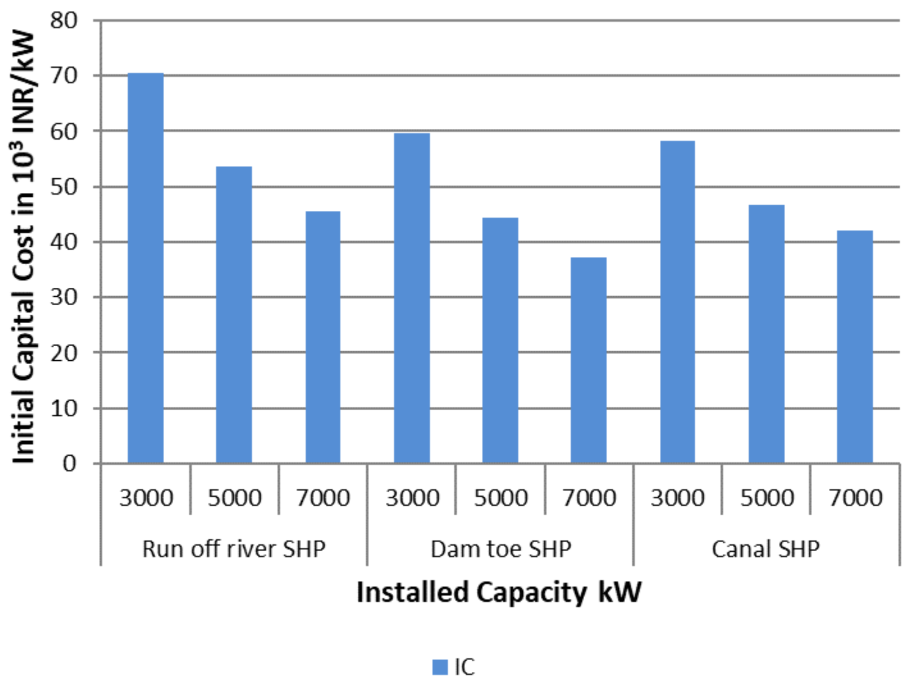

Figure 4. Variation of IC vs. LCC w.r.t head for 2000 kW plant.

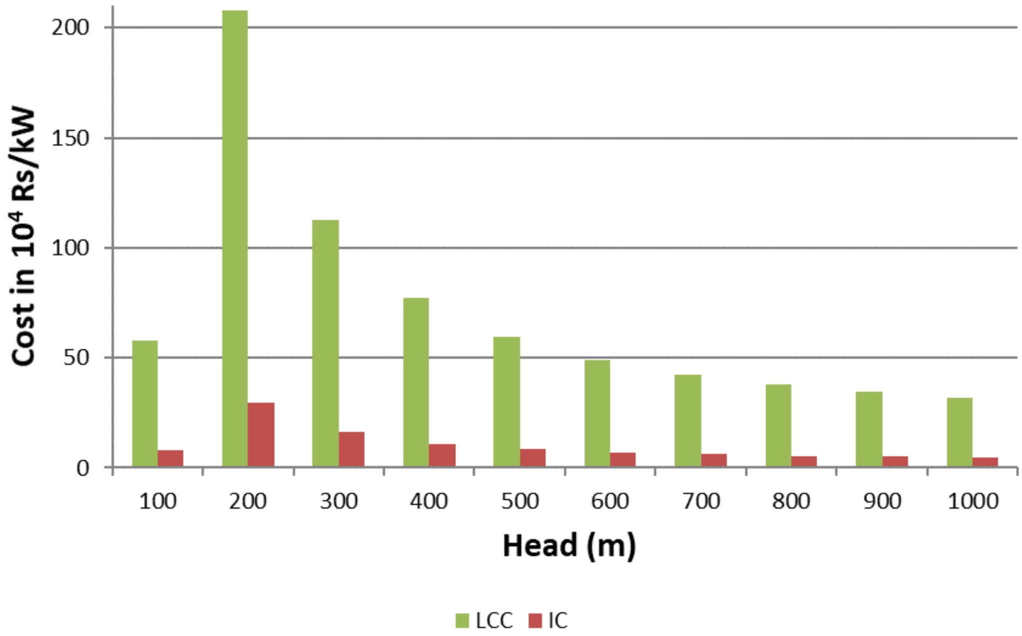

Figure 5. Variation of IC vs. LCC w.r.t head for 2000 kW plant.

(iii) From Figure 4, it can be observed that for the same head and capacity, IC of run-off-river is highest followed by dam-toe, further followed by canal-based plants. An exception can be found in canal-based SHP plants where the cost is more as compared to dam-toe plants. This is due to the impractical techno-economic feasibility of having a canal-based SHP plant with high heads.

(iv) LCC has been evaluated taking into account the present values of various cost components. Such as IC, OMC, RC and CER. The LCC of SHP plants for all cases has been calculated and is 85% or approximately seven times higher than the corresponding IC.

(v) Compared to the benchmarked cost of SHP in India, i.e., INR 100 Million per MW, the analyzed costs are very close to benchmarked cost with a minor deviation of +0.42 to −0.16 for all the low head SHP plants under consideration.

(vi) Compared to the average benchmarked cost for sale of electricity generated from SHP in India, i.e., INR 5 per kW, the obtained LCOE with and without CER cost considerations is less, indicating scope for reasonable profits and sustainable operation SHP over its lifetime. In the case of low head SHP schemes, the LCOE reduces significantly with increased capacity as illustrated in Figure 6. A deviation in two combinations (2000 kW, 200 m and 300 m) for high head SHP projects can be observed, illustrated in Figure 7, which are accounted to the impractical techno-economic feasibility of constructing the plant with a combination of penstock material, i.e., HDPE (200 m and 300 m) and turgo impulse for 200 m and Pelton for 300 m, respectively.

Overall, the variation of LCOE depends on the cost components and economic factors considered in its computation as well as the technology adopted by the SHP plants. It is to be noted that the cost components, economic factors and technologies adopted will vary from plant to plant as well as regulations adopted by the nations in constructing and operating these plants also will be different, resulting in variations in LCOE. Despite these variations, LCOE proves to be a powerful tool in accommodating all these variations and effectively evaluating the available alternatives and providing significant results which can be used to evaluate designs, develop operation and maintenance strategies and refurbishment activities.

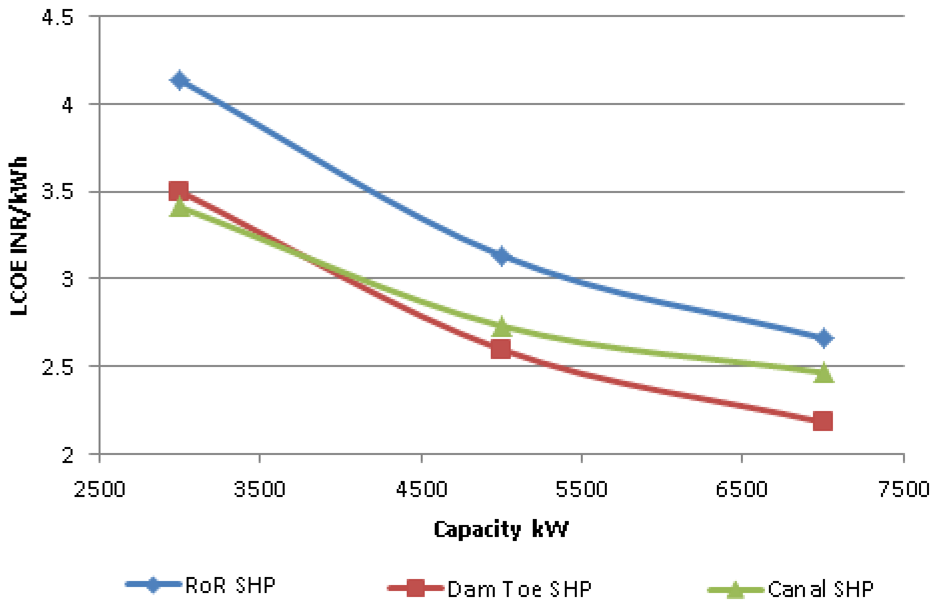

Figure 6. Variation of LCOE w.r.t capacity for low head SHP schemes.

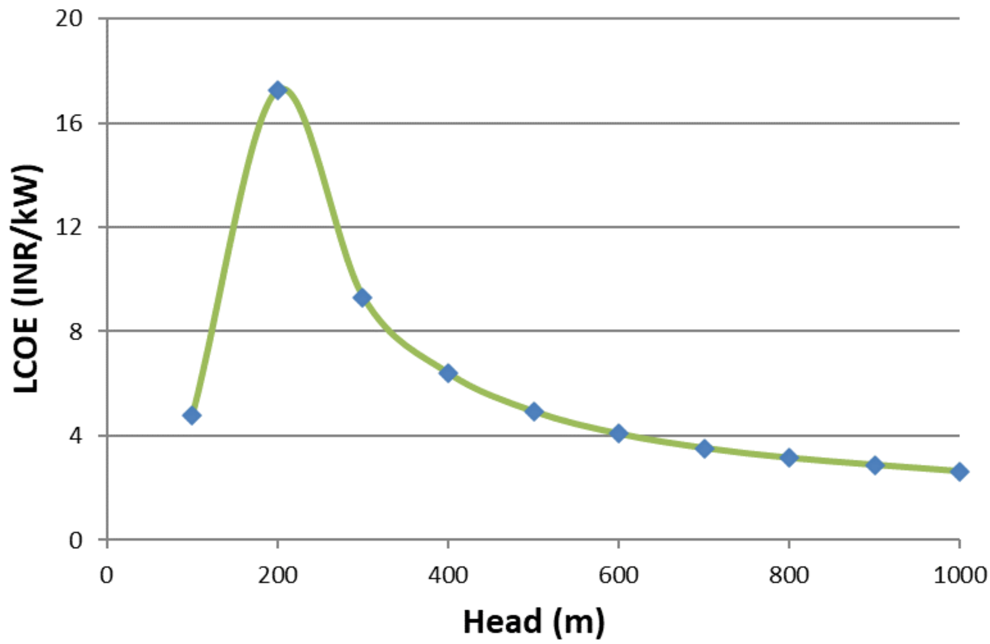

Figure 7. Variation of LCOE w.r.t head for 2000 kW high head SHP schemes.

4. Conclusions

This paper has computed the levelized cost of electricity generation by small hydropower projects under the Clean Development Mechanism. Under this, the SHP project can generate both electricity and tradable CERs simultaneously. The implication and applicability procedures of life cycle costing methodology based on net present value analysis to determine the levelized cost of electricity to small hydropower projects have been demonstrated. Using the correlations available for SHP projects, various SHP schemes have been studied and initial capital cost has been estimated. Then, for each SHP scheme under consideration, a life cycle cost based on the net present value was calculated by subtracting the discounted CER revenues from the initial capital investments, as well as the discounted OMC and RC costs, to arrive at the net cost of electricity to be generated over the life of each scheme. LCOE for each scheme has been calculated by dividing the net present cost by discounted flow of electricity.

The methodology was implemented on a range of low and high head small hydropower plants and the results are analysed. The various cost components of small hydropower plants and the range of factors affecting these costs are discussed. It has been observed that civil work costs in case of high head plants and electro-mechanical components in case of low head plants, both sensitive to head and capacity, are crucial in arriving at the plant's overall cost. Civil work costs account for significant costs, it is essential to look for improved and innovative designs in water conveyance systems, powerhouse buildings and other structures. Regarding electro-mechanical components, the turbine is the most important component and research has to be conceded in the areas of mini and micro technologies for cost reduction. In addition, it is evident that SHP schemes exhibit economies of scale in electricity generation under CDM, i.e., a plant with more capacity will have less per unit cost. Life cycle costing-based LCOE analysis demonstrated in this paper can be a useful tool for analysing changes in macroeconomic conditions that regulatory bodies and CDM authorities impose on SHP projects. The computation of LCOE based on LCC proves to be proficient in identifying the profit margins and chief cost determining parameters intended for initiating necessary cost reduction measures by SHP developers and operators.

Author Contributions: Conceptualization, E.R.P. and T.S.K.; methodology and formal analysis, E.R.P. and T.S.K.; writing—original draft preparation, E.R.P. and T.S.K.; writing—review and editing, T.S.K. and E.R.P.; visualization, T.S.K. and E.R.P.; A.T.H. provided supervision during the original draft preparation and helped during the project administration. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by The University of Oulu and The Academy of Finland Profi4 318930.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

AEP	Annual Energy Production	IC	Initial Capital
c	Cost of issuing 1 CER	INR	Indian Rupee
CAUX	Cost of auxiliaries	LCC	Life Cycle Cost
CCIV	Cost of civil works	LCOE	Levelized Cycle Cost of Electricity
CDC	Cost of desiltying chamber	NPV	Net Present Value
CDM	Clean Development Mechanism	OMC	Operation and Maintenance Cost
CDW	Cost of diversion weir	P	Plant Capacity
CDW&I	Cost of diversion weir and intake	PLF	Plant Load Factor
CEF	Carbon Emission Factor	Q	Discharge
CEM	Cost of electromechanical equipment	T	Project operating life
CER	Certified Emission Reductions	TV_O	Total Value
CF&S	Cost of forebay and spillway	UNFCCC	United Nations Framework Convention on Climate Change
CGE	Cost of generator exciter system	X	Returns from electricity sale
CI	Cost of intake	Y	Returns from CER sale
CPC	Cost of power channel	η	Efficiency
CPHB	Cost of power house building	ρ	Water density
CPST	Cost of penstock	ρ^X	Electricity cost

CS	Cost of spillway	ρ^{Y}	CER cost
CSHP	Cost of SHP plant	ρ_0^{-X}	Weighted average price of electricity
CT&SY	Cost of transformer and switchyard	ρ_0^{-Y}	Weighted average price of CER sale
CTG	Cost of turbine governor system	X_O	Electricity volume
CTR	Cost of tailrace	Y_O	CER volume
g	Acceleration due to gravity	w_τ	Input Price Vector
GCE	Gross Annual CO_2 Emissions	S_τ	State variables set
GHG	Greenhouse Gases	τ	CER issuance period
H	Head		

References

1. Zhao, Z.Y.; Li, Z.W.; Xia, B. The impact of the CDM (clean development mechanism) on the cost price of wind power electricity: A China study. *Energy* **2014**, *69*, 179–185. [CrossRef]
2. Spalding-Fecher, R.; Joyce, B.; Winkler, H. Climate change and hydropower in the Southern African Power Pool and Zambezi River Basin: System-wide impacts and policy implications. *Energy Policy* **2017**, *103*, 84–97. [CrossRef]
3. USEIA. *Levelized Costs of New Generation Resources in the Annual Energy Outlook 2021*; U.S. Energy Information Administration: Washington, DC, USA, 2021. Available online: https://www.eia.gov/outlooks/aeo/electricity_generation.php (accessed on 1 December 2021).
4. Branker, K.; Pathak, M.J.M.; Pearce, J.M. A review of solar photovoltaic levelized cost of electricity. *Renew. Sustain. Energy Rev.* **2011**, *15*, 4470–4482. [CrossRef]
5. Sims, R.E.H.; Rogner, H.H.; Gregory, K. Carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity generation. *Energy Policy* **2003**, *31*, 1315–1326. [CrossRef]
6. Larsson, S.; Fantazzini, D.; Davidsson, S.; Kullander, S.; Höök, M. Reviewing electricity production cost assessments. *Renew. Sustain. Energy Rev.* **2014**, *30*, 170–183. [CrossRef]
7. Edomah, N.; Foulds, C.; Jones, A. Influences on energy supply infrastructure: A comparison of different theoretical perspectives. *Renew. Sustain. Energy Rev.* **2017**, *79*, 765–778. [CrossRef]
8. Bhattacharyya, S.C. Economic Analysis of Energy Investments. In *Energy Economics*; Springer: London, UK, 2011; pp. 163–189. [CrossRef]
9. Kishore, T.S.; Patro, E.R.; Harish, V.S.K.V.; Haghighi, A.T. A Comprehensive Study on the Recent Progress and Trends in Development of Small Hydropower Projects. *Energies* **2021**, *14*, 2882. [CrossRef]
10. Cavazzini, G.; Santolin, A.; Pavesi, G.; Ardizzon, G. Accurate estimation model for small and micro hydropower plants costs in hybrid energy systems modelling. *Energy* **2016**, *103*, 746–757. [CrossRef]
11. Carapellucci, R.; Giordano, L.; Pierguidi, F. Techno-economic evaluation of small-hydro power plants: Modelling and characterisation of the Abruzzo region in Italy. *Renew. Energy* **2015**, *75*, 395–406. [CrossRef]
12. Zema, D.A.; Nicotra, A.; Tamburino, V.; Zimbone, S.M. A simple method to evaluate the technical and economic feasibility of micro hydro power plants in existing irrigation systems. *Renew. Energy* **2016**, *85*, 498–506. [CrossRef]
13. Raimondi, A.; Bettoni, F.; Bianchi, A.; Becciu, G. Economic Sustainability of Small-Scale Hydroelectric Plants on a National Scale—The Italian Case Study. *Water* **2021**, *13*, 1170. [CrossRef]
14. Balkhair, K.S.; Rahman, K.U. Sustainable and economical small-scale and low-head hydropower generation: A promising alternative potential solution for energy generation at local and regional scale. *Appl. Energy* **2017**, *188*, 378–391. [CrossRef]
15. Filho, G.L.T.; dos Santos, I.F.S.; Barros, R.M. Cost estimate of small hydroelectric power plants based on the aspect factor. *Renew. Sustain. Energy Rev.* **2017**, *77*, 229–238. [CrossRef]
16. Rahi, O.P.; Kumar, A. Economic analysis for refurbishment and uprating of hydro power plants. *Renew. Energy* **2016**, *86*, 1197–1204. [CrossRef]
17. Quaranta, E.; Aggidis, G.; Boes, R.M.; Comoglio, C.; De Michele, C.; Patro, E.R.; Georgievskaia, E.; Harby, A.; Kougias, I.; Muntean, S.; et al. Assessing the energy potential of modernizing the European hydropower fleet. *Energy Convers. Manag.* **2021**, *246*, 114655. [CrossRef]
18. Patro, E.R.; Voltz, T.J.; Kumar, A.; Grischek, T. Micro-hydropower in drinking water gravity pipelines: A case study in Uttarakhand, India. *ISH J. Hydraul. Eng.* **2018**, *26*, 332–342. [CrossRef]
19. Mishra, S.; Singal, S.K.; Khatod, D.K. A review on electromechanical equipment applicable to small hydropower plants. *Int. J. Energy Res.* **2012**, *36*, 553–571. [CrossRef]
20. Rahman, S.M.; Larson, D.F.; Dinar, A. Costs of greenhouse gas emissions abatement under the clean development mechanism. *Clim. Chang. Econ.* **2015**, *6*, 1550005. [CrossRef]
21. GIZ. *Carbon Market Roadmap for India Looking Back on CDM and Looking Ahead*; German Development Cooperation: New Delhi, India, 2020. Available online: https://www.giz.de/en/worldwide/368.html (accessed on 1 December 2021).
22. CEA. *CDM—CO_2 Baseline Database*; Central Electricity Authority: New Delhi, India, 2019. Available online: https://cea.nic.in/cdm-co2-baseline-database/?lang=en (accessed on 1 December 2021).
23. International Energy Agency India. *2020: Energy Policy Review*; IEA: France, Paris, 2020. Available online: https://www.iea.org/events/india-energy-policy-review-2020 (accessed on 1 December 2021).

24. Liu, D.; Liu, H.; Wang, X.; Kremere, E. *World Small Hydropower Development Report 2019*; United Nations Industrial Development Organization: Vienna, Austria, 2019. Available online: https://www.unido.org/our-focus-safeguarding-environment-clean-energy-access-productive-use-renewable-energy-focus-areas-small-hydro-power/world-small-hydropower-development-report (accessed on 1 December 2021).
25. Rahman, S.M.; Spalding-Fecher, R.; Haites, E.; Kirkman, G.A. The levelized costs of electricity generation by the CDM power projects. *Energy* **2018**, *148*, 235–246. [CrossRef]
26. Singal, S.K.; Saini, R.P.; Raghuvanshi, C.S. Analysis for cost estimation of low head run-of-river small hydropower schemes. *Energy Sustain. Dev.* **2010**, *14*, 117–126. [CrossRef]
27. Singal, S.K.; Saini, R.P. Cost analysis of low-head dam-toe small hydropower plants based on number of generating units. *Energy Sustain. Dev.* **2008**, *12*, 55–60. [CrossRef]
28. Singal, S.K.; Saini, R.P. Analytical approach for development of correlations for cost of canal-based SHP schemes. *Renew. Energy* **2008**, *33*, 2549–2558. [CrossRef]
29. Mishra, S.; Singal, S.K.; Khatod, D.K. Cost Optimization of High Head Run of River Small Hydropower Projects. In *Application of Geographical Information Systems and Soft Computation Techniques in Water and Water Based Renewable Energy Problems*; Springer: Singapore, 2018; pp. 141–166. [CrossRef]
30. Singh, V.K.; Singal, S.K. Operation of hydro power plants-a review. *Renew. Sustain. Energy Rev.* **2017**, *69*, 610–619. [CrossRef]
31. Department of Hydro and Renewable Energy. *Standards/Manuals/Guidelines for Small Hydro Development*; Roorkee: Uttarakhand, India, 2014. Available online: https://www.iitr.ac.in/departments/HRE/pages/Publications+Standard_and_Guidelines.html (accessed on 1 December 2021).
32. Lal, S.R.S.; Herbert, G.M.J.; Arjunan, P.; Suryan, A. Advancements in renewable energy transition in India: A review. In *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*; Taylor & Francis: Abingdon, UK, 2022; pp. 1–31. [CrossRef]
33. Kumar, K.; Saini, R.P. A review on operation and maintenance of hydropower plants. *Sustain. Energy Technol. Assess.* **2022**, *49*, 101704. [CrossRef]
34. Fonseca, M.; Bezerra, U.H.; Leite, J.C.; Rodríguez, J.L.M. Maintenance Tools applied to Electric Generators to Improve Energy Efficiency and Power Quality of Thermoelectric Power Plants. *Energies* **2017**, *10*, 1091. [CrossRef]
35. Vera-García, F.; Rubio, J.A.P.; Grau, J.H.; Hernández, D.A. Improvements of a Failure Database for Marine Diesel Engines Using the RCM and Simulations. *Energies* **2019**, *13*, 104. [CrossRef]