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A Cost-Benefit Analysis of Bakhtiari Hydropower Dam Considering the Nexus between Energy and Water

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Abstract: Hydropower stations have supplied most of the green electricity in various parts of the world. Nonetheless, the economic profit of hydro-electricity lies beyond its social costs in many cases. Despite the short-term economic benefits of large dams, their sustainable pros and cons are doubted. This study aims to investigate the long-term profitability of large hydropower stations by considering the nexus between the environmental, economic, and social aspects. Much progress has been made in simplifying feasibility studies of hydropower stations by developing comprehensive software and models according to the United Nations Sustainable development goals. Developed by International Atomic Energy Agency (IAEA), the SimPacts has become one of the most frequently-used simple models to estimate the external costs of electricity generation since 2003. Hydropower's Environmental Costs Analysis Model (HECAM) is a popular user-friendly version of the model that includes more details for benefits estimation. In the present investigation, sedimentation and evaporation effects of constructing hydropower dams are added to previous cost estimation factors to upgrade the HECAM model to HECAM II. Bakhtiari hydropower dam (located in Lorestan province in Iran) is employed as a case study to verify the new model. The results showed that the total cost and revenue, as well as the benefit to cost ratio, were 79.13 US$/MWh, 203 US$/MWh, and 2.57, respectively. The new HECAM II model showed that the operation of Bakhtiari Dam would alleviate the socio-environmental doubts through a long-term plan in the region.

Keywords: Bakhtiari Dam; environmental impact assessment; hydro project; social-economic feasibility; water-energy-food nexus

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1. Introduction

Construction of hydro-dams, similar to other structures of this type and scale, has always involved positive and negative consequences [1]. These consequences include physical, biological, and socio-economic aspects [2]. Inappropriate planning and mismanagement of dams usually result in negative impacts [3], such as the loss of property, employment, agricultural land and natural resources [4], food insecurity, spread of various diseases, increase in mortality rate, loss of educational opportunities, child labor to compensate for the household budget deficit, damage to socio-cultural identity, overexploitation of natural resources, environmental pollution, regional safety and security reduction [5]. Hydro dam assessment has been crucial for decision-making all around the world.

Many researchers have studied hydro projects using multi-aspect models [6]. Long time-series (1964 to 2018), including various climatic features, as well as Dez dam characteristics, were employed to bring out a water-energy nexus-based assessment. It was found that the initial design reservoir volume (3315 MCM) had shrunken to 2600 MCM as a result of sedimentation in the past 40 years of operation [7]. The complex relationship between the water, energy and food sectors necessitated constructive cooperation between various stakeholders [8]. An investigation on Grand Ethiopian Renaissance Dam revealed positive environmental and economic benefits [9]. However, the transboundary river basins needed deeper investigations to draw a conclusion. Some studies have shown that evaporation is a vital phenomenon by taking into account the nexus between water, food and energy in the hydro dams [10] and proposing using floating photovoltaic systems or any other floating objects to minimize evaporation at large water bodies [11]. South Asian countries with little precipitation might benefit from floating solar technologies to alleviate potable water shortages and improve electricity production [12]. However, the floating solar technologies might not be economically feasible in some of these countries [13]. Despite the significance of economics in employing innovative technologies to enhance dams' operation, most of the commercial assessment models neglect these parameters.

In general, none of the methods for predicting effects and locating dams are sufficiently flexible to allow periodic revisions and the inclusion of erratic variables [14]. The main problem of dams' impact assessment is the temporal difference between design and assessment stages in developing countries [15]. Some indicators, such as land use change along with agriculture and fisheries, as well as sedimentation, are among the neglected indicators in many studies [16]. In some developing countries, such as Iran, with a unique economic and political situation, environmental and social impact assessments are usually reported after site allocation for hydro projects [17]. This procedure causes serious socio-environmental problems in some cases, like the use of contingent valuation methods to evaluate the non-market and non-use values of the Glen Canyon Dam on the Colorado River. It should be noted that attention to tourism development, development of agriculture, control of greenhouse gas emissions, providing livelihoods for indigenous people, the effects of land use change, agricultural activities and fisheries and some important issues, such as the sediment trapping function of the dam, have been ignored in previous models. Despite progress in providing comprehensive approaches, an economic model encompassing influencing factors is scarce to evaluate the feasibility of hydropower dams.

A number of other studies have merely highlighted negative impacts of hydropower structures, regardless of their strategic role in power production, flood control and food supply [18]. The impacts of large dams have not been fully addressed because of the multidimensional, complex and dynamic nature of dam construction [19]. Price-based cost-benefit analysis is still in its early stages of development because of the non-subjectively distinguishable or non-economic nature of environmental assets. In spite of rich literature on the costs and benefits of damming from a single disciplinary viewpoint, only few studies have concurrently considered the biophysical, socio-economic and geopolitical effects of dams [20].

According to the effects of dam construction on various economic, social and environmental fields, simplified assessment approaches are not reliable enough for underestimating the prices of anthropogenic, natural, and cultural values. One of the common commercial models for hydropower valuation is provided by the SimPacts software. The software was first developed by International Atomic Energy Agency (IAEA) to estimate the external costs of electricity generation in 2003. Despite the robust logic and extensive calculations, the computations of the software are not comprehensive enough. This model encompasses only costs, and totally neglects the benefits. Moreover, the model ignores some of the most important environmental damages by the hydropower dams, including the costs of irrigation and drainage, electricity generation, aquaculture system upkeep and potable water supply systems. Hence, SimPacts software was upgraded to (HECAM) in a previous study [21]. The HECAM model is upgraded for more accurate results that could be considered as the novelty of the present research. Sedimentation and evaporation, for instance, were two important and hidden external costs that the model (HECAM), did not consider while realizing the costs of clean energy production. The objective of this study was to upgrade the HECAM model and provide a more comprehensive version (HECAM II) in detail. A socio-environmentally critical case study is introduced to validate the HECAM II model and the actual costs and benefits of hydropower generation are considered to draw a conclusion on the feasibility of the project taking the sustainable development goals into account. Although the HECAM provides a practical tool for decision makers, there is much left to do in order to reach maximum efficiency and this requires the cooperation of the scientific community from various fields.

2. Hydro Projects and Sustainable Development

Rapid development strategies have intensified anthropogenic climate change and inequality in many aspects among nations, with the result that sustainable development has been put forward by the research community. The terminology "sustainable development" represents fulfilling the present needs considering the requirements of the future generations [22]. More recently, much research has been devoted to study the interconnections (nexus) considering hydro reservoirs as case studies [23]. A recent survey on 57 World Bank Group-sponsored hydropower dam plant investments showed that dams produced a present net value of over half a trillion USD by 2016. The evaluated hydropower portfolio reduced over a billion tons of CO_2 that amounted to nearly USD 350 billion when taking the global environmental benefit into account [24]. Hence, hydro dams usually contribute to no poverty but assessing their impact on mitigating climate change needs multi-aspect models consisting of various media [25]. Another study showed that hydro dams could induce a decline in suspended sediment flux by 50% [26]. It is straightforward that such an effect necessitates considering the nexus between water and food while designing hydro dams [27]. Canpolat et al. [28] developed a model for the health risk assessment in huge water bodies, and showed that trace elements in surface and deep-water levels of a studied lake did not pose health risks to residents.

Unlike the economic, environmental, and technical aspects of sustainable development, the social impacts are more complicated to be assessed in hydro reservoirs [29]. The term "water for energy" was defined to justify the role of hydro projects for the supply of water and energy [30]. Optimal artificial intelligence-assisted management of multi-purpose hydro reservoirs showed the significance of responsible demand-based production of water and energy [31,32]. The long-term monitoring of reservoirs is necessary to show the spatial dispersion of life below water [33]. Roth et al. [34] developed a multi-scale approach for the development process of land settlement projects in the presence of dams. Hydro-diplomacy is a controversial topic that questions the role of dams in providing peace and justice. However, positive news are not scarce in terms of addressing the constructive role of common hydro projects between old enemies [35]. Complex hydro projects cannot be successfully conducted if there is no strong partnership between the stakeholders, especially if the case is located on a border run-off.

In this research article, first, a less-studied critical hydro project is analyzed to provide useful data for sustainable decision-making in a developing country. Second, the assessment is conducted with pre-construction conditions to avoid any costly decisions. Third, the model has been developed to be both simple for extensive application and comprehensive to be reliable. Fourth, social, environmental, economic, and ecological aspects of the project are considered to include most aspects of the sustainable development in the holistic model. Thus, we mean to shed light on less-seen prospects of a sensitive hydro project in a developing country by developing a multi-aspect model.

3. Case Study

Bakhtiari Dam will be located in the south-western slopes of the Zagros Mountains in south-west Iran [36]. It is planned to be constructed on Bakhtiari river bank that forms a boundary between Lorestan (right bank) and Khuzestan (left bank) provinces. It will be constructed in a narrow V-shaped gorge, which is suitable for a concrete arch dam [37]. At 315 m height, it will not only be the highest concrete arch dam, but the highest dam of any type in the world (higher than the 300 m high Nurek Dam in Tajikistan, and as long as the planned 335 m high Rogun Dam in Tajikistan) [38]. However, project alternatives with a full storage level of 810, 790 and 770 m are still under study.

An aerial view of the region under study is shown in Figure 1. The total length of the reservoir along the Bakhtiari river (which is called Zalaki river upstream) is 60 km, and its width is below 2 km. The catchment of the Bakhtiari Dam has a total area of 6503 km^2 [39]. The river originates from the heights of the Zagros Mountains in the south-east of Dorud and Aligudarz. The highest elevation of the catchment is 4080 m above sea level. Approximately 3.1 km downstream from the dam site, the Cezar and Bakhtiari rivers meet each other to form the Dez river. The dam site will be located at 50°46′48″ E and 41°57′32″ N. The Bakhtiari Dam will be a part of the cascade in the Dez-Karun river basin. The Dez dam is located approximately 76 km below Bakhtiari site, and was commissioned in 1978. It is 203.5 m tall with a storage volume of 3339 Mm^3, and its 65 km^2 reservoir rests 56 km along the Dez river. Only about 17 km downstream of this point, the Dez river enters the Dez reservoir. The whole 17 km distance has the character of a mountain stream, flowing in a mostly narrow bed between steep slopes. The Dez river feeds the Karun river that flows into the Arvandrud and that finally flows into the Gulf. The main emphasis in this study will be on the part of the downstream area which is directly influenced by the project, i.e., the 20 km down to the Dez reservoir.

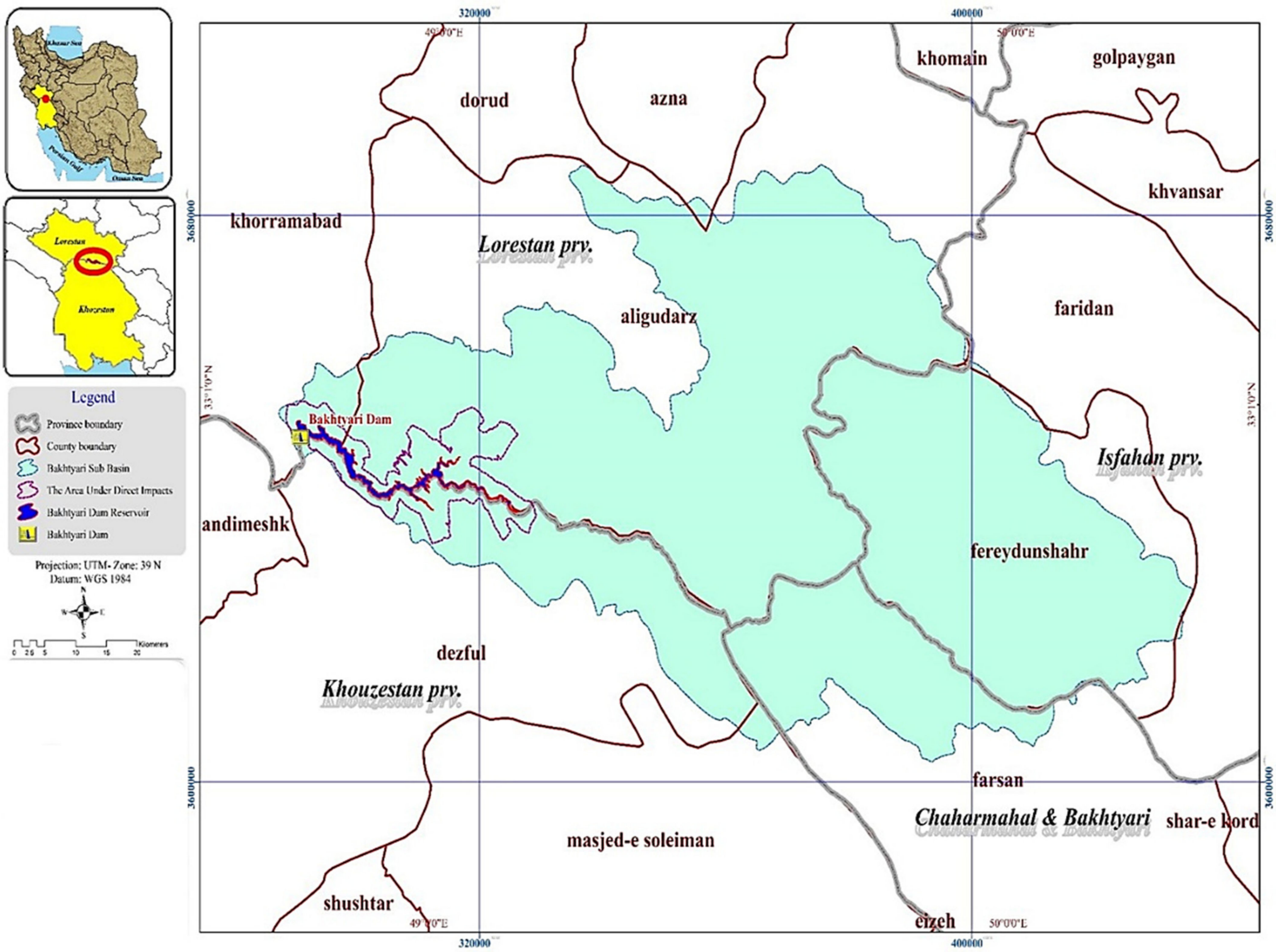

Figure 1. An aerial view of the area of study showing border details.

A closer aerial view of the region is shown in Figure 1 with less topographic details. Due to the mountainous nature of the project area, the reservoir is dendritic rather narrow and long (total length about 60 km) with steep shores. Immediately up- and downstream of the dam site, the river valley is a little wider. The layout of the project, and of the construction site as a whole, has to be adapted to this situation. The entire area is very rocky and without much vegetation. The lateral slopes of the reservoir mainly consist of steep mountainous slopes of bare rock. Only in some areas, the higher parts of these slopes are covered with patchy growth of trees, which hardly qualifies as forest. Settlements in the reservoir area are generally small and are located along the river. They are concentrated in locations with enough vegetation to provide pasture for the livestock. Human use of the reservoir area is restricted to a number of small seasonal settlements of the Bakhtiari tribe whose winter quarters and livestock pasture are at the site location. In addition to the Bakhtiari river, Sarkul is the main tributary of the reservoir. The catchment is a thinly-populated high mountainous area, with scarce vegetation cover. The river discharge pattern follows the distinct seasonal distribution of precipitation and snow melt, being high in winter and very low in summer. Administratively, the reservoir area belongs to two provinces: Lorestan to the north (right bank) and Khuzestan to the south (left bank). The dam site can be accessed only by train, and the closest station is the Tang-e-Panj railway station, which is located between Dorud and Andimeshk on the Tehran-Ahwaz railway line [40].

Several water management scenarios have been forecast for the region. According to one of the studied scenarios, some of the water from the Cezar river would be diverted to the Bakhtiari river upstream of the catchment area. No industrial or urban pollution sources have been detected within the Bakhtiari catchment yet. However, the Cezar river gets highly polluted by various industrial sources, such as the Dorud cement plant, the sewage from the Dorud and Sepidan cities and a number of small villages, as well as the agricultural sources within the Cezar catchment [41]. These pollution sources (mainly the untreated sewage) cause a high load of chemical and biochemical oxygen demand, nitrate, and phosphate compounds. Although initial environmental assessments prohibit such a plan, an individual environmental impact appraisal should determine the consequences of the ecological change in the catchment.

The studied case can be divided into five areas to facilitate an environmental impact assessment, including dam and powerhouse, reservoir and immediate surroundings, downstream, catchment, and river basin. Most of the construction activities take place with considerable environmental impact in the dam and powerhouse area. The power house will be either below or above ground level, located at the foot of the dam. The type and location (left or right bank of the river) are still under study, but this is a minor issue from an environmental point of view. The total installed capacity will be 1500 MW. There will be six Francis turbines with a capacity of 250 MW and a maximum water output of 103 m^3/s. An additional small unit of 10–15 MW will be installed to release a permanent minimum water flow [42]. The formation of a reservoir leads to the most important environmental impact of dam construction. During the construction phase, special attention should be paid to the aquatic environment. After commissioning the plant, the main impact would be the changes in the river discharge pattern (seasonal according to storage capacity and daily according to plant operation pattern). In the case of the Bakhtiari, most of these changes will not be felt further away than the Dez reservoir, i.e., over a stretch of river of about 17 km. The project, as such, does not have any direct influence on its catchment area, whereas the catchment area affects the project. The most important effects include eutrophication of the reservoir by nutrients caused by human activities.

Bakhtiari Dam was selected as the case study not only for its huge reservoir, but also for the critical region in which it is meant to be constructed. Oil-rich Khuzestan province contains reserves equal to approximately 8% of global crude oil, but suffers from little social development, poor air quality, and water mismanagement [43]. The same dilemma occurs in Lorestan province where social and economic underdevelopment is observed as compared to other provinces in Iran [44]. Despite rich natural and underground resources, the economic condition of the society strongly depends on water resources, since the agricultural sector provides local jobs in the region [45]. More recently, there was a field protest by the local residents regarding drought problems in Khuzestan for some weeks. Thus, the pros and cons of this project should be deliberately analyzed by a comprehensive assessment model in favor of sustainable development. The model is detailed in the next section.

4. Methods

The SimPacts and HECAM models are modified, in realization of the costs and benefits of constructing hydropower dams. The HECAM model has been described in detail elsewhere [46]. Sedimentation and evaporation were two new phenomena, which were included in HECAM II in order to bring out the actual costs and benefits of dam construction. Both the SimPacts and HECAM models lack these calculations. The Bakhtiari Dam was analyzed to validate the upgraded model.

The required investment for the hydropower dam is computed over its lifetime using the straight line depreciation method. It was assumed that the power plant would be depreciated over its lifetime in 50 years [47]. The annuity present value of investment of the power plant was US$721,671. The same procedure was applied to the dam structure. Fixed and variable costs of repair and maintenance were added to the former HECAM model. Some operating costs are fixed, but the costs that are independent of the production needed to be applied to the nominal capacity of the power plant. These costs were personnel salaries, charges, and irrigation of green spaces. In addition, variable costs, such as the costs of repair and replacement of parts, needed to be considered. The fixed costs were related to the nominal capacity (calculated based in kWh) and so were independent of production, while the variable costs depended on energy production. The costs were obtained on an annual basis. The real interest during the construction period was calculated based on the annual cash flow of the power plant at the annual interest rate, assuming that the payments were made in the middle of each year. Subsequently, the annuity investment costs of the dam and power plant were determined. The investment cost was calculated for a 750 MW power plant with 445 US$/kWh. Furthermore, the cost of reconstruction was calculated from the 25th year of the study period and the present value was calculated at an interest rate of 10% per year. The power plant construction period interest rate ($IDCF$) was obtained using Equation (1).

$$IDCF = \left[z_1 \times (1+i)^{(CS-1)+0.5} + z_2 \times (1+i)^{(cs-2)+0.5} + \cdots + z_n \times (1+i)^{0.5}\right] - 1 \quad (1)$$

where z_i, z_n are annual payment coefficients for power plant construction period (deduction), CS is the construction period (year), and i is the interest rate during construction that is usually considered to be equivalent to the annual discount rate (deduction rate). A reinvestment period of 25 years was regarded for the study period and the time of reconstruction. The hydrological study period was taken into consideration for about 50 years, while the lifespan of the power plant and dam were the same as and were twice the study period, respectively. The power plant re-investment in the 25th year of the dam age was considered for about a quarter of overall investment. Accordingly, considering the initial investment, the present value of reinvestment (CIF) was calculated using Equation (2).

$$CIF = \frac{SVF}{(1+i)^{15}} \quad (2)$$

where the SVF is the present value for the 50 years of the dam annuity calculated by the following equations:

$$SVF = A(50) \times B(100) \quad (3)$$

$$A(50) = \frac{i \times (1+i)^{50}}{(1+i)^{50} - 1} \quad (4)$$

$$B(100) = \frac{(1+i)^{25} - 1}{i \times (1+i)^{25}} \quad (5)$$

where A (50) is the present value of the annuity over a 50-year period and B (100) is the annuity factor over the 100-year period. Therefore, the investment cost for the power plant is calculated as follows:

$$FICH = PGH \times FUCP \times \left[FUCP \times \frac{RF}{(i+1)^{RY}}\right] \times (1 + IDCF) \times A(50) \tag{6}$$

$$FICD = PGH \times FUCD \times FUCP \times SVF \times (1 + IDCF) \times A(50) \tag{7}$$

where $FICH$ is the power plant's investment cost ($), PGH is the power plant's installed capacity (KW), $FUCP$ is the cost of the power plant construction ($/KW), $FICD$ is the cost of dam construction ($/KW), RY is the reconstruction cost, RF is the reconstruction factor, and $IDCF$ is the interest rate in the power plant construction period. Repair and maintenance costs are obtained using Equations (8) and (9).

$$DFOM = PGH \times DFOMUC \tag{8}$$

$$FVOM = TEG \times FVOMUC \times 0.01 \tag{9}$$

where $DFOM$ is the constant monetary present value of repair (and maintenance) costs during the lifespan of the power plant ($/Kwh), $FVOM$ is the power plant's variable monetary present costs of repair (and maintenance) during the study lifespan ($/Kwh), $DFOMUC$ is the power plant's annual fixed repair (and maintenance) costs per kW of nominal capacity, and $FVOMUC$ is the variable repair and maintenance cost per kWh net energy generation. Accordingly, the total cost of power generation (TCP) can be calculated using Equation (10).

$$TCP(US\,\$) = FICH + FICD + DFOM + FVOM \tag{10}$$

Total income of the 750 MW Bakhtiari Dam comes from electricity sales and the reduction in emission of greenhouse gases. The income from the sale of electricity generated by the power plant is one of the main benefits of constructing the Bakhtiari Dam. Therefore, calculations for this source of income were included in HECAM II model. The unit price of electricity sales was considered to be 5 ¢/kWh, based on calculations performed by a specialized company for the management of production, transmission and distribution of Iranian electricity. Another benefit of the hydropower plant's construction is a reduction in the emission of greenhouse gases. Having the global carbon penalty cost range of 10–44 US$/ton, the minimum amount of 10 US$/ton was selected as the sales price of carbon [48]. The difference in the amount of carbon dioxide produced by hydropower and thermal power plants was defined as the net income. In order to convert NO_X and SO_X to CO_2-equivalent, the price inventory of the Energy and Environment software was used that is developed by the Ministry of Energy of Iran Table 1.

Table 1. Income specifications of this section.

Parameter	Value	Unit
Annual energy production	1,729,224	MWh
CO_2 emission rate of thermal power plant equivalent per year	12,675,211.92	Ton/Year
SO_X emission rate of thermal power plant equivalent per year	58,793.616	Ton/Year
NO_X emission rate of thermal power plant equivalent per year	19,021.464	Ton/Year
Total emission of environmental pollutants equivalent to annual CO_2	12,694,293.43	Ton/Year
Income from saving environmental pollutants	126,942,934.3	$/year
Annual revenue from the sale of generated electricity	86,461,200	$/year
Total annual income	213,404,134.3	$/year

According to the inventory, social price of these three pollutants was calculated as US$284,675 per year for a 750 MWh hydropower plant and US$48,327,975 per year for a 300-Mwh thermal power plant (equivalent to operation of a 700-Mwh hydropower plant).

The income from the reduction in emissions of these pollutants was calculated using the Equation (11).

$$Rev._{pol.} = CP \times T_{emis.} \quad (11)$$

where $Rev._{pol.}$ is the revenue from reduction of pollutants, CP is the carbon price, and $T_{emis.}$ is the total emission level. Damming contributes to agricultural and industrial development by increasing the accessible water in a basin. Hence, a section entitled as "Irrigation and Drainage" was added to the HECAM model. In this section, the cost of water transfer and the income from the increase in the cultivated area can be computed. It is also possible to estimate the total revenue from each type of agricultural product. It was assumed that the cost of water transmission, including digging diversion tunnels and pumping, should have been added at one time at the initial stages of dam construction. Hence, the present value of annuity was obtained as yearly costs of irrigation and drainage for agricultural development, as given in Equation (12).

$$TCI\&D = WCT \times A(50) \quad (12)$$

where $TCI\&D$ is the present annuity value of irrigation and drainage cost ($), and WCT is the water transmission cost. The income of up to 10 products could be calculated in this model, in which the cultivation was feasible after the dam construction stage. For this, the agricultural product type, total production amount, and price per product were required as the model input. Considering the mountainous terrain in the catchment area of Bakhtiari Dam, agricultural development was neglected. Revenue from the construction of water transfer and drainage facilities to develop the area under cultivation of 10 crops is included in the new model; $TBI\&D$ (irrigation and drainage revenue) can be determined using Equation (13).

$$TBI\&D = \sum A_i \times P_i \times Pr_i \quad (13)$$

where A_i is the area under cultivation of the ith crop (km^2), P_i is the total production of the ith crop (tons/km^2), and Pr_i is the unit price of the ith crop ($/tons).

Dams, apart from their original applications in controlling floods and water storage, can be equipped with fish farming facilities to be a decent source of income in a catchment. This income source was neglected in the SimPacts model, but it was obtained in the HECAM II model using Equation (14).

$$TCF = TIF \times A(50) + FVOM + DVOM \quad (14)$$

where TCF is the total annual cost of fisheries ($), TIF is the total cost of construction of fish farming pools and facilities ($), $FVOM$ is the total annual cost of repair and maintenance ($), $DVOM$ is the cost of the needed materials ($/year), and $A(50)$ is the annuity coefficient during the study lifespan. The model is capable of calculating the income from fisheries of up to 10 fish types, using Equation (15).

$$TBF = \sum (FP_i \times FPr_i) \quad (15)$$

where TBF is the annual total revenue from aquaculture ($), and FP_i is the total production of the ith fish species (tons).

Flood control is another important application of damming that indirectly saves costs by preventing damage from flood, as given in Equation (16).

$$TFDC = FDC \times \left[1 + \frac{1}{(1+i)^{30}} \times \frac{A(30)}{A(20)}\right] \quad (16)$$

where $TFDC$ is the annual present value of flood damage ($) and FDC is the damage of flooding over a period of 30 years. Due to the fact that the flood period is considered to be equal to 30 years, because in this dam the study period is equal to 50 years, so during the life of the project, floods can occur 1.052 times at the bottom. Therefore, the cost is calculated based on the number of times the flood is likely to be repeated in the useful life of the dam. This was done by calculating the sub-flood area in the absence of the dam and considering the land and civil structures, and comparing this to the case in which the disaster is prevented by the dam in the corresponding GIS maps.

The total cost of water transfer and the annual maintenance and repair cost of water transfer equipment are calculated as the present value of annuity of water transfer cost in the HECAM II model. On the contrary, the total revenue was calculated as the income from an increase in "commercially available water" and the annual sales volume of water.

$$TCSF = TISF \times A(50) + FOMSF + VOMSF \quad (17)$$

where $TCSF$ is the annual cost of water transfer ($), $TISF$ is the cost of water transfer facilities, $FOMSF$ is the maintenance and repair cost of water transmission facilities ($), $VOMSF$ is the yearly cost of needed materials (US $), and $A(50)$ is the annuity coefficient in the study lifespan.

According to the grand plan of Bakhtiyari dam, a part of the water in the dam would be used as the drinking water. The annual income of the potable water transmission was calculated using Equation (18).

$$T_{rev.} = Incr._{w} \times W_s \quad (18)$$

where T_{rev}. is the total annual revenue from potable water (US$), $Incr._{w}$ is the increase in commercially available water (m^3), and W_s is the water selling rate (US$/$m^3$). In recent years, drought and a reduction in vegetation density have increased the erosion rate in Iran, especially in the study area. These phenomena would probably lead to the deposition of sediment at the intake of those dams that have been in operation for more than 30 years, leaving them out of the electricity generation cycle. Sediment trapping would be another essential function of damming. The balance and alignment of the Bakhtiari Dam are adjusted to collect all of the inflow sediment during its lifetime of 50 years and no additional alignment costs are required to manipulate the balance for sediment trapping at the downstream. Savings in sediment trapping costs can be calculated using Equation (19).

$$SSC = VS \times 10^6 \times CS \quad (19)$$

where SSC refers to the savings in the sediment trapping cost (M$), VS is the total volume of sediment trapping (mm^3), and CS is the total cost of sediment trapping (US$/ m^3). It should be pointed out that HECAM II could compute the cost of sedimentation. However, this option was not considered in the calculations due to the sediment trapping capability of Bakhtiari Dam. In order to calculate the total income of sediment trapping, the model uses the cost of sediment trapping of downstream dams. This reduction in the costs of sediment trapping is considered as an income and an advantage of damming, which is considered as the model input. In addition, the sediment trapping performance of the dam increases the volume of available water for industrial, agricultural and drinking uses. The HECAM II model estimates the total revenue in terms of the increase in available water by calculating the value of each additional cubic meter of water according to the water needs of downstream areas, as given in Equation (20).

$$W_{valu.} = \frac{AgrW_{vol.} \times AgrW_{valu.} + IndW_{vol.} \times IndW_{valu.}}{AgrW_{vol.} + IndW_{vol.}} \quad (20)$$

where $W_{valu.}$ is the total value of water at downstream areas (US$), $AgrW_{vol.}$ is the total volume of water at downstream areas for agricultural use (MCM), $AgrW_{valu.}$ is the value of water in agricultural sector (US$/m^3), $IndW_{vol.}$ is the volume of industrial and potable water (MCM), and $IndW_{valu.}$ is the value of water for industrial and drinking uses (US$).

$$Rev._{iwv} = Inc.W_{vol.} \times Inc.W_{vol.} \times 10^6 \quad (21)$$

where $Rev._{iwv}$ is the revenue from the increased water volume (US$), $Inc.\ W_{vol.}$ is the increased volume of water due to the improvement of the downstream reservoir by sediment trapping (MCM), and $W_{valu.}$ is the value of water at downstream areas (US$). The revenue from increased reservoir discharge by dam construction and electricity generation is calculated using Equation (22).

$$Rev.IPG = IPG \times P \quad (22)$$

where $Rev.IPG$ is the revenue from increased power generation at downstream areas (US$), IPG is the increased level of power generation (MWh/yr), and P is the unit price of electricity ($/kWh).

$$Rev._{Total} = RCST + Rev._{iwv} + Rev._{IEP} \quad (23)$$

where $Rev._{Total}$ is the total annual revenue (US$/yr), $RCST$ is the reduced cost of sediment trapping (US$/yr), $Rev._{iwv}$ is the revenue from the increased water volume and $Rev._{IEP}$ is the income from the increased energy production at the downstream (US$/yr).

Large volumes of water affect the surrounding climate, especially in terms of temperature and humidity. The most important of these effects are the cooling of the air in hot seasons and the warming of the air in cold seasons. The reason for this phenomenon is the surface evaporation from lakes. In case of small lakes, such as dam lakes, it is very difficult to determine temperature changes in their vicinity due to the sophisticated process of local winds. As a general rule, lakes show a beneficial effect on local microclimates. The impact of the Bakhtiari reservoir on the local climate is very low and might be negligible. The reservoir of this dam is relatively small, so the effect of its artificial lake on the microclimate is transient and is restricted to the areas adjacent to the reservoir. The temperature, humidity, pressure, and area of dam lakes are important factors in the evaporation of water from their surface. From this viewpoint, evaporation is a kind of cost because an opportunity is lost by evaporation. The volume of the reservoir of the Bakhtiari Dam is approximately 3100 mm^3. This will result in an average evaporative volume of about 3 m^3/s from the reservoir surface. The HECAM II model computes the evaporation cost using Equations (24) and (25).

$$Evapo_{vol.} = AER \times Total_{vol.} \quad (24)$$

$$Evapo._{cost} = Evapo._{vol.} \times W_{vol.} \times 10^6 \quad (25)$$

where $Evapo_{vol.}.$ is the annual volume of evaporation (MMC/yr), AER is the annual evaporation rate from the total volume of reservoir water (%), $Total_{vol.}$ is the total volume of reservoir (MCM), $Evapo._{cost}$ is the cost of evaporation (US$), and $W_{vol.}$ is the value of water downstream.

5. Results

The overall dam age was considered for half a century, and the scrap quantity was neglected while calculating the cost and revenue of hydropower generation in Bakhtiari Dam. Moreover, the revenue of fisheries was not considered because of the mountainous conditions of the study area and lack of suitable conditions for fish farming in the region. The total quantity of produced energy at this hydropower plant reached up to 1,729,224 MWh/yr, so the revenue generated by the sale of electricity was US$86,461,200. The annuity present value of investment for the power plant was determined as US$721,671. Tables 1–4 summarize the cost and revenue of hydropower generation by the Bakhtiari Dam in detail. According to the tables, the cost and income of power generation in the Bakhtiari power plant were expected to be equal to US$114,896,296 and US$213,404,134, respectively. It shows that the revenue of the power generation is about 1.8 times the total cost.

Table 2. Cash flow of payment during construction period based on the S curve.

Construction Period (Yr.)	1	2	3	4	5	6	7	8
Adjustment factor of construction & operation	1.0000	1.1075	1.1183	1.1656	1.2138	1.2606	1.3094	1.3656

Table 3. Cost of power generation estimated by HECAM II Model in Bakhtiari Dam.

Cost variable	Quantity
Escalation factor	0.5
AlF(ag)/AlF(t)	0.991553402
Annuity factor	0.100859174
Present value of annuity for investment in power plant	US$40,142,986
Present value of annuity for investment in power dam	US$72,835,211
Constant monetary present value of repair and maintenance costs during the operation period	US$1,468,500
Present value of repair and maintenance costs during the operation period	US$449,598
Total annual cost	US$114,896,296

Table 4. Revenue of power generation estimated by HECAM II Model.

Profit Profile Items	Profit	Unit
Annual power generation	1,729,224	MWh
Annual CO_2 emissions from an equivalent thermal power plant	12,675,212	Ton
Annual SO_x emissions from an equivalent thermal power plant	58,794	Ton
Annual NO_x emissions from an equivalent thermal power plant	19,021	Ton
Total CO2 equivalent environmental emissions per year	12,694,293	Ton
Revenue from lower rates of environmental emissions	12,694,230	US$
Annual revenue from sales of electricity	86,461,200	US$
Total annual revenue	213,404,134	US$

However, the revenue and expenses can be further updated to mimic a real case. The reservoir volume of the Bakhtiari Dam is estimated to be 3330 MCM and its storage volume would be approximately 3100 MCM. Due to the proximity of the Tang-Panj Station to the dam site, a statistical analysis of the hydrometric data of this meteorological station would represent the flooding status in the Bakhtiari River at the dam site. Hence, the Talezang hydrometric station was selected as the reference station. Approximately 60% of the Dez River would constitute the share of the Bakhtiari River flood discharge, according to the data provided by the Talezang hydrometric station. A flood peak value of 8.641 m^3/s with a return period of 10,000 years was considered for these calculations, and the probable maximum flood (PMF) was obtained to be 12.34 m^3/s. The construction of the dam prevents flood damage in the downstream areas. Considering the lifespan of the dam (50 years), 1.052 flood events are expected to occur at downstream areas. Accordingly, the total annual cost of flood prevention was estimated to be US$70,754, which is equivalent to 0.04 US$/MWh. The annual cost of transferring potable water from the Bakhtiari Dam to other regions was estimated to be US$3.013. Considering 400 MCM of water to be regulated and controlled in the Bakhtiari Dam at the time of exploitation, it is estimated that 24 MCM would be used to supply drinking water. Given the water sales price of about 0.5 US$/$m^3$, the total revenue was estimated to be US$12 million.

Approximately, 9 MCM of trapped sediment is annually accumulated in the Dez Dam. If the Bakhtiari Dam is constructed at the upper hand of this dam, 2 US$/$m^3$ would be saved for sediment trapping. Here, a reduction in the sediment entering the Dez Dam would lead to an increase in the volume of water stored in the reservoir. The increased water volume of the reservoir is expected to be about 600 MCM/yr. The water demand is divided to 3570 MCM for agricultural use and 280 MCM for drinking and industrial uses at the downstream of the Dez Dam. The unit monetary value of these types of water uses were also added to the HECAM II model. Accordingly, the total income from sediment trapping was estimated to be US$149,221,172. The stored water and hydro energy are positively correlated, so that increasing the stored water in the Dez Dam increases the amount of hydroelectricity generation [49]. The added volume of water due to sediment trapping would increase the energy production by 2%. According to the price per kilowatt hour of electricity, the annual income from the increased hydro energy production in the downstream dam is estimated to be 25,000 US$/yr. According to the Water Resources Development Agency, the total annual evaporation from the open sea level in this area is 1780 mm and its maximum monthly value amounts to 260 mm in June and July. This would result in an average evaporation rate of about 3 m^3/s from the dam reservoir. The evaporation rate was estimated to be 10% of the total annual volume of the reservoir that decreases the benefits downstream in various sectors of agriculture, drinking, and industry.

Figure 2 shows the upgraded revenue of constructing the Bakhtiari Dam. The main sources of income are sediment trapping, control of environmental emissions, and sales of hydroelectricity, respectively. With a dramatic difference, sales of potable water and flood prevention appear in the fourth and fifth positions of revenue sources. The final cost of constructing the Bakhtiari Dam is depicted in Figure 3. According to the figure, electricity generation and evaporation are the first and second major costs, respectively. Environmental damage and drinking water account for a small share of the total costs. No costs were determined for irrigation and drainage, and sediment trapping due to the special topographic position of the Bakhtiari Dam. The output of HECAM II showed that construction of the Bakhtiari Dam would cost, in total, US$145,564,015. However, the total revenue of dam construction was estimated to be US$374,696,061. This shows that the construction of the dam could have a net benefit of US$229,132,047, and the benefit/cost ratio would be 2.57, considering the technical, environmental, and social aspects of the project altogether. It should also be noted that only the main costs and benefits of dam construction (electricity generation, irrigation and drainage, drinking water production, and flood prevention) were calculated in this model. Therefore, the model can be extended by adding new items or more parameters.

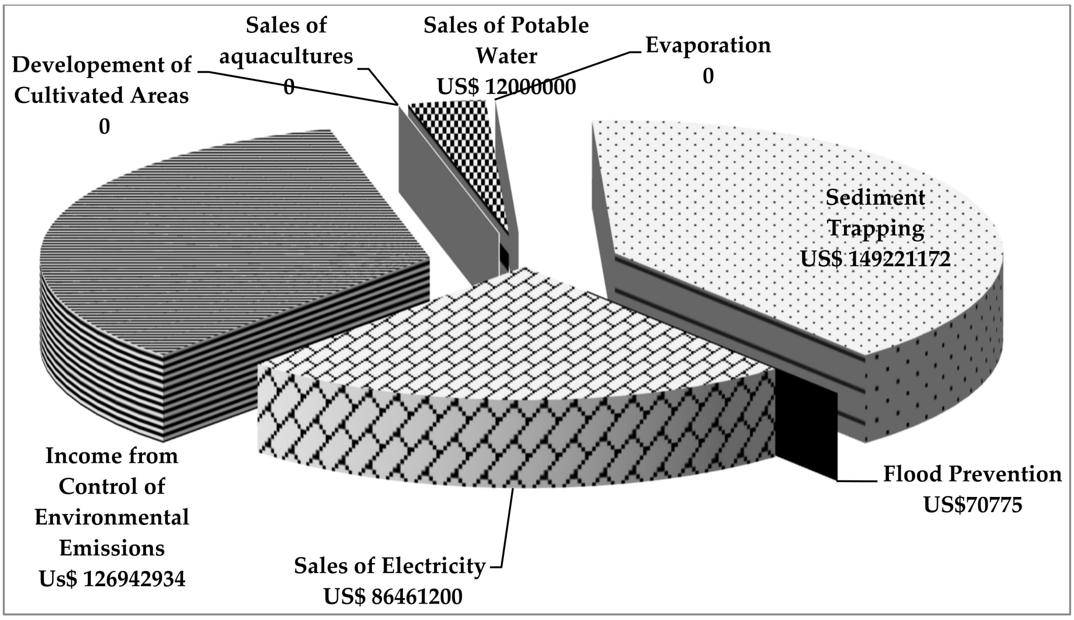

Figure 2. Net revenue of Bakhtiari Dam.

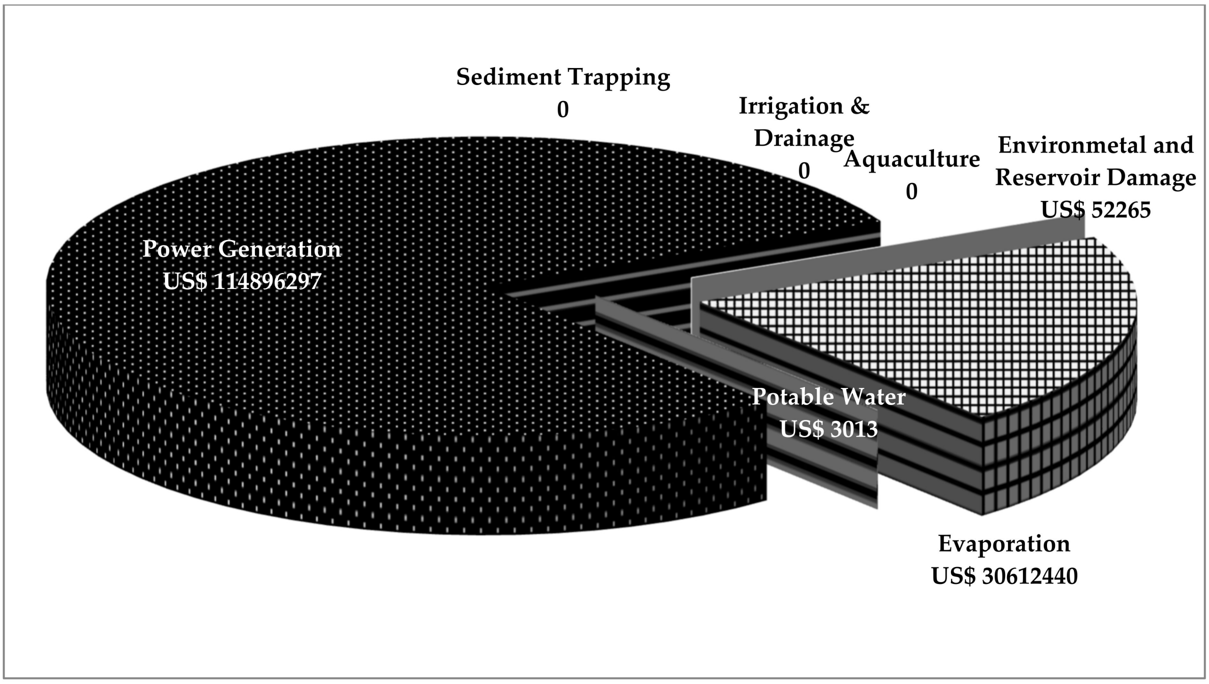

Figure 3. Total costs of constructing Bakhtiari Dam.

6. Discussion

The estimated costs and benefits of damming were compared with those quantities obtained by running the SimPacts model to verify HECAM II. According to the estimates of the SimPacts model, the dam construction externalities would be US$52,265, equal to 0.03 US$/MWh, while the HECAM II model estimates the cost of constructing the dam to be US$145,564,015. There is a relatively considerable difference of US$145,511,750 between the estimates of the two models. Such a cost underestimation is mainly due to ignoring the costs incurred by hydropower generation, irrigation and drainage, aquaculture, potable water, sediment trapping, and evaporation. Although SimPacts was partly revised in the HECAM I model, the upgraded HECAM II can be considered as an improved version to capture more realistically the costs and benefits of damming by taking sedimentation and evaporation into account. In the improved HECAM II model, the ability of using real areas of land uses and prices has been created. As is clear, the size of dam reservoir is definitely important in calculating the area of submerged forestlands, agricultural lands, and residential areas [50]. It is also important to estimate the amount of greenhouse gas emissions released from the reservoir surface during dam operation. The new HECAM II model has the ability to calculate the amount of greenhouse gas emissions based on the areas of submerged land uses.

Several sustainable development goals were considered in the HECAM II model in which the nexus among them was embodied in the economic equations. The SDGs 1 and 8 constituted the core concept of the commercialized model in which the SDGs 2, 6, and 7 were explicitly included by adding fishery, agricultural, water transmission, and hydropower generation equations. The SDGs 3, 10, and 11 were the spirit of the model that was based on responsible production (SDG 12). The SDGs 13, 14, and 15 were the new aspects introduced in HECAM II model. However, the model can be further developed by considering the effects of SDGs 4, 5, 9, 16, and 17. Overall, the application of HECAM II model showed that the Bakhtiari Dam can positively interfere with the development problems in the Khuzestan and Lorestan provinces. However, the project should be evaluated as a long-term solution to the complex sustainability problem in this region.

The model is compared to other analyses in Table 5. The table summarizes highlights of the present model and the previous ones. The case studies based on which the models are validated are given in the table. According to the table, the algebraic feasibility studies vary considering three main factors. First, the comprehensiveness of the analyses varies in different models. The rudimentary analyses are developed upon the economic profitability, whereas more advanced studies include environmental and social aspects, too. The present study offers one of the most extensive approaches by considering some detailed factors, such as the sedimentation and the evaporation in the cost-benefit analysis. However, none of the studies include all known modeling aspects. This is mainly due to the data shortage for validation. For instance, the tourism benefits were neglected in the HECAM II model. Second, the simplicity of the feasibility studies vary with each other. The feasibility approaches should conventionally be simple enough for commercial applications. Hence, cost-benefit approaches are superior to model-based methods and decision-making flowcharts. Finally, the quality of the used data and the executive test of the approaches vary depending on whether appropriate case studies are employed. It is evident that the verified approaches in real cases are more valid than hypothetical ones. Considering the current trend in utilizing various energy resources to generate electricity, the cost-benefit analysis can be performed on hybrid systems, too. This requires an individual study, but it is anticipated that the hybrid systems would have great advantages in terms of greenhouse gas emissions reduction and environmental protection.

Table 5. A comparison between similar feasibility analyses.

Contribution	Method	Shortcomings	Case Study	Model
Upgrading the HECAM model by adding evaporation and sedimentation costs	A cost-benefit analysis (CBA)	Neglecting hybrid systems and tourism benefits	Bakhtiari Hydropower Dam	HECAM II
Upgrading the SIMPACT model by adding various cost and benefit parameters	A cost-benefit analysis (CBA)	Ignoring some costs such as evaporation and sedimentation	Alborz Dam in Northern Iran	HECAM
Interactive impact of dams and power plants on water supply, environment and economy	A cost-benefit analysis (CBA)	Focusing solely on the cost of dams	Siah Bishe- Dam in Northern Iran	SimPacts
Evaluation of costs and benefits of dams based on multi-objective planning techniques	An integrated cost-benefit analysis	Valid by the IDAM tools with no upgrading opportunity	-	IDAM tool [51]
Inclusion of technical, ecological, and economical profitability in a multi-phase feasibility estimation	A logic-based decision-making flowchart	Elimination of many influencing factors	Cameroon	Three-phase [52]
Simplified economic feasibility	Model-based economic feasibility	Elimination of non-economic aspects	Egypt	Stepwise [53]

7. Conclusions

Both the costs and benefits of dam construction were considered in the developed HECAM II model in terms of the cost of electricity generation, irrigation and drainage, aquaculture, drinking water, evaporation, and sediment trapping, as well as the revenue of the electricity sale, reduction in greenhouse gases, development of cultivation area, aquaculture, water sales, flood protection, sediment trapping, and evaporation. The model was validated in the Bakhtiari Dam, in which the total cost and revenue were 79.13 US$/MWh and 203 US$/MWh, respectively. Hence, the benefit to cost ratio, and the annual net profit of constructing the Bakhtiari Dam were estimated to be 2.57 and US$229 million, respectively. The joint operation of the Dez and Bakhtiari Dams could considerably improve the economic benefits, particularly in terms of the control of sedimentation, and could solve the development problem in the region in a long-term plan. The HECAM II model can be an efficient commercial model to aid sustainable development decision makers and stakeholders by calculating the revenue and costs of hydropower dams.

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Nomenclature

Acronyms	Definition
HECAM	Hydropower's Environmental Costs Analysis Model
IAEA	International Atomic Energy Agency
SIMPACTS	Simplified Approach for Estimating Impacts of Electricity Generation
$IDCF$	Power Plant Construction Period Interest Rate
CIF	present value of reinvestment
SVF	present value for the 50 years of the dam annuity
$FICH$	power plant's investment cost
$FICD$	cost of dam construction
$DFOM$	constant monetary present value of repair (and maintenance) costs
$FVOM$	power plant's variable monetary present costs of repair (and maintenance)
TCP	$FICH + FICD + DFOM + FVOM$
$Rev._{pol.}$	revenue from reduction of pollutants
$TCI\&D$	present annuity value of irrigation and drainage cost
$TBI\&D$	irrigation and Drainage revenue
TCF	total annual cost of fisheries
TBF	the annual total revenue from aquaculture
$TFDC$	annual present value of flood damage
$TCSF$	the annual cost of water transfer
$T_{rev.}$	the total annual revenue from potable water
SSC	savings in sediment trapping cost
$W_{valu.}$	total value of water at downstream areas
$Rev._{iwv}$	revenue from increased water volume
$Rev.IPG$	the revenue from increased power generation at downstream areas
$Rev._{Total}$	total annual revenue
$Evapo_{vol.}$	annual volume of evaporation
$Evapo._{cost}$	the cost of evaporation

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