Feasibility assessment of wind, solar and hydropower self-production schemes for the Tweed Valley Eco-village in Scotland

Avaliação de viabilidade de esquemas de autogeração eólica, solar e hidrelétrica para a ecovila Tweed Valley, na Escócia

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Abstract: This paper evaluates the technical, economic and environmental feasibility of three renewable-energy self-production alternatives for the Tweed Valley Eco-village: wind, solar photovoltaic and hydropower. A natural-resource assessment indicates that the solar irradiation (3,070 kWh/m^2/day), wind speed (6.8 m/s at 45 m) and river flow (19.28 m^3/s) provide technical feasibility for the three energy self-production schemes. The paper assesses the economic feasibility of the energy generation schemes considering the financial support from the Community and Renewable Energy Scheme (CARES) and the current feed-in tariff (FIT) rates. The three schemes predict a payback time of less than 25 years. The hydropower scheme has the best economic feasibility in all economic indicators: a payback time of 11 years, a net present value (NPV) of £6,930.66, an internal rate of return (IRR) of 13.7%, and an average annual rate of return (ROR) of 37.6%. The offset greenhouse gas (GHG) emissions of each scheme were also calculated and valued using traded carbon price projections compared with a baseline scenario of emissions from grid electricity. The hydropower scheme will provide the highest mitigation, followed by wind and solar photovoltaic panels. Therefore, we conclude that hydropower would be the most feasible option.

Keywords: Renewable energy, solar energy, wind energy, hydropower, Tweed Valley.

1 Introduction

The scenario analysed in this paper is the Tweed Valley Eco-village, which comprises fifteen families that plan to build houses in Thornylee Forest in Galashiels Burgh, Scotland [1] [2]. Energy self-sufficiency from renewable sources is an important step in the concept of an eco-village. As the villagers' plan to use wood energy to heat their houses, the focus of this paper is restricted to electricity generation.

This paper compares the economic and environmental feasibility of wind, solar photovoltaic and hydropower schemes by investigating the baseline energy demand, energy generation potential, CO_2 emissions and economic feasibility using real performance data. In this paper, the environmental data of the area were employed with the technical specifications of the equipment for each energy source to estimate the potential electricity generation. Therefore, it includes the estimation of solar radiation, wind speed and stream flow and the possible efficiency of the energy equipment to convert these sources to electricity.

The technical feasibility and possible management options for wind, solar and hydropower energy schemes for Tweed Valley Eco-village were studied in detail before [1] [2]. However, since the publication of these studies, many natural-resource databases and models have become available that enhance the reliability of renewable-energy feasibility assessments. This paper focuses on the economic feasibility of these schemes, which has not been assessed.

The villagers plan to apply to the Community and Renewable Energy Scheme (CARES) of the Scottish government. In this context, this paper compares the economic feasibility of each electricity source regarding the payback time, average annual rate of return (ROR), net present value (NPV) and internal rate of return (IRR) for a project lifetime of 25 years. The economic feasibility includes the respective feed-in tariffs (FITs) for each energy source, initial investment, operational and maintenance costs and capital costs (loan payment with interest rates).

The paper also compares the greenhouse gas (GHG) emissions of each possible energy scheme with a baseline scenario of consumption from the electricity grid based on the emissions of the current mix of energy sources, which gradually changes with the government targets to reduce emissions from electricity generation in the United Kingdom (UK). The emissions were valued based on short-traded carbon prices for public policy appraisal in the UK.

The objective of this paper is to use the economic feasibility indicators and GHG offset emissions to provide a preliminary assessment of the best renewable schemes for energy self-production for the eco-village. The paper also evaluates the limitations and risks of each energy option. In this manner, the local community can move towards more detailed assessments for their preferred options.

2 Materials and methods

The baseline scenario and storyline for the Tweed Valley Eco-Village as well as renewable-energy resources assessment and renewable-energy technology feasibility assessment are presented below.

2.1 Baseline scenario and storyline for the Tweed Valley Eco-Village

An eco-village is currently planned in the Thornylee Forest [1] [2] that includes fifteen houses, a small hotel (co-house) and an education centre. The use of renewable energy corresponds to the concept of an eco-village and the ethical values of its inhabitants.

The Tweed Valley Eco-village project is located in Thornylee Forest in Galashiels, Scottish Borders, grid code NT423350 (Figures 1 and 2). The central coordinates are as follows: latitude 55.62 N and longitude 2.95 W in the WGS 1984 cartographic projection. The area is a forested hill (Figure 3) adjacent to the Tweed River (Figure 4). The valley is approximately 150 m above sea level, and the top of the hill is 375 m above sea level.

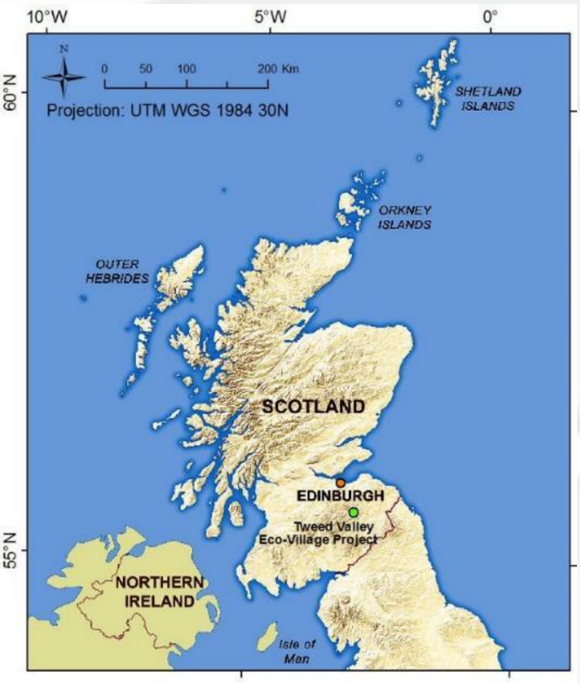

Figure 1: Location of the Tweed Valley Eco-village project in Scotland. Source: the author.

The mean average annual consumption of domestic electricity within the Scottish borders was 4,146 kWh per household in 2014 [5]. The consumption of the co-house and the education centre was considered to be equivalent to that of a normal household. For a baseline scenario, the estimated eco-village demand is approximately 70,482 kWh/year, which corresponds to an energy source of 8.04 kW. This consumption will cost approximately £10,080/year (US$14,525.35/year)[1] at Scottish Power based on the current prices of 16th May, 2016.

The inhabitants will apply for financial support from the CARES programme, which has a total budget constraint of £150,000 (US$216,151.05) per project to cover 90% of the agreed costs with an interest rate of 10% [6]. CARES covers projects with a maximum power consumption of 5 MW. The considered project lifetime for payment is 25 years, which is a typical limit employed by financial institutions due to future uncertainty [7].

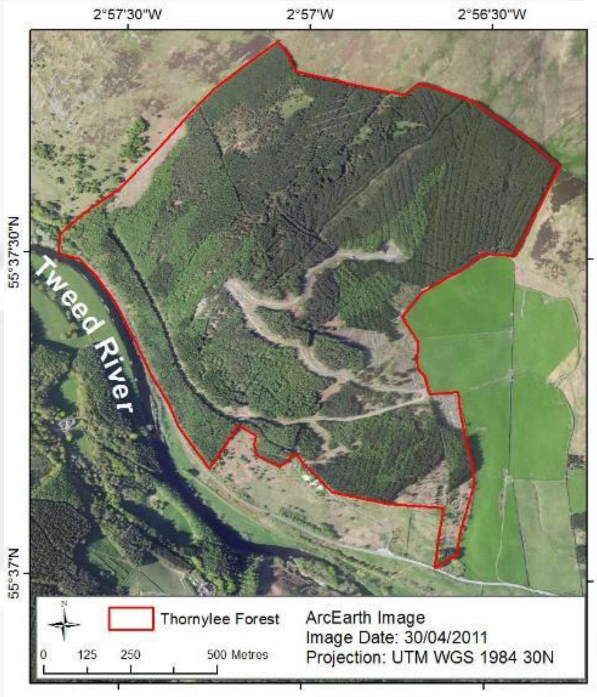

Figure 2: Satellite view of Thornylee Forest. Source: the author.

Figure 3: Thornylee Forest (2012) [3].

[1] In this paper, the exchange rate of the British Pound to the American Dollar is adopted as 1.441007, as on 16 May, 2016. In the absence of a reliable time series for a household consumption projection, a simplified assumption was employed, and the consumption was assumed to be constant from 2014 to 2016.

Figure 4: Tweed River in front of Thornylee Forest (2015) [4].

Regarding GHG emissions, the baseline scenario is the amount of emitted carbon dioxide (CO_2e) to produce electricity if the inhabitants import its totality from the Scottish grid. The emission intensity of GHG from the electricity supply in Scotland in 2013 was 229 kg CO_2e/MWh [8]. This value was assumed to linearly decrease to satisfy the UK government targets of 96 kg CO_2e/MWh in 2030 and 18 kg CO_2e/MWh in 2050 according to the projections [9] incorporated in the UK government plans [10]. In this baseline scenario, the average carbon intensity from 2016 to 2041 (25 years) is 121,156 kg CO_2e/MWh with 213,482.9 kg CO_2e emitted during this period.

2.2 Renewable-energy resource assessment

This paper focuses only on electricity generation and does not consider heating schemes as the inhabitants plan to use the abundant wood resources of the property for heating. Due to the lack of a local geological survey, the viability of geothermal energy (such as ground source heat pumps in a heating scheme) is uncertain; however, it may be a suitable option for a future feasibility assessment. Then, the villagers can compare the geothermal-energy option with other heating strategies, such as biomass (from the forest wood) and house insulation.

The most favourable renewable energy sources that were identified for the area are sunlight, wind and hydropower. Tidal and wave energy sources are not available for this location.

As Scotland is the windiest country in Europe [11], the wind potential of the selected site is worth exploring. The wind speed was calculated using the NOABL Wind Map database [12]. The potential energy power from this site was evaluated for two wind turbines using the WindCad Turbine Performance Model, which was provided by Bergey Windpower Co. for the turbine Excel-10 (10 kW)[2]. The model is based on empirical measurements that are compliant with IEC 61400-12-1 international standards [13]. The input variables of the model are average wind speed, Weibull shape factor (based on wind context: inland, coastal, and island), altitude, shear exponent (based on terrain roughness), anemometer height, tower height, and turbulence factor. The model suggests the parameters for these inputs based on distinct environmental contexts. Based on these variables, a wind speed frequency distribution is simulated and compared with a wind-speed power curve, resulting in the wind energy distribution plot that is summed into the total wind energy output.

The property is a south-facing slope, which favours solar energy production, and the solar photovoltaic panels can be installed on roofs or in open areas. The annual average solar irradiation for an optimized inclined plane and an optimized azimuth was simulated in the System PVGIS [14]. PVGIS uses European and global spatial databases for solar radiation, temperature and elevation to simulate beam, diffuse and reflected components of the clear-sky and real-sky global irradiance/irradiation on horizontal or inclined surfaces [15]. The algorithm is implemented in the script *r.sun*, which is openly available in the Grass GIS system [16]. The input variables for each site are geographical coordinates, photovoltaic technology, installed peak power and system losses. PVGIS also estimates the optimal inclination for the photovoltaic panels and losses due to temperature, low irradiance and angular reflectance [17].

The Tweed River flows in front of the village property and is a potential source of hydropower. The river bar in the area of the neighbour on the opposite side of the river has a feasible topography for a two-metre-high diversion from the upstream limit to the downstream limit of the property. Alternatively, a natural trough in the Tweed River adjacent to the property can be a proper site for a small hydropower dam with identical height. The flow of the Tweed River at Thornylee Forest was estimated by interpolating the flow of the gauging stations from the UK network (Figure 5) with daily data from 1962-2001. The interpolation method was a linear weighted average of the flow based on the distance from the eco-village to the gauging station 21003 and the distance from the eco-village to the gauging station 21006 subtracted from the contribution of the Ettrick Water (21007) (Figure 5)[3].

Among the types of hydropower turbines, the Archimedes Screw is advisable as it has less of an impact on fish migration [18] and good suitability for schemes with low head and low flow [19]. Assuming the common 70% capacity factor of an Archimedes Turbine [20], the potential for micro hydropower for the community demand was calculated in Equation 1 [21].

[2]The respective model, with the data and results in this paper, is available at https://goo.gl/02qWvO

[3]The gauged flow data and the interpolation results are available at https://goo.gl/hqf5gg

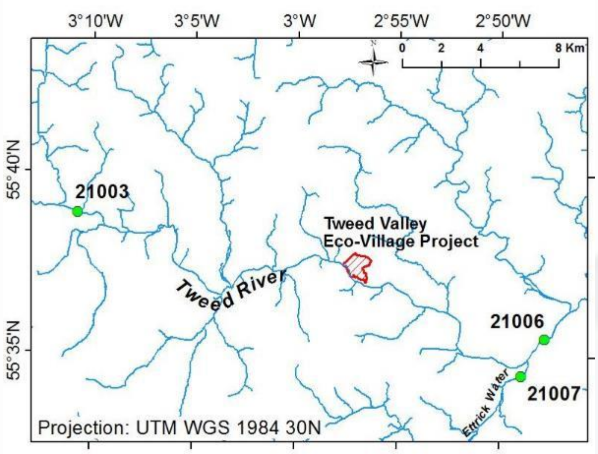

Figure 5: Location of the gauging stations. Source: the author.

$$P\ (kW) = \gamma\ x\ \eta\ x\ Q\ x\ H \qquad (1)$$

where

γ = Water specific weight (10 kN/m^3);

P = Power (8.04 kW);

H = Effective head (2 m);

η = Turbo-generator efficiency (70%);

Q = Flow (to be calculated), in m^3/s.

2.3 Renewable-energy technology feasibility assessment

The price of equipment for wind, solar PV and hydropower in this report are the average quoted prices by installers and manufacturers that were certified by the Microgeneration Certification Scheme in May and June 2016. The connection costs were included in these quotations.

The three assessed scenarios of renewable energy consider that the community will have access to the power grid, considering current policies regarding electricity prices and export tariffs for May 2016. The access to the grid also simplifies the challenges of fluctuation of energy self-production and demand for small power generation schemes. This paper compares the payback time, ROR, NPV and IRR for each energy scheme using the methods of Peake (2013) [22] and adapting the cash-flow spreadsheet model of the respective author[4]. The model assumed the usual expectation that the community will export 50% of the electricity to the grid and use the other half, which would be accounted into savings, for electricity not purchased [22].

The selected discount rate for the NPV was 10%, which matched the interest rate of the CARES programme. A degradation factor of 0.5% was employed for the solar photovoltaic panels [23]; a degradation factor of 0.9% was employed for onshore wind turbines [24][5], and the degradation factor for run-off river hydropower was assumed to be negligible. The retail prices index (RPI) was selected as the annual average of the last ten years (2.72%) in the UK [25]. The hydropower plant included a leasing cost of 2% of the annual income of the neighbour property owner on the other side of the Tweed River, according to the estimations of Litt (2015) [26]. For the feed-in tariffs (FITs), the values were based on the generation tariffs for installations in the eligibility dates between April 1, 2016 and June 30, 2016. Each family was assumed to separately apply for the FIT of the solar panel on the roof of its house.

This paper also estimated how much each option would offset the GHG emissions in 25 years compared with the grid supply scenario. The assumed emission intensity for the solar photovoltaic panels was 85 kg CO_2e/MWh, whereas the assumed intensity for wind and hydropower was 26 kg CO_2e/MWh [27][6], considering that manufacturing emissions in a life-cycle analysis, which distributes the payback time of the emissions during the expected life of the equipment [28]). The short-term traded carbon values for the UK public policy appraisal [29], which was updated by DECC (2015b) [30], was used as a monetary reference to compare the options. These values of offset GHG emissions were only employed as a reference and were not included in the cash flow to calculate the payback time, NPV, IRR and ROR.

3 Results and discussion

3.1 Renewable energy resource assessment

The most elevated area in the property is the top of a hill, which may have relatively higher wind power potential. However, the wind turbines must be erected 45 m above ground to avoid turbulence from the forest and local hilly topography. On the top of the forest hill, the wind speed is 6.8 m/s at 45 m according to the NOABL Wind Map [12] (Figure 6). The potential energy power from this site for the turbine Excel-10 (10 kW) was simulated as an effective output of 25,412 kWh/year (average effective potency of 2.9 kW) for each turbine.

The annual average solar irradiation for an optimized inclined plane of 39° and an optimized azimuth of -2 is 3,070 kWh/m^2/day with no annual irradiation deficit due to shadowing (horizontal) according to the System PVGIS [14] (Figure 7). As the houses are currently in the project phase, their roof can be designed for the optimized azimuth, inclination and available area, and the built-in solar panels on the roof help to reduce the installation costs. The PVGIS system indicated that an 85 kW system of solar photovoltaic panels can satisfy the village demand[7]. The approximated

[4]The respective model, with the data and results used in this paper, is available at https://goo.gl/xQu4iX

[5]Degradation data estimates were not obtained for small wind turbines. The reference factor is based on high power wind turbines [24], and the degradation may be even lower for small turbines.

[6]The values are averages from different sources. Photovoltaic power emissions vary from 13 to 731 kg CO_2e/MWh, and wind power emissions vary from 6 to 124 kg CO_2e/MWh [27].

[7]The detailed results from the PVGIS model are available at https://goo.gl/6kEe0Z

necessary roof space is 595 m^2, which is divided between 17 buildings (35 m^2 for each roof).

The average flow of the Tweed River at Thornylee Forest, which was estimated from the interpolation of the gauging stations, is approximately 19.28 m^3/s. Using Equation 1, the estimated necessary flow (Q) is 0.574 m^3/s, which is less than 3% of the average flow of the Tweed River. Therefore, a relatively steady flow can be maintained in the turbines throughout the year, and a diversion of this amount of flow would not expressively disrupt the river ecology.

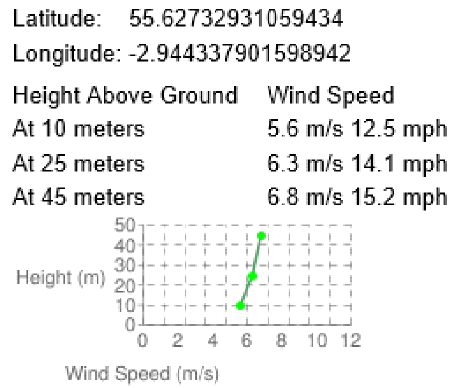

Figure 6: Average wind speed result in the NOABL Wind Map [31].

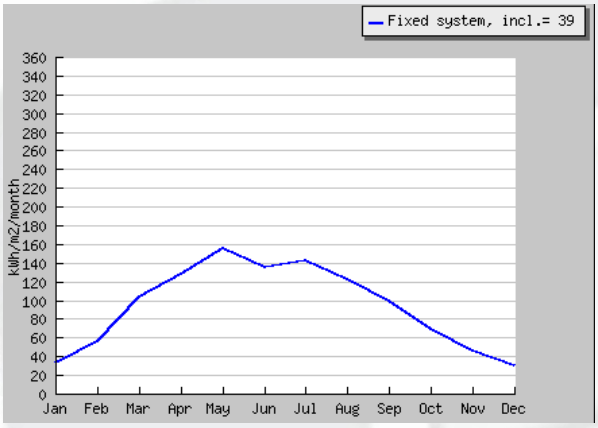

Figure 7: Monthly solar irradiation at Thornylee Forest [14].

3.2 Renewable energy resource assessment

Table 1 shows three possible energy self-production systems with their potency, installation costs and maintenance costs.

The quoted implantation costs for wind power were higher than the usual projects with the identical rated power due to the high tower (45 m) and the distance between the top of the hill where it would be installed and the grid connection (approximately 1 km). Each turbine with the respective tower would cost £50,000.00 (US$72,050.35), and the civil works for installation and grid connection would be approximately £15,000.00 (US$21,615.105). Consequently, the entire electricity demand of the village could not be satisfied with wind power within the CARES' budget limit. Therefore, the wind power scenario included only two wind power turbines, with an effective output of 5.8 kW (Table 1). The remaining demand is assumed to be supplied from the grid.

The solar and hydropower generators would be notably close to the grid connection. The manufacturers and installers also offered a cheaper price for the solar panels (17 panel sets of 5 kW for £7,000.00 [US$10,087.05] to fit the roof of each house) than the price for individual houses due to the larger number of panels. The quoted price for a 12 kW Archimedes screw turbine and its respective control system was £65,848.00 (US$94,887.43; 58% of implantation costs) with approximate civil-work costs of £33,152.00 (US$47,772.26; 29%) and estimated environmental and regulation costs of £14,850.00 (US$21,398.95; 13%).

Table 2 lists the payback time, ROR, NPV and IRR for each energy scheme. The complete spreadsheet model is provided as a supplementary material for this paper[4]. Table 2 also shows how much each option would offset the GHG emissions in 25 years compared with the grid supply scenario.

Table 1: Rated capacity, capacity factor, effective output, annual output, carbon mitigation, implantation costs and annual operational costs for solar photovoltaic, wind and hydro power schemes in the Tweed Valley Eco-Village.

Source	Rated Capacity (kW)	Capacity Factor	Effective output (kW)	Annual kWh output	Implantation costs		Annual operational costs	
					£	US$	£	US$
Solar PV	85	9.5%	8.08	70,780.8	119,000	171,479.83	500	720.50
Wind	20	29.0%	5.8	50,824	115,000	165,715.80	750	1,080.76
Hydro Power	12	70.0%	8.4	73,584	113,850	164,058.65	3250 (~3%)	4,683.27 (~3%)

Table 2: Economic feasibility indicators and offset GHG emissions for solar, wind and hydropower schemes.

	Solar Photovoltaic	Wind Power	Hydropower
Payback time (in years)	24	24	11
NPV (£)	-14,213.09	-13,557.70	6,930.66
NPV (US$)	-20,481.16	-19,536.74	9,987.13
IRR (%)	1.5	0.4	13.7
ROR (%)	3.3	0.7	37.6
Offset kg CO_2e emissions	63,704.38	112,465.99	175,800.83
Value of offset CO_2e emissions (£)	438.61	4,125.28	6,829.50
Value of offset CO_2e emissions (US$)	632.04	5,944.56	8,400.35

Table 2 indicates that the three energy sources will repay their investment in 25 years. However, the hydropower option has better payback time, NPV, IRR, ROR and offset CO_2e emissions. Wind and solar power have similar indicators: both have a payback time of 24 years and a negative NPV. Wind power has relatively higher offset CO_2e emissions and slightly better NPV than solar power but the lowest ROR and IRR. As the NPV and IRR account for a discount rate, they can be considered to be more robust for decision-making than the ROR. The negative NPV and low IRR and ROR for wind and solar power indicate, on strictly economic terms, other investments with better profit. However, this reasoning does not consider the symbolic values of the local community. Considering the projection of decreasing intensity of kg CO_2e/MW from the UK electricity grid, this scenario foresees that the solar photovoltaic panels will emit more CO_2e (in a lifecycle analysis, including manufacturing emissions) than the electricity provided by the grid after the ninth year (2025).

3.3 Critical Reflections

In accordance with the recommendations of Litt (2015) [26] and Taylor (2012) [32], all installers and manufacturers who were consulted for the wind and hydropower options emphasized that a final quotation should only be provided after a detailed field assessment. For wind power, monitoring the wind speed and direction with an anemometer is important to check the accuracy of the NOABL Wind Map [12].

For hydropower, although the gauging stations provide a relatively reliable time-series for the river flow, a more detailed field survey is necessary to design the options for diversions and/or dams, which better specifies the costs for civil projects. In addition to the better economic feasibility of the hydropower scheme, this type of project will require complex regulatory and environmental issues to be addressed and require an excellent relationship with the local environmentalist groups. The Tweed River is known to be important for the migration and reproduction of salmon and lampreys [33]. Therefore, among the civil project options (including dams and/or diversion), the option with fewer environmental impacts is preferred. The hydropower scheme will also demand a negotiation with the neighbouring property owner on the other side of Tweed River; thus, the projections included the leasing costs.

The study indicates that a feasibility study of the actual location can reveal some unexpected difficulties for some power options, such as the turbulence for wind power and the long distance from the top of the hill to the grid connection. For hydropower, the environmental significance of Tweed River is also an outstanding challenge that inclusively explains the choice of a run-of-river Archimedes screw turbine.

4 Conclusion

Based on the analysis in the previous sections, this paper presents the following conclusions:

- The preliminary natural-resource assessment indicates sufficient solar irradiation (3,070 kWh/m^2/day), wind speed (6.8 m/s at 45 m) and river flow (19.28 m^3/s) for the technical feasibility of the three sources of energy self-production.
- The wind power option will require a high tower (45 m) on the top of the hill to avoid turbulence from the forest and local topography, which increases its costs. Consequently, this option will not fulfil the energy demand of the village within the available budget.
- The three options (solar, wind and hydropower) have a payback time of less than 25 years.
- The hydropower option has the best economic feasibility in all indicators: payback time, NPV, IRR and ROR.
- The hydropower option also mitigates more GHG emissions (175,800.83 kg CO_2e) within 25 years with an estimated value of £6,829.50 (US$9,837.03), according to the UK policy standards.
- The negative NPV at 10% discount rate and the low IRR and ROR for wind and solar power indicate that other investments can generate better profit for the community.

Therefore, this paper evaluates that hydropower is the most viable option for a renewable energy scheme in the Tweed Valley Eco-village based on both economic aspects and climate change mitigation. However, additional detailed field studies should be conducted to estimate the alternatives for civil projects in terms of costs and possible mitigation of environmental impacts in the Tweed River. A favourable negotiation with the Scotland Environmental Protection Agency (SEPA) and local environmentalist groups is important to proceed with environmental and regulatory licenses.

If an eventual problem hampers the installation of the hydropower scheme, the wind power option may be preferred as it offsets almost twice the GHG emissions compared with the solar PV scheme, whereas the economic feasibility of both options is not significantly different. In this case, a preliminary field assessment should be conducted to determine whether the modelled wind speed and turbulence for the local area are reliable.

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