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Environmental and economic impacts of agrivoltaics in Bangladesh

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Abstract

The study entailed comparing agrivoltaics (growing crops under solar panels) to existing energy sources, namely: coal, oil, gas under fossil fuel and nuclear, hydropower, wind, and solar under renewable sources. The comparison is made along key aspects of power generation for Bangladesh: cost, emissions, land, and employment. The study examines the direct impacts along these aspects, as well as upstream economy-wide impact using an input-output model for land and employment. Under employment, it further looks at the number of total jobs, skill level, and gender disaggregation of yearly jobs generated, as well as the total yearly wage under the different sources of power generation. The methodology used encapsulates key considerations within the food–energy–environment nexus and provides policymakers with a framework that presents the implications of energy choices. The study results using this methodology further show that the transition to renewable energy could also accommodate those who stand to lose the most in large-scale transitions. The expansion of work opportunities for women, as well as low and middle-skill workers through agrivoltaic expansion, is a crucial factor within the just transitions framework.

1. Introduction

Bangladesh, like many countries around the world, finds itself at an energy crossroad. The country is poised to rise to a middle-income country with implications on its energy needs- but the prevailing low per capita energy intensity, low employment rates, and foreign exchange reserve challenges mean that Bangladesh must make choices about how to address these needs. The choices impact not only carbon emissions and thus climate change, but also employment and land use. Together these capture the health, economic, environmental, and climate change implications of the different energy pathways.

The Mujib Climate Prosperity Plan an initiative undertaken by the government of Bangladesh, aims to transform Bangladesh's future by promoting sustainable development and environmental resilience (Ministry of Environment Forest, and Climate Change, 2022). The goal is to raise the share of renewable energy sources in the overall energy mix to 40% by 2041 (Chowdhury, 2023). The Bangladeshi government aimed to have 10% of its energy mix come from renewable sources by 2021. However, the current renewable energy production stands at around 1205 MW, comprising just 4% of the total energy (SREDA, 2024). Currently, over 80% of the power mix comes from fossil fuel sources— oil, gas, and coal (SREDA, 2024). Foreign reserve constraints amidst rising costs of importing coal, gas, and oil provide an added impetus for alternative domestic renewable solutions. Solar photovoltaic technology is the most feasible option for Bangladesh in the transition to a low-carbon energy system. However, solar photovoltaic farms are land-intensive per unit energy output relative to existing fossil fuel options. Bangladesh is one of the most densely populated countries in the world with immense pressure on agricultural land. Agriculture remains the largest employment sector in Bangladesh, employing over 40% of the country's workforce (Ministry of Finance, 2022). Although agricultural share in the economy has been declining over the years, over 46% of all households in Bangladesh have derived some income from agriculture (BBS, 2019). Gains in agriculture accounted for 90% of the reduction in poverty between 2005 and 2010 (World Bank, 2016). A land policy draft by the Government of Bangladesh in 2016 discourages the use of agricultural land for non-agricultural purposes like industrial or infrastructural development. Hence, land shortages in the nation continue to hold back land use for renewable energy development.

A potential solution is to grow crops under solar photovoltaic farms— or agrivoltaics. Agrivoltaics will allow farmers to reap the benefits of the sun's energy twice when solar power is installed on the same property where crops are cultivated. As the country remains at the forefront of climate change and environmental degradation, promoting agrivoltaics could result in reducing water footprint and improving land use efficiency to achieve sustainability of food, energy, and environmental security. As a sizable portion of households depends on agriculture for income and livelihood opportunities, there is an added benefit of using agrivoltaics in employment generation for lower-income households.

Harvesting crops and solar energy using agrovoltaics on one crop-producing land could be a promising solution for Bangladesh's land scarcity and agriculture production. The solar energy generated from agrivoltaics and agricultural production under the solar panel can increase more than 30% in the economic value of the land (Dinesh & Pearce, 2016) and also increase the overall land productivity by 60% to 70% (Dupraz et al., 2011). Vegetables that grow under partial shade are best suited for cultivation under agrivoltaic systems, for example, tomato, cotton, potato, tea,

coffee, garlic, onion, turmeric etc. (Barron-Gafford et al., 2019). The cultivation of a crop under an agrivoltaic system should be supported by the growing demand for that crop in the nation's food market. With only 4 hours of gentle sunlight each day and minimal irrigation, garlic and onions can be grown. The added shade can further reduce irrigation requirements by minimizing evapotranspiration rates. Moreover, the production of vegetable crops under the panel can reduce soil erosion and the amount of dust on the solar panel (Mridha, 2021).
Allocating agricultural lands to produce energy could have an immense impact on the livelihood of agriculture-based households. Hence, simultaneous use of land for both farming and solar energy generation can be a win-win situation, if the right type of crops are planted in the agrivoltaics region, keeping in mind the demand for the crop.

2. Study Overview

In this paper, we assess the feasibility of agrivoltaics by comparing it to existing ways of producing energy, namely from fossil fuel and renewable sources. We thus compare power generation using agrivoltaics to coal, oil, gas for fossil fuel; nuclear, wind, solar, and hydropower under renewables. The comparison is made along key aspects of power generation for Bangladesh: emissions (GHG, copollutants), land, and employment. We look at not only the direct impacts along these aspects but the upstream economy-wide impact as well using an input-output model. Under employment, we look at the number of total jobs, skill level, and gender disaggregation of yearly jobs generated, as well as the total yearly wage under the different sources of power generation.

When considering land, we look at the land used for building the power plants under various sources, as well as land impacted. Usually, land estimates consider the land on which the plant is built as being completely used up. This results in making coal less land-intensive per unit of power generated than solar, but for agrivoltaics the actual land under the solar panels has dual use. Thus, when considering land impacted, solar agrivoltaics potentially becomes less land-intensive and coal more so than conventional estimates.

Taken together with the cost of each source, the paper thus provides the key implications of different energy pathways for Bangladesh. By comparing the different sources for these variables, the paper offers a way of guiding policymakers to choose different pathways, as well as offering a solution through agrivoltaics that addresses the key issues of land, employment, and carbon emissions that are relevant for Bangladesh. Our research thus centers on the interdependent food-energy-environment nexus using a model that puts these often artificially disparate considerations into the same framework. This allows the long-term tradeoffs between different energy sources to be more salient for decision-makers.

3. Data Sources

The main part of this study is a static calculation of the total effects in terms of land use, GHG emissions, co-pollutants: NO_x and SO_2, and employment for the three plans. The research uses an Input output or IO model to estimate these factor amounts. IO is a linear macroeconomic approach to describe industrial structure. Applied to economic and environmental indicators such as employment and land it yields total indicator intensities, that is the amount of a factor indicator required to produce and deliver a value unit of a particular commodity, energy for the purpose of this research. Total indicator intensities include direct and indirect contributions. The next section goes through the details of how this model is applied to calculate the total effects for the different energy sources. The IO table was obtained from General Economic Division (GED) of Bangladesh Planning Commission**.** (GED, 2017).

3.1 Variables

Employment data is the Employment Matrix of the 8th Five Year Plan (8FYP), also provided by the GED. Employment is understood as full-time-equivalent employment, measured as full-time employment plus 50 percent of part-time employment of employees, including employers, own account workers, and contributing family workers for the case study. The unit used is jobs-per-year. This measurement addresses the time aspect implicated in employment measurements. The jobs-per-year measure looks at the total jobs created over the total number of years that jobs have been created to distinguish between an economic activity that creates 10 jobs a year versus one that creates 10 jobs for 10 years. This follows the approach of the 2015 book, Global Green Growth. In addition, the GED provided disaggregated employment data for gender and three levels for skill category: low, medium, and high skill. The disaggregated data was provided in terms of jobs-per-year for each of the above categories.

Land data was obtained from EORA (MRIO EORA. 2013)-Direct land-use data for the direct use is from project documents of the power plants obtained from the Power Development Board under the Ministry of Power, Energy, and Minerals Resources of Bangladesh.

Emissions data includes greenhouse gas emissions and co-pollutants. Greenhouse gas emissions are expressed in CO2 equivalents in accordance with guidelines set out by the IPCC, which are calculated as a weighted sum of nominal emissions of various gas species using gas-specified global warming potentials with CO2 normalized to 1. The emission level for all the industries in the Input-Output table is estimated using the energy input by source for each industry or for average energy input using average emission intensity values. Co-pollutants include emissions of gases NOx and SO2. The emission was estimated using emission information from the Carbon Dioxide Information Analysis Center (CDIAC) data. CO2 emissions per kWh of fossil fuel sources are assumed to be: Coal 979.6E-6; Natural Gas 553.38E-6; and Oil 798.32E-6 mt.

3.2 Methods Section

We start with Bangladesh energy mix and expansion plans. Given the expansion projections, we compare an arbitrary unit of energy capacity to direct and upstream impacts of land, jobs, and emissions using IO. The following section is arranged with first: i.an energy overview of the energy sources- which includes Bangladesh's energy mix under different sources, expansion plans, and cost of each source (LCOE). This will give us the amount of money going into the economy for expansion under each source.

ii. then the methodology using the Input Output framework

We take the amount of money going into the economy for expansion under each source estimated in i. above to feed into out input output framework. This subsection details the method involved. The exercise will give us the direct and upstream factor intensities.

4. Energy Overview

4.1 Capacity Increase under Each Source

The first step involves looking at the current power generation and energy mix. The current power generation capacity in Bangladesh stands at 29,268 MW (SREDA, 2024). The capacity increased by 4,817MW in 2023 (The Daily Star, 2023). We see that under PSMP we aim to expand capacity to 57,000 MW by 2041 (MPEMR, 2018). Currently, the majority of energy will be sourced from gas and is expected to remain so by 2041. According to the PSMP, the percentage of coal usage will increase from 18% in 2023 to nearly 32%, almost doubling its current proportion by 2041 (PSMP, 2016). This indicates a need for an additional 12,828 MW of capacity expansion to accommodate the projected increase in coal usage. To reach 57000 MW in 2041, s massive expansion in capacity of 27,732MW is required. We use this amount to do a simple thought experiment to see what expansion under different will look like for direct and upstream factors of employment, land, and emissions. We take 10,000 MW which is almost a third of the expansion planned under the PSMP. We then convert the 10,000MW to generation in kWh. We then convert this to cost using different LCOEs. The levelized cost of electricity (LCOE) represents the average present value of generating electricity over the lifespan of a power generator. The estimation of the capacity factor plays a crucial role in determining LCOE, as it directly influences the total energy output generated by a specific installed power capacity.

Table 1 illustrates the current power generation mix in Bangladesh. As evident from the data, Bangladesh derives most of its energy from gas and coal. Renewable energy sources account for a mere 4.12% of the total energy mix, far below the national objective of 10% in 2020. 60% of all the renewable energy produced in Bangladesh came from hydropower, followed by 39% solar and 1% wind (Uddin et al., 2019).

Table 1: Power Generation Capacity for Different Sources (SREDA, 2024)

Current Generation (MW)	29268	
Fuel	**Share**	**Capacity (MW)**
Gas	49.35%	14508
Coal	18.49%	5412
Oil	23.85%	6982
Hydro	2.47%	723
Solar	1.62%	474
Wind	0.10%	30
Nuclear	-	-
Imported	4.12%	1160

Table 2 presents the anticipated energy composition for 2041. It is evident that the percentage of renewable sources, including solar, hydro, and wind, is projected to increase. Additionally, nuclear

power is expected to make a substantial contribution. There is an expected decrease in reliance on oil by 2041.
Note: The energy mix projection for 2041 is not derived from official national policies; instead, it is an approximate strategy outlined in the PSMP.

Table 2: Power Generation Capacity for Sources in 2041 (MPEMR, 2018), (CPD, 2023)

2041 Generation (MW)	57000	
Fuel	**Share**	**Capacity (MW)**
Gas	**35%**	**19950**
Coal	32%	18240
Oil	2%	1140
Hydro	3%	1710
Solar	8%	4560
Wind	8%	4560
Nuclear	7%	3990
Imported	5%	2850

Table 3: Comparison between power generations in 2023 vs. 2041 energy projection in Bangladesh

Source	**2023 Energy Mix (MW)**	**2041 projection (MW)**	**Additional Generation Required (MW)**
Gas	14508	**24510**	10002
Coal	5412	18240	12828
Oil	6982	1140	-5842
Hydro	723	1710	987
Solar	474	4560	4086
Wind	30	4560	4530
Nuclear	-	3990	3990

Table 3 compares the current energy mix with the projected increase for 2041. Apart from oil, additional generation is needed for all energy sources, with the highest demand expected for coal.

We look at current capacity, use the power mix to look at capacity under each of the sources. We then calculate generation by considering the different capacity factors as given in appendix Table A2.

4.2 Levelized Cost of Electricity (LCOE)

We translate this capacity into costs under different sources, namely: coal, oil, gas for fossil fuel; nuclear; and hydropower, wind and solar for clean renewables using the following cost information LCOE (IRENA, 2023).

Renewable power has grown exponentially globally since 2010 due to declining manufacturing costs and ambitious national and regional targets. The global average levelized cost of energy (LCOE) for solar PV and onshore wind is lesser compared to gas and coal. Therefore, investments in renewable energy are a more economical choice for most countries, leading to installations setting new records every year. The LCOE for different technologies are added in the following Table 4.(IRENA, 2023).

Table 4: Levelized Cost of Electricity for Different Sources

Technology	LCOE (USD/KW-h)
Solar PV	0.049
Wind	0.081
Hydro	0.061
Coal	0.084
Gas	0.144

Assuming a 10,000 MW increase in capacity for each energy source by 2041, we multiplied this by the capacity factor (CF) and Levelized Cost of Electricity (LCOE) to determine the Plan Cost, as illustrated in Table 5. Subsequently, we multiplied this by the respective job intensities to ascertain the job inputs for each energy source.

Table 5: Additional Generation and Plan Cost for Different Sources

Source	Additional Capacity (MW)	Capacity Factor	Additional Generation GWh	Plan Cost ($)
Gas	10000	0.55	48180	6.9E+09
Coal	10000	0.43	37230	3.1E+09
Oil	10000	0.25	21900	3.3E+09
Hydropower	10000	0.35	30660	1.9E+09
Solar	10000	0.15	13140	6.4E+08
Wind	10000	0.15	13140	1.1E+09
Nuclear	10000	0.80	70080	7.0E+09
Agriculture	10000	0.25	21900	1.6E+09
Agrivoltaics	10000	0.15	13140	1.6E+09

4.3 Agrivoltaics Cost Input

We do a similar LCOE-type calculation for agrivoltaics, which involves calculating what a unit of power produced will mean for agriculture yield on that land, and the investment requirements, both fixed and variable for that level of output.

To produce 1 megawatt (MW) of energy using solar photovoltaic (PV) technology, approximately 3.5 acres of land are required. Given that 1 kilowatt (KW) is equivalent to 10^-3 MW, the land required to generate 1 KW of energy amounts to 0.0035 acres. In Bangladesh, the average cost of cultivating 1 acre of Aman rice, inclusive of land preparation, is 2170 BDT (Bangladeshi Taka) (Saiful, 2013). Therefore, the cost of producing energy equivalent to 0.004 acres, calculated as

2170 BDT multiplied by 0.0035, equals 7.5 BDT. This translates to an agricultural cost per KW-hour, often referred to as the levelized cost of energy (LCOE) for agriculture, of 7.5 BDT per KW-hour or approximately 0.072 USD per KW-hour, as illustrated in Table 6.

Table 6: Levelized Cost of Electricity for Agricultural Production

Land required for 1MW of solar energy	3.5 acres
Land required for 1 KW of solar energy	0.0035 acres
Average cost of cultivation including land preparation of 1 acre of Aman rice	2170 BDT
Cost of producing 0.0035 acres	2170x0.0035= 7.5 BDT
Cost of agriculture per KW in BDT	7.5 BDT/KW-h
LCoE of agriculture per KW in USD	0.072 USD/KW-h

We then multiply these dollar figures to factor intensities (employment, land, and emissions) for the 8 energy sources (coal, gas, oil; solar, wind, hydropower; nuclear and agrivoltaics) we estimated from the IO framework.

4.4 Input Output Table

The categories from the Input-Output (IO) table are provided in the appendix. To ensure consistency among the tables, the 86 industries listed in the IO table were clustered with analogous industries based on employment, wage levels, and land data.

4.5 Empirical Strategy

Previous work using IO to look at economic and environmental impacts include the work of Isard et al. (1972) studying a proposed marina in Massachusetts and Goldrick and James (1994) who used national IO with combustion emission model and regional water quality and air pollutant dispersion models to look the impacts on employment, emission, and water pollution of coal power plant in Hunter Valley. So we have dollar input amounts for each source: coal, gas, solar etc. We create a new source agrivoltaics: for employment we add the values for solar to the values for agriculture obtained from our IO analysis.

For land, we assume that the same energy capacity production ‘leaves’ almost the entire land on which the solar panels were built unused. We say almost not fully because some land is used up for housing ‘technicians’. The rest of the land on which crops are cultivated is also not fully available, due to expected crop yield loss we assume 70% land is available.

5. Methodology

The result of generalized input output analyses is a $f \times n$ matrix of factor multipliers, that is embodiments of f production factors per unit of final consumption of commodities produced by n industry sectors, denoted here by matrix **F**. A multiplier matrix **M** can be calculated from the $f \times n$ matrix **F** containing sectoral production factor usage, and from a $n \times n$ direct requirements matrix **A** according to:

$$M = \mathbf{F}(\mathbf{I} - \mathbf{A})^{-1}$$

where **I** is the $n \times n$ unity matrix.

Steps:

 Input Output Matrix **A**= (Input/Output)

 Leontief Inverse $(\mathbf{I}\text{-}\mathbf{A})^{-1}$ = (Output/Input)

 Calculate the Factor–Output Ratio for each individual levels of industry Sort the Factor – Output Ratio according to the Input-Output table

 Factor/Input = (Factor/Output)*(Output/Input)

or $\mathbf{M} = \mathbf{F}(\mathbf{I}\text{-}\mathbf{A})^{-1}$

The diagonal elements in the **M** matrix give the direct factor required and the off--- diagonals are the indirect factors generated. For instance if f=1, that is, we were looking at one factor input, say labor or employment, then the diagonal elements would give direct employment figures and the off---diagonals would be the indirect employment generated.

1. Input Output Table**.**

Let the elements of matrix **A** =
$$\begin{matrix} x & y \\ m & n \end{matrix}$$

where x,y,m,n are scalar numbers between 0 and 1.

Let the first industry be manufacturing and second be agriculture.

So to produce 1 unit ($1 in our example) of output in manufacturing industry we need:
x units (i.e. $x) of input from manufacturing & m units (i.e. $m) of input from agriculture.
Similarly to produce 1 unit ($1 in our example) of output in agriculture industry we need:
y units (i.e. $y) of input from manufacturing and n units (i.e. $n) of input from agriculture

2. Output Input Table

Output Input: The OI table gives the amount of Output in all industries in an economy generated from 1 unit of Input in each industry. We now get an Output Input matrix from the IO matrix through the following steps:

If I is the 2X2 Identity Matrix

$$\begin{matrix} 1 & 0 \\ 0 & 1 \end{matrix}$$

then its Leontiff Inverse $(\mathbf{I}\text{-}\mathbf{A})^{-1}$ gives us the OI Matrix .

Note: the elements in **I-A** are

$$\begin{matrix} 1-x & -y \\ -m & 1-n \end{matrix}$$

also between 0 and 1.

Let the elements of its inverse i.e. $(\mathbf{I}\text{-}\mathbf{A})^{-1}$ $\begin{matrix} X & Y \\ M & N \end{matrix}$

The diagonal elements *X* and *N* are therefore >1
And the off---diagonal elements *Y* and *M* are between 0 and 1. So with 1 unit ($1 in our example) Input in manufacturing industry we get: *X* units (i.e. $X) of Output in manufacturing (own industry) and *M* units (i.e. $M) of Output in agriculture and with 1 unit ($1 in our example) of Input in agriculture industry we get: *Y* units (i.e. $Y) of Output in manufacturing and *N* units (i.e. $N) of Output in agriculture (own industry)

3. Employment Output Table. The Employment Output Table gives employment (in $ in our example) generated in each industry for unit ($1) Output in that industry. We assume Employment is the only Factor in this example.

4. Employment Input (EI) Table. Employment Input Table gives the total amount (in $) Factor or Employment generated in all industries with unit ($1) input in each industry

For $1 input in manufacturing, total employment generated is $ *aX* + *Bm*. For $1 input in manufacturing, direct employment generated (in Manu.) is $ *aX* recall *a* is Employment in manufacturing per $1 (unit) Output in manufacturing. and *X* is Output in manufacturing for $1 input in manufacturing. For $1 input in manufacturing, indirect employment generated (in Agri.) is $ *bM* recall *b* is Employment in Agri. per $1 (unit) Output in agriculture and *M* is Output in agriculture for $1 input in manufacturing.

For $1 input in agriculture, total employment generated is $ *aY* + *bN*. For $1 input in agriculture, direct employment generated (in Agri.) is $ *bN* recall *b* is Employment in agriculture per $1 (unit) Output in agriculture. and *N* is Output in agriculture for $1 input in agriculture. For $1 input in agriculture, indirect employment generated (in Manu.) is $ *aY* recall *a* is Employment in manufacturing per $1 (unit) Output in manufacturing. and *Y* is Output in manufacturing for $1 input in agriculture.

The total, direct and indirect employment figures for each individual energy sector can thus be calculated using industry weights for energy source, that is, how much of each industry is used for a given energy source for that factor disturbance, water and energy use, it yields total indicator intensities, that is the amount of a factor indicator required to produce and deliver a value unit of a particular commodity, energy for the purpose of this research. Total indicator intensities include direct and indirect contributions.

6. Results

We employed a dollar-for-source approach to analyse the upstream impacts across four dimensions using an Input-Output (IO) Model:

1. Employment & Wage Levels
2. Land Use
3. Gas Emissions

Additionally, we disaggregated employment data by gender and skill levels within various sectors including coal, gas, hydropower, solar, nuclear, oil, wind, and agrivoltaics. This enabled us to discern how different economic activities affect distinct demographic groups and skill levels. Table 7 illustrates job intensity in relation to gender and overall job intensity, utilizing employment per output data sourced from each sector via Input-Output (IO) data analysis. Meanwhile, Table 8 represents job intensity categorized by skill level and land utilization, utilizing employment per output data and land data respectively, sourced the same IO analysis.

Table 7: Levelized Cost of Electricity (LCOE), Job intensity and Gender-wise job output for different sources

Source	LCOE ($/kWh)	Job Intensity ($/$)	Job Intensity (millions/yr)	Male Job Output (millions/$)	Female Job Output (millions/$)
Gas	1.4E-01	3.4E-04	1.2E-10	3.1E-10	2.7E-11
Coal	8.4E-02	3.8E-04	1.5E-10	1.5E-10	2.7E-11
Oil	1.5E-01	3.4E-04	1.2E-10	3.1E-10	2.7E-11
Hydropower	6.1E-02	4.1E-04	1.8E-10	1.6E-10	1.0E-10
Solar	4.9E-02	4.6E-04	1.7E-10	2.0E-10	4.6E-11
Wind	8.1E-02	4.8E-04	2.0E-10	2.0E-10	3.6E-11
Nuclear	1.0E-01	5.0E-04	1.2E-10	1.4E-10	2.3E-11
Agriculture	7.2E-02	5.9E-04	6.5E-09	3.7E-09	3.2E-09
Agrivoltaics	1.2E-01	1.0E-03	6.7E-09	3.9E-09	3.2E-09

Table 8: Job Intensity by Skill Level and Land Output for different sources

Source	LS Job Intensity (millions/yr)	MS Job Intensity (millions/yr)	HS Job Intensity (millions/yr)	Land (ha/$)
Gas	2.0E-10	8.4E-11	8.2E-12	4.5E-04
Coal	9.0E-11	5.1E-11	1.0E-11	4.7E-04
Oil	2.0E-10	8.4E-11	8.2E-12	4.5E-04
Hydropower	8.7E-11	7.6E-11	3.0E-11	1.8E-05
Solar	1.0E-10	7.0E-11	1.0E-11	1.0E-05
Wind	1.2E-10	7.9E-11	1.3E-11	1.3E-05
Nuclear	7.5E-11	5.0E-11	8.4E-12	1.2E-05
Agriculture	4.8E-09	2.0E-09	7.3E-11	4.2E-04
Agrivoltaics	4.9E-09	2.0E-09	8.3E-11	3.0E-06

Table 9: Wage Input and Gender-wise Job Input for different sources

				Job Input		Wage Input
Source	**Additional Capacity (MW)**	**Additional Generation GWh**	**Plan Cost ($)**	**Male (millions/yr)**	**Female (millions/yr)**	**Wage ($/$)**
Gas	10000	48180	6.9E+09	2.1E+00	1.9E-01	2.3E+06
Coal	10000	37230	3.1E+09	4.7E-01	8.4E-02	1.2E+06
Oil	10000	21900	3.3E+09	1.0E+00	8.9E-02	1.1E+06
Hydro	10000	30660	1.9E+09	3.0E-01	1.9E-01	7.6E+05
Solar	10000	13140	6.4E+08	1.3E-01	3.0E-02	3.0E+05
Wind	10000	13140	1.1E+09	2.2E-01	3.8E-02	5.1E+05
Nuclear	10000	70080	7.0E+09	9.6E-01	1.6E-01	3.5E+06
Agriculture	10000	21900	1.6E+09	5.8E+00	5.0E+00	9.3E+05
Agrivoltaics	10000	13140	1.6E+09	6.1E+00	5.2E+00	1.7E+06

Table 10: Land Input and Job Input by skill level for different sources (LS-low-skill, MS-medium skill, HS- high skill)

Source	Additional Capacity (MW)	Additional Generation GWh	Plan Cost ($)	LS (million/yr)	MS (millions/yr)	HS (millions/yr)	Land Input (ha)
Gas	10000	48180	6.9E+09	1.4E+00	5.8E-01	5.7E-02	3.1E+06
Coal	10000	37230	3.1E+09	2.8E-01	1.6E-01	3.2E-02	1.5E+06
Oil	10000	21900	3.3E+09	6.5E-01	2.8E-01	2.7E-02	1.5E+06
Hydropower	10000	30660	1.9E+09	1.6E-01	1.4E-01	5.7E-02	3.4E+04
Solar	10000	13140	6.4E+08	6.4E-02	4.5E-02	6.7E-03	6.5E+03
Wind	10000	13140	1.1E+09	1.2E-01	8.4E-02	1.4E-02	1.4E+04
Nuclear	10000	70080	7.0E+09	5.2E-01	3.5E-01	5.9E-02	8.4E+04
Agriculture	10000	21900	1.6E+09	7.6E+00	3.1E+00	1.1E-01	6.6E+05
Agrivoltaics	10000	13140	1.6E+09	7.8E+00	3.3E+00	1.3E-01	4.8E+03

6.1 Employment

In this section, we present results of estimates on employment created through spending on energy related sectors, comprising of fossil fuel sectors, renewable energy and agrivoltaics. We report a set of estimates of overall job generated through investments in the different energy related sectors. This includes both direct and indirect employment. I first present the full set of results in terms of jobs-per-year created per $1 spent. To facilitate comparisons on job creation levels across sectors, weighted averages of employment creation figures for fossil fuels, renewables, and agrivoltaics are presented.

Table 7 presents employment generated from direct energy related sectors and from their respective upstream economic activities. The results are presented for each of the nine energy related sectors. The estimates show that overall employment creation in Bangladesh through spending in agrivoltaics will be much higher than the employment generated through the fossil fuel and renewable sectors. Assuming a 10,000 MW increase in capacity for each energy source by 2041, we multiplied this by the capacity factor (CF) and Levelized Cost of Electricity (LCOE) to determine the Plan Cost. Subsequently, we multiplied this by the respective job intensities to ascertain the job inputs for each energy source.

Agrivoltaics is projected to yield the highest levels of male and female employment compared to other sources. Agrivoltaics will generate approximately 6.64 million jobs for men and 5.57 million jobs for women per year, which is significantly higher than other sources. (Fig.1) The gender-based percentage difference is minimal in agrivoltaics compared to other sources. The installation and maintenance of agrivoltaic systems create new jobs in both the renewable energy and agricultural sectors Agrivoltaics are anticipated to generate 7.8 million low-skilled jobs and 3.3 million medium-skilled jobs, with 6.1 million jobs projected for men and 5.2 million jobs for women.

Job input from agrivoltaics is expected to significantly boost the number of low-skilled and medium-skilled laborers. However, the count of high-skilled laborers will likely remain consistent with other sources. Gas demonstrates the second-highest job input after agrivoltaics across genders and skill levels. (Fig. 2)

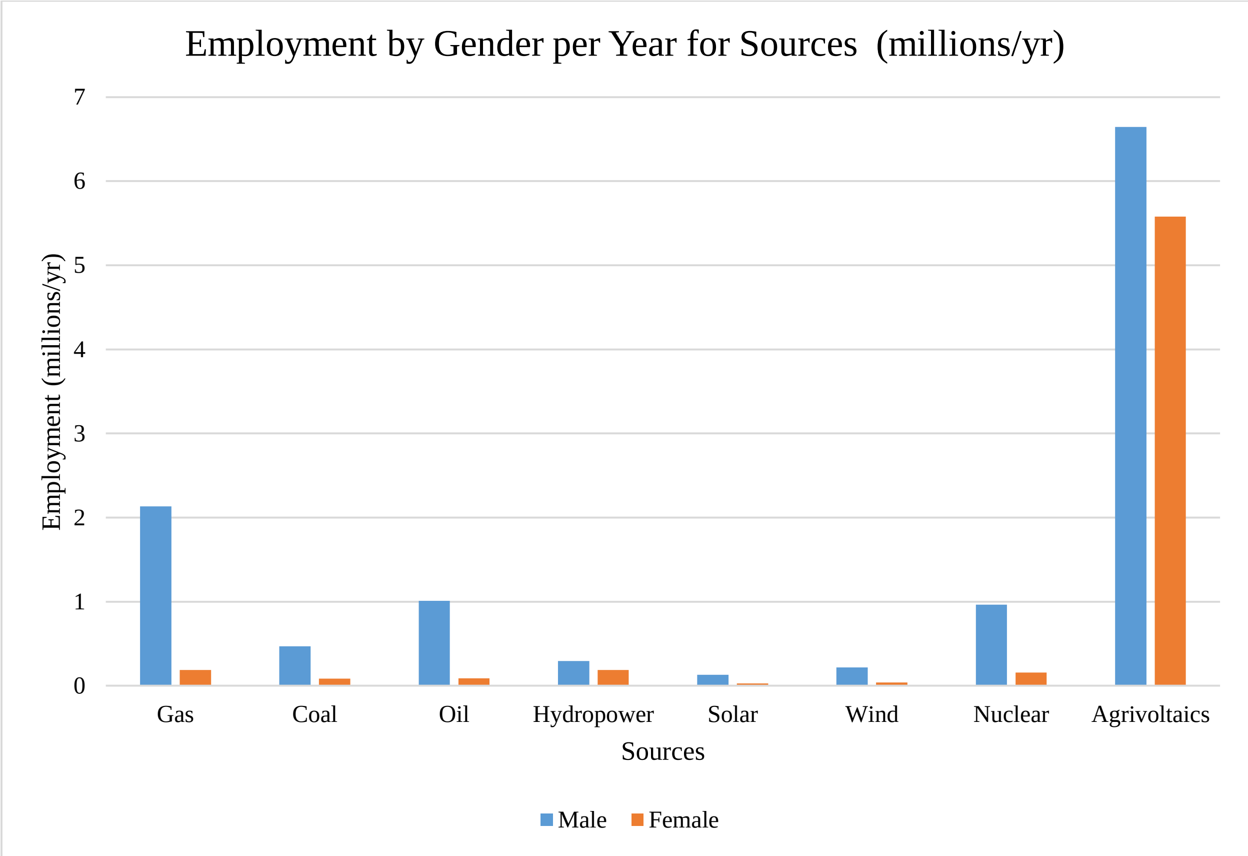

Figure 1: Annual Job Input (millions/yr) by Gender for Each Source

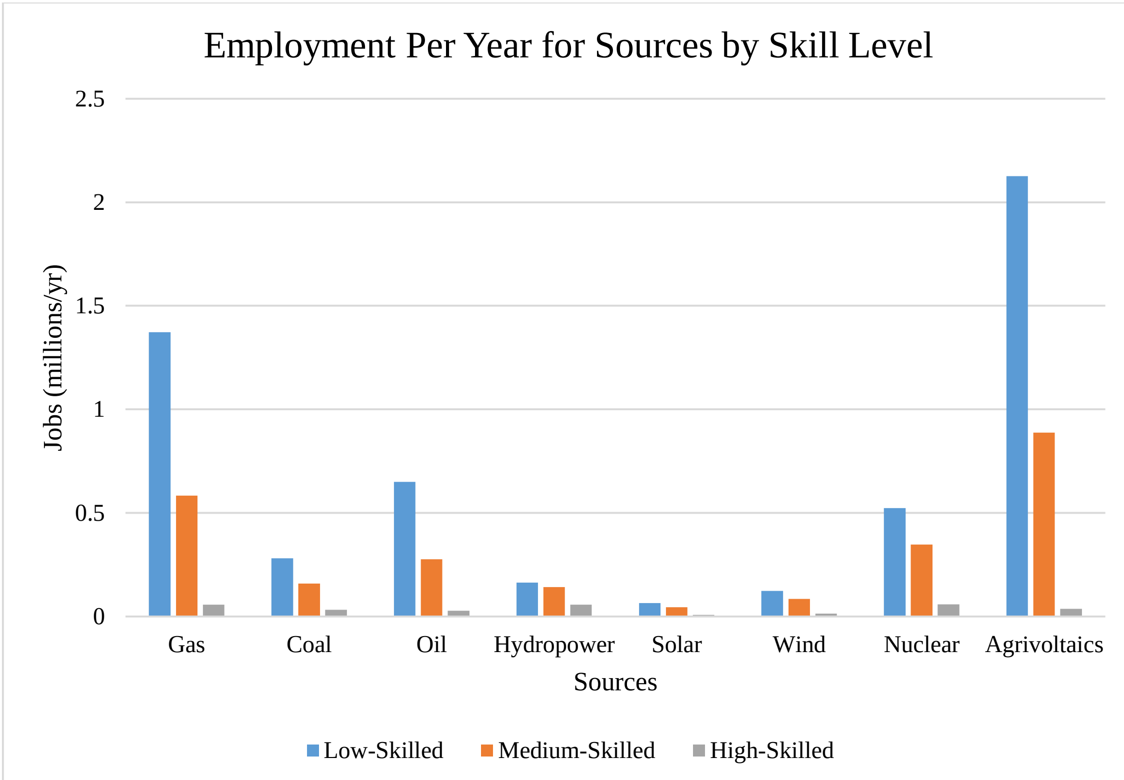

Figure 2: Annual Job Input by Skill Levels (millions/yr) for Each Source

6.2 Wage Level

The graph indicates that the nuclear sector exhibits the highest average wage level at $3.5 million per year, with gas trailing closely behind. Agrivoltaics ranks third, with an average wage level of $1.6 million per year. Despite slightly lower figures, agrivoltaics presents significant economic opportunities, signaling its potential for robust employment and income generation. (Fig. 3)

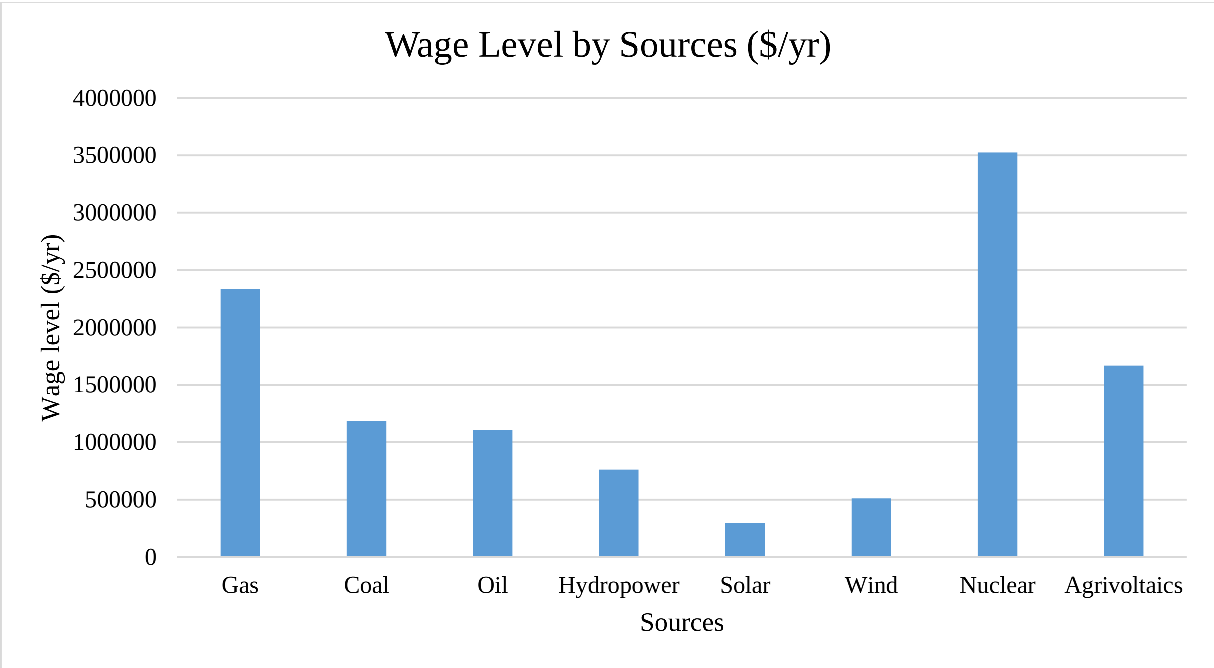

Figure 3: Wage Level Input for Different Sources ($/yr)

6.3 Land

We present the model used for the land-impacted variable by first reviewing the model for land-use variable. Indirect land-use refers to all the land used by upstream activities for power generation. Thus the total indicator intensity for land include direct and indirect contributions, for instance:

- Direct or zeroth-order land used by the commodity (unit of energy produced): the land on which the plant is built.
- First-order indirect contribution: land used for producing supporting goods and services for the plant and workers— where they stay, food produced, or roads or energy used for producing the equipment used for construction of the plant.
- Second-order indirect contribution: land used or water used for producing energy needed for the equipment used for constructing the plant and so on.

The highest land demand will be observed in the oil and gas sectors, reaching 3.15 million hectares per year and 1.5 million hectares per year, respectively. Though direct land use shows solar to be more land intensive than fossil fuels, but when analysing upstream impacts we see that it is no longer true. Land intensity, particularly when considering land use from upstream activities, shows agrivoltaics to be the least land-intensive option. Figure 4 shows that the land input required for agrivoltaics stands at 4,845 hectares per year, significantly lower than that for fossil fuels.

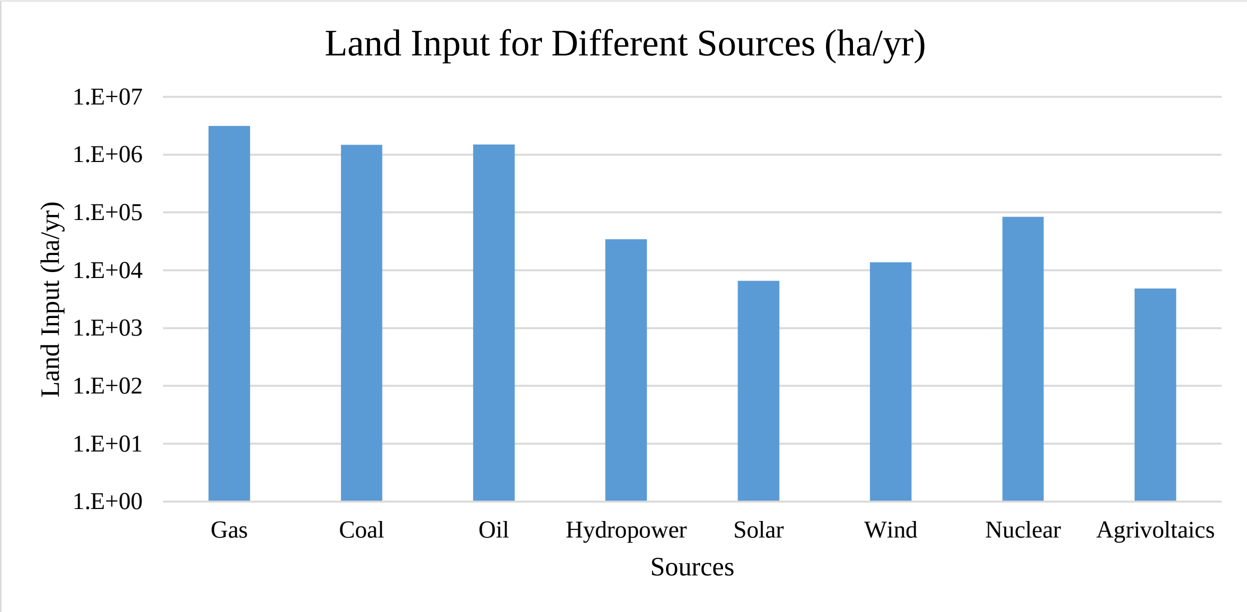

Figure 4: Land Input for Different Sources (ha/yr)

6.4. Gas Emissions

We assume zero direct emissions for renewable sources and thus only provide estimates for the fossil fuel sources. In 2041, the projected generation indicates that CO2 levels will notably higher than those of SO_x and NO_x emissions. Across all emission types, coal is expected to emit the highest levels of SO_x, NO_x, and CO_2, followed by gas and then oil.

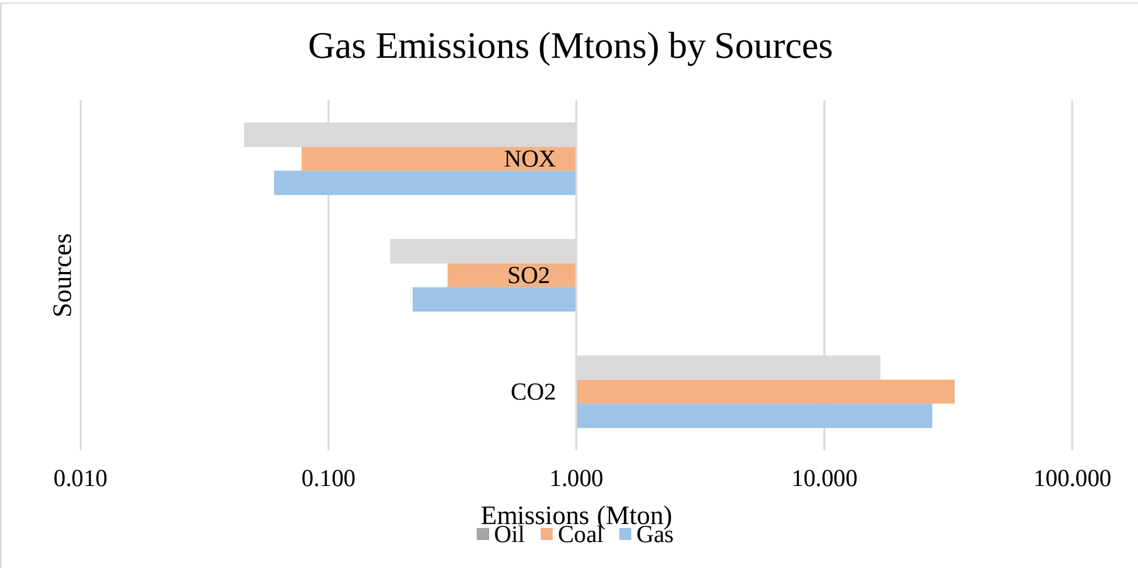

Figure 5: Emissions of NOx, SOx, and CO2 for Each Source (Oil, Gas, Coal) (Mton/yr)

7. Discussion

In comparing agrivoltaics to existing power sources (namely coal, gas, oil, nuclear, wind, hydropower, and solar) with respect to the key aspects of power generation (cost, employment, land use, emissions) we find agrivoltaics addresses many of the issues around renewable expansion in Bangladesh. We use an IO method to estimate the upstream, economy-wide impacts for the different sources.

Land intensity, particularly once taking into account land use from upstream activities shows agrivoltaics to be the least land-intensive option. In terms of cost, the LCOE for solar has been rapidly declining and is expected to decline in the coming years. The cost of photovoltaic modules has decreased over time, resulting in reduced installation costs. It's anticipated that the levelized cost of energy (LCOE) for photovoltaic technology will decrease by 50% by 2050 (PV Magazine, 2023). By growing crops on the same land there is added revenue generation potential from the same land.

We find that agrivoltaics has the potential to employ more people per year compared to unit power generated under existing sources. In terms of direct employment solar generates less employment relative to fossil fuel sources as the latter involves land works and more construction. As most input parts for all power generation are imported, this lack of construction and earthworks means solar employs less direct employment. This issue is addressed under agrivoltaics through employment generated through agriculture, which remains one of the most labour intensive sectors. The labour intensity value for agrivoltaics is estimated at 6.7x10-9 million jobs per dollar which is higher than solar (1.7x10-10 million jobs per dollar). This is reflected in our findings that Job input from agrivoltaics is expected to significantly boost the number of low-skilled and medium-skilled laborers at 2.12 million low-skilled workers and 0.88 million workers, as compared to the second-highest gas, which will generate employment for 1.37 million workers annually and 0.58 million medium-skilled workers annually. However, the count of high-skilled laborers for agrivoltaics will likely remain similar to other sources for the same unit of power generated at 0.035 million per year Our research indicates that agrivoltaics is poised to have a notable impact on the employment landscape, particularly in terms of low-skilled and medium-skilled labor. Specifically, it is projected to create opportunities for approximately 2.12 million low-skilled workers and 0.88 million medium-skilled workers annually. In comparison, the next highest contributor, gas, is anticipated to employ 1.37 million low-skilled workers and 0.58 million for medium-skilled roles. However, the count of high-skilled workers for agrivoltaics will likely remain similar to other sources at 0.035 million per year.

Agrivoltaics is projected to yield the smallest gender employment gap compared to other energy sources, with only a 16% difference between male and female employment. In contrast, the difference in employment rates between men and women is much larger, reaching 91%, in the cases of oil and gas. We see that employment under power generation tends to be male-dominated. Pursuing agrovoltaics reduces the gender gap, which is not surprising as agriculture is one of the highest employment sources for women. These values are for the formal sector. There is a large scope for employment generation in the informal sector under agriculture, which in Bangladesh particularly benefits women. (Asian Development Bank, 2010) Therefore, the actual gains for women, and the gender gap, are potentially even lower under agrivoltaics than found in this paper.

The job disaggregation estimates show that low and medium-skill workers as well as female workers will benefit the most from the expansion of work opportunities. The methodology encapsulates key considerations within the food–energy–environment nexus showing the implications of different energy pathways. The results show that the transition to renewable energy could accommodate those who stand to lose the most in large-scale transitions. The expansion of work opportunities for women, as well as for low and middle-skill workers through agrivoltaic expansion form key considerations within the just transitions framework.

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Appendix

Table A1: Full List of I/O Industries (GED, 2017)

Industries
Paddy
Wheat, pulse, oil seed
Jute
Sugarcane
Potato, vegetable
Cotton
Tobacco
Tea
Spice
Fruit cultivation
Other crop
Livestock rearing
Poultry rearing
Shrimp
Fishing
Forestry and logging
Rice milling
Grain milling
Fish Process
Oil industry
Sweetener Industry
Beverage
Tobacco
other
Tea Product
Cigarette industry
Bidi industry
Jute fabrication
Yarn
Dying and bleaching
Hand loom
Cloth milling
Woven
Knitting
Footwear
Other leather
Tanning
Wood and cork product
Paper Industry
Printing and publication
Petroleum Refinery

Basic chemical
Fertiliser industry
Pharmaceuticals
Plastic Products
Glass industry
Clay industry
Cement
Basic metal
salt
Electricity
Gas extraction and distribution
Water
Building
Kutcha house
Agricultural costruction
Other construction
Machinery and equipment
Manufacture of electrical equipment
Transport equipment
Furniture
Misellaneous
Mining
Wholesale Trade
Retail Trade
Air Transport
Water Transport
Land Transport
Railway Transport
Other Transport
Housing and Real Estate Service
Health Service
Education Service
Public Administration and Defense
Bank and Other Financial Services
Insurance
Professional Service
Entertainment
Hotel and Restaurant
Communication
Other Services
ICT

Table A2: Capacity Factors for Various Sources

Assumed Capacity Factors	
Fuel	Average Capacity Factor
Gas	0.55
Coal	0.425
Oil	0.25
Hydropower	0.35
Solar	0.15
Wind	0.15
Nuclear	0.8

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