Energy Return on Energy and Carbon Investment of Wind Energy Farms in Thailand

Watcharapong Tantawat[1,*], Aumnad Phdungsilp[1], and Suparatchai Vorarat[1]

ARTICLE INFO

Article history:
Received: 26 March 2022
Revised: 26 April 2022
Accepted: 21 May 2022

Keywords:
Energy return on investment
Carbon emission assessment
Energy ratio analysis
Wind energy
Onshore wind farms

ABSTRACT

This paper presents the Energy Return on Energy Invested (EROI) and Energy Return on Carbon Emissions (EROC) of 22 existing large onshore wind energy farms in Thailand. The estimation of EROI and EROC of each wind energy farm allows comparison of energy and environmental performance of each wind energy farm. Data on the 22 wind energy farms in Thailand were collected from the Electricity Generation Authority of Thailand and the Energy Regulatory Commission of Thailand. The results are showed that the total energy and carbon emissions of 22 wind energy farms over a 25-year life span are 8,755,010.26 GJ and 4,576,324.89 tCO_2eq. The carbon emission intensity of wind energy farms in Thailand is 62.16 gCO_2eq/kWh, which is tremendously higher than those for wind energy farms in China, Italy, and New Zealand. The EROI of 22 wind energy farms is ranged from 21.04 to 44.36. The weighted average EROI based on the installed capacity of the 22 wind energy farms in Thailand is 30.64. The EROC is ranged from 36.94 GJ/tCO_2eq to 93.72 GJ/tCO_2eq with the weighted average of 59.62 GJ/tCO_2eq. Transportation contributes to the largest share of expended energy, accounting for 29.64% of total expended energy and the foundations of turbines are responsible for 35.09% of total carbon emissions for the wind energy farms.

1. INTRODUCTION

Energy and climate change are a big concern in society nowadays. It is found that the temperature has increased across Thailand over the past half-century [1]. Thailand has ratified the Paris Climate Agreement on 21 September 2016 to support the international efforts for limiting an average global temperature. Thailand's Nationally Determined Contribution (NDC) aims to reduce greenhouse gas (GHG) emissions by 20% from the BAU (business-as-usual) level by 2030 and up to 25% with international support [2]. The NDC was formulated based on the integrated national energy plan to provide the development policy direction. In addition, Thailand has announced the transition towards carbon neutrality by 2050 and net zero emissions by 2065 at the COP 26 in Glasgow. Accordingly, renewable energy sources will account for approximately 50% share of new power generation installed in the power system. In Southeast Asia, Thailand was the first country that announces an official policy on renewable electricity generation from small power producers [3]. Wind energy is one of high potential renewable energy resources for electricity generation in Thailand. According to the Alternative Energy Development Plan (AEDP: 2018-2037), the electricity generation from wind energy currently accounts for 14% of total national electricity mix (1,504 MW out of 10,715 MW). The growth in commercial electricity generation from wind energy has increased from 90 MW in 2012 from the first wind energy farm to 1,474 MW in 2021 with a total of 29 wind energy farms. There is likely to be more wind energy farms in Thailand in the near future. Therefore, it is a need to study the energy outputs and related carbon emissions from electricity generation from wind energy farms. This would provide insights to encourage the pathways achieving carbon neutrality.

Life cycle assessment (LCA) is an effective tool for analyzing environmental impacts of wind energy farms. For example, Ardente et al. [4] used LCA to analyze the carbon emissions of an Italian wind energy farm. It was found that the carbon emissions resulting from the Italian case is 14.8 gCO_2eq/kWh [4]. The study compared the global warming potential (GWP) of onshore single turbines and onshore wind farms by using LCA. The results in [4] show that the GWP of onshore single turbines tends to higher than onshore wind farms. However, a study on the LCA-based approach for estimating embodied energy and carbon emissions of wind energy farms in Thailand is limited because details of wind energy farms are not available for LCA calculation. These details data include locations of wind turbines,

---

[1] *Graduate Programe in Engineering Management, College of Innovative Technology and Engineering, Dhurakij Pundit University, Bangkok, 10210, Thailand.*

**Corresponding author:* Watcharapong Tantawat; Phone: +66-88-5125252; Email: w.tantawat@hotmail.com.

models of wind turbines, sizes of concrete foundations, sizes of concrete foundations. These data are difficult to obtain because they are confidential information from the private sector perspective.

In the literature, the Energy Return on Investment (EROI) and Energy Return on Carbon Emissions (EROC) are useful indicators to reflect the energy outputs from the investment and carbon footprint on renewable energy project. EROI is also called the Energy Return on Energy Investment (EROEI). The analysis of EROI was pioneered by [5], which is defined as a ratio between the amount of energy delivered to energy systems and the amount of energy used directly and indirectly in the processes. EROC is a specific carbon footprint ratio. It expresses in electricity generation per unit of carbon emission. EROI and EROC can be determined using the LCA approach. EROI of wind energy technology is generally higher than other technologies and increasing in the future [6]. EROI is a suitable cut-off factor from an economic aspect to analyze the global available wind energy potential. Many countries have reported that the EROI is less than 10 for the case of wind energy [7].

A previous study by [8] analyzed the EROI and EROC of 11 wind energy farms in New Zealand. It demonstrated that the weighted average EROI based on the installed capacity of wind energy farms over a 20-year life span is 34.3. The highest value is 57.7, while the lowest value is 6.5. The average EROC for New Zealand's wind energy farms is 477 GJ/tCO$_2$eq. The reason for the high EROI of wind energy farms in New Zealand is due to high average wind speeds resulting in high-capacity factors and consequently high EROI value.

This study aims to fulfill research gaps in the literature by estimating the energy expended and direct and indirect carbon emissions related to wind energy farms in Thailand. The calculation tool adopts the same basic of LCA approach but avoids using specific LCA software for better transparency in the calculation. A comparison of the energy and environmental performance of each wind energy farm is presented in terms of EROI and EROC. In this study, EROI and EROC of electricity generation from 22 existing large onshore wind energy farms in Thailand are estimated. The installed capacity of each wind energy farm is higher than 10 MW. Wind turbines of a capacity exceeding 1 MW are used for these wind energy farms. The plant’s lifetime of 22 wind energy farms is 25 years. The calculation tool developed by [8] is adopted to calculate the EROI and EROC of individual wind energy farm. Carbon emission factors in the context of Thailand are used in the calculation.

2. DATA COLLECTION AND METHODS

The flowchart methodology of this research is presented in Figure 1.

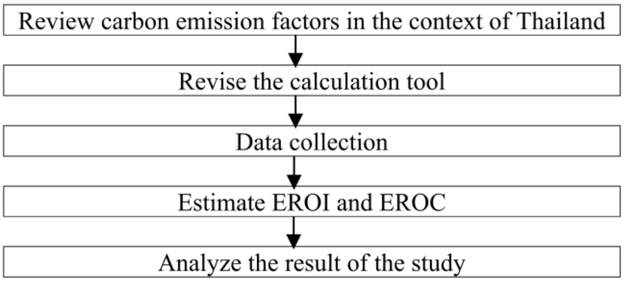


Fig. 1. Flowchart methodology of this research.

2.1. Data collection

In this study, the electricity generation of 22 existing large onshore wind energy farms is referred to the actual yearly electricity purchased from the Electricity Generating Authority of Thailand (EGAT) of each wind farm in a previous year in kWh/year. Data related to installed capacities, number of wind turbines, model of wind turbines, manufacturing countries of wind turbines, and locations of each wind energy farm were collected from the Energy Regulatory Commission of Thailand (ERC). Hub heights and blade diameters of wind turbines were collected from WindPRO software, which is a well-known wind energy software for wind energy simulation [9]. The distances of ocean shipping and land transportation of each wind energy farm were estimated with web mapping platforms, namely Sea-Distances and Google Maps, respectively. The relevant data of the 22 wind energy farms are presented in Table 1.

2.2. Methods

2.2.1. Estimation of EROI and EROC

The EROI and EROC enable to analyze and compare energy outputs and carbon emissions of different types of energy technologies both renewable and nonrenewable energy technologies. EROI for a wind energy farm is calculated using total electricity outputs during the lifetime divided by expended energy for construction as well as operation and maintenance. EROC is defined as a specific carbon footprint ratio expressed in electricity generation per unit of carbon emission (GJ/tCO$_2$eq). EROI and EROC are linked together and both based on the LCA approach. The life cycle stages considered in this study are illustrated in Figure 2.

Fig.2. Life cycle of the existing wind energy farms.

The EROI and EROC of a wind energy farm is calculated with the life cycle stages, as follows:

$$\text{EROI} = \frac{E_{\text{generation}}}{E_{\text{road}} + E_{\text{cable}} + E_{\text{earth work}} + E_{\text{materials}} + E_{\text{transportation}} + E_{\text{operation}}} \qquad (1)$$

Table 1. Data of the 22 existing onshore large wind energy farms in Thailand

Wind Farm	Collected from EGAT	Collected from ERC					Collected from WindPRO		
	Actual Annual Electricity Generation (kWh)	Location (Coordinate)	Installed Capacity (MW)	Number of Wind Turbines	Turbine model	Manufacturing country of wind	Hub Height (m)	Diameter of Blade (m)	Mean Power Density @Height 100m
Wind Farm A	171,193,345.0	15.113N 101.505E	103.50	45	Siemens SWT-2.3-101	Denmark	80.0	101	248
Wind Farm B	142,872,432.5	15.113N 101.505E	103.50	45	Siemens SWT-2.3-101	Denmark	80.0	101	248
Wind Farm C	85,863,239.5	16.685N 100.993E	60.72	24	GE 2.5-120	Germany	85.0	120	276
Wind Farm D	124,483,950.0	15.605N 101.547E	80.00	32	Goldwind GW121/2500	China	90.0	121	224
Wind Farm E	141,908,861.5	15.425N 101.489E	60.00	30	GE 120-2.1	China	80.0	116	246
Wind Farm F	81,006,170.0	15.119N 101.488E	50.00	25	Gamesa G114/2.0	Spain	108.0	112	299
Wind Farm G	72,274,286.0	7.997N 100.322E	36.00	20	Vestas V110-1.8	Denmark	80.0	100	247
Wind Farm H	93,720,713.0	7.997N 100.322E	45.00	25	Vestas V110-1.8	Denmark	80.0	100	247
Wind Farm I	90,738,013.0	7.997N 100.322E	45.00	25	Vestas V110-1.8	Denmark	80.0	100	247
Wind Farm J	126,780,715.0	15.174N 101.492E	67.50	33	Gamesa G114/2.0	China	108.0	112	265
Wind Farm K	112,461,075.5	14.932N 101.515E	50.00	20	Gamesa G126/2.5	China	127.5	145	229
Wind Farm L	242,443,022.5	15.338N 101.482E	90.00	30	Vestas V136-3.0	Denmark	132.0	136	295
Wind Farm M	237,125,630.0	15.366N 101.450E	90.00	30	Vestas V136-3.0	Denmark	132.0	136	350
Wind Farm N	246,910,242.5	15.275N 101.465E	90.00	30	GE 137-3.0	USA	134.0	130	367
Wind Farm O	216,596,324.5	15.087N 101.510E	90.00	30	GE 137-3.0	USA	134.0	130	250
Wind Farm P	76,779,245.0	15.633N 101.649E	45.00	18	Gamesa G126-2.5	Spain	127.5	145	181
Wind Farm Q	76,232,040.0	15.667N 101.692E	45.00	18	Gamesa G126-2.5	Spain	127.5	145	167
Wind Farm R	108,138,867.5	15.468N 101.413E	47.50	19	Gamesa G126-2.5	Spain	127.5	145	342
Wind Farm S	76,329,005.0	15.500N 101.448E	40.00	16	Gamesa G126-2.5	Spain	127.5	145	242
Wind Farm T	67,261,616.0	16.378N 104.414E	44.85	13	Vestas V136-3.45	Denmark	132.0	136	400
Wind Farm U	146,030,422.5	15.541N 101.559E	80.00	32	Gamesa G126-2.5	Spain	127.5	145	213
Wind Farm V	207,758,650.0	15.224N 101.505E	90.00	30	GE 137-3.0	USA	134.0	130	271
Total	29,449,078,66.5		1,453.57	590					
Weighted average	150,440,418.3		73.50	30					

where:

$E_{generation}$ = Estimated electricity generation, GJ/turbine;

E_{road} = Access roads, GJ/turbine;

E_{cable} = Transmission cables, GJ/turbine;

$E_{earthwork}$ = Earthworks, GJ/turbine;

$E_{materials}$ = Wind turbine materials, GJ/turbine;

$E_{transportation}$ = Transportation, GJ/turbine; and

$E_{operation}$ = Operation and maintenance, GJ/turbine.

$$\mathrm{EROC} = \frac{E_{\mathrm{generation}}}{C_{\mathrm{road}} + C_{\mathrm{cable}} + C_{\mathrm{earth\ work}} + C_{\mathrm{materials}} + C_{\mathrm{transportation}} + C_{\mathrm{operation}}} \tag{2}$$

where, EROC is expressed in GJ/tCO$_2$eq, C represents carbon emissions in tCO$_2$eq/turbine, and other subscriptions are similarly definitions, as described in Eq. (1).

2.2.2 Estimated electricity generation

The electricity generation from wind energy farms over the plant's lifetime ($E_{\mathrm{generation}}$) was estimated from EGAT's actual electricity purchased (E_{purchase}) of each wind energy farm. E_{purchase} in kWh/year of the year 2020 was converted to energy output in GJ/turbine. The study assumed that a wind farm can generate the same annual electricity output as the year 2020. Accordingly, the estimated energy output over the plant's lifetime per wind turbine can be calculated using Eq. (3):

$$E_{\mathrm{generation}} = \frac{0.09E_{\mathrm{purchased}}}{n} \tag{3}$$

where, n represents the number of wind turbines of each wind energy farm.

2.2.3 Embedded energy and carbon emissions

Calculation of the EROI and EROC developed by Walmsley et al. [8] was adopted in this study. The calculation uses correlations from LCA studies to estimate the embedded energy and energy-related emissions of individual wind energy farm. It was chosen for this study because less inputs are needed and data available from public sources. On the other hand, some detailed LCA data require confidential information such as locations of wind turbines, models of wind turbines, and sizes of concrete foundations. The detail information can be obtained from the owners or developers of wind energy farms only. According to [8], data for estimating expended energy and carbon emissions include wind turbine materials, concrete foundations, access roads, transmission cable, earthworks, transportation, and operation and maintenances, as presented in the following sections.

2.2.4 Wind Turbine Materials

Primary data of wind turbine materials from manufacturers were not available for the public. Therefore, the weights or mass (m) of wind turbine materials were derived from Eq. (4)–(7).

$$m_{\mathrm{structural\ steel}}\ (\mathrm{t/turbine}) = 0.0214H^{2}+0.0845^{H}+87 \tag{4}$$

$$m_{\mathrm{blade}}\ (\mathrm{t/turbine}) = 1.37\times10^{-6}D^{3.44} \tag{5}$$

$$m_{\mathrm{concrete}}\ (\mathrm{t/turbine}) = 0.163H\times D \tag{6}$$

$$m_{\mathrm{reinforcing\ steel}}\ (\mathrm{t/turbine}) = 0.00634H\times D \tag{7}$$

The turbine tower height (H) and blade diameter (D) of each wind turbine was collected from WindPRO software (see Table 1). The embeded energy (EF) and carbon emissions (CF) of a wind turbine are estimated with the mass associated with wind turbine components, as shown in Eq. (8)–(9). The EF and CF factors of materials and components of a wind turbine were estimated by [8], as presented in Table 2.

$$E_{\mathrm{materials}} = EF_{s,s}\times m_{\mathrm{structural\ steel}} + EF_{GB} + EF_{GN} + E_{FF}\times m_{\mathrm{blade}} + E_{FC}\times m_{\mathrm{concrete}} + EF_{S,R}\times m_{\mathrm{reinforcing\ steel}} \tag{8}$$

$$C_{\mathrm{materials}} = CF_{s,s}\times m_{\mathrm{structural\ steel}} + CF_{GB} + CF_{GN} + C_{FF}\times m_{\mathrm{blade}} + C_{FC}\times m_{\mathrm{concrete}} + CF_{S,R}\times m_{\mathrm{reinforcing\ steel}} \tag{9}$$

Table 2. Embodied energy factors of a wind turbine

Components	Embedded Energy	Carbon Emissions
Structural steel	$EF_{S,S}$ 31.40 GJ/t	$CF_{S,S}$ 1.24 tCO$_2$eq/t
Gearbox	EF_{GB} 799 GJ/turbine	CF_{GB} 54.46 tCO$_2$eq/turbine
Generator	EF_{GN} 789 GJ/turbine	CF_{GN} 54.55 tCO$_2$eq/turbine
Fiberglass (blade)	E_{FF} 29.30 GJ/t	CF_{F} 0.69 tCO$_2$eq/t
Concrete	E_{FC} 1.19 GJ/t	CF_{C} 0.15 tCO$_2$eq/t
Reinforcing steel	$EF_{S,R}$ 8.60 GJ/t	$CF_{S,R}$ 0.35 tCO$_2$eq/t

Source: [8] and [10]

2.2.4 Earthworks

Earthworks are associated with concrete foundations of wind turbines. Construction of foundations requires soil excavation, compaction, and backfilling. Earthworks considered in this study assumed that all wind turbine models have the same amount of embedded energy for the earthworks as well as the same amount of carbon emissions. According to [8], the energy associated with earthworks ($E_{\mathrm{earthworks}}$) at the site is 1.1 GJ/turbine and the carbon emissions of earthworks ($C_{\mathrm{earthworks}}$) is 5.6 tCO$_2$eq/turbine.

2.2.5 Access Roads

Wind energy farms require roads that can be accessed to all locations of the installed wind turbines. For transportation and maintenance, the roads must be newly built, so that trailers containing heavy components of wind turbines can run along them. The embedded energy of road per unit length was taken from [8], which is 1.86 GJ/m. Accordingly, the total embedded energy from road and road between turbines (E_{road}) is estimated using Eq. (10):

$$E_{\mathrm{road}} = 1.86\times(L_{\mathrm{main}}+L_{\mathrm{sub}}) \tag{10}$$

Data were available for total lengths of road per wind turbine (L_{main}) and total lengths of road between turbines (L_{sub}) for only six existing wind energy farms, as presented in Table 3. Therefore, L_{main} and L_{sub} per wind turbine were estimated by averaging actual L_{main} and L_{sub} of the six wind energy farms. The weighted average of L_{main} and L_{sub} based on the installed capacity of 22 wind energy farm are 1,005.8 m/turbine and 159.05 m/turbine, respectively.

Table 3. The actual length of the roads

Wind Farm	No. of Turbines Installed	L_{main} (m)	L_{Sub} (m)
Wind Farm E	30	21,592	6,862
Wind Farm L	30	20,260	4,207
Wind Farm M	30	53,420	3,712
Wind Farm N	30	38,000	3,895
Wind Farm O	30	20,239	4,995
Wind Farm V	30	27,533	4,959
Total	180	181,044	28,630
Average Length Per Turbine		1,005.80	159.05

Thus, the E_{road} was estimated by multiplying with the weighted average of L_{main} and L_{sub} in Eq. (10), which is given E_{road} equals to 2,166.621 GJ/turbine. The carbon emissions of road construction in Thailand by [11] has evaluated carbon footprint of road construction. It is revealed that the estimated carbon emission factor of a road is 0.950 tCO_2eq/m. Then, the carbon emissions of road and road between turbines (C_{road}) in Eq. (11) is estimated by multiplying with the weighted average of L_{main} and L_{sub}, given C_{road} equals to 1,106.607 tCO_2eq/turbine.

$$C_{road} = 950\times(L_{main}+L_{sub}) \quad (11)$$

2.2.6 Transmission cables

Underground cables are used to transmit electricity from each wind turbine. The transmission cables connect all wind turbines with substations. The length of required underground cabling was estimated at 1.5 times distances between turbines [12]. The embodied energy and carbon emissions per km from cabling are estimated as 0.271 GJ/m and 0.0213 tCO_2eq/m, respectively [8]. In this study, the total embedded energy from cabling (E_{cable}) and carbon emissions from cabling (C_{cable}) were estimated with the weighted average of L_{main} and L_{sub}, resulting E_{cable} equals to 64.65 GJ/turbine and C_{cable} equals to 5.081 tCO_2eq/turbine.

2.2.7 Transportation

In a case of Thailand, all turbines installed in existing onshore wind energy farms are manufactured and shipped from abroad. Maritime transport is arranged for turbine components, including towers, nacelles, hubs, and blades. The embodied energy factors for ocean shipping and land transport of wind turbine components per km are 0.00025 GJ/t.km and 0.00125 GJ/t.km [5]. In addition, a study by [13] suggests that carbon emission factors for ocean shipping by breakbulk and land transportation by trailers are 0.0000056 $tCO_2eq/t.km$ and 0.000054 $tCO_2eq/t.km$, respectively. The embodied energy ($E_{transport}$) and carbon emissions ($C_{transport}$) for transport per turbine can be estimated, as shown in Eq. (12)-(13):

$$\begin{aligned}E_{transport} = {} & [(0.00025S)\times(m_{tower\&naclles\&hubs} \\ & + m_{blade})]+[(0.00125L_{transport}) \\ & (m_{tower\&naclles\&hubs} + m_{blade} \\ & + m_{concrete} + m_{reinforcing\ steel})]\end{aligned} \quad (12)$$

$$\begin{aligned}C_{transport}\ (= {} & [(0.0056S) \\ & \times(m_{tower\&naclles\&hubs} \\ & + m_{blade})] \\ & + [(0.054L_{transport}) \\ & \times(m_{tower\&naclles\&hubs}+m_{blade} \\ & +m_{concrete}+m_{reinforcing\ steel})]\end{aligned} \quad (13)$$

where, S represents the ocean shipping distance and $L_{transport}$ is the land transport distance of each wind energy farm referred to a country of manufacture of wind turbines as well as the coordinate of each wind energy farm, as presented in Table 1. S and $L_{transport}$ of each wind energy farm were estimated by applying the web mapping platforms namely SEA-DISTANCES.ORG and GOOGLE MAPS, as shown in Table 4.

2.2.8 Operation and maintenance

Total embedded energy for operation and maintenance ($E_{operation}$) for the service life of 25 years of each wind energy farm was used in the calculation. The $E_{operation}$ can be estimated as 1,462.5 GJ/turbine. A study by [14] suggests that carbon emission factor from energy consumption for electricity generation of a wind energy farm in Thailand is 569.2 gCO_2eq/kWh. Accordingly, carbon emissions from operation and maintenance ($C_{operation}$) of each wind energy farm can be estimated by multiplying carbon emission factor with $E_{operation}$, resulting in $C_{operation}$ for 25 years equals to 231.237 tCO_2eq/turbine.

The above equations were applied with key parameters of wind energy farms in Table 4 for estimating the EROI and EROC of 22 wind energy farms in Thailand. Results from the calculation showed the expended energy and carbon emissions of each wind farm. In addition, total expended energy and carbon emissions of each wind energy farm were broken down into seven main areas, including turbine, concrete foundation, earthworks, access roads, transmission cables, transportation, and operation and maintenance.

3. RESULTS

3.1. Electricity Generation from Wind Energy Farms in Thailand

The total installed capacity of wind turbines in 22 wind energy farms is 1,454 MW with 590 wind turbines. The total electricity of wind energy farms supply to Thailand's national grids over the plant’s lifetime is 73,622.7 GWh or 265,041,707.98 GJ. Total electricity delivered to the grid is less than the full installed capacity of wind turbines because the electricity delivered to the grid has been limited in accordance with the contracted capacity of each wind farm. On average, 30 wind turbines with the installed capacity of 73.50 MW are installed for a large onshore wind energy farm in Thailand. One wind energy farm can produce 150,440,400 kWh of electricity per year approximately.

3.2. Expended Energy and Carbon Emissions of Wind Energy Farms in Thailand

The total expended energy and carbon emissions of 22 wind energy farms over the plant's lifetime were 8,755,010.26 GJ and 4,576,324.89 tCO_2eq, as shown in Table 5 and 6. The embedded energy expended for a wind energy farm in Thailand was 118.92 kJ/kWh and the carbon emission intensity was 62.16 gCO_2eq/kWh. The EROI of wind energy farms ranged from 21.04 for wind farm Q to 44.36 for wind farm E as shown in Fig. 3. It was found that the weighted average EROI based on the installed capacity of 22 wind energy farms in Thailand is 30.64. Likewise, The EROC ranged from 36.94 GJ/tCO_2eq for wind farm Q to 93.72 GJ/tCO_2eq for wind farm E with the weighted average of 59.62 GJ/tCO_2eq. Fig. 4 presents a breakdown of total expended energy and carbon emissions from 22 wind energy farms. It is shown that transportation accounts for the largest share of expended energy, representing 29.64% of total expended energy and foundation contributes a significant part, representing 35.09% of total carbon emissions.

Table 4. The key parameters used for estimating EROI and EROC

Wind Farm	Energy Output Over 25 Years (GJ)	Number of Wind Turbines	Hub Height (m)	Blade Diameter (m)	Mass of Turbine Materials (ton/turbine)				Ocean Shipping Distance (km)	Land Transport Distance (km)
					Structural Steel	Blade	Concrete	Reinforcing Steel		
Wind Farm A	15,407,401.05	45	80.0	101	230.72	10.76	1,317.04	51.28	33,908.3	335
Wind Farm B	12,858,518.93	45	80.0	101	230.72	10.76	1,317.04	51.28	33,908.3	335
Wind Farm C	7,727,691.56	24	85.0	120	248.80	19.46	1662.60	64.67	33,908.3	335
Wind Farm D	11,203,555.50	32	90.0	121	267.95	20.02	1,775.07	69.04	5,165.2	416
Wind Farm E	12,771,797.54	30	80.0	116	230.72	17.32	1,512.64	58.84	5,165.2	365
Wind Farm F	7,290,555.30	25	108.0	112	345.74	15.35	1,971.65	76.69	31,848.8	333
Wind Farm G	6,504,685.74	20	80.0	100	230.72	10.39	1,304.00	50.72	33,849.0	970
Wind Farm H	8,434,864.17	25	80.0	100	230.72	10.39	1,304.00	50.72	33,849.0	970
Wind Farm I	8,166,421.17	25	80.0	100	230.72	10.39	1,304.00	50.72	33,849.0	970
Wind Farm J	11,410,264.35	33	108.0	112	345.74	15.35	1,971.65	76.69	5,165.2	343
Wind Farm K	10,121,496.80	20	127.5	145	445.66	37.31	3,013.46	117.21	5,165.2	314
Wind Farm L	21,819,872.03	30	132.0	136	471.03	29.93	2,926.18	113.82	33,849.0	970
Wind Farm M	21,341,306.70	30	132.0	136	471.03	29.93	2,926.18	113.82	33,849.0	970
Wind Farm N	22,221,921.83	30	134.0	130	482.58	25.63	2,839.46	110.44	35,101.0	354
Wind Farm O	19,493,669.21	30	134.0	130	482.58	25.63	2,839.46	110.44	35,101.0	352
Wind Farm P	6,910,132.05	18	127.5	145	445.66	37.31	3,013.46	117.21	31,848.8	441
Wind Farm Q	6,860,883.60	18	127.5	145	445.66	37.31	3,013.46	117.21	31,848.8	421
Wind Farm R	9,732,498.08	19	127.5	145	445.66	37.31	3,013.46	117.21	31,848.8	367
Wind Farm S	6,869,610.45	16	127.5	145	445.66	37.31	3,013.46	117.21	31,848.8	373
Wind Farm T	6,053,545.44	13	132.0	136	471.03	29.93	2,926.18	113.82	33,849.0	745
Wind Farm U	13,142,738.03	32	127.5	145	445.66	37.31	3,013.46	117.21	31,848.8	382
Wind Farm V	18,698,278.50	30	134.0	130	482.58	25.63	2839.46	110.44	35,101.0	350
Total	265,041,707.98	590								
Weighted average	13,539,637.65	30								

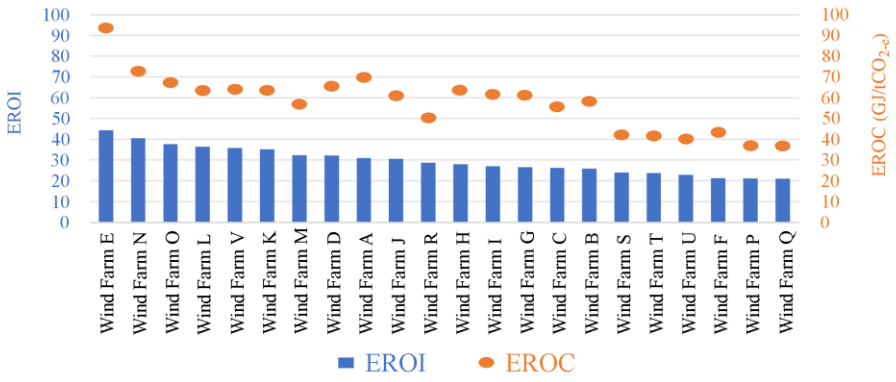
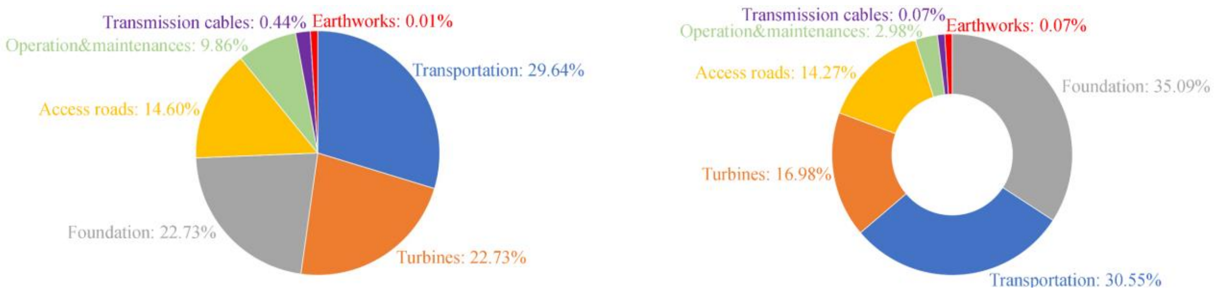


Fig. 3. EROI and EROC of existing onshore wind energy farms in Thailand



4a. The breakdown of the total expended energy

4b. The breakdown of the total carbon emissions

Fig. 4. Breakdown of Thailand large onshore wind energy farm expended energy and carbon emissions

Table 5. Expended energy and EROI of the 22 onshore wind energy farms

Wind Farm	Expended Energy (GJ)							EROI
	Wind Turbine Materials	Foundations	Earth Works	Access Roads	Transmission Cables	Transportation	Operations and Maintenances	
Wind Farm A	118,240.20	90,352.80	49.50	97,497.95	2,909.42	122,448.33	65,812.50	30.98
Wind Farm B	118,240.20	90,352.80	49.50	97,497.95	2,909.42	122,448.33	65,812.50	25.86
Wind Farm C	70,544.43	60,831.36	26.40	51,998.90	1,551.69	74,631.54	35,100.00	26.22
Wind Farm D	96,511.52	86,595.20	35.20	69,331.87	2,068.92	47,377.05	46,800.00	32.13
Wind Farm E	84,594.88	69,180.60	33.00	52,924.44	2,789.40	34,513.24	43,875.00	44.36
Wind Farm F	78,082.11	75,144.75	27.50	54,165.53	1,616.35	96,948.37	36,562.50	21.28
Wind Farm G	52,339.23	39,759.00	22.00	43,332.42	1,293.08	79,506.03	29,250.00	26.50
Wind Farm H	65,424.04	49,698.75	27.50	54,165.53	1,616.35	99,382.53	36,562.50	27.49
Wind Farm I	65,424.04	49,698.75	27.50	54,165.53	1,616.35	99,382.53	36,562.50	26.61
Wind Farm J	103,068.38	99,191.07	36.30	71,498.49	2,133.58	49,477.06	48,262.50	30.54
Wind Farm K	81,611.01	91,880.60	22.00	43,332.42	1,293.08	40,840.20	29,250.00	35.12
Wind Farm L	118,318.52	133,829.10	33.00	45,508.62	1,710.15	255,978.64	43,875.00	36.41
Wind Farm M	118,318.52	133,829.10	33.00	106,265.52	1,508.93	255,978.64	43,875.00	32.34
Wind Farm N	115,624.67	129,862.80	33.00	77,924.70	1,583.32	179,695.73	43,875.00	40.50
Wind Farm O	115,624.67	129,862.80	33.00	46,935.24	2,030.47	179,436.38	43,875.00	37.65
Wind Farm P	73,449.91	82,692.54	19.80	38,999.18	1,163.77	105,075.08	26,325.00	21.08
Wind Farm Q	73,449.91	82,692.54	19.80	38,999.18	1,163.77	103,448.94	26,325.00	21.04
Wind Farm R	77,530.46	87,134.57	20.90	41,165.80	1,228.42	104,561.61	27,787.50	28.66
Wind Farm S	65,288.81	73,376.48	17.60	34,665.94	1,034.46	88,485.52	23,400.00	23.97
Wind Farm T	52,277.56	56,986.41	14.30	28,166.07	840.50	97,977.48	19,012.50	23.71
Wind Farm U	130,577.62	147,008.96	35.20	69,331.87	2,068.92	178,271.94	46,800.00	22.89
Wind Farm V	115,624.67	129,862.96	33.00	60,435.30	2,015.83	179,177.19	43,875.00	35.80
Total	1,990,165.38	1,989,823.94	649.00	1,278,308.43	38,146.16	2,595,042.34	862,875.00	
%	22.73%	22.73%	0.01%	14.60%	0.44%	29.64%	9.86%	
Weighted average								30.64

Table 6. Carbon emissions and EROC of the 22 onshore wind energy farms

Wind Farm	Carbon Emissions (tCO_2eq)							EROC (GJ/tCO_2eq)
	Wind Turbine Materials	Foundations	Earth Works	Access Roads	Transmission Cables	Transportation	Operations and Maintenances	
Wind Farm A	46,889.688	72,863.222	252.000	49,797.337	228.674	39,881.684	10,405.665	69.93
Wind Farm B	46,889.688	72,863.222	252.000	49,797.337	228.674	39,881.684	10,405.665	58.36
Wind Farm C	27,885.868	49,056.426	134.400	26,558.580	121.959	29,176.642	5,549.688	55.80
Wind Farm D	38,061.813	69,833.266	179.200	35,411.440	162.612	19,543.297	7,399.584	65.67
Wind Farm E	33,522.677	55,789.661	168.000	27,031.300	219.240	12,608.840	6,937.110	93.72
Wind Farm F	30,529.751	60,599.115	140.000	27,665.187	127.041	42,984.250	5,780.925	43.44
Wind Farm G	25,945.830	40,078.780	140.000	27,665.187	127.041	32,219.168	5,780.925	61.62
Wind Farm H	25,945.830	40,078.780	140.000	27,665.187	127.041	32,219.168	5,780.925	63.92
Wind Farm I	40,299.272	79,990.832	184.800	36,518.047	167.694	22,016.149	7,630.821	61.89
Wind Farm J10	40,299.272	79,990.832	184.800	36,518.047	167.694	22,016.149	7,630.821	61.08
Wind Farm K	31,669.345	74,095.644	112.000	22,132.150	101.632	26,225.500	4,624.740	63.67
Wind Farm L	45,795.148	107,924.138	168.000	23,243.650	134.413	159,100.922	6,937.110	63.56
Wind Farm M	45,795.148	107,924.138	168.000	54,275.400	118.598	159,100.922	6,937.110	57.01
Wind Farm N	44,692.234	104,725.852	168.000	39,800.250	124.445	108,448.714	6,937.110	72.88
Wind Farm O	44,692.234	104,725.852	168.000	23,972.300	159.590	108,291.465	6,937.110	67.46
Wind Farm P	28,502.410	66,686.080	100.800	19,918.935	91.469	67,332.191	4,162.266	36.99
Wind Farm Q	28,502.410	66,686.080	100.800	19,918.935	91.469	66,286.072	4,162.266	36.94
Wind Farm R	30,085.878	70,390.862	106.400	21,025.542	96.551	66,987.194	4,393.503	50.40
Wind Farm S	25,335.476	59,276.515	89.600	17,705.720	81.306	56,689.233	3,699.792	42.18
Wind Farm T	19,844.564	46,767.126	72.800	14,385.897	66.061	60,872.638	3,006.081	41.74
Wind Farm U	50,670.952	118,553.031	179.200	35,411.440	162.612	114,215.362	7,399.584	40.24
Wind Farm V	44,692.234	104,725.852	168.000	30,867.495	158.440	108,134.317	6,937.110	64.22
Total	777,005.122	1,695,473.972	3,617.600	714,869.490	3,282.776	1,470,161.693	149,379.102	
%	16.98%	35.09%	0.07%	14.27%	0.07%	30.55%	2.98%	
Weighted average								59.62

4. DISCUSSION

Results of this study are shown that wind energy does not produce the highest energy output when compared with other electricity generation technologies. The estimated EROI in this study is in the range of 21.04–44.36, whereas EROI for other energy technologies such as photovoltaics (19–38), oil (10–30), and coal (40–80) [15]. In the literature, many countries have the EROI less than 10 of wind resource available [7] but Thailand has the EROI more than 10. Fig. 5 shows the wind power densities at available lands in Thailand at the same or higher than wind power densities at the 22 existing wind energy farms. New wind energy farms located in these lands can provide the EROI more than 10.

The estimated carbon emission intensity in this study was 62.16 gCO_2eq/kWh for onshore wind energy farms in Thailand, which is tremendously higher than those for wind energy farms in China (16.4–28.2 gCO_2eq/kWh) [17], Italy (8.8–18.5 gCO_2eq/kWh) [4], and New Zealand (7.6 gCO_2eq/kWh) [8]. The study found that carbon emission intensity for the wind energy farms in Thailand is higher than nuclear power plant (10.9–13.9 gCO_2eq/kWh), hydropower (3.1–3.9 gCO_2eq/kWh), and solar photovoltaic (16.0–40.0 gCO_2eq/kWh), but significantly lower than thermal power plant (810–820 gCO_2eq/kWh) and biomass-based power plant (200 gCO_2eq/kWh) [17].

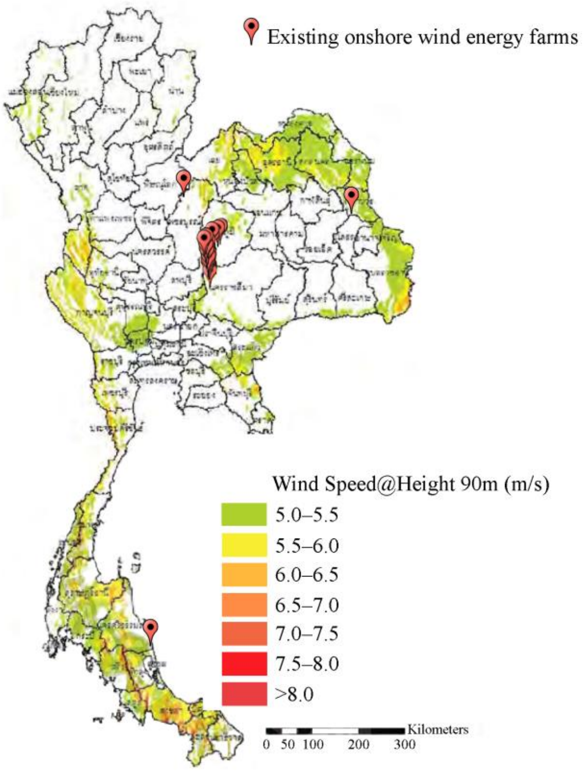


Fig. 5. Wind resource available for new wind energy farms in Thailand. Source: [16]

Transportation is the most expended energy of the 22 wind energy farms because of long ocean shipping distances from manufacturing countries to Thailand. Most of these manufacturing countries are not located in Asia. However, ocean shipping distances of wind energy components tend to decrease because wind turbines are mostly shipped from China. At present, not only Goldwind which is a Chinese wind turbine manufacturer, other manufacturers such as GE, Siemens Gamesa, Vestas already have their distributed factories in China. The shorter ocean shipping distance can result in higher EROI value of wind energy farms. In addition, transport of wind turbines by breakbulks or trains is an option to reduce the environmental impacts in long-distance transportation [18]. Moreover, the use of concrete to build towers of wind turbines onsite instead of steel towers transported oversea can reduce carbon emissions. The reason is that carbon emitted from concrete towers is less than from steel towers [19]. Also, building towers onsite emits carbon less than manufacturing and transporting towers overseas.

Foundation of turbine is responsible for a large share of carbon emissions from the wind energy farms, because of large concrete foundations are used to support wind turbines. The width and depth of a typical gravity foundation used in wind energy farms are 15-20 m and 2-3 m below the ground level [20] and large volumes involved in construction of wind turbine foundations are associated with CO_2 emissions. A previous study by [20] compared the carbon emissions of overdesigned structural concrete with mix design concrete. The comparison showed that the overdesigned structural concrete emitted more than 11% of carbon than the appropriate mix design concrete. This leads to the opportunity to reduce carbon emissions from concrete through selection of materials and mix design.

Selection of recycled concrete and appropriate mix design can minimize the associated emissions with wind turbine foundations without compromising strength of material and performance requirements.

Also, the use of large wind turbines to decrease the numbers of wind turbine installed in a wind energy farm would increase the EROC. The reason is that EROC tends to increase with the size of the wind turbines. Gupta and Hall [21] explains that larger wind turbines can be more efficient because they have larger rotor diameters and can operate at lower wind speeds, that can capture more energy. Also, large wind turbines are taller and can take the advantages of higher wind speeds. Walmsley et al [8] also argued that new technologies of turbine blade enable for large blade diameters that lead to the increasing EROI and EROC values.

5. CONCLUSIONS

The energy expended and carbon emissions over a 25-year life span for 22 existing large onshore wind energy farms in Thailand were estimated. This study presents a comparison of energy and environmental performance of each wind energy farm in terms of EROI and EROC. The results are shown that the expended energy and carbon emissions of the 22 wind energy farms in Thailand over 25 years are 8,755,010.26 GJ and 4,576,324.89 tCO_2eq. The weighted average EROI is 30.64, with the highest is 44.36, while the lowest is 21.04. The weighted average EROC is 59.62 GJ/tCO_2eq, which is in the range of 36.94 GJ/tCO_2eq to 93.72 GJ/tCO_2eq. Transportation of wind turbines from their manufacturing countries to Thailand represents the most expended energy whereas concrete foundation for wind turbine contributes to the largest share of carbon emissions. This study suggests that the energy and environmental performance of wind energy farms can be improved by reducing ocean shipping distances and minimizing the size of concrete foundation.

6. LIMITATIONS AND RECOMMENDATIONS FOR FURTHER STUDIES

The calculation in this study excluded the energy expended and carbon emissions of substations of wind energy farms, main substations of Provincial Electricity Authority of Thailand (PEA), and transmission cables connecting wind energy farms to the main substations. The reason is that the transmission cables and the substations are used not only for wind energy farms but also for other electricity sources. Breakdown of the use of transmission cables and substations for wind energy farms and other electricity sources requires data from PEA. These data are confidential and cannot collect from the relevant sources. Moreover, decommissioning was not addressed in this study because decommissioning of wind energy farms in Thailand has not been prescribed in power purchasing agreements between EGAT and power producers owning the wind energy farms.

This study provides the implication for developers of wind energy farms in Thailand and would also adapt to other countries. Developers can apply details of engineering designs for construction of wind energy farms with the calculation tool used in this study to estimate the EROI and EROC. The use of data obtained from engineering designs in details can result in more accurate EROI and EROC. $E_{generation}$ over a plant's lifetime can be predicted by using energy yield analysis software such as Openwind, WindFarmer, and WindSim. However, the inputs required by the software are details of wind energy farms. The software requires data that is commercial in confidence, such as the exact location of each wind turbine, specification of wind turbines, that developers can access from engineering designs.

In addition, the calculation can be used to assess the carbon emissions during the development phase of new wind energy farms. Developers can include carbon emission impact assessment into the Environmental Impact Assessment (EIA) of wind energy farms for adding a new dimension to the EIA. In order to echo the national power development plan regarding carbon neutrality, carbon emission impact assessment should be included in an investment decision-making process for new wind energy farms.

REFERENCES

[1] Manton, M.J.; Della-Marta, P.M.; Haylock, M.R.; Hennessy, K. J.; Nicholls, N.; Chambers, L.E.; Collins, D.A.; Daw, G.; Finet, A.; Gunawan, D.; Inape, K.; Isobe, H.; Kestin, T. S.; Lefale, P.; Leyu, C.H.; Lwin, T.; Maitrepierre, L.; Ouprasitwong, N.; Page, C.M.; Pahalad, J.; Plummer, N.; Salinger, M.J.; Suppiah, R.; Tran, V.L.; Trewin, B.; Tibig, I.; and Yee, D. 2001. Trends in extreme daily rainfall and temperature in Southeast Asia and the South Pacific: 1961–1998. International Journal of Climatology 21: 269-284.

[2] United Nations Framework Convention on Climate Change (UNFCCC). 2021. Thailand Mid-century, Long-term Low Greenhouse Gas Emission Development Strategy. Retrieved March 23, 2022 from https://unfccc.int/documents/307950.

[3] Pattanapongchai, A.; Limmeechokchai, B.; Matsuoka, Y.; Kainuma, M.; Fujino, J.; Akashi, O.; and Motoki, Y. 2011. Subsidy for Clean Power Generation and CO_2 Mitigation in Thailand: The AIM/Enduse Modeling. GMSARN International Journal 5(3): 189-194.

[4] Ardente, F.; Beccali, M.; Boyle, M.; Cellura, M.; and Brano, V.L. 2008. Energy performances and life cycle assessment of an Italian wind farm," Renewable and Sustainable Energy Reviews 12(1): 200-217.

[5] Hall, C.A.S. 2017. Energy Return on Investment: A Unifying Principle for Biology, Economics, and Sustainability. Cham, Switzerland: Springer International Publishing.

[6] Diesendorf, M.; and Wiedmann, T. 2020. Implications of Trends in Energy Return on Energy Invested (EROI) for Transitioning to Renewable Electricity. Ecological Economics 176:1-8.

[7] Dupont, E.; Koppelaarb, R.; and Hervé, J. 2018. Global available wind energy with physical and energy return on investment constraints. Applied Energy 209:322-338.

[8] Walmsley, T.G.; Walmsley, M.R.W.; and Atkins, M.J. 2017. Energy return on energy and carbon investment of wind energy farms: A case study of New Zealand. Journal of Cleaner Production 167(20): 885-895.

[9] Woo, J.; Kim, H.; Kim, B.; Peak, I.; and Yoo, N. 2012. AEP Prediction of a Wind Farm in Complex Terrain - WindPRO Vs. WindSim. Journal of the Korean Solar Energy Society 32(6):1-10.

[10] Rule, B.M.; Worth, Z.J.; and Boyle, C.A. 2009. Comparison of life cycle carbon dioxide emissions and embodied energy in four renewable electricity generation technologies in New Zealand. Sci. Technol 43: 6406–6413.

[11] STS Engineering Consultants and Infra Plus. 2016. The executive summary report on a carbon footprint development project for construction and maintenance of high way. Retrieved March 23, 2022 from http://km.doh.go.th/doh/uploads/Knowledge/21334/t53aqr9ibdbfppsslo1drq1i42_Summary_Th.pdf.

[12] Fernado, A.T.D. 2019. Embodied energy analysis of New Zealand power generation systems (Master of engineering). University of Canterbury, Christchurch, New Zealand.

[13] Thailand Greenhouse Gas Management Organization (Public Organization). 2021. Carbon emission factors in industry. , [Online]. Retrieved March 23, 2022 from http://thaicarbonlabel.tgo.or.th/admin/uploadfiles/emission/ts_b934985782.pdf.

[14] Thailand Greenhouse Gas Management Organization (Public Organization). 2019. Thailand volunrary emission reduction program: 2x12 MW Lamtakhong wind turbine generators, monitoring report. Retrieved March 23, 2022 from http://ghgreduction.tgo.or.th/th/tver-database-and-statistics/t-ver-registered-project/download/2122/969/123.html.

[15] Raugei, M.; Fullana-i-Palmer, P.; and Fthenakis, V. 2012. The energy return on energy investment (EROI) of photovoltaics: Methodology and comparisons with fossil fuel life cycles. Energy Policy 45: 576-582.

[16] Promsen, W. 2011. Development of Wind Maps for Thailand by Using Atmosheric Mesoscale Model. PhD Dissertation, Graduate School, Silpakorn University, Bangkok, Thailand.

[17] Li, Q.; Duan, H.; Xie, M.; Kang, P.; Ma, Y.; Zhong, R.; Gao, T.; Zhong, W.; Wen, B.; Bai, F.; Vuppaladadiyam, A.K. 2021. Life cycle assessment and life cycle cost analysis of a 40 MW wind farm with consideration of the infrastructure. Renewable and Sustainable Energy Reviews 138: 1-12.

[18] Wang, Y.; and Sun, T. 2012. Life cycle assessment of CO_2 emissions from wind power plants: Methodology and case studies. Renewable Energy 43: 30-36.

[19] Tremeac, B.; and Meunier, F. 2009. Life cycle analysis of 4.5 MW and 250 W wind turbines. Renewable and Sustainable Energy Reviews 13(8): 2104-2110.

[20] Berndt, M.L. 2015. Influence of concrete mix design on CO_2 emissions for large wind turbine foundations," Renewable Energy 83: 608-614.

[21] Gupta, A.K.; and Hall, C.A.S. 2011. A review of the past and current state of EROI data. Sustainability 3: 1796-1809.