ERJ
Engineering Research Journal
Faculty of Engineering
Minoufiya University

AIRBORNE EMISSIONS FROM WIND TURBINES AND PHOTOVOLTAIC LIFE CYCLES

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ABSTRACT

Atmospheric emissions occur mainly in the operational phase of the oil cycle. In case of renewable energy sources, emissions occur mainly in the material processing and component manufacturing stages of wind turbine life cycle. For this purpose material and energy use for a typical wind energy converter HSW-250 are determined. In case of photovoltaic energy production, devices have no moving parts, in contrast to thermal power systems, so, they have demonstrated long-term reliability in both space and terrestrial applications. They could be widely applied in Egypt particularly in remote areas where reliable and maintenance-free operation is at a premium. Airborne emissions occur mainly during the manufacturing phase of PV modules and system components. In this research the system features, system technology, photovoltaic life cycle, material and energy used during the life cycle stages were analyzed. Finally the airborne emissions through the PV life cycle were obtained. Quantities of atmospheric emissions released in the PV life cycle stages have been calculated. Results show that the predominant share of emissions is caused by activities during the material processing and module production stages. Airborne emissions from PV life cycle were calculated in detail.

تنشأ الانبعاثات الجوية الضارة بطريقة رئيسية عن دورة استهلاك الوقود النفطي. أما في حالة مصادر الطاقة المتجددة، فإن هذه الانبعاثات تنشأ أثناء مراحل تصنيع المواد والآلات المستخدمة في تأنيس طاقة الرياح، وإعادة تدوير معداتها. ولهذا الغرض، تم في هذا البحث دراسة المواد واستخدام محول طاقة الرياح من نوع HSW-250.
أما في حالة التوليد الضوئي الفولطي من طاقة الشمس فإن المعدات اللازمة ليس بها أجزاء متحركة، وذلك بالمقارنة بنظم الطاقة الحرارية، ولهذا السبب نجد أنها تتمتع باعتمادية عالية طويلة الأمد في الاستخدامات المختلفة بنوعيها: الفضائية والأرضية. ويمكن استخدام طريقة التوليد الضوئي الفولطي هذه على نطاق واسع في مصر، خصوصا في المناطق النائية حيث تظهر قيمة التشغيل عالى الاعتمادية وعديم الحاجة إلى الصيانة. ومن المعلوم أن الانبعاثات الضارة لا تنشأ إلا أثناء مراحل تصنيع المواد اللازمة لمكونات الوحدات المستخدمة في التوليد الضوئي الفولطي.

ويتم في هذا البحث دراسة التوليد الضوئي الفولطي وتحليل ملامح نظمه، وتقانات إنتاجه، ودورة حياة معداته، والمواد والطاقة المستخدمة في دورة حياة معداته، كما تمت دراسة الانبعاثات الضارة طوال مدة الحياة المشار إليها، وحساب كمياتها بالتفصيل.
وقد خلصت الدراسة إلى أن الجزء الأعظم من هذه الانبعاثات ينشأ في مراحل تصنيع المواد اللازمة لمكونات الوحدات المستخدمة في التوليد الضوئي الفولطي.

1. INTRODUCTION

Egypt has already crossed the phase of demonstration and pilot projects to the actual implementation of large scale wind farms. The first small scale wind farm of 5 MW was installed at Hurghada, on the Red Sea coast. It was intended as a pilot wind farm. It contains different designs and sizes of wind turbines ranging from 100-300 kW and is operating successfully [1].This wind farm is connected to the local distribution network of the city. A lot of experience is gained in erection, operation, and maintenance of this wind farm. The project is under expansion to increase the contribution of environment-friendly energy to satisfy the energy demand of tourist- villages. The first large scale wind farm connected to the national grid was installed at Zaafarana, on the Gulf of Suez, on several phases. The first phases are now in action, with capacities of 63, 77, and 80 MW. These phases were supported by the Danish, German and Spanish governments, in addition to 320 MW expected to be finalized by the end of 2008 supported by the Japanese, German and Danish governments. On the third phase the capacity reached 135 MW, funded by Germany and Japan. The Total installed capacity of Zaafarana wind farm will reach 545 MW, In addition to about 200 MW planned to be privately financed through the "Build, Operate, Transfer" (BOOT) system.

The Hurghada Wind Farm, selected as the reference location, offers the possibility to examine one homogenous technology. The technical data of the

the front with anti-reflection painting and an Al-coated Tedlar foil for the back side are used. Finally, frames and junction boxes are integrated.

3.1.3. Materials used for system components

Due to the typical system structure, the material quantities used for mounting, cabling and power conditioning can be accurately estimated. The following materials have been used in the reference plant "SERRE 3.3 MWp PLANT". The component weights per kWp are:

- Mounting: Photovoltaic field consisting of 9 identical sub-fields with mono-crystalline silicon modules mounted on a galvanized steel support structure (modular) designed for various types of land and need a high level of shop prefabrication, thus limiting on-site erection work. Using data from Table 10, the materials used for mounting is 212 kg/kWp steel, 600 kg/kWp cement, and 1200 kg/kWp aggregates.
- Cabling: Two different types of cables are mainly used. The wiring cables are used for the connection between modules and parallel strings board while cable ducts are for connecting the parallel strings board with the direct current boards. For a typical 3.3 MWp plant 450 m wiring cables and 45000 *m* cable ducts were specified. Material-required are 10818 kg copper and 535 kg PVC.
- Power Conditioning: The inverter with integrated supervision, control and protection is the main component used. Low and high frequency transformers are commonly used for galvanic separation from the grid. The materials required for high frequency transformation are negligible. Furthermore, junction boxes, measurement equipment and power switches have to be taken into account. The energy consumption for this power conditioning system is calculated as follows: **60.7 *kWh/kWp*** electrical energy, **145.1 *kWh/kWp*** fuel and **23.8 *kWh/kWp*** non-energy consumption [2].
- Foundation: Average foundation weight for large-scale power generation system is **1780 *kg/kWp*** (**600 *kg/kWp*** cement and **1200 *kg/kWp*** aggregates).

3.2 Photovoltaic Life Cycle

As any other energy system, analyzing the complete life cycle, Photovoltaic is not entirely free of environmental impacts. However, compared to conventional energy systems, its main environmental impacts do not occur at the operating stage, where photovoltaic is almost entirely benign, but take place during component production.

The full PV life cycle has the following stages:

Resource extraction, resource transportation, material processing, module production, component manufacturing, module & component transportation, PV construction & operation, decommissioning, and product disposal

Analysis of energy use and emissions of most of the major air pollutants (particularly carbon dioxide, sulphur dioxide and oxides of nitrogen) are discussed. Emissions are expected to be broadly proportional to the energy consumed during the aforementioned stages.

Resource extraction

The same procedure as mentioned in wind energy section is adopted considering total material weights of 7105 tonnes and the life time energy output of 198 GWh. Heat, electric, and total emissions per kWh due to resource extraction are shown in Table 7.

Transportation

There are no special features for the transportation of PV silicon modules and system equipment. The material to be transported is not dangerous (no fuel etc.) and damaged modules could be considered as normal waste in the case of accidents. The transportation costs are related to the volume and weight, where the most preferable means of transportation are Lorries.

The total material weight of the assumed plant is **7105 *tonnes***. A distance of **100 *km*** is a representative value for transportation from the production point to the reference location. As discussed before, emissions due to the transportation related to PV plant life time output are: **0.281 *g/MWh*** SO_x, **0.842 g/MWh** NO_x, **0.062 g/MWh** TSP, and **0.281 *kg/MWh*** CO_2. The same emissions are representative for the transportation of resources.

Emissions due to component processing

The primary energy used for the production of each material per kWp is calculated. The same procedure is used to determine emissions due to system components processing. To standardize the emissions to a unit output of electricity, emissions are related to the expected electricity production during the life time of the reference system. The results are shown in Table 8.

Emissions due to module production

Table 9 shows the material release into the atmosphere for mono-crystalline silicon during the production of the PV modules [2]. At present, the impacts of these materials are not clearly quantifiable. A partial characterization of the materials is described by Hagedorn et al [6]. The specific energy consumption (SEC) considers the process energy and auxiliary energy for the several steps. The cumulated energy (CE) includes all processes, starting with exploitation and preparation of raw materials, process energy, cumulated energy of input materials and production equipment. Table 9 shows atmospheric emissions due to module production.

Installation

The expenditure for installation needs about 8 man-days which mainly include preparation work for the mechanical integration and electrical installation. These data are based on information from PV installation companies.

Operation

The simple structure of the systems and the total absence of rotating parts, fuel, and material for preventive maintenance characterize the operation phase of the PV energy supply. In spite of the simplicity of the PV system structure, different failures occur during the operation of these PV plants. The main reason is that the system technology is still in the prototyping stage. Mismatch and technical deficiencies are typical in products that have not been produced in series.

Maintenance

Maintenance operations on PV modules are only Preventive maintenance and cleaning from dust precipitation. The PV electrical installations are correspondent with typical electrical installations, and, therefore, require very low maintenance. Furthermore, industrial power electronics are almost maintenance free throughout their whole life cycle.

Waste disposal

Photovoltaic modules are not recycled today as the quantities are not large enough. Special burdens when recycling PV silicon cells are not expected. The PV module consists mainly of silicon, glass, and frame material. The waste modules can be considered as a valuable material for re-use with a high degree of purity. During operation the PV modules are exposed to hard environmental conditions and therefore require a very compact construction. This makes the separation of the materials relatively difficult. There will be many improvements in the recycling concepts and technologies in the future.

3.2.1 Airborne emissions from the PV life cycle

In the present study, it has been assumed that fossil and hydropower energies available in Egypt are used for the production of photovoltaic solar energy system. Quantities of atmospheric emissions released in the PV life cycle stages have been calculated. Results show that the predominant share of emissions is caused by activities during the material processing and module production stages. Figure 2 illustrates emission factors per unit PV output, which were obtained from the present study on PV life cycle. Total emissions during life cycle are used for the quantitative evaluation of PV externalities, and for comparison with other electric energy production technologies.

4. CONCLUSION

In the present study, quantities of atmospheric emissions released in the WEC life cycle stages have been calculated. Results show that the predominant share of emissions is caused by activities during the material processing and component manufacturing stages. It has been assumed that fossil and hydropower energies available in Egypt are used for the production of wind energy and photovoltaic solar energy systems. Quantities of atmospheric emissions released in the PV life cycle stages have been calculated. Results show that the predominant share of emissions is caused by activities during the material processing and module production stages. Airborne emissions from PV life cycle are 126.142 g/MWh SO_x, 115.603 g/MWh NO_x, 7.457 g/MWh TSP and 68.6 kg/MWh CO_2, while airborne emissions from WEC life cycle are 19. 575 g/MWh SOx, 62.761 g/MWh Nox, 2.074 g/MWh TSP and 18.06 kg/MWh CO_2.

REFERENCES

[1] "Egypt's Renewable Energy strategy and Programs", the Renewable Energy and Sustainable Development Seminar, New and Renewable Energy Authority (NREA), Cairo, 26-27 may, 1997.

[2] F. Raptis and F. Kaspar, "Assessment of the External Costs of the Photovoltaic and Wind Energy Life Cycle", Prepared for the Commission of the European Union DGXII in the frame of the contract JOU2-CT-0264, August 1995.

[3] Ibrahim Abd El-Gillil, "Industrial Energy use in Egypt", Organization of Energy Planning, June 1992.

[4] (OECP) "Energy in Egypt "Organization for Energy Conservation and Planning", Yearly Report. (1994-1997).

[5] A. Iliceto, R. Vigotti, "The Largest PV installation in Europe: Perspectives of Multi-Megawatt PV", World Renewable Energy Congress-V, 20-25, Florence, Italy, Sept. 1998.

[6] Hagedorn, G.; Hellriegel E.: Forschungsstelle ftir Energiewirtschaft, Munchen; Forschungszentrum Julich; umweltvorsorgeprufung bei Forschungsvorhaben-Am Beispiel von Photovoltaik-Band S: Umweltrelevante Stoffstrome bei der Herstellung Verschiedener Solarzellen; BMFT-Vorhaben 426-3590-PU 14120, Jun-1992.

[7] El-Kordy, M. N., "Environmental impact in the Evaluation of Using Renewable Energy Systems", Ph.D. Thesis, Faculty of Engineering, Al-Azhar University, 1999.

Table 1: Technical Data of "HSW 250" WEC [2]

Technical data of the " HSW 250 " WEC, [HSW, GERMANY]	
Rotor Diameter Number of blades Rated speed Speed range Position in related to tower	 25 M 3 39.3 rpm 26.2 - 39.3 rpm Up - wind
Rotor blade Airfoil Material	 NACA4424-18 Glass-fibre reinforced plastic (GRP)
Generator Type Rated output Rated voltage Rated frequency Rotational speed	Induction machine 3-phase, 4/6 pole 67.5/250 kW 380/220 V 50 Hz 1000/1500 rpm
Yaw system	Automatic wind direction control via Slewing ring worm
Tower Material Height Diameter	 Steel (bolted pipes segments) 27.3 m 1.2/2.4 m
Power characteristics Rated power Cut-in wind speed Rated wind speed Cut-out wind speed Maximum wind speed	 250KW 4m/s 14m /s 23M/s 60 m/s
Concept	Parallel operation with the grid
Energy data Estimation over life time	Assuming 3000 hr/yr 22.5 GWh
Life time	30 yr
Control system Aerodynamic Electrical	Stall Thyrosoft - controller
Safety devices	Hydraulic brake system (disc-brake on the slow and on the generator side)

Table 2: Emissions per (MWh) Of WEC Due To Resource Extraction

Emissions source	**SOx** (g/MWh)	**NOx** (g/MWh)	**TSP** (g/MWh)	**CO_2** (kg/MWh)
Heat energy	0.48	0.3	0.05	0.125
Electric energy	0.035	0.161	0.004	0.045
Total	**0.515**	**0.461**	**0.054**	**0.170**

Table 3: Emission Factors for the Production of 1 MWh Electrical and Heat Energy in Egypt

Energy	Primary energy (kWh)	Efficiency %	SOx (g)	NOx (g)	TSP (g)	CO_2 (kg)
Heat mix	1291	0.775	1155	760	110	308
Power mix	2273	0.44	314	1423	36	399

Table 4: Emissions Due To Material Processing Stage

Material	SO_x (g)	NO_x (g)	TSP (g)	CO_2 (kg)
Aggregates	138.27	119.35	11.68	42.52
Aluminium	10018.21	8647.8	846.41	3080.96
Cement	7761.91	6700.15	655.78	2387.07
Copper	4359.06	3793.86	371.33	1351.64
Steel	91408.27	78904.43	7722.85	28111.38
GRP	38691.22	45507.04	3785.34	15513.73
Plastic	5021.26	5905.8	491.25	2013.34
Total per WEC	**157434.2**	**149578.43**	**13884.65**	**52500.66**
Total per (MWh)	**7**	**6.65**	**0.62**	**2.33**

Table 5: Emissions Due To WT Component Manufacture Stage

Sox (g/MWh)	NOx (g/MWh)	TSP (g/MWh)	$C0_2$ (kg/MWh)
12	55	1.4	15.5

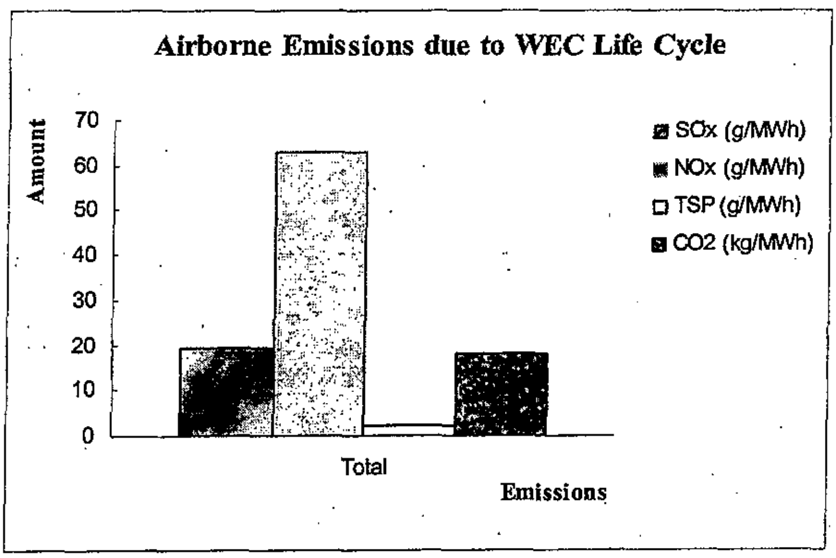

Fig.1 Airborne Emissions from WEC Life Cycle

Table 6: Technical Data of "Serre 3.3 MWp" Plant, Direct Current Grid Connected

SERRE PLANT MAIN FEATURES [6]		
Peak power	3.3	(MWp)
Yearly producibility	1830	(kWh/kWp)
Life time	30	yr
Yearly producibility Estimation over lifetime	6.03 180.9	(GWh) (GWh)
Plant total area	70000	(m^2)
Modules area	30000	(m^2)
Number of modules	66000	
Amount of excavated ground	50000	(m^3)
Support structure weight	700	(tons)
Foundation volume	2600	(m^3)
Foundation weight	1780	(kg/kWp average)

Table 7: Emissions per (KWh) of PV Plant due to Resource Extraction

Energy	SO_x (g/MWh)	NO_x (g/MWh)	TSP (g/MWh)	CO_2 (kg/MWh)
Heat Electricity	6.9 0.5	4.3 2.4	0.7 0.1	1.825 0.6605
Total	**7.4**	**6.7**	**0.8**	**2.4855**

Table 8: Emissions due to System Component Processing

Material	SO_x (g)	NO_x (g)	TSP (g)	$C0_2$ (kg)
Aggregates	8.2961	7.8607	0.8021	2.8348
Cement	465.7146	441.2687	45.0294	159.1348
Copper	20.7403	19.6516	2.0054	7.0870
Steel	741.6238	702.6952	71.7067	253.4131
PVC	12.2283	14.3825	1.1964	4.9031
Power Cond. (power mix)	19.0575	86.3657	2.1849	24.2163
Power Cond. (heat mix)	167.5025	110.2181	15.9526	44.6673
Total per kWp	**1435.1632**	**1382.44**	**138.8775**	**496.2565**
Total per MWh	**26.1804**	**25.2187**	**2.5334**	**9.0528**

Table 9: Atmospheric Emissions due to Module Production

	SO_x (g)	NO_x (g)	TSP (g)	CO_2 (kg)
Modules: electric Energy	1549.8	2007.6	218.4	2356.2
Modules: fuel use	3500	2500	?	747.1
Total per (kWp)	**5049.8**	**4507.6**	**218.4**	**3103.3**
Total per (MWh)	**92**	**82**	**4**	**56.5**

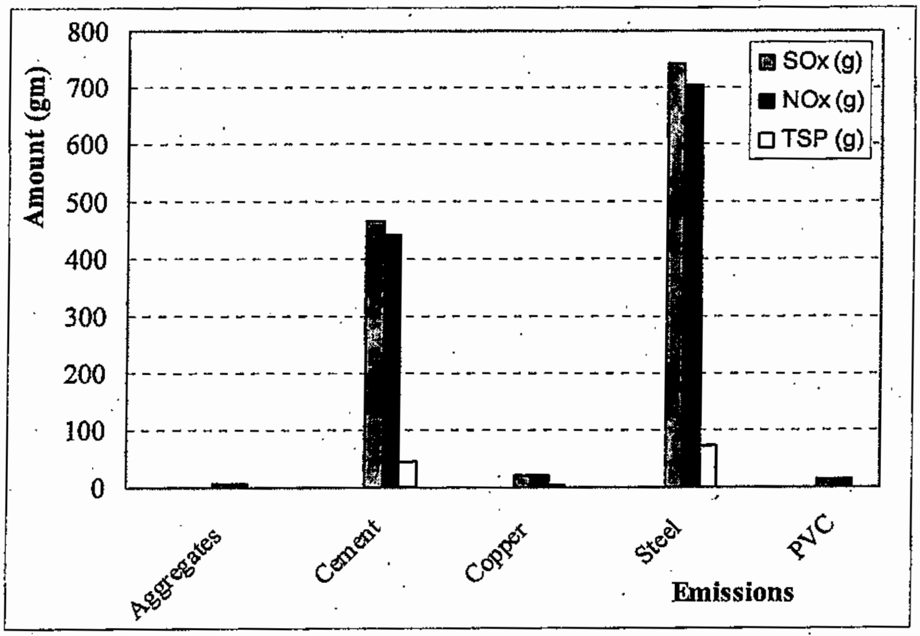

Fig. 2 Airborne Emissions due to PV life cycles