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RENEWABILITY AND LIFE CYCLE ENERGY EFFICIENCY OF PHOTOVOLTAIC SYSTEMS: ASSESSING THE IMPLICATION OF SOLAR RADIATION AND CONVERSION EFFICIENCY ON ENERGY DISPLACED

SAULES BATERIJU SISTĒMU ATJAUNOJAMĪBA UN ENERGOEFEKTIVITĀTE: SAULES ENERĢIJAS SAULES RADIĀCIJAS UN KONVERSIJAS EFEKTIVITĀTES NOVĒRTĒJUMS

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Introduction

Renewable energy sources such as solar, wind, hydro and biomass may play a significant role the sustainable energy development of energy supply in the future due to the minor impacts they are expected to have on the environment and their high technical potential.

Photovoltaic systems cause no emissions during their use. Nevertheless, as with any other industrial product, photovoltaic systems hold expenditures for materials and energies in regards to production and thus affect the environment. In order to better analyze the energy and environmental profile of such systems, the system boundaries need to be expanded, taking into account also the “hidden impact” related to production, transport and disposal.

This paper uses life cycle assessment (LCA) technique to derive a complete and extended energy and environmental profile of amorphous silicon (a-Si) photovoltaic system. The investigation is focused on the question, whether the national differences of the electricity supply within Nordic and Baltic countries have an effect upon the results of an ecological assessment of a photovoltaic system.

Considering the use of photovoltaic system in the different countries attention is paid not only to country-specific irradiation conditions, but also to different substitution of the primary energy, as well as the related avoidance of greenhouse gas emissions.

In order to give a round picture in respect to differences within Baltic and Nordic countries, three countries are chosen, which fulfill the following requirements:

- Great importance for the use of renewable energy
- High/medium national overall efficiencies of electricity supply and
- Medium/low Carbon dioxide emission factors.

This leads to the selection of Latvia, Finland and Denmark in reference to the use of photovoltaic systems.

Methodology

In order to achieve the goal mentioned above, the life cycle assessment (LCA) methodology is used. The LCA methodology allows to assess the potential environmental impacts of a product or service during its whole life cycle [1]. Life cycle assessment methodology is ruled by ISO 14040 standards. A LCA study contains four steps: 1) Goal and scope definition; 2) Inventory analysis; 3) Impact assessment; and 4) Interpretation of results. Detailed data on photovoltaic production are gathered from literature. Background inventory data are mainly based on ecoinvent [2]. The modelling is facilitated using the LCA software Simapro 7.0 [3]. Given the complexity of the system studied and the wide range of material involved in the analysis, a streamlined life cycle assessment has been applied to an 8 kW_p amorphous photovoltaic system. The results are reported in terms of energy consumption and CO_2 emissions. One additional parameter namely "energy pay back ratio" is used in this paper. This parameter compares the energy consumed over the whole life cycle with the energy generated during operation.

Goal and scope

The purpose of this study is to answer the question identified in the Introduction: "Do the national differences of the electricity supply within Nordic and Baltic countries have an effect upon the results of an ecological assessment of photovoltaic systems". To make the result comparable with other studies, the functional unit for this life cycle assessment is the production of 1 kWh of electricity at low voltage.

The execution of the LCA will adhere to the protocols defined in the standard ISO 14040-14043 [4] concerning definition and selection of relevant parameters. This means that the scope has been defined in enough details to assure that quality, quantity, and details are consistent and adequate to the goal defined. The LCA will profile and assess the resource consumption and emissions generation from material production to disposal of photovoltaic module. The focus is on energy use and climate change although other impact categories such as acidification, eutrophication, photo-oxidant formation, human and ecotoxicological impacts might be also important.

Life cycle inventory

Module production

The cell materials include silicon and contact metal. The life cycle energy and emissions for producing and purifying silicon are taken from literature. All module components other than the cell materials (glass, EVA, wires, tapes, cords, and containers) are categorized as encapsulation; these components comprise more than 90% of module materials. The energy used and emissions generated during the module production are modeled using Simapro software.

Module manufacturing

The manufacturing of photovoltaic module includes film deposition, etching, cleaning, and module assembly. Sulfuric acid or nitric acids are used for etching and cleaning. In addition to chemicals, water and electricity are also used during manufacturing. Water is used for etching and cleaning, while electricity is used for module assembly. The water from tape and the electricity mix in ecoinvent are used in the inventory.

Balance of the system (BOS)
The balance of the system comprises equipments such cabling, interconnection components, mounting materials, an inverter, and protection devices [5]. The balance of system energy and emissions are modeled using Simapro software.

Transportation
Trucks are used for the transport of photovoltaic module from the manufacturing site to the point of use. The modeling assumes a round trip of 1200 km from manufacturing site to the point of use. It is further assumed that the photovoltaic system considered in this study is land filled at the end of its technical life time without any material or energy recovering process. The distance between the point of use and landfill is 40 km. The inventory assessment for the transportation subsystem includes the energy required and emissions generated for the transportation of photovoltaic by trucks. The trucks use diesel as fuel source and, as for the module production and manufacturing energy and emissions are modeled using Simapro software.

Summary of the evaluated system

Table 1 summarizes some key characteristics of the conceptual amorphous silicon (a-Si) grid-connected photovoltaic system, laminated directly onto standard galvanized aluminum standing seam roofing panels in Riga (Latvia; latitude: 57° N , yearly average global insolation on a horizontal plane: 900 kWh/m^2/yr)[6].

Table 1.

Main characteristic of the evaluated systems

Life cycle component		**Reference**
PV cell type	a-Si	[7]
Module efficiency	7%	assumption
Module area	120 m^2	assumption
Module encapsulation	Glass-Tedlar	[7]
Module frame	Aluminum	[7]
Module weight	*1290 kg*	calculated
Inverter weight	*32 kg*	calculated
Wiring	*20 kg*	calculated
System size output	*8 kW$_p$*	[7]
System lifetime	*30 years*	[7]

Life cycle inventory results

Table 2 reports the overall life cycle inventory (LCI) of the main inputs and emissions for 1 kWh electricity produced

Table 2.

Life cycle inventory of the main inputs and emissions

Life cycle component		Energy (kJ/kWh_{el})	Emissions ($g\ CO_2\ eq/kWh_{el}$)
PV modules	Materials and manufacturing	286.82	16.98
	Engineering and Administration	101.71	5.79
Balance of System (BOS)	Inverters	10.05	0.72
	Wiring	5.07	0.34
Installation		42.71	3.12
Operation and maintenance		34.44	2.81
Decommissioning and disposal		4.27	0.35
Total Life Cycle Energy Input		**485**	**30**

Life cycle impact assessment

Energy performance and greenhouse gas emissions assessment.
<u>Energy consumption at different stages</u>

The energy consumption at diffirent stages of life cycle of the a-Si photovoltaic module is shown is Figure 1. As it can be seen in Figure 1, most of the energy is consumed during photovoltaic material production and manufacturing which consumed nearly 273 kJ/kWh. Encapsulation and processing represent 72% of PV material production and manufacturing energy consumption.

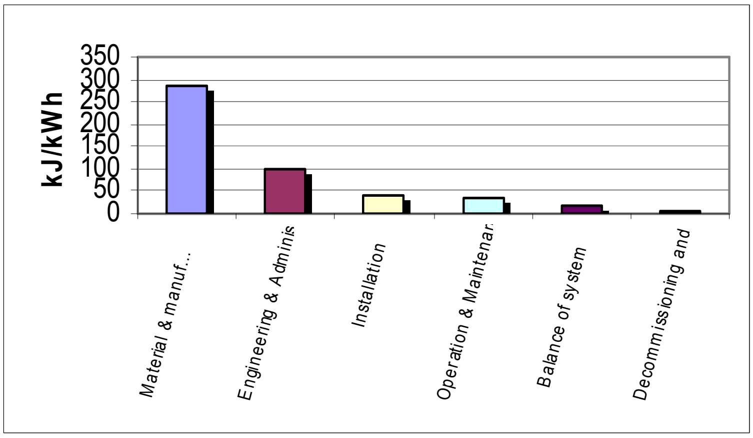

Figure 1. Life cycle energy consumption for an 8 kW_p a-Si system

Energy payback ratio

The energy payback ratio is the ratio of the total energy produced during a system's normal lifespan, by the energy required to build, maintain and fuel it. The energy payback ratio is calculated by dividing the total amount of energy generated by the photovoltaic during it life span by the total amount of energy used to manufacture a module from raw material, install and operate it over its life time.

The energy pay back ratio of the investigated a-Si photovoltaic is 7.2. This energy payback ratio is limited by the module's 7% conversion efficiency.

Depending on PV location, cell technology, conversion efficiency, solar radiation and the effect of probable future improvement in production technology, the energy payback ratio could rich 17 as shown in Figure 2

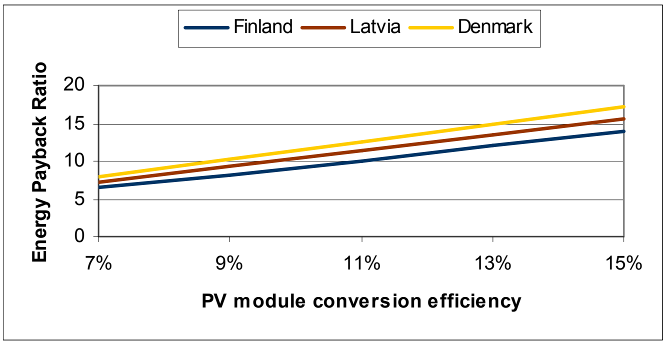

Figure 2. Effect of conversion efficiency and insolation on PV energy payback ratio

Greenhouse gas emissions

The greenhouse gas emitted during the studied life cycle stages are measured as an equivalent of CO_2 using an integrated time horizon of 100 years. CML characterization factors for the direct global warming potential of air emissions are the basis of this calculation [8]. The life cycle greenhouse gas emission is 30 g CO_2 equ/kWh which is relatively low in comparison with other energy options that have a large application potential.

Figure 3 shows the emission of greenhouse gas by stage. Photovoltaic material production and manufacturing account for 56%, engineering and administration 18%, installation 10% operation and maintenance 9% of the life cycle CO_2 emissions respectively.

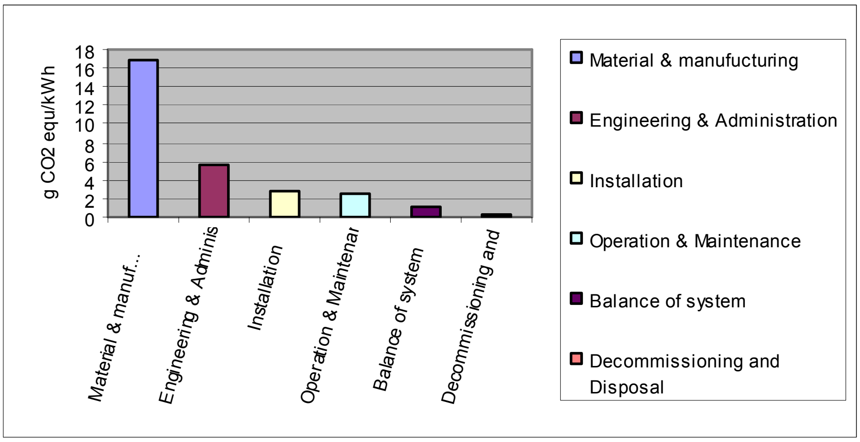

Figure 3. Life cycle greenhouse gas emissions factor for an 8 kW_p a-Si system

Future improvement in photovoltaic conversion efficiency will reduce the greenhouse gas intensity for production of electricity from photovoltaic as shown in Figure 4.

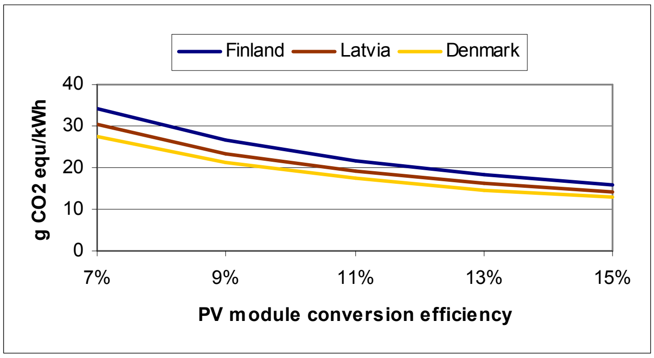

Figure 4. Effect of conversion efficiency and insolation on the greenhouse gas emission factor

Environmental benefits

Environmental benefits are evaluated here in terms of fossil energy displaced and avoided emissions of CO_2.

Primary energy displaced

To calculate the primary energy displaced by the output energy from photovoltaic, the efficiency of the electricity production and transmission were assumed to be 28, 30, and 32 % in Latvia, Finland and Denmark respectively. As it is shown in Figure 5, the use of photovoltaic results in highest primary energy substitution in Latvia.

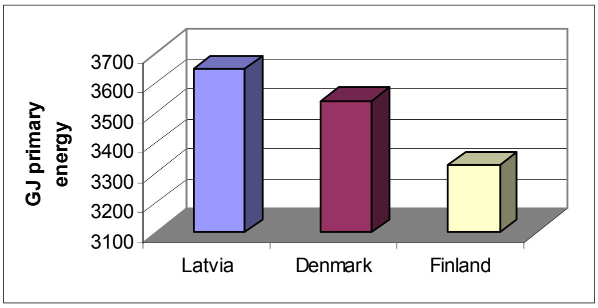

Figure 5. Primary energy displaced by the use of a-Si photovoltaic power system in the selected countries

Avoided greenhouse gases emissions

The avoided emissions of carbon dioxide have been calculated using the average Danish, Finnish and Latvian carbon dioxide equivalent intensity for electricity generation emission factor of 450, 200, and 190 g CO_2 equ/kWh respectively [9]. As shown in Figure 6, the use of a-Si photovoltaic results in highest avoided emissions in Denmark

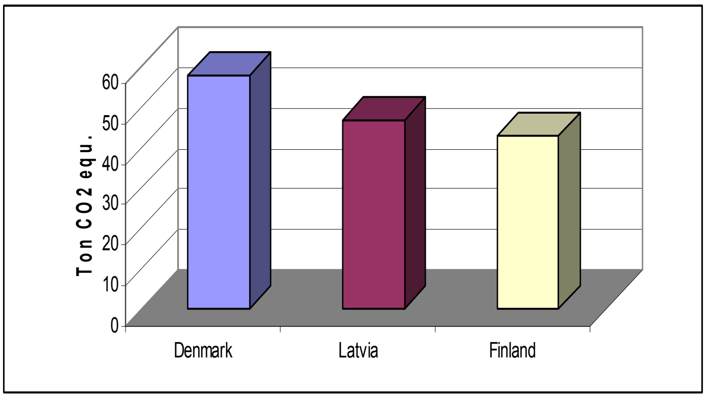

Figure 6. Carbon dioxide avoided by the use of a-Si photovoltaic power system in selected countries

Conclusion

Life cycle results show that indirect emissions of CO_2 occur in other stages of the life cycle of photovoltaic systems but are significantly lower than the avoided carbon dioxide emissions. By comparison of national differences of the electricity supply within Nordic and Baltic countries, Latvia come off best with the highest primary energy substituted while Denmark come off best with the highest CO_2 emissions avoided.

As the operation of photovoltaic power plant does not involve the combustion of carbon-containing fuels and can therefore lead to a significant CO_2 mitigation potential, photovoltaic technologies are in a very good position to be included in a portfolio of low-carbon energy technologies for a future sustainable energy supply, especially if further cost reduction can be also achieved.

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Njakou Djomo S., Blumberga D. Saules bateriju sistēmu atjaunojamība un energoefektivitāte: saules enerģijas saules radiācijas un konversijas efektivitātes novērtējums.

Ir paredzēts, ka saules bateriju sistēmai būs arvien svarīgāka loma atjaunojamās enerģijas tirgū, jo daudzas valstis meklē fosilo kurināmo izmantošanas un siltumnīcefekta gāzu emisiju samazināšanas risinājumus.

Lai izanalizētu saules bateriju sistēmu enerģētisko un vides profilu, ir jāpaplašina sistēmas robežas, ņemto vērā arī „slēptās ietekmes", kas saistītas ar saules bateriju sistēmu ražošanu, transportēšanu un noglabāšanu tehniskā dzīves cikla beigās. Šajā rakstā tiek piemērota dzīves cikla metodika, lai iegūtu pabeigtu un paplašinātu konceptuālas, tīklam pieslēgtas Latvijas saules bateriju sistēmas enerģētisko un vides profilu. Saules baterijas ir ražotas kā amorfa silikona (a-Si) paneļi, kas pārklāj standarta galvaniskos alumīnija jumta paneļus, nodrošinot apmēram 120 m^2 *pārklājuma laukumu. Procesa dati iekļauj kvarca samazinājumu, krama attīrīšanu, vafeļu un paneļu ražošanu, paneļu uzstādīšanu, demontāžu un noglabāšanu. Pētītās saules bateriju sistēmas ekspluatācijas dzīves cikls ir pieņemts 30 gadu apmērā. Rezultāti rāda, ka enerģijas atmaksāšanās attiecība ir 7.2, bet dzīves cikla enerģijas patēriņš un siltumnīcefekta gāzu emisijas ir atbilstoši 485* kJ/kWh_{el} *un 30 g* CO_2*-ekv/* kWh_{el}.

Njakou Djomo S., Blumberga D., Renewability and life cycle energy efficiency of photovoltaic systems: assessing the implication of solar radiation and conversion efficiency on energy displaced.

Photovoltaic systems are expected to play an increasingly important role in the renewable energy market, as many countries search for ways to reduce fossil fuels depletion and emissions of greenhouse gas.

In order to analyze the energy and environmental profile of photovoltaic systems, it is necessary to expand the system boundaries, taking into account also "hidden impacts" related to production, transportation and disposal of the system at the end of its technical life. This paper uses life cycle methodology to derive a complete and extended energy and environmental profile of a conceptual grid-connected photovoltaic system in Latvia. The photovoltaic is manufactured as panels from amorphous silicon (a-Si), laminated directly onto standard galvanized aluminum standing seam roofing panels providing approximately 120 m^2 *of surface area. The process data include quartz reduction, silicon purification, and wafer and panel production, panel installation, dismantling and disposal. The operational life time of the investigated photovoltaic system is assumed to be 30 years. The results show that the energy payback ratio of the studied system is 7.2 and the life cycle energy consumption and greenhouse gas emissions are 485* kJ/kWh_{el} *and 30 g* CO_2*-equ./* kWh_{el} *respectively*.

Ньякоу Джомо С., Блумберга Д., Возобновляемость и энергоэффективность системы солнечных батарей: оценка солнечного излучения солнечной энергии и эффективности конверсии.

Ожидается, что системы солнечных батарей будут играть всё более значительную роль на рынке возобновляемой энергии, так как многие страны ищут пути уменьшения использования фоссильных топлив и эмиссий парниковых газов.

Чтобы проанализировать энергетический и экологический профиль систем солнечных батарей, необходима расширить границы системы, беря во внимание также «скрытые влияния», связанные с производством, транспортировкой и захоронением системы в конце технического жизненного цикла. В данной статье применена методика жизненного цикла, чтобы получить законченный и расширенный энергетический и экологический профиль концептуальной, подключённой к сети системы солнечных батарей в Латвии. Солнечные батареи произведены как панели из аморфного силикона (a-Si), которые покрывают стандартные гальванизированные алюминевые панели на крыше, обеспечивающие приблизительно 120 м^2 площади покрытия. Данные процесса включают уменьшение кварца, кремниевую очистку, производство вафель и панелей, уснановку панелей, демонтаж и захоронение отходов. Эксплуатационный жизненный цикл исследуемой системы солнечных батарей принят как 30 лет. Результаты показывают, что отношение энерегетической окупаемости 7.2 , а потребление энергии жизненного цикла и эмиссии парниковых газов 485 кДж/кВтч$_{эл}$ и 30 г CO_2-экв./ кВтч$_{эл}$ соответственно