Life-Cycle Greenhouse Gas Analysis
for the
Proposed Baldock Solar Highway Project

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Analysis and report by:
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**EXECUTIVE SUMMARY**

The proposed Baldock Solar Highway project would consist of the installation of 6,994, 250-watt photovoltaic (PV) panels that would be capable of producing up to 1,971 megawatt-hours (MWh) of electricity during the first year of operation. The annual output of the project would be enough to supply approximately 12% of ODOT’s electricity needs in the PGE service area.

A life-cycle greenhouse gas (GHG) analysis was conducted on behalf of the Oregon Department of Transportation (ODOT) to quantify net GHG emissions over the life cycle of the proposed Baldock solar power facility. This analysis follows the conventions of current GHG inventory protocols and best practices and includes the following emissions sources and reductions:

**Life-cycle Stage 1 – Before (Planning and Construction)**
- Embodied emissions from the production of the PV panels and other construction materials
- Embodied emissions from engineering services
- Tailpipe emissions (not life-cycle) from construction, material transport and commute vehicles’ fuel use

**Life-cycle Stage 2 – During (Operation - Electricity Generation and Maintenance)**
- Displaced grid electricity generation emissions from the project’s solar power generation (0 - 30 years)
- Embodied emissions from the production of maintenance materials
- Tailpipe emissions from maintenance materials transport and commute vehicles’ fuel use
- Grid electricity emissions from onsite use by lights and security cameras

**Life-cycle Stage 3 – After (Transport and Disposal of Facility Building Materials)**
- Life-cycle emissions from material transport vehicles’ fuel use
- Recycling of PV panels and construction materials

**HIGHLIGHTS OF ANALYSIS**

  - **Gross Emissions**: GHG emissions from the construction and operation of the facility.
  - **Emissions Reductions**: Displacement of Northwest Power Pool (NWPP) grid electricity generation with solar electricity.

- The carbon emissions displaced by this solar power facility over its life cycle are roughly 4 times that produced during construction. The facility reaches carbon payback 6.2 years after construction.

- The embodied emissions from the production of the photovoltaic (PV) panels and other construction materials represent 92% of the gross project emissions (3,739 of 4,058 MT CO₂e).
  - PV panels contribute 70% of gross emissions while other materials (mainly aluminum) are 22%.
  - End-of-life recycling of construction materials will reduce net project emissions by -547 MT CO₂e.

- Life-cycle emissions from fuel use during construction, material transport and employee commute make up 4% of gross project emissions or 172 MT CO₂e.

- All other sources of emissions (engineering services, electricity use) account for the remaining 4% of gross project emissions.

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1 This is a conservative estimate of guaranteed output. Actual output is likely to be greater.
2 Life-cycle GHG emissions for a construction project of this type include those emissions associated with the “before”, “during” and “after” stages of the Solar Power Facility. The “before” stage includes the emissions associated with construction materials, fuel use, etc. The “during” stage includes emissions associated with operating the facility (replacing inverters, cleaning) as well as auxiliary functions such as the emissions from the production of electricity consumed by the facility. The “after” stage includes decommissioning the facility and recycling the materials.
4 30 years is based on a conservative estimate of the PV panels’ productive life, but use of the generated electricity from this facility is determined by a 25-year power purchase agreement with options to renew for up to 3 five-year terms, for a total of 40 years. After the terms of the agreement expire, the facility could be decommissioned or could continue to generate electricity until the end of the module’s useful life.
5 Metric tons of carbon dioxide equivalent (MT CO₂e) is the internationally recognized unit for reporting the six Kyoto Protocol greenhouse gases.
6 The carbon intensity of NWPP electricity was reduced by ~2% per year based on current trends and goals of Oregon’s Renewable Portfolio Standard.
7 Embodied emissions include the production energy and process emissions associated with raw material extraction, processing, product manufacture and all transportation up to the point of retail (cradle-to-gate).
8 This estimate does NOT include poly-silicon from the PV panels due to limited available research on the subject.
Figure 1: Net Greenhouse Gas (GHG) Reduction of Baldock Solar Power Facility

Figure 2: Baldock Solar Power Facility – Project Life-Cycle Emissions

* End-of-life GHG credit for recycling includes all aluminum, steel, copper and glass. This credit does not include the poly-silicon in the PV panels due to limited available research on the subject. It’s important to note that SolarWorld is contracted to recycle the panels when the facility is decommissioned.
INTRODUCTION

In 2008, the Oregon Department of Transportation (ODOT) and Portland General Electric (PGE) completed the nation’s first solar photovoltaic project in the highway right of way, partially lighting an interchange. The 0.1 MW\textsubscript{dc} array has 594, 175-watt SolarWorld panels which, as of June 24, 2011, have produced over 299,780 kilowatt-hours of renewable energy since commissioning on December 19, 2008. The project “feeds” the electricity into the grid during daytime hours, and draws from the grid at night to light the interchange. (See: [http://live.deckmonitoring.com/?id=solarhighway](http://live.deckmonitoring.com/?id=solarhighway))

Based on the success of this demonstration project, ODOT and PGE have explored options for additional solar highway projects. One of these projects, located at the Baldock safety rest area 14 miles south of Portland along northbound I-5, will have \~7,000 solar panels with a maximum capacity of 1.75 megawatts\textsubscript{dc} generating more than 1.9 million kilowatt hours of renewable energy during the first year of generation. ODOT ultimately hopes to expand the Solar Highway Program to a statewide total of about 50 megawatts of generation capacity – the amount of ODOT’s annual statewide electricity consumption.

This report summarizes the Baldock project’s life-cycle greenhouse gas emissions (GHGs), estimates the total mitigated emissions during the life of the project, and calculates the “carbon payback period” (i.e., the period necessary for the project to become carbon-neutral).

SCOPE OF ANALYSIS

The carbon footprint boundaries include the following emissions sources, listed in order of life-cycle stage:

**Life-cycle Stage 1 – Before (Planning and Construction)**
- Embodied emissions from the production of the PV panels and other construction materials
- Embodied emissions from engineering services
- Life-cycle fuel emissions\textsuperscript{10} from construction, material transport and commute vehicles’ fuel use

**Life-cycle Stage 2 – During (Operation - Electricity Generation and Maintenance)**
- Displaced grid electricity generation emissions from the project’s solar power generation (0-30 years)\textsuperscript{11}
- Embodied emissions from the production of maintenance materials
- Life-cycle emissions from maintenance materials transport and commute vehicles’ fuel use
- Grid electricity emissions from onsite use by lights and security cameras

**Life-cycle Stage 3 – After (Transport and Disposal of Facility Building Materials)**
- Life-cycle emissions from material transport vehicles’ fuel use
- Recycling of PV panels and construction materials

The methods used in this analysis follow standards set by established international GHG inventory protocols\textsuperscript{12} where applicable, and best practices where established protocols or methods don’t currently exist or are cost prohibitive. This analysis is based on preliminary project plans and data. All values presented in this report are subject to change as the project design and plans are finalized. Because this project is still in the design stage, not all data was readily available, to the extent required by GHG protocol. This necessitated making assumptions in order to create a model from which emissions were estimated.

\textsuperscript{9}Life-cycle GHG emissions for a construction project of this type include those emissions associated with the “before”, “during” and “after” stages of the facility’s existence. The “before” stage includes the emissions associated with production of the PV panels, other construction materials and the construction process. The “during” stage includes emissions associated with maintaining the facility as well as auxiliary functions such as the emissions that result from the production of electricity for the facility’s lighting. The “after” stage includes the method of disposal for materials.

\textsuperscript{10}Life-cycle fuel emissions include fuel production emissions as well as tailpipe emissions.

\textsuperscript{11}30 years is based on a conservative estimate of the PV panels’ productive life, but use of the generated electricity from this facility is determined by a 25-year power purchase agreement with options to renew for up to 3 five-year terms, for a total of 40 years. After the terms of the agreement expire, the facility could be decommissioned or could continue to generate electricity until the end of the module’s useful life.

RESULTS

The results of this analysis are broken into two primary sections: Net Greenhouse Gas (GHG) Emissions and Gross Emissions from Project Development. The net GHG emissions section describes the balance between the project’s emission sources as well as reductions to estimate the proposed facility’s net carbon impact. The section on Gross Emissions from Project Development is a detailed discussion of only emission sources resulting from the project’s planning, construction, maintenance and decommissioning.

Net Greenhouse Gas (GHG) Emissions: -11,586 MT CO$_2$e

The net project emissions are the gross emissions resulting from project planning, construction and maintenance minus the emissions displacement of grid electricity by carbon-free solar and end-of-life material recycling (except PV panels – see Note below).

\[
\text{Net Emissions} (-11,586 \text{ MT CO}_2\text{e})^{13} = \text{Gross Emissions (4,058)} + \text{Emissions Reductions (-15,645)}
\]

The annual net GHG emissions reductions from the Baldock Solar Highway project are equivalent to the amount of carbon sequestered by 73 acres of pine forest in 1 year.

The gross emissions from project development include the embodied emissions that result from PV panel and other construction materials production, fuel combustion emissions from construction equipment, transporting materials and employee commute, etc. These emissions are estimated at 4,058 MT CO$_2$e and are shown as the left bar in Figure 3. The gross emissions are described in detail beginning on page 8.

Two sources of emissions reductions (or credits) are included in this analysis:

- Displacement of carbon-intensive NWPP grid generated electricity for the first 30 years of electricity generation$^{14}$
- Recycling the PV panels and construction materials at the end of the facility’s useful life in ~30 years.

**Note:** While end-of-life recycling for the poly-silicon in the PV panels is offered by SolarWorld and could result in a potentially substantial GHG benefit, it is not included in this analysis due to the uncertainty associated with the timeframe (~30 years from now) and limited available research on the scale of GHG reductions.

Combined, the sources of emissions reductions total -15,645 MT CO$_2$e.

Figure 3 compares the gross

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$^{13}$Metric tons of carbon dioxide equivalent (MT CO$_2$e) is the internationally recognized unit for reporting the six Kyoto Protocol greenhouse gases.

$^{14}$The PV panels could produce electricity for much longer than 30 years, but only the first 30 years of NWPP displacement are included in net GHG emissions.
emissions from project development (left bar) to GHG reductions (middle bar) and shows the net project GHG emissions (right bar) at -11,586 MT CO\textsubscript{2}e. The net GHG emissions represent the difference between the gross project emissions and the emissions reductions, but do not include the reductions from end-of-life recycling (see above Note).

**Displacement of NWPP Grid Electricity (30-year estimate): -15,097 MT CO\textsubscript{2}e**

The solar electricity generated by this facility will displace the electricity generated by the regional grid, the Northwest Power Pool (NWPP). The NWPP grid resource generation mix used to produce electricity includes carbon-intensive fossil fuel sources (natural gas and coal), which results in a significantly higher GHG emissions per unit of production compared to electricity produced from PV panels (see the Benchmarking section of this report). The emissions reductions from NWPP grid electricity displacement uses greenhouse gas emissions factors from the EPA’s *Emissions & Generation Resource Integrated Database (eGRID)* and discounts the factors over the next 30 years to account for anticipated reductions in the carbon intensity of the NWPP grid (the result of Renewable Portfolio Standards being implemented in the region). The RPS standards require that large utilities in the state will be required to increase renewable sources of electricity to 25% of new generation by 2025.

Generating electricity with PV panels does not directly generate GHG emissions, unlike coal or natural gas. The emissions associated with solar energy are generated upstream during the production of the PV panels and building materials, during the construction of the facility, and intermittently through maintenance of the facility. Once the upfront emissions investment has been made during project development and construction, the electricity produced is carbon free, except for intermittent, low maintenance needs. The carbon payback for this facility is 6.2 years after the facility begins generating electricity.

**End-of-Life Recycling of Construction Materials (~30 years from now): -547 MT CO\textsubscript{2}e**

When materials are recycled, they displace virgin materials that would otherwise need to be mined from the earth and processed into the raw materials consumed by industry to create new products. By displacing the need for virgin materials, the energy and associated emissions are also displaced. The use of post-consumer recycled content significantly reduces the energy and emissions intensity of the products created with that material compared to virgin materials.

This section of the analysis estimates the quantity of emissions that will be displaced by recycling select components of the PV panels and other construction materials at the end of the facility’s productive life. This estimate includes four primary materials: aluminum, steel, copper and glass. Components containing aluminum including the PV mounting system and the PV panel frames; components containing steel including the PV mounting system, inverters and security fencing; components containing copper including wire, and glass used in the PV panels, are included in this analysis.

Recycling the poly-silicon contained in the PV panels at end-of-life is technically feasible. However, the practice is not yet commonplace and therefore research on the carbon benefit is limited. The PV panels used at the Baldock facility will be recycled by SolarWorld at the end of their useful life, but this analysis excludes the potential associated carbon benefit due to the uncertainty associated with the timeframe and limited available research on the scale of GHG reductions.
Gross Emissions from Project Development: 4,058 MT CO₂e

The gross greenhouse gas emissions that are generated as a result of this project can be summarized into six categories:

- **PV Panels:** Embodied emissions from the production of photovoltaic (PV) panels.
- **Construction Materials:** Embodied emissions from the production of construction materials.
- **Engineering Services:** Embodied emissions from engineering services.
- **Fuel:** Fuel combusted by construction equipment, freight vehicles and employee commute vehicles.
- **Onsite Electricity Use:** Electricity consumption by the facility in the course of daily operation.

Figure 4 shows the scale of emissions from the life-cycle categories described above. The embodied emissions from the PV panels are the largest project source at 70% of gross emissions. The materials used to construct and maintain the facility are the second largest emissions source at 22%, followed by fuel use at 4%, engineering services at 3% and finally, onsite electricity use at <1%. The total gross emissions from development of the solar power facility are estimated at 4,058 MT CO₂e.

**PV Panels: 2,857 MT CO₂e**

The largest source of GHG emissions associated with the proposed facility is the production of the photovoltaic (PV) panels. These embodied emissions are the result of the energy consumption and associated emissions from raw material extraction, material processing, product manufacture and all transportation up to the point of retail.\(^\text{15}\)

Of the total emissions from this category, 69% are the result of processing silica (sand) into high-grade polycrystalline silicon (poly-Si) and production energy required to produce the silicon wafer. Due to the energy intensity of the poly-si production, emissions will vary significantly.

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\(^\text{15}\) SolarWorld provided the proprietary data used to calculate emissions for this category. This is a point of differentiation and improved accuracy over the analysis for the West Linn Solar Power Facility, which utilized publically available academic research to estimate GHG emissions from PV panel production.
depending on carbon intensity of the producer country’s electricity generation.

The second largest source of emissions is the module assembly at 22%. This category includes the embodied energy in module components (e.g. the aluminum frame, glass, packaging materials, etc.) and the production energy required to transport and assemble the parts into a finished module. The remaining 9% of emissions are the result of energy used to produce the cells. For more information on PV production see the research paper titled, *Health and Safety Concerns of Photovoltaic Solar Panels* on the Oregon Department of Transportation, Solar Highway website.¹⁶

**Construction Materials: 903 MT CO₂e**

The embodied emissions in the materials used to construct the solar power facility are the second largest source of emissions. Aluminum used in the PV panel mounting system makes up 66% of the category emissions. Steel is used in the facility’s PV mounting assembly, security fence and inverters and makes up 13% of category emissions. Plastic conduit and drainage pipes make up 4% of emissions and copper wiring makes up 2% of emissions. Other miscellaneous new construction materials are accounted for in the remaining “other” category at 15%.

**Vehicle and Equipment Fuel: 172 MT CO₂e**

Operating equipment and vehicles during construction and in the movement of materials requires the combustion of fuel, which in turn generates GHG emissions. In addition to the combustion of the fuel, these emissions also account for the upstream emissions generated during the petroleum extraction and refinement.¹⁸ Fuel will be used in three vehicle groups during the development of this project: material transport, construction equipment and employee commute. This category accounts for tailpipe emissions from fuel combustion, not upstream emissions from fuel production. The largest emissions source in this category is construction equipment at 38%. This group includes equipment such as graders, backhoes, excavators, etc. The second largest source of emissions in this category is employee commute at 32%. These emissions are the result of contractors traveling from their home or place of business to the job site. Material transport is the final source of emissions in this category at 30%. This source includes transporting the PV panels and other construction materials (initial construction and maintenance).

¹⁷ It is assumed that construction equipment and material transport vehicles run on diesel, while employee commute vehicles run on gasoline.
¹⁸ Life-cycle carbon intensities for diesel and gasoline were taken from Oregon Department of Environmental Quality, Low-Carbon Fuel Standards research. The carbon intensity table may be downloaded online at [http://www.deq.state.or.us/aq/committees/docs/lcfs/appendixB.pdf](http://www.deq.state.or.us/aq/committees/docs/lcfs/appendixB.pdf).
Engineering Services: 117 MT CO₂e

The development of a large-scale solar power facility requires the knowledge, skills and expertise of many industry professionals from a variety of organizations and disciplines. This category provides a sense-of-scale estimate of the emissions associated with bringing these critical engineering and other services to market. Emissions from this category are the result of office electricity and natural gas use, fleet vehicles, solid waste generation, etc. that are a necessary part of the daily operations of every business.

Onsite Electricity Use: 10 MT CO₂e

This category estimates the emissions resulting from electricity consumed by the facility’s lighting fixtures and security cameras over 30 years of operation by the facility. Plans have not been finalized for the lighting or security systems so electricity use was estimated and emissions were calculated based on those estimates. This estimate assumes 8 150-watt lighting fixtures running for security and maintenance purposes only 6 hours per day for 45 days per year for 30 years and 5 3-watt security cameras operating 24 hours per day for the 30 years.

Emissions Equivalencies

This analysis uses the internationally recognized GHG inventory unit, metric tons of carbon dioxide equivalent (MT CO₂e), to describe the project emissions. Carbon dioxide equivalent (CO₂e) is a means of describing the cumulative effect of all greenhouse gases weighted by their 100-year global warming potential. The CO₂e unit used to quantify greenhouse gas emissions is unfamiliar to most audiences. This section presents project emissions in “everyday” equivalents and provides sense-of-scale comparisons, and utilizes the Environmental Protection Agency’s Greenhouse Gas Equivalencies Calculator.

One metric ton (MT) of CO₂e is equivalent to any one of the following:
- Carbon sequestered by 0.2 acres of fir forest for 1 year
- Emissions from a typical passenger vehicle driven 2,134 miles
- CO₂ emissions from 114 gallons of gasoline consumed

Figure 8 shows the volume needed for 1 metric ton of carbon dioxide (blue cube), the scale of this volume is compared to a human figure and housing units.

Net project emissions (-11,586 MT CO₂e)
over 30 years are equivalent to any one of the following:
- Carbon sequestered by 93 acres of fir forest for 30 years
- Removing 85 passenger vehicles from the road for 30 years
- Displacing the combustion of 1.4 million gallons of gasoline over 30 years

Gross project emissions (4,058 MT CO₂e) are equivalent to any one of the following:
- Carbon sequestered by 865 acres of fir forest for 1 year
- 796 passenger cars driven for 1 year
- 455 thousand gallons of gasoline combusted
Figure 9 shows the difference between life-cycle emissions (per MWh generated) from electricity generated by the NWPP grid in 2005 and the Baldock Solar Facility. The orange bar represents the emissions associated with the fuel supply chain, which includes the emissions generated during fuel extraction, processing and transportation. For the Baldock Solar Power Facility this includes the emissions that result from PV module production (silica mining, silicon processing, wafer and cell production, module assembly and direct material embodied emissions). The fuel supply chain for the NWPP grid primarily includes the extraction, processing and transport of coal and natural gas. The blue bar represents the direct GHG emissions from the combustion of fuels to generate electricity. The proposed Baldock Solar Power Facility would not require the combustion of fuels to generate electricity, while average NWPP grid electricity includes the combustion of coal, natural gas, oil, etc. The brown bar represents all other gross project emissions included in this analysis. Equivalent other gross project emissions (brown bar) are not available for all NWPP generation sources (coal and gas fired power plants), which would include: embodied emissions in facilities and equipment, fuel used to construct and maintain the facility, employee commute, etc.

As can be seen on Figure 9, the life-cycle GHG emissions for each kilowatt of electricity produced by the NWPP grid are almost 6 times that of electricity that would be generated by the Baldock Solar Power Facility or 964 pounds CO₂e / kWh versus 169 pounds CO₂e / kWh respectively. This comparison is not apples-to-apples, as the “other gross project emissions” is not accounted for in the NWPP GHG intensity value, which would make the NWPP carbon intensity per KWh higher than what is shown. If the “other” emissions (i.e. construction materials, construction / transport / commute fuel use, engineering services) are removed from the Baldock Solar Power Facility the GHG intensity of the NWPP grid is almost 8 times that of the proposed Baldock facility.

It is important to note that while solar generated electricity is much less carbon intensive than NWPP generated electricity, it is currently an intermittent source. In other words, PV modules only generate electricity during the daytime and particularly when the sun is shining. While that intermittency roughly aligns with peak demand for electricity it is still necessary to match the solar generation potential with “firm” generation capacity such as natural gas turbines, which fills the demand gap at night and on cloudy days.

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19 This graphic is based on life-cycle values presented in a report titled Life-Cycle Analysis of Current Coal, Gas and Nuclear Electricity Systems and Electricity Mix in the USA. The report provides values for the fuel supply chain and direct GHG emissions from fuel combustion for all the common types of electricity generation resources utilized by the U.S. electricity grid including: coal, natural gas, oil, hydro, nuclear, wind, wood, solar, etc. These values were used to generate a weighted average of the life-cycle carbon intensity for NWPP grid electricity (kg CO₂e / kWh) based on the known percentage of electricity resources that make up the NWPP grid in 2005 as reported by the EPA’s eGRID.

20 The GHG intensity for the Baldock Facility represents the gross project emissions divided by the MWh produced over its 30-year lifespan.

21 The fuel supply chain value does not include all sources of emissions generated by facility development. These values only include the upstream emissions associated with fuel production. Equivalent analyses to this report were not available for all generation sources that supply electricity to the NWPP grid.
BIBLIOGRAPHY


