RENE092 – KORTRIGHT ENERGY YIELD TEST STANDARD
PUBLIC FINAL REPORT

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Sustainable Technologies Evaluation Program

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THE SUSTAINABLE TECHNOLOGIES EVALUATION PROGRAM

The Sustainable Technologies Evaluation Program (STEP) is a multi-agency program, led by the Toronto and Region Conservation Authority (TRCA). The program helps to provide the data and analytical tools necessary to support broader implementation of sustainable technologies and practices within a Canadian context. The main program objectives are to:

- monitor and evaluate clean water, air and energy technologies;
- assess barriers and opportunities to implementing technologies;
- develop tools, guidelines and policies, and
- promote broader use of effective technologies through research, education and advocacy.

Technologies evaluated under STEP are not limited to physical products or devices; they may also include preventative measures, alternative urban site designs, and other innovative practices that help create more sustainable and livable communities.

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- Dr. Hany Farag, and Sarah Kandil, of York University provided academic expertise for the power quality monitoring and analysis.
- Tanya Deer of Relsol Inc. provided data analysis and industry expertise, specifically focusing on the IEC 61853-2 PV module thermal model and the IEC 61853-4 climate datasets.
- Indoor PV module characterizations according to IEC 61853-1 & -2 were provided by Exova.
- Leidos provided PVSyst modelling expertise and implemented the IEC 61853-3 calculation procedure.
- SolarShare provided real-world PV system performance data that was used to ground-truth PVSyst simulation data in the analysis of IEC 61853-1 power matrix.
- TRCA Restoration Services and Earth Rangers provided PV sites used for power quality monitoring.

EXECUTIVE SUMMARY

This report summarizes work that took place between 2012 and 2016 by the TRCA under the NRCAN ecoEnergy Innovation Initiative (ecoEII) funding agreement titled "RENE092 – Kortright Energy Yield Test Standard." The objective of the project was to provide background research to inform the development of photovoltaic standards in two different areas: PV module performance rating and PV inverter grid interconnections.

The IEC 61853 series of standards provides notable benefits over conventional PV module performance rating at standard test conditions (STC) by providing a rating related to real-world expected performance. It consists of four parts. Parts 1 and 2 concern procedures for expanded module characterization and are already published. Parts 3 and 4 concern climate datasets and calculation procedures necessary to determine the module rating, termed the Climate Specific Energy Rating (CSER). Parts 3 and 4 are not yet published but are nearing the end of the committee draft (CD) stage within the IEC at the time of writing.

This project included a number of tasks supporting the development of IEC 61853. Essentially, the series of standards was implemented and through that process, experience and data was obtained to support the development and improvement of the standards. While much of the research has been made available in publically-accessible reports on the STEP webpage, the key outputs of the work were comment forms submitted to the IEC regarding the suggested standard revisions – many of which have already been incorporated into the standards. In general, the comments encompass the finding that some of the procedures within IEC 61853 have been found to be sufficient while others need further work.

This project also looked at a very specific component of PV inverter grid interconnections, namely, current harmonic emissions. Current harmonic emissions emanate from many sources, including PV inverters, and can be harmful to electronic equipment. For this reason, component and utility-level standards provide requirements for maximum allowable emissions from PV inverters or PV installations connected to the electricity grid. This project used power quality monitoring to look at those requirements against the range of conditions occurring in real-world operation. It found that very low level power operation is not considered in the standards but probably should be because such conditions would frequently occur and significant current harmonic emissions were observed at low power in certain niche cases. However, the authors do note that this is an issue that can be easily rectified and it is not an important barrier for higher-level penetration of PV within electrical power systems.

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1.0 INTRODUCTION

1.1 Overview

This report summarizes work that took place between 2012 and 2016 by the STEP program of the TRCA under the NRCAN ecoENERGY Innovation Initiative (ecoEII) funding agreement titled "RENE092 – Kortright Energy Yield Test Standard." As stated in the reporting guidelines: "a major focus of the ecoEII program is to ensure that the experience gained by the proponent during the execution of the project is provided to stakeholders, companies or municipalities that are interested in considering investment or further research in a similar project." This public-facing report fulfills that requirement. Specific items to be addressed as outlined in the reporting requirements, include, but are not limited to:

- What was the R&D gap and why was this project needed?
- Project objective
- Project evolution:
    - Identification and securing partners, permits etc.
        - R&D Activities performed
        - Challenges encountered
    - Conclusions:
        - Benefits and outcomes of the project
        - What are the next steps for R&D in this area?

1.2 Standards

The Standards Council of Canada states that "..standards are guidelines that establish accepted practices, technical requirements, and terminologies for diverse fields." They are important for many reasons. For example, among other things, they are used to:

- ensure that consumer products are safe to use;
- ensure that products meets certain performance requirements; and
- foster trade and innovation across different jurisdictions by providing common sets of requirements.

There are numerous standards in the realm of photovoltaics (PV) and, for standards to achieve their intended goal, it is important that their development is informed by research. This project provided research necessary to bolster the quality and effectiveness of PV standards in two different areas: PV module performance rating and PV inverter grid interconnections.

1.3 PV Module Performance Rating

PV module performance ratings describe how much power a module produces under certain conditions and are important for consumer decision-making and financial evaluations of investments in PV installations. PV modules are typically rated at a single operating point, referred to as standard test conditions (STC), that is defined by a module temperature of 25°C, an irradiance of 1000 W/m^2 and an AM1.5 irradiance spectrum, as per International Electrotechnical Commission (IEC) 61215. While STC arose as a convention that was convenient for laboratory testing, it is not necessarily representative of real-world module performance due to a host of factors that are not taken into account within an STC rating. This has the potential to introduce consumer uncertainty when selecting modules. Furthermore, it does not foster innovation in module design features, simply because any performance enhancements that improve real-world performance may not actually end up in an improved module rating at STC.

The IEC 61853 series of standards addresses these concerns by providing a module rating that is more representative of the expected real-world module performance. The series of standards consists of four parts. Parts 1 and 2 concern procedures for expanded module characterization and are already published. Parts 3 and 4 concerns climate datasets and calculation procedures necessary to determine the module rating, termed the Climate Specific Energy Rating (CSER). Parts 3 and 4 are not yet published but are nearing the end of the committee draft (CD) stage within the IEC. This project included a number of tasks supporting the development of IEC 61853.

1.4 PV Inverter Grid Interconnections

Electronic devices are designed to function within certain electrical power tolerances and if the electrical power from the electricity grid is outside of these tolerances, electronic devices may malfunction or be damaged. The extent to which the electrical power is within expected tolerances is described by the term “power quality,” and power quality may be “good” if it obeys expected tolerances or “bad” if it significantly deviates from them. A key component of good power quality is the mitigation of harmonic components. Harmonic current components are small current signals that occur at integer multiples of the fundamental frequency of 60 Hz (ie. at 120 Hz, 180 Hz, 240 Hz, etc.) that distort the purely sinusoidal shape of the current waveform. Current harmonic emissions arise from the nonlinear switching technology used in many electronic devices, including PV inverters. It is important that PV inverters produce good power quality such that this does not become a barrier for the high penetration of PV.

U.S and Canadian standards exist to help ensure good power quality from the inverters themselves (CAN/CSA-C22.2 NO. 107.1-01 and UL 1741) and also at the utility interconnection (CAN/CSA-C22.2 NO. 257-06 and IEEE 1547). While the standards agree on the current harmonic emission requirements for PV inverters, they differ on how compliance with those requirements is evaluated. In all cases, they evaluate the current harmonic emissions when the inverter is operating in a steady-state and at a rating point that is above 33% of the rated inverter capacity. However, an actual PV installation will see a much wider range of operating points, including frequent low-level and highly variable irradiance conditions and it is possible that there may be notable power quality issues outside of the recommended measurement conditions given within the standards. This project used long-term monitoring to determine the power quality of solar PV inverters across a wide range of real-world operating conditions to determine whether the requirements of the standards are sufficient at preventing high current harmonic emissions once installed.

2.0 BACKGROUND

2.1 IEC 61853

The four parts of IEC 61583 are summarized in Table 2-1.

Table 2-1. Summary of IEC 61853

Standard	Description
IEC 61853-1	o Characterizes the module power production at different operating points of module temperature and irradiance
IEC 61853-2	o Determines the module incidence angle modifier (IAM) o Determines the module spectral reponse o Determines coefficients for the PV module thermal model
IEC 61853-3	o Provides a calculation procedure such that the module performance in IEC 61853-1 & -2 can be used alongside the climate data files of IEC 61853-4 to determine a climate specific energy rating (CSER) for each climate datafile
IEC 61853-4	o Consists of hourly climate datafiles for different representative locations around the world

2.1.1 IEC 61853-1

The power produced by a PV module varies with the magnitude of the incident irradiance and the module temperature. Within IEC 61853-1, PV module power production is determined at 22 different module temperature and irradiance operating conditions (listed in Table 2-2). There are different procedures possible for populating this matrix that are outlined in IEC 61853-1. These are listed below.

- Procedure 1[1]: a simplified procedure for linear modules;
- Procedure 2: a procedure in natural sunlight with tracker;
- Procedure 3: a procedure in natural sunlight without tracker, and
- Procedure 4: a procedure with a solar simulator.

Table 2-2 IEC 61853-1 test conditions

Irradiance [W/m^2]	Module Temperature [°C]			
	15	25	50	75
1100		x	x	x
1000	x	x	x	x
800	x	x	x	x
600	x	x	x	x
400	x	x	x	

[1] Note that the procedure numbers are used as a shorthand in this report and are not actually present in the standard.

200	x	x
100	x	x

While Procedures 1, 2 and 4 are established approaches, Procedure 3 is new with this standard and a minimum amount of guidance is offered. Essentially, the module under test is instrumented and then left to operate as normal on a static array for a duration of time that is sufficient for the desired operating conditions to occur naturally.

2.1.2 IEC 61853-2

When light is transmitted from one medium to another (for example, from air to glass) there is also some amount of reflection that occurs at the interface. The amount of reflected radiation increases at higher incidence angles. For a PV module, the relationship between the incidence angle and the fraction of irradiance transmitted through the front glass and into the PV cells is defined by an incidence angle modifier (IAM). The IAM is a useful parameter for energy yield modelling and can be measured using procedures outlined in IEC 61853-2 according to an indoor or an outdoor method.

Solar irradiance occurs in a spectrum of different wavelengths. The spectrum may change according to different factors, chiefly among them being the mass of air that light travels through before being incident on a PV module. This can change over the course of a day and with the elevation of the PV installation. The behaviour of a PV module with respect to spectral changes in described by its spectral response, which can be measured using a procedure outlined in IEC 61853-2.

PV module power output lowers with increasing cell temperature due to loses in the open circuit voltage. The module back-surface temperature can be modelled by a simple equation with two coefficients that takes into account the ambient temperature, wind speed and irradiance. IEC 61853-2 provides a procedure for determining the model coefficients according to experimental measurements.

2.1.3 IEC 61853-3 & -4

Part 3 of the standard includes a procedure that calculates the energy output of a PV module on an hourly basis for the period of a year. For each hourly iteration, the procedure starts with plane-of-array (POA) irradiance data and other climate data available from climate data files (IEC 61853-4). The irradiance data is then corrected, firstly, for angle of incidence (AOI), and secondly, for spectral mismatch. The module temperature is calculated based on an experimentally derived thermal model (IEC 61853-2) of the modules and climate data for that hour. The energy output is then calculated by comparing the module temperature and corrected irradiance against a two-dimensional matrix for module power production as a function of irradiance and module temperature (IEC 61853-1). The yield for the year is determined by summing the hourly results and this is then used to calculate the CSER value.

The CSER is essentially a performance ratio. A performance ratio relates actual energy yield to an “expected” energy yield in the case where all the energy was assumed to be produced under STC conditions. The numerator of the ratio is the actual energy yield over a year (or a modelled energy yield in the case of the CSER value) and it takes into account all loses due to temperature, spectrum, incidence angle, etc. and the denominator is an idealized estimate of energy production based on the module STC rating and the irradiation over a year without taking into account any losses. The performance ratio is a useful metric because it normalizes for the module STC power rating and the annual irradiation. In this way, it contains information about energy loses that other metrics, like energy yield, do not.

2.2 Power Quality and Grid Interconnection

In Canada, the recommended practices for interconnecting an inverter-based distributed resource (DR), such as a PV installation, with a low-voltage electrical power system (EPS), are given in CAN/CSA-C22.2 NO. 257-06. The comparable U.S. standard is IEEE 1547. In general, both standards recommend that harmonic current injection into the utility EPS shall not exceed the limits specified in Table 2-3.

Table 2-3. Harmonic current injection limits suggested by CSA 257 and IEEE 1547

Individual harmonic order h (odd harmonics)[b]	$h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	Total demand distortion (TDD)
Percent (%)	4.0	2.0	1.5	0.6	0.3	5.0

[a] I = the greater of the Local EPS maximum load current integrated demand (15 or 30 minutes) without the DR unit, or the DR unit rated current capacity (transformed to the PCC when a transformer exists between the DR unit and the PCC).
[b] Even harmonics are limited to 25% of the odd harmonic limits above.

In order to verify that the harmonic current emissions are within the given limits, IEEE 1547 stipulates that both the total demand distortion (TDD) and the individual harmonic distortion factors up to the 40th order should be calculated while the DR is operating at 33%, 66% and 100% of the rated load. In contrast, CAN/CSA-C22.2 NO. 257-06 states that the individual inverters that make up a DR system must use inverters which are compliant with CAN/CSA-C22.2 NO. 107.1-01. In this case, the only operating point in the testing procedure is at 100% of the rated load. There is discussion towards updating that provision to 33%, 66% and 100%, as in the case of the IEEE 1547, in the next revision.

These standards seek to quantify the harmonic current emissions of grid-tie PV systems at a small number of different operating points to ensure that they are below recommended limits. This is both a reasonable and a practical stipulation. However, the fact still remains that these testing points do not fully represent a PV installation's wide range of real-world operating points. Actual PV installations produce variable power from 0 to 100% of the rated capacity and furthermore, they are subject to periods of highly variable irradiance due to cloud cover or cloud lensing effects. Rapidly changing irradiance conditions can be both frequent and large in magnitude.

2.3 Summary

Sections IEC 618532.1 and 2.2 provided a brief over of the standards considered in this project. For each of these standards, certain questions remain unanswered but are key to the standards' development. These are outline in Table 2-4 and were explored in this project.

Table 2-4. Unanswered questions necessary for the standards' development

Standard	Question No.	Description/Outputs
IEC 61853-1	1	o Are the temperature and irradiance conditions in IEC 61853-1 sufficient for a Canadian climate? Should points be added or deleted to better represent the Canadian climate?
	2	o Does Procedure 3 (the new procedure) produce results that are in agreement with the other established procedures?
IEC 61853-2	3	o Do the indoor and outdoor IAM procedures agree?
	4	o Is any further guidance required in regards to the sensor type used in the IAM measurement?
	5	o Is the procedure to determine the module thermal model achievable and is their sufficient guidance within the standard?
IEC 61853-3 & -4	6	o Since the CSER is a performance ratio, does the IEC 61853-3 procedure agree with predictions from industry standard software like PVSyst? Does it agree with real-world data?
	7	o Does the standard provide sufficient guidance to complete the calculation procedure?
	8	o How much do IAM and spectral corrections matter within the calculation procedure?
	9	o How different are the climate profiles that were selected in IEC 61853-4?
	10	o Do the current climate data files sufficiently represent a Canadian climate? How might a Canadian climate data file be incorporated into the standard?
CSA 107.1 CSA 257 IEEE 1547 UL 1741	11	o Are there any notable issues related to current harmonic emissions that may occur outside of the operating points considered in these standards (possibly due to transient or low-irradiance conditions)?

3.0 OBJECTIVES

Specific objectives of the project are laid out in Table 3-1 and this table is taken from the original proposal. Note that questions were formulated in Table 2-4 and added to Table 3-1because the objectives of the activities present in Table 3-1 is not always clear without further context.

Table 3-1. Project objectives as originally proposed

Activities	Year	Principal Milestones (identify "go-no go" decision points	Outputs - identify whether interim (I) or final (F)	Question (Table 2-4)
Project Design	2012-2013	Populate IEC 61853 (part 1) Power Matrix using indoor and outdoor test procedures on inaugural 3 test modules	(I) Develop procedure guideline	2
	2012-2013	Establish feasibility of IEC irradiance and temperature conditions for Ontario environment and develop recommendations	(F) Evaluation Study	1
	2012-2013	Design monitoring protocol for Solar City sites	(I) Develop protocol,	1
Project Implementation	2012-2013	Report on indoor and outdoor methodology results IEC 61853-1	(i) Assessment of Methodologies	2
	2013-2014	Perform Spectral calibration procedure on selected modules	(I) Develop procedure guideline	6,7
	2013-2014	Perform angle of incidence procedure on selected modules	(I) Develop procedure guideline	3, 4
	2013-2014	Establish feasibility of IEC irradiance and temperature conditions for Canadian environment	(F) Evaluation of findings	1
Data Acquisition	2013-2014	Perform yield calculation for test modules as per IEC 61853-3	(I) Develop procedure guideline	6
	2013-2014	Populate IEC 61853 (part 1) Power Matrix using indoor and outdoor test procedures on 2nd generation of test modules from Canadian Manufacturer	(I) Peer review	2
	2013-2014	Evaluate Energy Yield Calculation (model) from Section 1 power measurements with measured energy yield from real field conditions tested by TRCA. (1st generation)	(I) Peer review; develop internal report	6
	2014-2015	Systems Analysis comparing performance of project arrays relative to models derived from standard	(I) Peer review; develop internal report	6,7,8,9,10
	2014-2015	Preliminary comparisons between Yield Model, Energy yield from field conditions, and PV Syst. Modeling software	(I) Peer review of findings	6,7,8,9,10
	2014-2015	Report from utilities of preliminary findings regarding power quality and transience; recommendations for further investigation	(I) Peer review of findings	11

Analysis and Reporting	2015-2016	Yield report for 3rd and 4th generation test modules	(F) Publish Report	6
	2015-2016	System analysis of 2nd and 3rd Solar City site	(F) Publish Report	1
	2015-2016	formula for the application of power and energy ratings as per the IEC 61853 to standard Canadian Weather Data for Energy Calculations file (CWEC)	(I) Peer review of formula	
	2015-2016	Case study of formula application	(F) Publish Report	7
	2015-2016	Report from utilities identifying key findings and areas for further research	(F) Publish Report	All

4.0 FINDINGS

The table below provides answers to the research questions posed in Table 2-4. Details on the methods and findings can be found in the Addendum to this report.

Table 4-1. Answers to questions posed in this project

Standard	Question No.	Answers to research questions
IEC 61853-1	1	Q. Are the temperature and irradiance conditions in IEC 61853-1 sufficient for a Canadian climate? Should points be added or deleted to better represent the climate? A. Some of the operating points in this standard will never occur in a Canadian climate and, because the standard only considers operating points with module temperatures above 15°C, a number of Canadian locations are not represented. Additional operating points at 5°C are recommended.
	2	Q. Does Procedure 3 (the new procedure) produce results that are in agreement with the other established procedures? A. No. Unlike IEC 60904-1, which informs the procedures in this standard, the procedure in natural sunlight without tracker does not incorporate any mechanisms to ensure that the module rear-surface temperature is representative of the cell temperature. This introduces a high degree of variability and error. It is recommended that this procedure be removed until this issue can be rectified.
IEC 61853-2	3	Q. Do the indoor and outdoor IAM procedures agree? A. Yes. Good agreement was seen when PV-based irradiance devices were used. Small deviations between successive days of outdoor testing were observed when a thermopile pyranometer was used. The impact of that observation on the test procedure is inconclusive because the testing took place over an entire day rather than only for an hour and in the vicinity of solar noon.
	4	Q. Is any further guidance required in regards to the sensor type used in the IAM measurement? A. It would be beneficial if the standard described exactly how to use the IAM of an irradiance sensor within the calculation

		procedure.
	5	Q. Is the module thermal model procedure achievable and is their sufficient guidance within the standard? A. The procedure needs significant work. Especially since there are greater ramifications of this beyond IEC 61853. IEC 61215 now looks to IEC 61853-2 for the nominal module operating temperature procedure (NMOT).
IEC 61853-3 & -4	6	Q. Since the CSER is a performance ratio, does the IEC 61853-3 procedure agree with predictions from industry standard software like PVSyst? Does it agree with real-world data? A. Yes, sufficient agreement with both was demonstrated.
	7	Q. Does the standard provide sufficient guidance to complete the calculation procedure? A. Yes. Comments were provided to IEC regarding additional changes to the standard. Most comments were accepted and it is the author's opinion that the updated procedure provides sufficient guidance.
	8	Q. How much do IAM and spectral corrections matter? A. Depending on the location and the module spectral response, IAM and spectral corrections can have a negligible effect to as much as a 5-6% (each) change in CSER. It is important that both corrections are taken into account within the standard because climate conditions of different geographical areas introduce important variations in the CSER value.
	9	Q. How different are the climate profiles that were selected? A. The original climate datafiles that were explored in this work were not sufficiently different from each other. However, the most recent draft has updated and improved the climate datafiles such that are sufficiently different from each other and therefore more representative of the global climate.
	10	Q. Do the current climate data files sufficiently represent a Canadian climate? How might a Canadian climate data file be incorporated into the standard?

		A. It is the authors opinion the original climate datasets explored in this study did sufficiently represent a Canadian climate (as much as could be expected given that 6 datafiles are intended to represent the different climate regions of the entire world). The climate datafiles have since been updated to include a Canadian location. It is the author's opinion that the updated datafiles still sufficiently represent a Canadian climate.
CSA 107.1 CSA 257 IEEE 1547 UL 1741	11	Q. Are there any notable issues related to current harmonic emissions that may occur outside of the operating points considered in these standards (possible due to transient or low-irradiance conditions)? A. Yes. In the current standards, it is possible for an inverter to be compliant yet have potentially problematic levels of current harmonic emissions during low power operating points. It is recommended that the standards also have specific current harmonic emission limits when operating at low power (for example, at 10% of its rated load).

5.0 CONCLUSION

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6.0 NEXT STEPS

- Given that IEC 61853-3 and -4 are still in the committee draft stage, comments resulting from this project have already been submitted and incorporated into those standards. At this point in time no further work is needed following up on the conclusions of this project.
- A number of comments were submitted to IEC in regards to the IEC 61853-2 module thermal model procedure. Several refinements to the standard are needed, especially since IEC 61215-2 now looks to this standard for part of the nominal module operating temperature (NMOT) procedure.
- The IEC 61853-1 procedure in natural sunlight without tracker needs to be refined. As currently worded, due to the limited guidance, it will produce erroneous results.
- Additional operating conditions at 5°C should be added to the IEC 61853-1 power matrix.
- CAN/CSA-C22.2 NO. 107.1-01 should be revised to include a low power operating point (on the scale of 10% of the rated inverter capacity, or less) in the current harmonic emission requirements.