ARTICLE IN PRESS

Renewable and Sustainable Energy Reviews xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Measurement uncertainty in energy monitoring: Present state of the art

Herman Carstens[a,*], Xiaohua Xia[a], Sarma Yadavalli[b]

[a] Centre for New Energy Systems (CNES), Department of Electrical, Electronic, and Computer Engineering, University of Pretoria, South Africa
[b] Department of Industrial and Systems Engineering, University of Pretoria, South Africa

ARTICLE INFO

Keywords:
Measurement and verification
Energy metering
Project risk
Measurement error models
Calibration
Metrology
Mismeasurement
Errors-in-variables

ABSTRACT

Measurement uncertainty is a key component in the overall uncertainty calculation for Measurement and Verification (M & V) projects. However, in some cases, it is reduced to outlier detection or basic uncertainty propagation calculations. In other cases, funds are spent on determining uncertainties that have little effect on project decisions. Therefore a need exists for a fuller treatment of the subject in the light of literature from M & V and other fields. This paper surveys general M & V literature, as well as relevant research from metrology, electrical engineering, economics, decision analysis, and statistics. Electrical metering and sub-metering uncertainty is investigated, as well as often-overlooked considerations such as power quality and the cost of calibration. The effect of mismeasurement on energy models and practical techniques for mitigating such effects are assessed. Last, research on building simulation and project decisions in the light of measurement error is surveyed. Bayesian methods are found to be a recurring theme in much of the research being conducted on all of these aspects. Power quality and mismeasurement effects have also been found to make a material difference in project evaluation. The survey is concluded with recommendations for further research in the light of current trends in data analysis and energy evaluation.

1. Introduction

The International Performance Measurement and Verification Protocol (IPMVP) [1] notes that three forms of uncertainty arise in energy Measurement and Verification (M & V): measurement uncertainty, sampling uncertainty, and modelling uncertainty [1]. Although research on combining sampling and modelling uncertainty has been done by Ye et al. [2,3] and Carstens et al. [4] on lighting projects, and Sun on building energy performance [5], measurement uncertainty is usually assumed to be negligible. Nevertheless, the cost-effective allocation of measurement resources continues to be a pertinent question for decision makers. The aim of this survey is to introduce M & V professionals and researchers to the salient literature on various topics related to measurement uncertainty in energy monitoring.

While one usually associates measurement in M & V with electricity meters, instruments measuring with error also include surveys and questionnaires [6], tracking databases, non-intrusive load monitoring, and inspection reports [7]. These instruments may measure or record any number of variables such as occupancy [8], floor area, schedules, income, the proportion of Miscellaneous Electrical Loads (MELs) [9,10], etc. Sometimes data such as plug load energy use are used as a proxy to measure occupancy [11]. More about this in Section 3.5.

Are cheaper, smarter meters and the big data revolution not going to render measurement uncertainty concerns obsolete? Advanced Metering Infrastructure (AMI) is being rolled out in the United Kingdom (UK) and Europe, although state regulation is more fractured in the US [12]. Although these regions represent only 12.4% of the world population, they consume 66.2% of the world's electricity.[1] The nature of M & V in these regions is changing, with promising results for M & V 2.0 already being published [13]. On the other hand (or hemisphere), 17% of the world population still have no access to electricity, and 38% still cook using biomass [14]. Many of these live in sub-Saharan Africa, and

Abbreviation: AMI, Advanced Metering Infrastructure; ANSI, American National Standards Institute; ASHRAE, American Society of Heating, Refrigeration, and Air Conditioning Engineers; CCC, California Commissioning Collective; CDM, Clean Development Mechanism; CFL, Compact Fluorescent Lamp; DMM, Digital Multimeter; CT, Current Transformer; DAQ, Data Acquisition (board); ECM, Energy Conservation Measure; EPC, Energy Performance Contract; ESCO, Energy Services COmpany; EV, Expected Value; G14, ASHRAE Guideline 14-2002 and 14-2014; GP, Gaussian Process; GUM, Guideline for the expression of Uncertainty in Measurement; HVAC, Heating, Ventilation, and Air Conditioning; IPMVP, International Performance Measurement and Verification Protocol; IEC, International Electrotechnical Commission; IEEE, Institute for Electrical and Electronic Engineers; ISO, International Standard Organization; MC, Monte Carlo; MEL, Miscellaneous Electrical Load; MID, Measurement Instrument Directive; MCMC, Markov Chain Monte Carlo; M & V, Measurement and Verification; MEM, Measurement Error Model; MLE, Maximum Likelihood Estimation; OLS, Ordinary Least Squares; NREL, National Renewable Energy Laboratory; PDF, Probability Density Function; SEE Action, State and Local Energy Efficiency Action group; SEM, Stick-on Electricity Meter; TUR, Test Uncertainty Ratio; UMP, Uniform Methods Project; UUT, Unit Under Test

* Corresponding author.
E-mail address: hermancarstens@gmail.com (H. Carstens).

[1] World Bank Open Data Portal. URL: beta.data.worldbank.org.

http://dx.doi.org/10.1016/j.rser.2017.10.006
Received 6 September 2016; Received in revised form 16 August 2017; Accepted 3 October 2017
1364-0321/

Please cite this article as: Carstens, H., Renewable and Sustainable Energy Reviews (2017), http://dx.doi.org/10.1016/j.rser.2017.10.006

for the companies serving these billion people, the big data revolution is still some way off.

We should also note that AMI improves sampling rather than measurement uncertainties. Even so, investigations into big data in energy monitoring [13,15,16] are welcome, although bigger data are no remedy if it is still measured with error. Although the tools and methods are improving and becoming automated, measurement error will continue to be relevant to M & V professionals. However, it does not seem to be discussed directly in most M & V literature, and we hope that this work goes some way in addressing this gap.

This survey is structured around the following questions:

- What does current literature say about measurement uncertainty? How is it addressed in metrology?
- What are the sources of electrical metering uncertainty? What are the effects of mismeasurement, has it been documented in energy monitoring, and how can it be mitigated?
- How does measurement uncertainty affect project decisions?

2. Background

2.1. Measurement uncertainty in M & V literature

Measurement uncertainty is acknowledged in M & V literature, although firm guidance is seldom given. A summary of guideline characteristics in this respect can be found in Table 1. The American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE's) Guideline 14-2002 [17,18] (henceforth referred to as G14) is the foremost technical resource for M & V. It provides comprehensive guidance on instrumentation, data-handling, uncertainty calculations, as well as a catalogue of uncertainties for a wide variety of energy-related measurement instruments. It has recently been updated to a 2014 version [19], although the original remains useful. 'G14' will refer to both, unless stated otherwise. G14 and the California Commissioning Collective [20] (CCC) adopt Reddy and Claridge's alternative fractional-savings parametrisation of measurement uncertainty [21]. The IPMVP [1,22] provides general guidance on uncertainty but does not address measurement uncertainty in much detail. The National Renewable Energy Laboratory (NREL's) Uniform Methods Project (UMP) [23] establishes best practices for energy data collection and is the only guideline to discuss mismeasurement at all. ASHRAE Guideline RA96: *Engineering Analysis of Experimental Data* [24] also deserves mention. It is a general quantitative introduction to handling measurement uncertainty in engineering measurements and could be applied to some M & V cases. The State and Local Energy Efficiency (SEE) Action group's *Energy Efficiency Programme Impact Evaluation Guide* [25] (hereafter referred to as the SEE Action Guide) is also notable and does give practical guidance on uncertainty. Finally, some preliminary work on the relative contributions of measurement and sampling uncertainty in M & V has also been presented by Carstens, Xia, and Yadavalli [26], and a method for low cost calibration of energy meters proposed [27]. Recently, Ligier et al. [28] proposed a method for accounting for M & V uncertainty alongside building simulation, and did consider measurement uncertainty in the model.

Greenhouse Gas reduction programmes often require M & V. Vine et al. reported on different options considered for dealing with measurement uncertainty in such cases [29]. Although this was a work in progress in 2002, it is still relevant, since the debate around the advantages and disadvantages of different measurement approaches is explained well. Discount factors to compensate for the uncertainty of various methods are also listed. The scale of the United Nations Framework Convention for Climate Change's Clean Development Mechanism (UNFCCC CDM) methodology specifications dwarfs other M & V documentation. It contains over two hundred methodologies for different project scales and applications. Accuracy requirements vary, but the 90/10 criterion is most common, although Sonnenblick and Eto [30] have shown that this precision level is only necessary for projects where the savings to cost ratio to be verified is small. In many cases, 90/50 is adequate for identifying project cost-effectiveness, that is, whether or not a project saved energy.

Shishlov and Belassen [31] provided a useful review of how monitoring uncertainty is approached in the CDM. For example, CDM AM0046 requires Compact Fluorescent Lamp Retrofit programmes to be monitored very stringently at the insistence of regulators, even requiring custom-made meters. Michaelowa, Hayashi, and Marr [32] who developed the methodology noted that no projects were completed under AM0046 until the alternative AMS II.C [33] was adopted. Later AMS II.J [34] was also adopted. In it, every CFL is deemed to operate for 3.5 h/day, eliminating the need for measurement. Even so, they assert that there are still projects that would reduce emissions but are ineligible. These difficulties illustrate that measurement goals should always be construed in the larger project and social context. Achieving

Table 1
The treatment of measurement uncertainty in leading M & V guidelines.

Name	Year	Level of detail	Features	Reference
G14	2002, 2014	10	• Most comprehensive treatment of M & V uncertainty	[18,19]
			• Excellent methods	
			• Instrument uncertainty database	
			• Itemized measurement costs	
			• Technology slightly dated in 2002 version	
IPMVP	2012	5	• Introductory treatment	[1,22]
			• Sensitivity and Uncertainty Analysis worked examples	[1]
CDM	2015	8	• Approach varies between methodologies	[41,31]
			• Emphasis on being conservative	[32]
			• Discount factors used for >95/5 measurement error	[35]
			• 95/10 assumed for unknown measurement error	[35]
			• Deemed Savings also used	[34]
			• MC recommended for complex cases	
UMP	2014	6	• Varies with authors of chapters	[23]
			• Errors-in-variables discussed in Chapters 13, 23	[43,44]
			• Metering error discussed in Chapter 9	[45]
			• Survey error discussed in Chapter 11	[46]
SEE Action Guide	2012	4	• Practical guidance	[25]
			• Discussion of uncertainty and project risk	
CCC	2012	6	• Appendix on uncertainty analysis	[20]
			• Adopts and simplifies fractional savings approach	

Abbreviations: CCC, California Commissioning Collective; CDM, Clean Development Mechanism; G14, ASHRAE Guideline 14-2002 and 14-2014; IPMVP, International Performance Measurement and Verification Protocol; SEE Action Guide: State and Local Energy Efficiency Programme Impact Evaluation Guide; UMP, Uniform Methods Project.