Applied Energy 111 (2013) 247–256

Contents lists available at SciVerse ScienceDirect

Applied Energy

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

Mathematical description for the measurement and verification of energy efficiency improvement ☆

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HIGHLIGHTS

- A mathematical model for the measurement and verification problem is established.
- Criteria to choose the four measurement and verification options are given.
- Optimal measurement and verification plan is defined.
- Calculus of variations and optimal control can be further applied.

ARTICLE INFO

Article history:
Received 6 February 2013
Received in revised form 17 April 2013
Accepted 18 April 2013

Keywords:
Energy efficiency
Measurement and verification
Modeling

ABSTRACT

Insufficient energy supply is a problem faced by many countries, and energy efficiency improvement is identified as the quickest and most effective solution to this problem. Many energy efficiency projects are therefore initiated to reach various energy saving targets. These energy saving targets need to be measured and verified, and in many countries such a measurement and verification (M&V) activity is guided by the International Performance Measurement and Verification Protocol (IPMVP). However, M&V is widely regarded as an inaccurate science: an engineering practice relying heavily on professional judgement. This paper presents a mathematical description of the energy efficiency M&V problem and thus casts into a scientific framework the basic M&V concepts, propositions, techniques and methodologies. For this purpose, a general description of energy system modeling is provided to facilitate the discussion, strict mathematical definitions for baseline and baseline adjustment are given, and the M&V plan development is formulated as an M&V modeling problem. An optimal M&V plan is therefore obtained through solving a calculus of variation, or equivalently, an optimal control problem. This approach provides a fruitful source of research problems by which optimal M&V plans under various practical constraints can be determined. With the aid of linear control system models, this mathematical description also provides sufficient conditions for M&V practitioners to determine which one of the four M&V options in IPMVP should be used in a practical M&V project.

1. Introduction

With the current economic growth, energy supply cannot meet the increasing demand in many countries. To solve the energy supply problem and also to protect the environment, renewable energy sources are developed, and many energy efficiency projects are also implemented across the world. These energy projects are often started with specific energy saving targets, and the success of these projects need to be determined by checking whether the relevant energy saving targets have been reached. This kind of checking process is called measurement and verification (M&V), and is often carried out by project developers or an independent third party inspection body. The M&V inspection body will undertake a monitoring process and deliver the corresponding energy saving assessment. These energy saving M&V activities are usually guided by the International Performance Measurement and Verification Protocol (IPMVP) [1]. There are also some other energy saving M&V guidelines which are essentially similar to IPMVP, and these guidelines include, but are not limited to, the M&V Guideline for the Federal Energy Management Program [2]; the M&V Guideline of the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) [3]; the South African M&V guideline for Demand Side Management projects [4]; and the Australian best practice guideline [5].

Helpful M&V methodologies and examples are given in the above energy saving M&V guidelines. These M&V methodologies from different guidelines are essentially the same with what is

☆ A preliminary version of this paper has been published in the IEEE AFRICON 2011, Zambia, 13–15 September 2011.

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0306-2619/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2013.04.063

proposed in the IPMVP, in which four M&V methods, Option A, Option B, Option C, and Option D, are given. The first two methods, Options A and B, are applicable to energy subsystems which can be isolated from the whole energy system, where the notion of energy system refers to a system consisting of all energy related facilities and factors under consideration. The later two methods, Options C and D, are applicable to the whole energy system level and do not consider subsystems independently. Option A is defined as partially measured isolated retrofit and only key system parameters are monitored. Option B is applied to the isolated retrofit with full measurement, and all the system parameters are monitored. Option C is designed for monitoring at the whole facility level, and interactions within the system are often ignored. Option D is a comprehensive calibrated simulation, whereby computer simulations for the system performance is performed to calculate energy savings. Although these M&V methods are discussed in these existing M&V guidelines, it is still difficult to find a proper M&V method or plan for a complex energy project so that the reported performance is accurate enough. It is therefore interesting to find out how these general M&V guidelines can be applied in various specific energy projects. Ref. [6] discusses the M&V method for a motor sequencing control of a conveyor belt system, [7] gives a general method for calculating plant-wide industrial energy savings, [8,9] propose a bottom-up approach to energy saving calculations; [10–14] study the uncertainties in M&V, [15] considers the Louisiana home energy rebate offer program, [16] proposes general guidelines for energy modeling in M&V, [17] provides the M&V strategies for energy savings certificates, [18] discusses the M&V for demand response, [19,20] describe the M&V experiences in the United States and South Korea, [21] gives an M&V system design for buildings, [22] provides a case study for a underground pumping system in a mine, and [23] discusses the general M&V process in South Africa.

As defined in [1], the concept Energy Conservation Measure (ECM) is "used to mean measures to improve efficiency or conserve energy or water, or manage demand". All the existing ECM M&V studies compare the energy/power consumption after an ECM with the baseline energy/power consumption to find the corresponding savings. The baseline consumption is assumed to be the corresponding energy/power consumption at the post-implementation period if the ECM was not implemented so that the baseline consumption and actual consumption during the post-implementation period will have the same exact ambient environment such as temperature, and production. However, the baseline consumption at the post-implementation period is never measurable. Therefore, it is either assumed to be the same as the baseline measured or calculated at the pre-implementation period, or adjusted to the post-implementation period based on the pre-implementation baseline consumption data. There is no theoretical analysis to explain how the post-implementation baseline consumption can be obtained from the pre-implementation consumption. In practical ECM M&V projects, the selection of the IPMVP M&V Options A, B, C, and D is usually determined by experience. An M&V plan is also obtained by the experience of M&V professionals, and as such an M&V plan may be far from optimal when there are particular requirements on accuracy and M&V cost. Therefore, scientific ways to select IPMVP M&V options and optimize M&V plans need to be addressed.

This paper aims to provide a mathematical description for ECM M&V problems so that scientific rules behind existing M&V practices are discovered, and M&V option selection and M&V plan development in M&V practices are also guided by scientific principles. In this way, M&V becomes a rigorous branch of science. To this end, general energy system modeling and ECM M&V modeling processes from existing M&V practices are summarized, the concepts of baseline and optimal M&V plan are further defined. The notions of exogenous functions and service level functions are introduced so that baseline at the post-implementation stage can be characterized as functions of exogenous and service level functions. The criteria to select the four M&V Options A, B, C, and D are discussed from a control system point of view. With the above mathematical description, the optimal M&V plan problem is formulated as a calculus of variation or optimal control problem. Since M&V cost and/or M&V uncertainty can be put as objectives or constraints in the M&V plan optimization model, M&V cost and M&V uncertainty can be minimized.

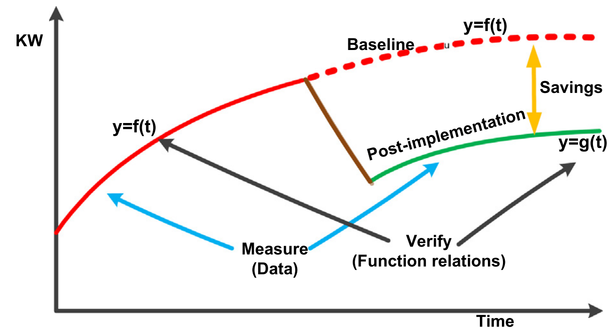

Fig. 1. What is M&V.

The paper is organized as follows. A mathematical description on energy modeling, M&V modeling, and the corresponding applications are given in Section 2. The mathematical formulation of optimal M&V plan is introduced in Section 3, and conclusions are made in Section 4.

2. A mathematical description of M&V for ECM projects

2.1. What is M&V

The general principle of M&V is illustrated in Fig. 1. The power consumption before the implementation of any ECM project is called the baseline power consumption. This baseline power consumption is marked in red[1] and expressed as the function $y = f(t)$ in Fig. 1, where y is the power consumed at time t. If the ECM was not implemented, the power consumption could still be represented by the function $y = f(t)$ (see the red dotted line). With the implementation of the ECM, power consumption level becomes lower at the post-implementation period, and this post-implementation power consumption can be characterized by another function, $y = g(t)$. The difference between $f(t)$ and $g(t)$ gives the savings from the ECM. However, the determination of the savings $f(t) - g(t)$ is not straightforward since $f(t)$ at the post-implementation stage does not physically exist and therefore cannot be measured. The determination of $f(t)$ at the post-implementation stage becomes the most tricky part in M&V, and it will be discussed in the following subsections.

2.2. Energy system modeling

There are plenty of study on various energy system modeling in literature (see, for example, [24–27]). This section introduces general energy modeling notations and terminologies to facilitate the discussions on M&V modeling. Consider the performance of an energy system over a given time period $[t_0, t_f]$. Let $z(t) = (z_1(t), \ldots, z_n(t))^T$ be an n-dimensional vector denoting all variables in the energy system, and $p(t) = (p_1(t), \ldots, p_m(t))^T$ an m-dimensional

[1] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.