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Review

Sustainability and process control: A survey and perspective

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1. Introduction

Sustainability has been defined as the concept of meeting the needs of the present without compromising the ability of future generations to meet their own needs [1]. Other definitions have also appeared, emphasizing that sustainability views economic, social and environmental systems as interacting ones, and therefore requires a balanced approach to managing their resources [2–4]. Therefore, by its very nature, sustainability recognizes complexity, interactions between human activities and the environment, integration of different sub-systems, as well as the need to assess and optimize system-wide effects of localized decisions and actions.

Driven in large part by concerns on climate change and its connection to fossil fuel utilization, as well as the growing realization of the common threads connecting food, water and energy, over ever-expanding boundaries, sustainability is becoming a pervasive trend, a guiding and organizing principle which is expected to define societal and economic development in this century. At the same time, it is also becoming a major driver of technological innovation. Terms such as renewable energy, green engineering [5], green manufacturing [6], green chemistry [7], green design, green products, and industrial ecology [8] reflect major scientific and technological pursuits, underwritten by sustainability considerations. At their heart is the quest for energy efficiency, waste minimization, use of renewable raw materials and energy sources, and the assessment/tracking of material and energy flows over expanded boundaries.

Within this framework, this paper aims to survey process control research related to sustainability, and to provide a perspective on future research directions. Our thesis is two-fold:

1. Process control is a key enabling technology for developing and implementing sustainable solutions in the process and energy industry sectors.
2. Sustainability practices create operational challenges which in turn motivate new fundamental problems in control method development.

To be able to provide a meaningful survey, we need some boundaries on its scope. The paper will not address subjects such as product and process design, steady state optimization, supply chain optimization, and life cycle analysis. These are key sustainability drivers, and although they fall within the premise of systems engineering solutions, they are not directly related to dynamics and control. Excellent discussions and reviews on such topics can be found, for example, in [9–14]. The paper will also not cover process monitoring and process analytics in general, a vast subject on its own right. Energy storage technologies (e.g. batteries and electrolyzer-fuel cell systems) will be discussed briefly in the context of integration of renewables; a detailed discussion on the control of these units will not be included due to the vast body of literature in this area too. The literature to be surveyed will be (with very few exceptions) from the last 15 years.

From a process systems and control perspective, the following goals (adopted from the sustainability scorecard presented in [15]) can be identified as relevant to sustainability practices:

1. Economic:
   (a) recover, reuse, recycle of material and energy
   (b) minimize raw material costs and energy costs
   (c) minimize capital costs
   (d) increase process and energy efficiency
2. Environmental:
   (a) minimize carbon footprint
   (b) minimize water footprint
   (c) minimize emissions/waste
   (d) harvest and use renewable energy
   (e) maximize eco-efficiency
3. Social:
   (a) process safety

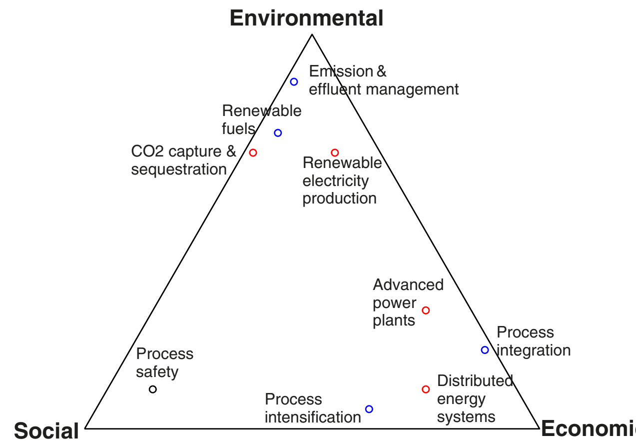

Fig. 1. Sustainability goals and the corresponding technology drivers.

These goals motivate various sustainability-related technology drivers, such as process integration, process intensification, renewable energy production, and emission and effluent management. Fig. 1 depicts some of these drivers and their relation to the economic, environmental and social goals listed above. The exact location of each theme on this diagram obviously reflects the collective judgement of the authors, but we believe it is generally accurate. For example, process integration primarily targets economic benefits via recovery and recycle of material and energy. On the other hand, CO_2 capture and sequestration focuses on environmental goals rather than economic ones. Process intensification, as in the case of micro-reactors, in addition to economic benefits also addresses social ones like process safety through minimization of hazardous chemical inventory.

The above considerations provide the framework for this survey. The paper is organized along two broad themes: *process systems*, encompassing mainly chemical and petrochemical plants, and *energy systems*. In the former theme, process integration and process intensification are discussed first, as two major strategies for achieving sustainability. Emphasis is placed on the unique control challenges that result from these strategies and the fundamental control problems that they motivate. Control research on processes for emission/effluent management and renewable fuel production (from biomass or algae) is subsequently discussed. Under the broad theme of energy systems, the discussion focuses on power plants (including CO_2 capture and sequestration and nuclear power plants), renewable electricity production (wind, photovoltaics, concentrated solar and hydropower) and distributed energy systems (including smart grids, microgrids, and HVAC and cogeneration systems). In the final section, we discuss research on integration of operational hierarchies (e.g. integration of scheduling and control, or optimization and control), highlighting the common occurrence of these problems in both process and energy systems. We also discuss broader system integration opportunities that give rise to similar problems.

2. Process systems

Sustainability is closely tied with the design of process systems. It is achieved through recovery and recycle of mass and energy, efficient management of carbon cycle, emission and waste reduction,