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Assessment of long-term energy efficiency improvement and greenhouse gas emissions mitigation potentials in the chemical sector

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ABSTRACT

The industrial sector accounts for more than one-third of global energy consumption and greenhouse gas (GHG) emissions. In the sector, the chemical industry makes up nearly 30% of global industrial energy consumption. In this study, a framework is developed to apply bottom-up energy modelling for analyzing energy efficiency improvement and GHG mitigation potential in the chemical sector. Also, techno-economic and policy analyses are used to analyze the applicability and economic performance of different mid- to long-term energy efficiency measures. The comprehensive, data-intensive, and technology-rich model is flexible and can be used to study the GHG mitigation potential in different regions. A case study was conducted for Alberta, one of the biggest industrial hubs in Canada, using the Long-range Energy Alternative Planning model. Twenty-eight GHG mitigation scenarios in the petrochemical and fertilizer industries (the two major chemical industry sub-sectors) were developed. The costs of implementing each mitigation measure were calculated and used to develop cost curves. The results suggest that cumulative mitigation potential from the chemical industry would be 7.1 and 29.7 megatonnes CO_2 equivalent in the periods ending 2030 and 2050, respectively. We also found that more than 75% of the emissions reductions are achievable with negative cost.

1. Introduction

The industrial sector accounts for more than one-third of global energy consumption and greenhouse gas (GHG) emissions [1,2]. Energy consumption in industries increased more than 66% between 1971 and 2014 [3]. With historical annual average increases of 2.2% in energy consumption [2], in 2011 the chemical sector accounted for almost 28% (including feedstock) of total energy consumption in the industrial sector globally[1] [1]. In terms of cost, energy can be up to 60%–80% of total production costs in the chemical industry [2]. High levels of energy consumption, along with associated environmental impacts and costs, highlight the importance of energy conservation in the sector.

1.1. Brief literature review

The existing literature on energy efficiency improvement in the sector generally focuses on the major energy consumers such as the petrochemical and fertilizer sub-sectors. Some of these studies focus on specific energy efficiency technologies. For example, in 2009 Ren and Patel compared the energy and emission intensity of petrochemical products using different conventional and biomass feedstock [7]. An International Energy Agency (IEA) study found that catalytic processes could help reduce the energy intensity of chemical processes by 20–40% in the long term. The study also highlighted the importance of biomass and renewable hydrogen in reducing emissions from the sector [8]. Innovative technologies in the naphtha cracking process (the most energy-intensive process in the chemical industry) were analyzed by Ren et al. in 2006. Their results suggest a 20% energy intensity improvement potential in the process [9]. Similarly, the impacts of demand-side management (the application of energy-efficient motors) and on-site cogeneration technology on the overall energy consumption of the chemical plants were assessed in by Pillay and Fendley [10] and Szklo et al. [11]. Menezes et al. assessed the economic feasibility of steam traps

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[1] i.e., in 2011, total energy consumption in the chemical sector was reported to be 949 Mtoe.

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Abbreviations

ACCA	Accelerated capital cost allowance
AED	Alberta Economic Development and Trade
AESO	Alberta Electricity System Operator
AI-EES	Alberta Innovates - Energy and Environmental Solutions
BAU	Business as usual
CAD	Canadian dollar
CO_{2eq}	CO_2 equivalent
CSC	Cost of saved carbon
CSE	Cost of saved energy
FPSC	Formulated products and specialty chemicals
GHG	Greenhouse gas
LEAP	Long-range Energy Alternatives Planning system
LTS	Low temperature shift
MDEA	Methyldiethanolamine
MEA	Monoethanolamine
MT	Million tonne
Mtoe	Million tonne oil equivalent
NEB	National Energy Board
N-Fertilizers	Nitrogen fertilizers
NPV	Net present value
NRCan	Natural Resources Canada
O&M	Operation and maintenance
PJ	Petajoule
SEC	Specific energy consumption
SOA	State of the art
USD	United States dollar

and insulation for energy efficiency improvement in the steam system of a petrochemical plant in Brazil [13–15].

Other studies assess the implementation of energy efficiency measures through high-level scenario and policy analyses. For example, Fan et al. used decomposition analysis to evaluate the impacts of industry output, structure, and technical factors on the GHG emissions from China's petrochemical industry [16]. Griffin et al. identified the opportunities for energy efficiency improvement and emissions reduction in the UK chemical sector [14]. The high-level approach used in that study led to a qualitative analysis of short- to mid-term (process improvement, process substitution, and carbon sequestration) and long-term (i.e., use of biomass as feedstock) energy efficiency improvement options in the sector. Chan et al. identified the major energy-consuming chemical sub-sectors in Taiwan and compared their energy intensity with global best practices to assess the energy intensity improvement potential [15]. Levi and Cullen, analyzed chemical flows from resources to final products and highlighted the importance of material flow analysis in attempts to mitigate GHG emissions [17]. Ren analyzed the barriers and drivers of energy efficiency improvement in the chemical industry [18]. Zhou et al. developed different scenarios to estimate the GHG mitigation potential in China's ammonia industry. In that study, a top-down approach focusing on fuel consumption with less emphasis on technological energy efficiency improvement was used for scenario analysis [19]. The long-term impacts of different energy efficiency clusters on sectoral GHG emissions were quantified by developing three top-down scenarios in the UK [20] and in Thailand [21].

A review of the literature suggests that the application of technology-level analysis to develop systems-level energy efficiency strategies is less common in the studies that focus on the chemical sector. A few studies assessed overall energy saving potential in the industry at the systems level. Table 1 provides an overview of existing studies on different aspects of energy savings in the chemical sector.

As Table 1 shows, a limited number of studies use a bottom-up approach to analyze energy consumption in a system as a whole. A bottom-up approach provides the opportunity to assess energy consumption at a process/facility level, from which a systems-level analysis could be conducted. Despite the proven features for system analysis [23,24], the application of bottom-up energy modelling in the industrial sector is limited. This is basically due to the complexity of the industrial sector, variations in industrial products, and the role of energy carriers both as a source of energy and in some industries as a feedstock.

1.2. Aims and objectives

The current study aims to address the existing gaps in the literature and develop a comprehensive framework to analyze the energy efficiency improvement and GHG mitigation potential from the chemical industry and the associated costs in the mid- to long-term. To this end, a combination of techniques including energy modelling and scenario analysis, techno-economic assessment, and policy analysis is applied. The specific objectives of this research are to:

- Develop a comprehensive and flexible framework for analyzing the long-term GHG mitigation from different industrial sectors;
- Apply the framework and develop a data-intensive, technology-rich, and transferrable model to analyze the process-level energy consumption in different chemical sub-sectors;
- Identify the major energy consuming sub-sectors and the areas with potential for energy efficiency improvement;
- Identify the process-level energy savings technologies within the chemical sector;
- Assess the applicability of the energy saving options and their potential for GHG system-level GHG mitigation in mid-to long-term;
- Analyze the economic performance of different energy efficiency options; and
- Develop an emissions reduction cost curve to assess and prioritize options based on their GHG mitigation potential and on associated cost.

In order to meet these objectives, a case study was conducted for Alberta's (a western province in Canada) chemical sector. In Alberta, the sector is responsible for 12% and 9.6% of industrial energy consumption and GHG emissions, respectively. The considerable GHG emissions from the chemical industry and the expected increasing trend make the sector one of the most important areas to achieve GHG mitigation.

To the author's knowledge, there are currently no studies in the literature that assess the long-term energy-efficiency improvement and GHG mitigation potential in the Canadian chemical sector. Therefore, the contribution of the of the current work is two-fold: a) to develop a comprehensive and data-intensive framework that is flexible and transferable to study the long-term GHG mitigation potential in the chemical sector in other jurisdictions and b) to conduct a case study and analyze the low-carbon pathways through which Alberta's chemical sector could develop.