Energy sustainability and industry 4.0

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Abstract. The world is witnessing the fourth industrial revolution, as known as Industry 4.0, which integrates advanced manufacturing and operations techniques with the most recent digital and information technologies to create dynamic, interconnected, and smart manufacturing ecosystems. The underlying components of Industry 4.0 such as smart factories and technology trends also need an ever-increasing powering, and energy sustainability has strong ties to Industry 4.0. The Industry 4.0 offer numerous opportunities for energy sustainability, and the present research applies the interpretive structural modelling (ISM) not only to model the Industry 4.0 functions for energy efficiency but also sustainability. With the mentioned methodology, the research performs a systematic review of the literature to first identify the energy efficiency sustainability functions of Industry 4.0. Besides, the research further determined the opinion of a group of experts to map and analysed the interrelationships among the sustainability functions identified. The results in this research indicates that sophisticated precedence relationships exist amongst numerous energy sustainability functions of Industry 4.0. In particular, ‘Matrice d’Impacts Croisés Multiplication Appliquée àun Classement’ (MICMAC) analysis indicates that the digital transformation of energy sector (Energy 4.0) itself, smart grids, and process optimization are the more immediate energy sustainability impacts of Industry 4.0. This research enable Industry 4.0 players including industrialists, academicians, consumers, and even governments to understand better the opportunities that Industry 4.0 may offer for energy sustainability.

1. Introduction

The world is witnessing the digitization of the ways products and services are designed, developed, and delivered. This digitally-enabled transition is commonly referred to as the Fourth Industrial Revolution or Industry 4.0 [1]. Industry 4.0 is characterized by its technology trends such as Augment and Virtual Reality AVR), Industrial Internet of Things (IIoT), (Artificial Intelligence (AI), Big Data, and cloud computing, among many other digital technologies [2]. Establishment and development of design philosophy of Industry 4.0 that include vertical and horizontal integration, interoperability, product individualization, modularity, and real-time capability, among many other principles is highly depends of these digital technologies [3].

The manufacturing efficiency functions of Industry 4.0 is indeed well-documented [4]. Experts, however, believe that Industry 4.0 and sustainable energy transition may share several particularities,
and the digital transition initiated by Industry 4.0 may offer drastic opportunities for energy sustainability [5]. Consistently, this research aims to model the process through which Industry 4.0 may contribute to energy sustainability. However, there is lack of research discussing the Industry 4.0 and energy sustainability throughout energy sustainability. The objective of present study is to model the process through which Industry 4.0 may contribute to energy sustainability.

2. Interpretive structural model of energy sustainability
ISM technique was used to identify the possible opportunities that Industry 4.0 may offer for energy sustainability and identify their interrelationships. Sequence and direction on sophisticated relationships between variables can be established and imposed by using ISM [6]. ISM is highly depends on the opinion of group of experts, and this research collected the opinions of four Industry 4.0 and energy sustainability experts.

2.1. Listing Industry 4.0 energy sustainability functions
In this research, a content centric review of literature was performed in order to identify the opportunities that Industry 4.0 may offer for energy sustainability. Table 1 lists and briefly explain seven opportunities that Industry 4.0 offers for energy sustainability. Next, a discussion session was organized with the group of experts, where the seven potential functions were discussed. The experts decided to maintain the number of functions by using the Nominal Group Technique (NGT)1.

| Energy sustainability function | Description | Source |
|--------------------------------|-------------|--------|
| Improved methods of production (IMP) | The underlying digital technologies of Industry 4.0, such as intelligent automation, IIoT, CPPS, and could data accelerate the deployment of renewable energy in the manufacturing setting. These technologies lead to the reduction of carbon emissions, optimization of energy use, and the improvement of productivity and cost savings | Ghobakhloo (2019) [4] |
| Energy sector transformation (IST) | The deployment of more sustainable energy systems will substantially alter the way energy is produced, delivered, and consumed. Smart grids, for example, offer better energy management capabilities and involve the consumers in energy management practices. | Di Silvestre et al. (2018) [9] |
| Improved production management (IPM) | The production monitoring capabilities of Industry 4.0, such as real-time production efficiency monitoring, equipment availability assessment, and intelligent quality control offer massive opportunities for production efficiency, waste reduction, manufacturing reliability, and quality excellences, opportunities that directly lead to energy efficiency and sustainability. | Ghobakhloo and Fathi (2019) [2] |
| Informed decision making (IDM) | The information processing capabilities of technologies such as cloud data, artificial intelligence, and data analytics would enable an analysis of a massive amount of data generated during the entire life cycle of products and services. The information processing capability of Industry 4.0, therefore, supports energy sustainability by the deep mining of existing data, the creation of relevant statistics, and the streamlining of informed decision-making. | Dalenogare et al. (2018) [10] |
| New business models (NBM) | Industry 4.0 connectivity supports the development of new business models such as manufacturing-as-a-service, product-as-a-service, | Ghobakhloo (2018) [1] |

1NGT is a learning and development tool that facilitate effective group decision making [7]. This technique generates information in response to an issue that can then be prioritized by a group of experts [8].
individualized manufacturing, or lean-digitized production, leading to significant productivity and energy efficiency.

Smart energy management systems (SEMS) Underlying digital technologies of Industry 4.0, smart communicative data technologies, in particular, would enable grid operators and energy consumers to have real-time control of their energy needs, consumptions, and costs, further supporting the global move towards more reliable, affordable, and clean energy. Marinakis et al. (2018) [11]

Value chain digitization (VCD) The emergence of digital supply networks, the digitization of the entire value creation network, and the new ways for integration with suppliers and customers offer valuable energy-friendly opportunities such as product individualization capability or efficient product and service development processes. These opportunities for eliminating unnecessary functionalities have profound energy sustainability implications. Müller et al. (2019) [12]

2.2. Establishing the contextual relationships
At the first stage of ISM, the contextual relationships between the determinants were developed by capturing the opinion of experts with the uses of brainstorming or nominal technique [4]. Four symbols (V, A, X, O) were used to identify the relationship between each pair of the determinants in ISM approach [13, 14]:

V: attribute i determines attribute j;
A: attribute i is determined by attribute j;
X: attributes i and j determine each other;
O: attributes i and j are unrelated.

2.3. Developing structural self-interaction matrix
By using the rules explained above, the contextual relationships between all the variables was denoted and the Structural Self-Interaction Matrix (SSIM) is established. SSIM matrix was established based on the discussion with the experts who participate in the NGT session and presented in Table 2. For instances, the table indicated that: the sustainability functions ‘improved methods of production’ and ‘value chain digitization’ mutually determine each other, given their relationship is symbolized as (X).

|      | VCD | SEMS | NBM | IDM | IPM | IST | IMP |
|------|-----|------|-----|-----|-----|-----|-----|
| IMP | X   | A    | V   | O   | V   | A   | -   |
| IST | O   | V    | V   | O   | A   | -   | -   |
| IPM | A   | A    | V   | V   | -   | -   | -   |
| IDM | A   | A    | V   | -   | -   | -   | -   |
| NBM | A   | O    | -   | -   | -   | -   | -   |
| SEMS| A   | -    | -   | -   | -   | -   | -   |
| VCD | -   | -    | -   | -   | -   | -   | -   |

2.4. Developing the initial reachability matrix
Initial reachability matrix (Table 3) was developed after SSIM. According to the standard rules within ISM principle, initial reachability matrix can be obtained by substituting V, A, X, O by 1 or 0, as shown as below [6]:

|      | VCD | SEMS | NBM | IDM | IPM | IST | IMP |
|------|-----|------|-----|-----|-----|-----|-----|
| IMP |     | 1    |     | 1   |     | 1   |     |
| IST | 1   |     | 1   |     | 1   |     | 1   |
| IPM |     | 1    |     | 1   |     |     | 1   |
| IDM | 1   |     | 1   |     |     |     | 1   |
| NBM |     | 1    |     |     |     |     | 1   |
| SEMS| 1   |     |     |     |     |     |     |
| VCD |     |     |     |     |     |     |     |
The entry \((i, j)\) is set to 1 and entry \((j, i)\) is set to 0 if the \((i, j)\) entry in the SSIM is V. The entry \((i, j)\) is set to 0 and entry \((j, i)\) is set to 1 if the \((i, j)\) entry in the SSIM is A. Both \((i, j)\) and \((j, i)\) entries are set to 1 if the \((i, j)\) entry in the SSIM is X. Both entry \((i, j)\) and \((j, i)\) are set to 0 if the \((i, j)\) entry in the SSIM is 0.

**Table 3.** Initial reachability matrix for the Industry 4.0 energy sustainability functions.

|     | IMP | IST | IPM | IDM | NBM | SEMS | VCD |
|-----|-----|-----|-----|-----|-----|------|-----|
| IMP | 1   | 0   | 1   | 0   | 1   | 0    | 1   |
| IST | 1   | 1   | 0   | 0   | 1   | 1    | 0   |
| IPM | 0   | 1   | 1   | 1   | 1   | 0    | 0   |
| IDM | 0   | 0   | 0   | 1   | 1   | 0    | 0   |
| NBM | 0   | 0   | 0   | 0   | 1   | 0    | 0   |
| SEMS| 1   | 1   | 1   | 1   | 0   | 1    | 0   |
| VCD | 1   | 0   | 1   | 1   | 1   | 1    | 1   |

The final reachability matrix, which obtained by implementing transitivity property according to the established relationship in initial reachability matrix, was showed in Table 4. Attributes X and Z are necessarily related both attributes related indirectly through attributes Y. Due to the direction between attributes is not taken into consideration, \((X, Z)\) entry becomes 1*.

**Table 4.** Final reachability matrix with driving power and dependence.

|     | IMP | IST | IPM | IDM | NBM | SEMS | VCD | Driving power | Ranking |
|-----|-----|-----|-----|-----|-----|------|-----|---------------|---------|
| IMP | 1   | 1*  | 1   | 1*  | 1   | 1*   | 1   | 7             | 1       |
| IST | 1   | 1   | 1   | 1*  | 1   | 1    | 1*  | 7             | 1       |
| IPM | 1*  | 1   | 1   | 1   | 1   | 1*   | 0   | 6             | 2       |
| IDM | 0   | 0   | 0   | 1   | 1   | 0    | 0   | 2             | 3       |
| NBM | 0   | 0   | 0   | 0   | 1   | 0    | 0   | 1             | 4       |
| SEMS| 1   | 1   | 1   | 1   | 1*  | 1    | 1*  | 7             | 1       |
| VCD | 1   | 1*  | 1   | 1   | 1*  | 1    | 1   | 7             | 1       |

2.5. **Partitioning the reachability matrix**

According to the ISM methodology suggested by Warfield [14], reachability and antecedent set for each attribute can be derived by using the final reachability matrix. Each reachability set involves the attribute itself and all other attributes which it determines, as same as antecedent set [15]. The intersection of the reachability and the antecedent sets are determined by intersection set for each attribute [16]. The attributes are hierarchized. The top position of the hierarchic level is granted to the attribute itself or attributes which intersect the reachability set or vice versa. Subsequently, by repeating the procedure with set aside the attributes that have been identified, the hierarchic level of the other attributes is obtained. Table 5 shows the final level for each determinants.
2.6. Identifying Industry 4.0 energy sustainability functions model

To model the process through which Industry 4.0 offers opportunities for energy sustainability, the extraction levels identified in Table 5 are used to build the final model of ISM. After removing the transitivities\(^2\) between various energy sustainability functions, the Industry 4.0 energy sustainability functions model is developed as Figure 1.

\(^2\)Transitivity is the assumption in ISM philosophy which indicates that attribute X is necessarily related to attribute Z if both attributes related to attribute Y. However, this role is removed during visualisation of final ISM model although transitivity is applied. For instance, attribute X do not show linkage to attribute Z in the final ISM model although transitivity property is applied.

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### Table 5. The hierarchy level of energy sustainability functions of Industry 4.0 (iterations 1 to 4).

| Factors | Reachability set | Antecedent set | Intersection set | Level |
|---------|------------------|----------------|------------------|-------|
| **Iteration 1** | | | | |
| IMP | IMP, IST, IPM, IDM, NBM, SEMS, VCD | IMP, IST, IPM, SEMS, VCD | IMP, IST, IPM, SEMS, VCD | |
| IST | IMP, IST, IPM, IDM, NBM, SEMS, VCD | IMP, IST, IPM, SEMS, VCD | IMP, IST, IPM, SEMS, VCD | |
| IPM | IMP, IST, IPM, IDM, NBM, SEMS | IMP, IST, IPM, SEMS, VCD | IMP, IST, IPM, SEMS, VCD | |
| IDM | IDM, NBM | IMP, IST, IPM, IDM, SEMS, VCD | IDM | |
| NBM | NBM | IMP, IST, IPM, IDM, NBM, SEMS, VCD | NBM | I |
| SEMS | IMP, IST, IPM, IDM, NBM, SEMS, VCD | IMP, IST, IPM, SEMS, VCD | IMP, IST, IPM, SEMS, VCD | |
| VCD | IMP, IST, IPM, IDM, NBM, SEMS, VCD | IMP, IST, SEMS, VCD | IMP, IST, SEMS, VCD | |
| **Iteration 2** | | | | |
| IMP | IMP, IST, IPM, IDM, SEMS, VCD | IMP, IST, IPM, SEMS, VCD | IMP, IST, IPM, SEMS, VCD | |
| IST | IMP, IST, IPM, IDM, SEMS, VCD | IMP, IST, IPM, SEMS, VCD | IMP, IST, IPM, SEMS, VCD | |
| IPM | IMP, IST, IPM, IDM, SEMS | IMP, IST, IPM, SEMS, VCD | IMP, IST, IPM, SEMS | |
| IDM | IDM | IMP, IST, IPM, IDM, SEMS, VCD | IDM | II |
| SEMS | IMP, IST, IPM, IDM, SEMS, VCD | IMP, IST, IPM, SEMS, VCD | IMP, IST, IPM, SEMS, VCD | |
| VCD | IMP, IST, IPM, IDM, SEMS, VCD | IMP, IST, SEMS, VCD | IMP, IST, SEMS, VCD | |
| **Iteration 3** | | | | |
| IMP | IMP, IST, IPM, SEMS, VCD | IMP, IST, IPM, SEMS, VCD | IMP, IST, IPM, SEMS, VCD | III |
| IST | IMP, IST, IPM, SEMS, VCD | IMP, IST, IPM, SEMS, VCD | IMP, IST, IPM, SEMS, VCD | III |
| IPM | IMP, IST, IPM, SEMS | IMP, IST, IPM, SEMS, VCD | IMP, IST, IPM, SEMS | III |
| SEMS | IMP, IST, IPM, SEMS, VCD | IMP, IST, IPM, SEMS, VCD | IMP, IST, IPM, SEMS, VCD | III |
| VCD | IMP, IST, IPM, SEMS, VCD | IMP, IST, SEMS, VCD | IMP, IST, SEMS, VCD | |
| **Iteration 4** | | | | |
| VCD | VCD | VCD | VCD | IV |
Value chain digitization (VCD)

Improved methods of production (IMP)

Energy sector transformation (IST)

Informed decision making (IDM)

Improved production management (IPM)

New business models (NBM)

Smart energy management systems (SEMS)

Figure 1. The ISM-based model of energy sustainability functions of Industry 4.0.

3. Conclusions
The present study is mainly concerned with the opportunities that current trend, Industry 4.0 may offer for energy sustainability. The content-centric review of the literature and the expert panel, collectively, identified seven Industry 4.0 energy sustainability functions, namely improved methods of production, energy sector transformation, improved production management, informed decision making, new business models, smart energy management systems, and value chain digitization. The ISM results showed that sophisticated precedence relationships exist among the energy sustainability functions of Industry 4.0. The ISM model obtained in this study revealed that Industry 4.0 contributes to energy sustainability by digitizing the entirety of value chains, from suppliers to manufacturers, and even end consumers. The digitization of value chains and the resulting production and value delivery effectiveness, coupled with the digitization of the energy industry itself would enable businesses to achieve energy sustainability thanks to the better decision making processes, and the emergence of new business models such as product-as-a-service business model. Shortly, this research can be used as a reference for company that looking into implementing Industry 4.0. Throughout this research, the company can prioritised which sustainability function during the transformation into Industry 4.0.

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