A Multi Agent-Based Optimisation Model for the Distribution Planning and Control of Energy-Based Intermittent Renewable Sources

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SUMMARY

Recent work on the management of renewable energy sources focuses on developing innovative tools and techniques to control the different behaviours of energy generation systems (e.g. the intermittent production of wind power). These tools contribute to achieving a proper balance between energy supply and consumer demand and guarantee a sustainable energy level in storage devices that can face potential generation shortages. In contrast, previous studies mainly focused on stimulating consumer response to market prices so as to rationalise consumption, especially during peak periods. This study investigates the impact of supplier decisions about using different renewable energy sources on the distribution planning and control of energy for the best consumer demand satisfaction and achieving a sustainable energy level in different located storage devices. A Multi Agent-Based Heuristic Optimisation model is developed to deliver this aim. The heuristic optimisation part of this model is proposed to optimise the energy level across differently located storage devices. It also guarantees the best energy exchange between regions at the strategic planning level. A sensitivity analysis study is conducted to verify the behaviour of the proposed model towards various demand levels, followed by a comparison study to justify the proposed agent-based heuristic model's superiority. The results highlight the impact of using intermittent renewable sources including solar, wind, hydro and storage devices on energy production, control and distribution. In addition, a sustainable level of storage in devices placed at different locations is achieved by optimising the energy storage operation. This sustainable storage aids any insufficient energy generated from intermittent sources to satisfy consumer requirements. The best energy exchange between regions is also presented.

KEYWORDS

Renewable energy network; Distribution planning and control; Renewable energy sources; Storage device; Agent-based optimisation.

1. INTRODUCTION

The generation, control of storage and best distribution of energy in a more sustainable way while minimising global warming and reducing emissions in the environment are crucial needs. These needs create a significant challenge faced by energy operators, leading to a call for green energy. This energy is generated from natural resources, such as solar, wind, tides and geothermal heat, which are naturally replenished. The best use of these resources requires best management practice. This practice is achieved by developing sophisticated energy planning, distribution, and control systems [1]. These systems should be innovative and sustainable enough to minimise climate and global warming changes to satisfy consumers' demand [2].

When suppliers plan to generate energy, they need to decide how to maintain the required amount of energy by the distributor, with or without storage devices. Suppliers should consider all technical constraints on the supply side, including the relationships between the capacity and energy level of storage devices located in different areas and the generation of electrical power from various sources to respond to different consumers' demands. In addition, it is vital to achieving a sustainable level of differently located energy storage devices to aid any region that falls short in energy due to generation disruptions. On the demand side, customers should manage their energy requirements, including patterns of energy consumption and technology adoption. This paper is motivated by the challenge of achieving the best management practice of the integrated supplier, distributor, and consumer sides in renewable energy networks. This practice includes guaranteed sustainable energy levels across differently located storage devices and the best energy exchange between locations/regions.

This paper proposes a multi agent-based heuristic optimisation model to achieve the best practice of energy production planning, storage control, and distribution in integrated renewable energy sources, suppliers, distributors, and consumers' networks. The production planning includes identifying the best production levels of energy. The energy control includes achieving the best energy level across differently located storage devices. The energy distribution should guarantee the best satisfaction of regions' demands by supporting each other in case of generation disruption.

The benefits of the proposed model are summarised as follows:

1- It assists renewable energy operators to measure the impact of applying various possible renewable energy sources/technologies on consumer demand satisfaction.
2- It enables operators to control the energy storage operation by achieving a sustainable energy level in differently located storage devices and distributors to generate the best distribution plans for energy.
3- It also contributes to the formulation and implementation of strategic renewable energy management policies, including encouraging suppliers to increase their investments to include higher numbers of sources and various renewable energy sources in hub regions and achieving the best management of the hydro source of energy in other regions.

The paper is organised as follows: Section II reviews the literature of the Agent-Based Modelling (ABM) approach and its applications in renewable energy planning, distribution, and control. The development of a multi agent-based model and a heuristics optimisation algorithm for best practice of distribution planning and control of renewable energy is discussed in Section III. In Section IV, numerical simulations based on a real-life case study evaluate the significance between different association levels, including a sensitivity analysis study to compare different demand levels. Section V presents a comparison study with the Centralised agent-based approach, followed by the main conclusions and recommendations in the last section.

2. RELATED WORK

2.1. ABM IN PLANNING AND DISTRIBUTION OF RENEWABLE ENERGY

The ABM approach is a way to model the dynamics of complex systems [3]. This approach was used in renewable energy production management and consumer demand requirements. [4] developed a multi-agent system to coordinate and control the power generated from renewable energy sources and their consumption units. [5] presented an ABM model for residential model adoption of solar PhotoVoltaic (PV) systems to evaluate its adoption across households. [6] developed an ABM model to assist utility companies in better understanding the impacts of consumers' behaviours and preferences on including renewable sources in their energy mix. [7] used ABM to show how a Virtual Power Plan (VPP) can be used to optimise its energy supply schedule for the grid. [8] proposed an innovative architecture for a distributed energy management system utilising the agent-based approach to control the complex energy management of distributed generation systems. [9] used ABM to describe the dynamics of an urban microgrid integrating different renewable energy sources, consumer behaviour and various storage facilities for best energy management practice in terms of reliability and economic indicators. [10] proposed an advanced Battery Energy Storage System (BESS) allocation method based on multiple agents' collaboration during an energy transaction process in a distribution system. [11] developed an ABM framework for dynamic simulation of local resource production, storage and consumption. [12] developed a Multi-Agent System (MAS) for best practice of infrastructure, including the monitoring and coordinating a smart grid environment with renewable sources and configurable storage devices. However, the developed MAS focused on distributing storage devices rather than the end-user side. [13] presented the application of ABM in facing different consumer energy choices, focusing on identifying specific ways to improve understanding of different themes of energy demand sides for the best design of flexible renewable energy policies. [14] proposed a multi-agent optimisation approach to incorporate a flexible residential Demand Response (DR) into the power system and electricity market to minimise time delay and electrical energy cost incurred by household appliances. [15] presented an ABM approach to model flexibility of the demand-side, investigating the elasticity of the demand-side to the change in price. [16] developed an agent-based model to generate different residential demand profiles in urban areas. [17] proposed a multi-resolution Agent-Based Modelling and Simulation (ABMS) framework for estimating domestic electricity consumption, considering the behaviour of household individuals. [18] developed a socio-technical system including consumer and supplier behaviour using the ABM approach.

Previously, the ABM approach addressed vital aspects of the renewable energy management process, including resource production, supply schedule, energy transaction process, customer preference and the demand side of energy. However, the focus was on only one or more integrated components of the grid network, but not the grid as a whole.

The ABM approach was also used in electricity market analyses. [19] designed a novel ABM model to explore the future development of urban supply systems of energy in liberalised markets. Authors in [20] developed an agent-based model depicting the electricity system as a socio-technical system to analyse policy instruments' impact on renewable energy market integration. [21] used the ABM method to mimic investors' decision-making in the electricity sector, replicating the liberalised electricity market dynamics. [22] presented a novel ABM system focused on the demand-side behaviour in a system reserve provision incorporated into a stochastic market. [23] used a flexible and modular ABM to simulate EU climate and energy policies. [24] developed a novel agent-based model assessing future diffusion processes of renewable technologies under different policy regimes. The model assisted in designing support policies and pointed out existing investment opportunities of renewable energy for the beneficiaries of stakeholders. [25] developed a model for Electricity System Management using an ABM approach, including consumers (heterogeneous), legal entities (aggregators), the system operator, and market policies and strategies. [26] addressed the challenges of the social dynamics of energy end-use modelling using the Agent-based approach, describing the complexities inherited in socio-technical systems.

However, most of these ABM models were used as market simulators for electricity market analyses, including bidding strategies, economic performance, market and consumer policies for the best adoption of renewable energy sources.

2.2. ENERGY DEVICES MANAGEMENT IN RENEWABLE ENERGY NETWORKS

The integration of renewable energy sources with storage devices and the latter's role in future power systems was studied [27]. [28] investigated distributed energy storage devices considering optimal placement, sizing, and control. [29] achieved best practice of energy management of integrated renewable sources, including battery devices and load control.

[30] achieved cooperative planning in active energy distribution systems, combining renewable energy sources and storage devices, and integrating conventional electric grids with distributed energy storage systems, while [31] considered the financial benefits of the latter study. [32] developed a general grid model to provide the optimal production and/or storage levels, sizes and strategies in energy generation and storage sizing problems. The impact of wind-turbine generation on the electricity system's short-term operation was also addressed by [33]. [34] investigated the power balancing problem in a power grid consisting of combined renewable energy sources with storage devices and flexible loads. [35] estimated the required capacity of generation and storage for combined renewable and conventional sources. [36] ensured the best load-sharing of energy based on source capacity by developing an intelligent control strategy for a grid network consists of PV and a multi-battery bank. In [37], an agent-based framework was proposed to model, simulate, and evaluate the overall energy production using PV modules and auxiliary propane generators, battery packs as energy storage units, and a set of consumer units in the simulation environment. Energy distributors were not modelled in the presented framework, and customers' preferences were only based on the resource transportation cost rather than the energy tariff of each source. In addition, it is only possible to connect and transfer resources between storages that process the same resource type, which makes the exchange capability of energy between these storages restricted. The same framework was improved and used in [38], focusing on water management. However, the framework considered only one source of water, which restricts consumers' preference by the resource transfer cost. In [39], a heuristics algorithm was developed and embedded within an agent-based model to achieve the best storage in storage devices allocated in different cities with limited energy exchange within cities. The limitation of this heuristic's algorithm is that it did not consider energy exchange between regions. The focus was only on the energy exchange limited between cities rather than regions.

2.3. CONTRIBUTION

In general, most of the above-related works indicated that the ABM approach was used to model individual components of the renewable energy network rather than fully integrated components of suppliers, distributors, and consumers, with a wide range of applications in the electricity market analysis and customer preferences. However, very few papers focused on the distribution planning and control of joint energy supply network components, including supply with intermittent renewable energy sources, distribution and consumer demand, still require more investigation. The control of storage energy levels at storage devices for efficient, robust, and reliable energy consumption is still required. Also, neither the optimisation and control of storage levels of differently located devices nor the exchange capability have been addressed in such joint energy supply networks, and hence, the proposed heuristics optimisation algorithm is introduced.

This work presents an improved heuristics algorithm that minimises the impact of energy shortages across different regions rather than cities, considering surpluses and shortages of energy at each region and making energy exchange between regions possible. The work extends that of [39] by presenting an agent-based model that includes a different purpose, structure, and functionality heuristics algorithm than presented in [39] for strategic planning and distribution of energy to support any region struggling to satisfy its energy requirements. The proposed algorithm should also assist any region short of electricity to satisfy its demand by receiving energy from one of its possible neighbour regions.

3. A MULTI AGENT-BASED OPTIMISATION MODEL FOR RENEWABLE ENERGY DISTRIBUTION PLANNING

3.1. THE MULTI AGENT-BASED MODEL

The developed multi agent-based optimisation model comprises several competitive agents, including *Suppliers* S_m (agent), each of which has r energy Sources/Technologies (sub-agent). The first supplier agent has different types/numbers of renewable energy generation sources classified by their types. The first source is Solar PV, one of the most widely recognised renewable energy sources [40]. It has a strong availability, daily and seasonal variation, which clouds can substantially reduce. The second source is the Wind Turbine, in which its generated power is a cubic function of wind speed, and any changes in this speed significantly impact the generated power. The third source of energy is Hydro, in which the generation cost of using this source is relatively low, making it a competitive and more flexible source of renewable energy. The fourth important source of energy is the Storage Device. The main motivation of using such a device is to cover demand shortages caused by a fluctuated energy production. This fluctuation is due to uncertain weather conditions.

The second agent comprises distribution companies or *Distributors*. This agent includes several distributors D_l that are used to transmit energy from the preferred supplier to the designated consumer. The third agent is called the *regional demand* (agent). Each region involves different location cities, and each city (sub-agent) has its demand. Examples of such demand types are industry, academic institutions, household (domestic), transportation, commercial, etc. Figure 1 depicts the integrated renewable energy network components in terms of a multi agent-based model.

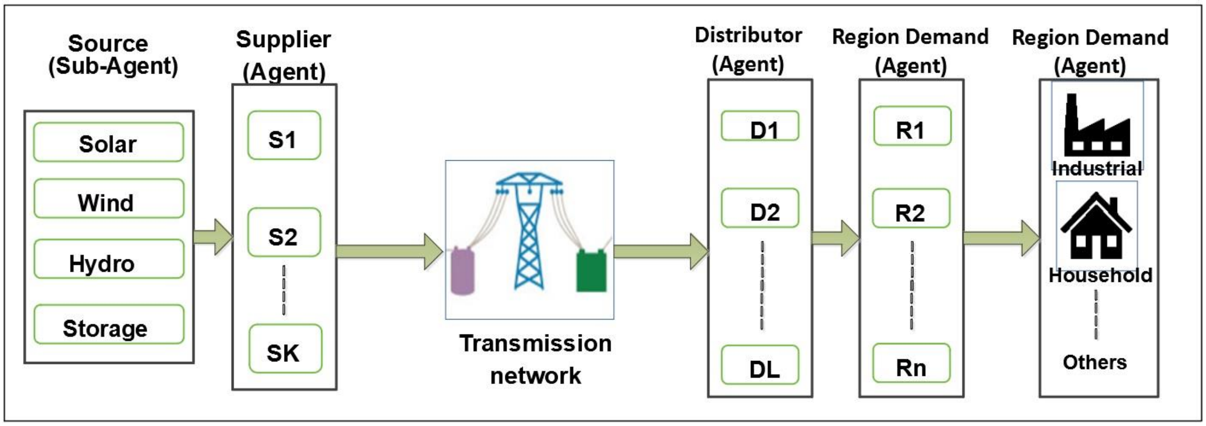

Figure 1 Multi agent-based model of integrated renewable energy network [39]

In Figure 1, each supplier could provide energy to one or more distributors through a set of pre-defined rules based on its generation capacity. These rules are essentially formulated from the attributes of each type of energy source. They depend on a function of each source's power output and available storage levels. This function enables each supplier to know its generation capacity and maximum energy storage and location. In general, short-term energy trading could be risky due to the volatile characteristic of renewable energy sources and other unpredictable demand behaviours. Therefore, bids (offers) based on supply and demand practices decide the price. On such basis, the guidelines and rules for operating practices are summarised by the supplier as follows:

- The suppliers offer a function of linear marginal cost to express their supply interests. The distributors will then collect all the bids submitted by suppliers and clear the market by minimising total generation costs. Distributors obtain optimal generation clearing costs in the day-ahead market (as load-serving agents) using forecasting or estimating the required load by the region demand agent, represented by each of its demand type sub-agents.
- The energy generated by each supplier is then identified, considering constraints of source capacity and weather conditions. All the required traded quantities provided by both the suppliers and distributors must be reported to the agent-based optimisation model user one day ahead. The energy generated and others provided by auxiliary storage devices should satisfy the demand target. If any deviation leads to penalties, the supplier should select the already contracted quantity elsewhere to

provide it within the requested short term. In other words, for any over-or under-supply of energy, suppliers will afford penalties for bringing on more energy from storage locations or applying curtailments to meet transmission constraints. Similarly, distributors will share higher costs if more energy is required than the quantity cleared in the day-ahead market due to unforeseen factors such as weather changes or forecast mismatches.

However, the proposed ABM model intends to schedule the energy for already settled quantities and prices of the day-ahead market.

- The distributor has multiple options of buying energy from one or more than one supplier to meet the consumers' demand and achieve profit and market contribution targets. At the same time, consumers have multiple options for buying energy from different distributors, according to these distributors' sale rules. The main aim of the consumer is to pay less for full energy satisfaction at a sustainable level.

The agent-based modelling approach is selected due to its capability for exploring the effect of variation in energy generation, along with changing consumers' consumption, on the supplier selection decisions and the energy volume purchased by consumers.

The following two sections will discuss both the proposed message-sequence model and the heuristics algorithm.

3.2. THE PROPOSED MESSAGE PROTOCOL MODEL

The Message Protocol Model developed by [39] is used to present the collaboration theme between all the integrated renewable energy distribution network agents, as shown in Figure 2.

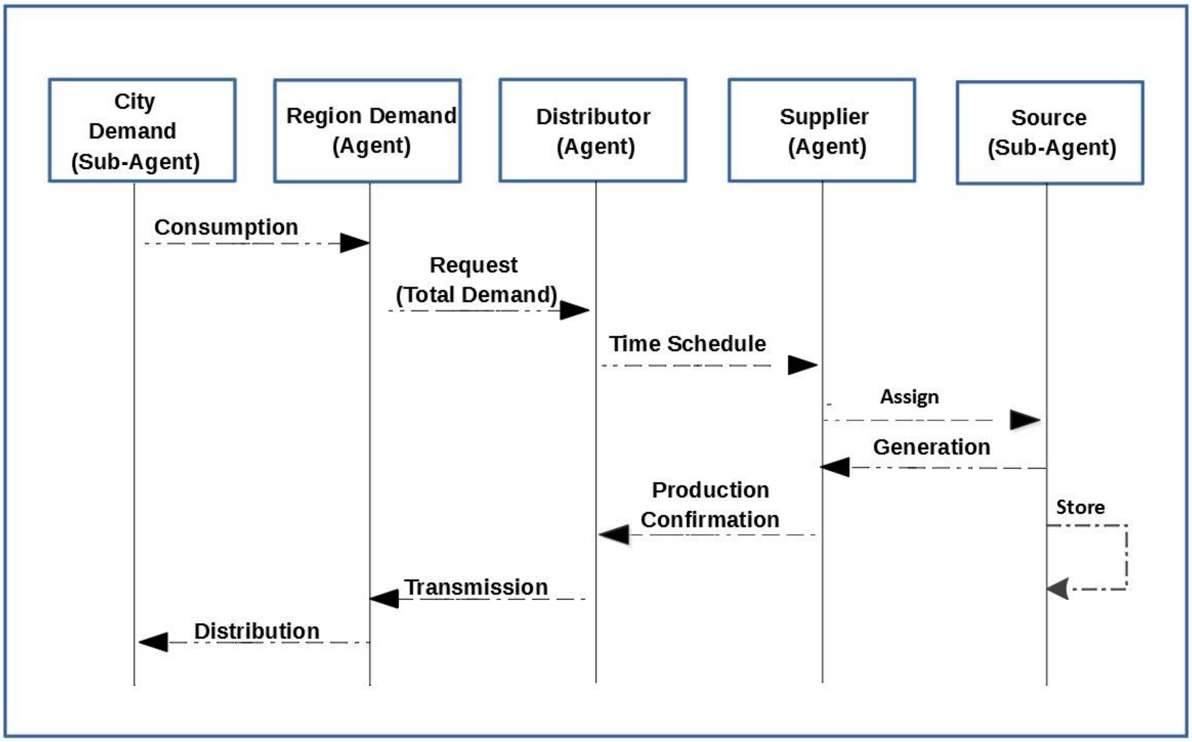

Figure 2 Message Protocol Model [39]

In this message model, the consumers' consumption represented by the city demand sub-agent is sent to the region demand agent to calculate the requested regional energy demand. The calculated regional demand is sent to the distributor agent, and this agent will collaborate with the suppliers, informing them of the required demand level and the possible schedule to satisfy that demand. The suppliers will then assign the available sources to predict the possible amount of energy generated, considering uncertainty in weather changes, and send an updated confirmation back to inform the distributors about a possible generation capacity. Storage devices are considered to satisfy the total region demand. Such devices are used to store any surplus energy (used) to provide it if a fluctuated energy generation (shortage) occurs.

Furthermore, if storage devices allocated in a region cannot cover the demand shortage, an order will be sent to other storage devices in other regions, asking them for energy aid. The supplier will then send a generation notification to the distributor to confirm that the required energy volume is available. The distribution companies (distributors) will be responsible for transmitting the requested energy to the region agent, distributing the received energy across different cities according to their energy requirements.

In general, the expected output of the proposed algorithm is achieving the best plans of storage of energy in storage devices allocated in different regions. This plan guarantees the best satisfaction of energy demand and faces any generation disruption contingencies.

The proposed heuristics algorithm to maintain sustainable energy storage in all the devices across different cities/regions is discussed in the next section.

3.3. THE MULTI AGENT-BASED HEURISTIC OPTIMISATION MODEL

A heuristic algorithm is developed for the best practice of planning and distribution of renewable energy networks. This algorithm guarantees a sustainable storage level of energy to cover the desired demand as much as possible if any generation disruptions occur. This algorithm achieves gradual and robust energy storage in all differently located devices to respond instantaneously to any energy generation disruptions. The energy exchange capability across all regions is proposed to advance the previously developed algorithm in [39] for more strategic energy exchanging between regions (rather than local cities) if more than one of them falls short of energy. Figure 3 presents the architecture of the multi agent-based model with the improved heuristic algorithm.

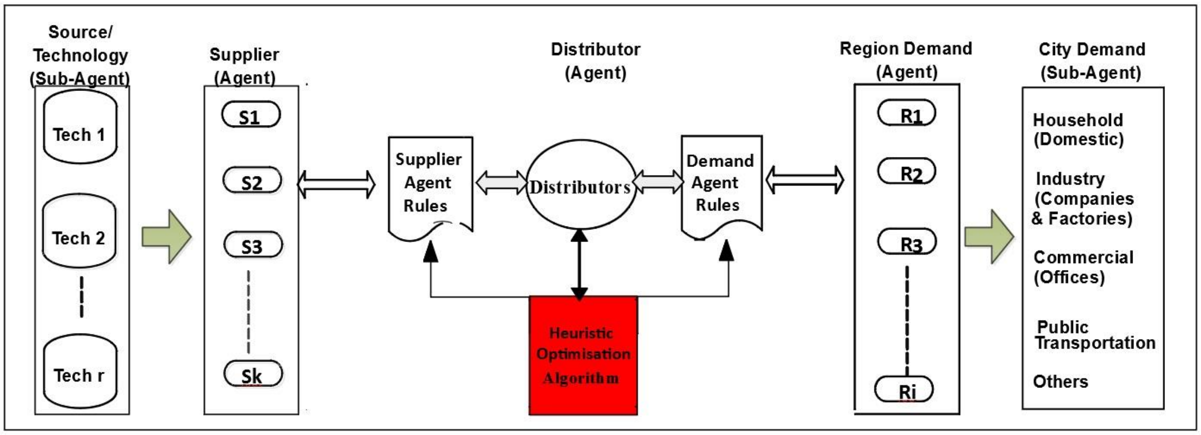

Figure 3 Architecture of the multi agent-based heuristic algorithm [39]

In Figure 3, the proposed heuristic algorithm will optimise production levels and achieve the most sustainable energy storage per region. In addition, it reduces the energy surplus and/or shortage incurred and controls the exchange of energy between regions and supports any region needing energy.

Denotations of the proposed heuristic algorithm

C: Consumption or demand
DIS: Distributed energy
Sh: Shortage
P: Production
SU: Surplus
PSC: Energy stored in a device
S: Supplier
SC: Storage Capacity
SC_{Max}: Maximum storage level of device SC
EE: Energy Exchange between all regions.
DI: Distributor liaise between supplier and consumer

The optimal level selection of the energy storage and exchange are determined in the range (min-max) of variable SC and EE

The proposed heuristics algorithm steps are:

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Step 1. Define the expected energy Consumption $C$ for different consumers, the generated energy Production $P$ by the Supplier $S$, DIstributor options $DI$, minimum and maximum levels of both Storage devices $SC$ and Energy Exchange $EE$ for each region.
Step 2. Set Time (T=24) for processing the interaction between suppliers, the distributor and consumers.
Step 3. Compare the generated energy Production $P$ by the Supplier $S$ with the distributed energy volume $DIS$ provided by the DIstributor $DI$ to cover the energy Consumption $C$,
    Step 3.1 If $P > C$, Then $DIS = C$, do Step 5.
    Step 3.2 If $P < C$, Then $Sh = C - P$, then do
Step 4. Use $SC$ starting with the maximum energy level devices until $Sh = 0$, do
    Step 4.1 Retrieve energy $PSC$ from storage devices $SCs$, starting with the largest energy level device,
    Step 4.2 If $PSC < Sh$, Update $Sh = Sh - PSC$, $PSC = 0$, do Step 7.
    Step 4.3 If $PSC > Sh$, Update $PSC = PSC - Sh$, $Sh = 0$,
    do Step 7.
Step 5. Calculate $SU = P - DIS$ for this region for each supplier $S$, do
Step 6. Update $SC$ storage level in this region for all involved storages, $PSC = PSC + SU$, do
    Step 6.1 Charge storage devices with energy starting with the least energy level devices,
    Step 6.2 If all $SCs$ are not fully charged, then $SU = 0$, do Step 8.
    Step 6.3 If all $SCs$ are fully charged, then Update the $Su$ volume by $SU = SU - \sum(SC_{Max} - PSC)$, do
Step 7. If all Suppliers $S$ not done, do Step 3.
Step 8. If all Suppliers done, do
    Step 8.1If $Sh > SU$ for all suppliers $S$, Update $SU = SU - Sh$, $SU = 0$, $EE = 0$, do Step 9.
    Step 8.2 If $SU > Sh$ for all suppliers $S$, Update $SU = SU - Sh, EE = SU$, do
Step 9. If all regions done do Step 10, otherwise move to the next region and do Step 3.
Step 10. If $Sh \geq EE$ for all regions, Update $EE = EE - Sh$, $EE = 0$, otherwise $Sh = 0$.
Step 11. Stop when T is reached and update the system.
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In the above algorithm, the purpose of Steps 1 and 2 is to define all the required inputs. Step 3 represents the core of the proposed algorithm. It compares Production and Demand and calculates the required amount of energy and the incurred shortage if any. In more detail, the energy production P by the supplier S and the distributed volume DIS by the distributor DI was compared, according to the required consumption C by consumers. It is worth mentioning that devices of each supplier with the least energy located in its region start charging first if there is a production Surplus (SU) as in Step 6. Alternatively, they retrieve energy by selecting a device with a maximum SC to cover any incurred shortage Sh in energy supply (as in Step 4). Then, the SU and Sh for all suppliers S will be calculated, and EE and Sh for each region will be updated accordingly, as in Step 8. If all regions are completed, the value of Sh from the comparison with all three regions EE will be calculated, as in Step 9. The system is then updated, $Sh = 0$, as no energy shortage is allowed, as in Step 10. The system operates continuously until the set time **(T)** of processing is reached. This algorithm applies to different storage devices' capacities, including those in different locations.

In the next section, a computational study based on a real-life case study is conducted to justify the developed ABM model.

4. EXPERIMENTAL WORK AND RESULTS DISCUSSION

4.1. MODEL INPUTS

A computational study is conducted based on real-life inputs provided by the Iraqi Ministry of Electricity. One of the inputs is the current energy tariff used by different consumer demand types. Table 1 shows the current tariff in Iraqi dinar (ID) imposed on different consumer demand types, including domestic homes, commercial enterprises, and businesses with a class tariff according to energy usage. The government and industry, including manufacturing, transport and agricultural consumers, have one tariff for all energy levels used. Each type of consumer has an expected pattern of energy usage, checked against the expected consumer behaviour to schedule energy availability optimally. According to the day and season, these energy usages vary hourly throughout the day.

Table 1. The Current Tariff in Iraq*

Categories	Class–kwh/month	ID/kWh	Cent/kWh
Domestic	1-1500	10	0.83
	1501-3000	35	2.92
	3001-4000	80	6.64
	Over 4001	120	9.96
Commercial			
	1-1000	60	4.98
	1001-2000	80	6.64
	Over 2001	120	9.96
Government		120	9.96
Industry		60	4.98
Agriculture		60	4.98

*Annual Statistical Report of Energy in Iraq (Arabic Version), Republic of Iraq 2018, 26

In Table 1, for example, if the total consumed energy by a customer in one month is 1500 kWh of domestic use, then this consumer must pay around 15,000 ID (10*1500). This consumer should pay around 32,5000 ID (10*1500+35*500) when the total energy usage is increased up to 2000 kWh. This action means that if the consumer responds to the price change, then the consumer will save energy by making optimal use of it by using LED lights, for example, and subsequently reducing energy demand.

The third column cent/kWh represents the cost incurred in cents for every 1 kWh consumed of energy. For example, the government sector's consumption of 1 kWh of energy costs $9 and 96 Cent without adhering to any consumption class-kWh/month. Other inputs include the total energy demand/consumption per hour for the 3 regions in Iraq, including the North, Middle and South of Iraq. The regional consumer demand behaviour was considered on a 24 hour basis. The pattern of this behaviour (energy usages) varies due to hourly tariff changes during the day, where the daily consumption growth of different consumer sectors is estimated using different statistical methods. For example, the average demand for energy consumption in different cities in the North region of Iraq is represented by two local distribution companies, as shown in Figure 4.

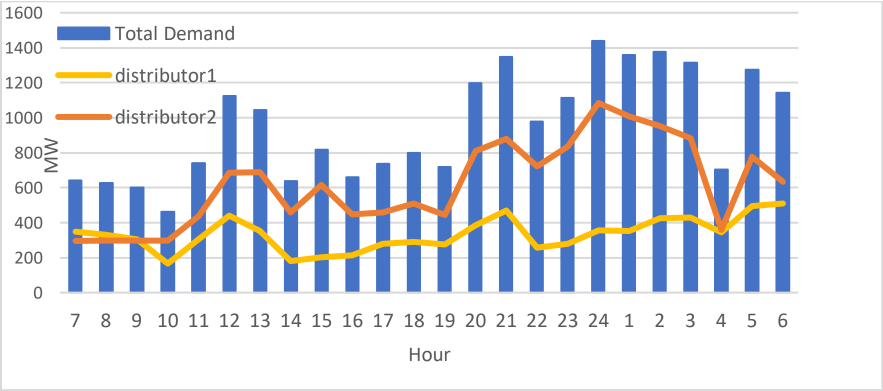

Figure 4 The energy distribution by two distributors in the North region of Iraq (24 hours)

Source: Annual Statistical Report of Energy in Iraq (Arabic Version), Republic of Iraq 2018, 26

Figure 4 presents the energy distribution comparison by two distribution companies, 1 and 2, against the required energy demand in the North region of Iraq. These distributors have different rules and tariffs for energy sales. Figure 4 also shows that distributor 1 ensures a smooth energy consumption compared with the required energy demand by imposing different tariffs during the day. This consumption is attributed to the consumers' reactions to that energy sale rule by reducing their consumption.

The rest of the inputs are related to renewable energy production from different sources under unexpected weather changes. These inputs are generated from the simulation of actual data of German energy production systems from both Solar and Wind energy systems [41].

Another input is the energy volume generated quarterly by Hydro stations placed downstream of the Mosul dam, one of the largest dams located in the North region of Iraq. Figure 5 illustrates the quarterly profile of the generation of energy using a typical Hydro energy source located in the North region of Iraq.

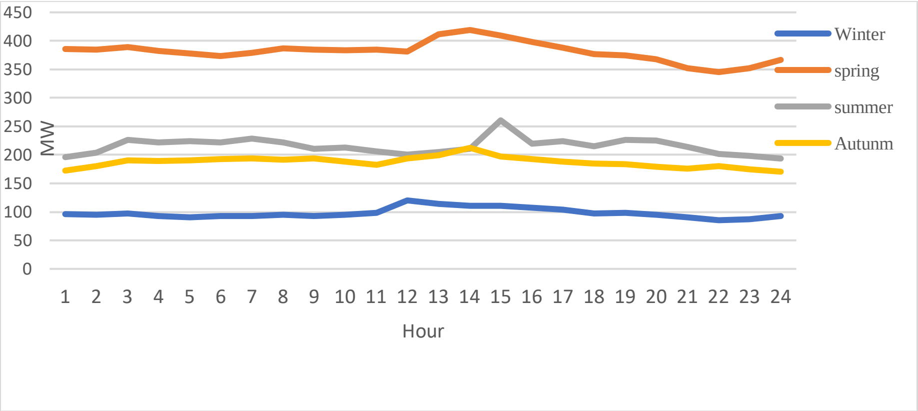

Figure 5 Hydro generation profile in the North region of Iraq (quarterly basis)
Data source: Electricity I.M. and Brinckerhoff P. (2010). Load Forecasting in Iraq

Figure 5 shows a historical daily energy generation pattern by a Hydro station located in the Mosul dam in the North region of Iraq through different seasons. Such an energy resource is relatively more stable than other renewable sources in the area, such as wind energy, which is a cubic function of wind speed. Wind speed varies from one hour to another through different seasons. The time of sunrise at different seasons also gives an inherent intermittence production level through one day for solar power.

The rest of the inputs that the developed agent-based heuristics model requires are presented in Table 2. The information required by an individual agent is used to identify the response of the proposed system to internal or external parameters' variations over various ranges.

Table 2. Inputs of energy consumption (MW) provided by (2-3) suppliers and distributors for 3 regions

Region	Supplier	Max-Min Source Type Available (Current)	Distributor	Demand MW (Max Consumption Weekday)			
				Winter	Spring	Summer	Autumn
North	3	Hydro-Wind	3	1940.1 1531.8**	2151.5 1516.4	2107.1 1592.2	2334.6 1328.7
Middle	2	Solar-Wind	2	665.9 599.1	800.1 506.4	800.1 597.3	672.59 397.7
South	3	Wind-Hydro	2	1430.5 1128.3	1641.1 1165.3	1641.1 1676.2	1446.2 992.8

**Weekend

The developed energy distribution system is structured to represent different scenarios for most combinations of the primary contents in Table 2.

4.2. EXPERIMENTS AND DISCUSSION

Multiple scenarios are developed to test the behaviour of the proposed system, including its regional energy exchange capability achieved by using storage devices. The developed scenarios in this computational study are summarised as follows:

Scenario 1 Impose an energy tariff to control the consumption rate. This scenario tests the effect of different energy tariffs on energy consumption.

Scenario 2 Change the number of suppliers, source type and capacity. This scenario aims to identify the effect of changing numbers on the maximum energy storage capacity.

Scenario 3 Use mixed energy sources and storage devices. This mixture of energy sources identifies the impact of using diverse energy sources on consumer consumption satisfaction.

Scenario 4 Enable Energy Exchange between cities. This scenario presents the capability of energy exchange among regions.

Four scenarios, including different energy production and demand volumes, are implemented running the developed multi agent model-based heuristics algorithm, and outcomes analysed. In the proposed heuristics algorithm, the supplier agent seeks to arrive at the optimal sustainable energy levels in different locations' storage devices.

The agents of m distributors then distribute the energy volume generated from equation (1) to satisfy regional requirements that include different customer demand types in different cities within the region(s). Furthermore, household consumption of energy is a challenging task, as it is related to the physical and technical characteristics of the houses in which people reside. The standard electricity usage (in kWh) varies from one consumer to another, each of whom can control usage time to reflect their needs and responses to energy pricing systems. Therefore, the consumer response to changed energy prices is rapidly transmitted to the energy demand output (Scenario1), as shown in Figure 6, while the consumption curve looks smoother and requires a lower energy storage capacity.

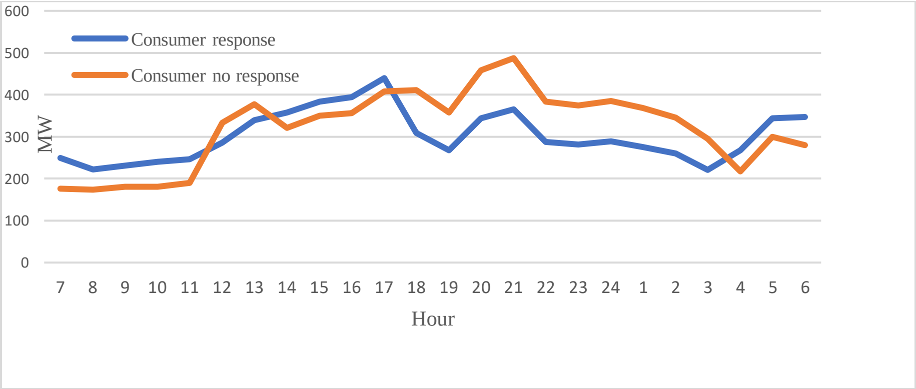

Figure 6 The energy consumption in two cases; with and without consumer response

The assumption of the consumer response to the imposed tariff is created to motivate control of the consumption rate. The model assumes consumers respond to the imposed tariff by controlling their consumption rate. This scenario is created to test the effects of such a tariff on the consumer consumption curve.

After running the model, the results for one region (as an example), which includes three cities and has different consumer types (Residential, Industrial and Others) with 3 suppliers and 2 distributors (Scenario 2), are shown in Table 3.

Table 3. Optimal energy storage capacity – Three cities (North Region of Iraq)

Details	Renewable	Production	Amount energy provides for DI		Amount energy storage by location			Max-Storage Capacity MW
Supplier S	Source Type r	Min-Max MW	DI_1 b_{11}	DI_2 b_{21}	City 1 c_{11}	City 2 c_{12}	City 3 c_{13}	SC_{max}
1	Solar	0 -790	0.6	0.3	0.45	0.19	0.36	785
	Wind	9 -273.25						
2	Solar	0 -237.99	0.2	0.3	0.32	0.51	0.17	535
	Hydro	193.5-260.5						
3	Wind	16.2-427	0.2	0.4	0.33	0.19	0.47	780
	Hydro	261.3-351.7						

Table 3 presents the fluctuations in energy production and the distributor's decisions to buy the amount of energy from different suppliers, which leads to increasing levels of energy stored in differently located storage devices, with a high volume of energy generated from wind and a minimal amount of energy generated from the Hydro sources. For example, the amount of energy that distributor 1 buys from supplier 1 is 60%, 20% is bought from supplier 2, and 20% from supplier 3. This buying plan leads to a decrease in the energy storage level for supplier 1. The energy level in storage devices also oscillates depending on the energy consumption level and season. For instance, city 1 consumes more than cities 2 and 3; therefore, supplier 1 allocated 45% of the energy storage level to city 1, 19% to city 2 and 36% to city 3. In addition, the type of renewable energy source is supplier dependent. Energy from supplier 1 has been produced from Solar and Wind energy sources, while supplier 2 is dependent on Hydro and solar energy sources, and supplier 3 has used Hydro and Wind sources to provide the energy. The total energy production from each supplier 1, 2 and 3 are provided in Figures 6, 7 and 8.

Figures 7, 8 and 9 present consumer consumption, energy production/generation, and the achieved storage level behaviours of suppliers 1, 2 and 3, respectively, in the Summer season (Scenario 3). The reason behind selecting this season is the increasing level of consumption required by consumers, caused by the increasing temperature.

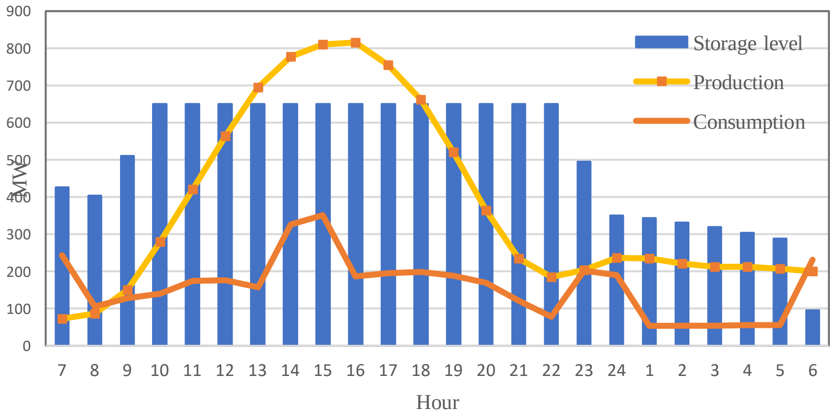

Figure 7 Energy storage, production and consumption levels (Supplier 1)

Summer Season (mixed sources: solar source and wind)

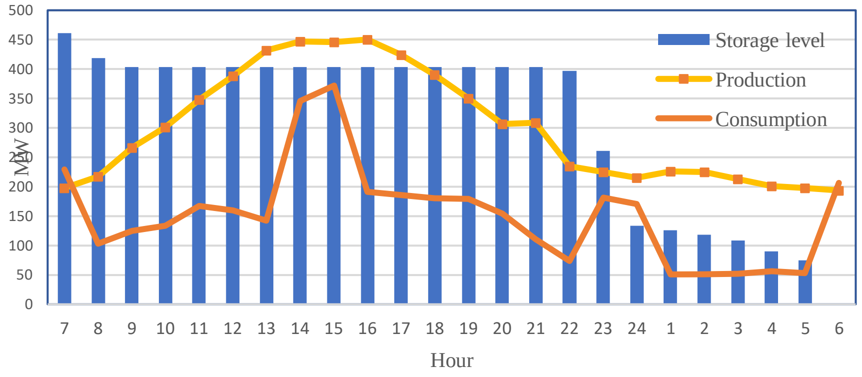

Figure 8 Energy storage, production, and consumption levels (Supplier 2)
Summer Season (mixed sources: hydro source and solar)

Figures 7 and 8 show that the energy levels in storage devices are almost full. This full storage is attributed to the fact that both suppliers 1 and 2 mainly use a solar energy source in the Summer season, which has long sunny days. In addition, it can be noticed that the behaviour of the consumption rate increases during the afternoon time (after 1 pm) and keeps decreasing in the evening time (after 7 pm). Such consumption behaviour leads suppliers to satisfy as much as possible consumers' demand and maintain sufficient and sustainable levels of energy stored in storage devices.

Furthermore, in Figure 9, the curve of energy production seems to be much smoother, along with a low level of stored energy, when including sources of Wind and Hydro that are viable through this season.

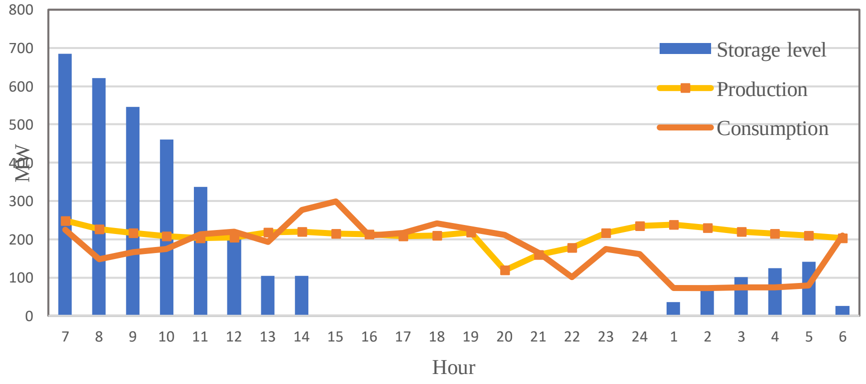

Figure 9 Energy storage, production and consumption levels (Supplier 3)
Summer Season (mixed sources: wind source and partial hydro)

If consumer demand has been satisfied and storage devices are full in one region, a regional Energy Exchange (EE) capability is utilised by targeting other storage devices located in different locations/ regions. Outputs of the optimal EE of Scenario 2 are extended further to include three regions, four seasons and different production and consumption rates (for 1 day). See Table 4 for Scenario 4 outputs.

Table 4 Optimal Max EE for all Iraqi regions (Scenario 4)

Region	Capacity for Source Type (MW) r				Max Energy Exchange (MW) EE			
i	Solar	Wind	Hydro	Storage	Winter	Spring	Summer	Autumn
North	1300	1000	1500	1475	953 -993	320 -421	761 -34.5	318 181
Middle	2200	300	250	2125	518 -895	2542 -114	1761 0	163.5 -974.7
South	1200	3500	150	2500	305 -220	1231 -147	302 -326.8	172.5 -382.8

The max EE in Table 4 represents the total energy of SU, calculated using equation 2, while Sh is represented by the negative values (min) of EE. For example, the wind speed attribute changes in different seasons, represented by a high speed in the Spring, Winter and Autumn seasons, generating a high volume of energy. It is clear from the above Table that the least amount of energy shortage (147 MW) is recorded during the Spring season in the South region of Iraq. This storage level is due to achieving the maximum production level during Spring due to the high wind speed. In the North region of Iraq, hydro energy generation increases in both Summer and Spring, while in the Middle region, the energy from solar sources increases only in the Summer season. Thus, varying demand and output levels across seasons lead to fluctuating energy production levels and shortfalls or surpluses.

4.3 SENSITIVITY ANALYSIS

In this section, a sensitivity analysis is conducted to verify the behaviour of the developed model against various demand behaviour profiles. Demand satisfaction is selected for being one of the primary key performance indicators that reflects the performance of production systems. Sensitivity analysis is used to explore the robustness and accuracy of the developed model under uncertain demand conditions [42]. This analysis will help understand the impact of consumer demand changes, for example, on the level of energy exchanged between different regions.

Table 5 demonstrates the impact of demand on the energy exchanged level between regions.

Table. 5 The impact of demand behaviour on three regions energy exchange levels

Region/ Demand Behaviour			Season/ EE (MW) Energy Exchange			
North	Middle	South	Winter	Spring	Summer	Autumn
Increase	Decrease	Oscillate	3300 -107.2	4832.2 -220.1	804.1 -1839	2010.5 -1667.1
Oscillate	Decrease	Increase	3299.5 -109.7	4831.2 -219	799.5 -1838.5	1548 -2849
Decrease	Oscillate	Decrease	3299.1 -106.5	4834.4 -214.6	803.8 -1839.4	1562.5 -2846.7
Increase	Increase	Oscillate	3300.5 -113.2	4829.6 -225	802.4 -1838.9	1550.8 -2851

Table 5 shows that demand growth depends on weather conditions (season) between different regions. This analysis shows that the energy shortage is positively correlated to the demand growth’s Decrease and Oscillation. It is also negatively correlated to demand growth’s Increase and Oscillation. The correlation is evident when, e.g., the energy shortage’s value is reduced in Spring (by -220.1) and Summer (by -1839), in case there is demand growth patterns of Decrease and Oscillation.

5. Comparison Study

The comparison study is conducted to determine the effectiveness of the developed multi agent-based heuristic model for optimal planning, control, and distribution of renewable energy.
In this comparison study, both the multi agent-based optimisation and the Centralised multi agent-based approaches are compared to justify the first approach's superiority over the Centralised approach. The latter is deemed suitable for comparison because it is a good fit to the parameters of the problem situation compared to other approaches.

A Centralised multi-agent-based model is developed by creating a super/governing agent that performs global measurements of objectives and directs the agents, including their sub-agents, to improve globally measured objectives, including energy production and storage and exchange levels. This super agent receives information from all agents, including customer, distributor, and supplier. It will then decide which distribution company is the most appropriate to each customer based on the latter's preferences. The distribution company selected by the super agent will then send the consumer's demand to the super agent, asking them for their decision on which supplier to select. The selected supplier decides which source to use. The only source controlled by the super agent is the storage device, which controls its selection and storage process. It is worth mentioning that the storage device selection and storage levels control was previously optimised using the Proposed heuristics algorithm.
The measurement criterion used for the comparison was the achieved energy storage level and the total energy exchanged among the regions. Table 1 presents the optimal energy exchanges among all the regions and the achieved energy storage levels using both the Proposed and the Centralised models.

Table. 6 Optimal Energy Storage and Exchange for all Iraqi regions using the Proposed and Centralised agent-based models.

Region i	Production Capacity (MW)			Model	Energy Storage (MW)	Energy Exchange (MW)			
	Solar	Wind	Hydro			Winter	Spring	Summer	Autumn
North	1300	1000	1500	Proposed MAB	1475	953 -993	320 -421	761 -34.5	318 181
				Centralised MAB	1625	400 -2029	1692 609	1600 -153	1600 -1504
Middle	2200	300	250	Proposed MAB	2125	518 -895	2542 -114	1761 0	163.5 -974.7
				Centralised MAB	2125	1811 -607	2125 -710	1149 -1308	1091 -1382
South	1200	3500	150	Proposed MAB	2500	305 -220	1231 -147	302 -326.8	172.5 -382.8
				Centralised MAB	2225	5793 1550	3526 1313	2200 -707	2200 -1249

In Table 6, for the North region, the maximum energy provided by the Solar source is 1300MW, Wind source is 1000MW and Hydro 1500MW. The achieved energy storage using the Proposed agent-based heuristic optimisation model in this region is 1475MW. For Winter, after running the Proposed model for 24 hours, a surplus of energy of 953MW is obtained. This surplus could be supplied/exported to other needy regions upon request. A shortage of -993MW represents the energy imported by the North region from other regions when the produced energy is insufficient at different times per day.
In Autumn, the same region has a surplus of 318MW and could be exported to any region upon request. The same region achieves an extra surplus of 181MW in the same season. This surplus could be provided to any other region when requested. This energy surplus is attributed to the utilised hydro source that works efficiently to generate energy during Autumn, as this season is a rainfall season.

For the Centralised model, the North region provides a surplus of 400MW, exported to any other region. At the same time, a shortage of -2029MW of energy is incurred due to inefficient production planning achieved by this approach. The Centralised model overproduced energy in Winter and Spring seasons for the South region. These surplus energy volumes reflect the poor practice of production planning.
Ideally, the best plan should guarantee the best energy satisfaction per region with minimum energy shortage during the day, i.e., energy production should be optimised to satisfy the region's requirements with less shortage incurred. This shortage pushes the region to import energy from other regions. However, the best balance between energy surplus and shortage ensures optimal energy production and storage plan.

Therefore, the Proposed agent-based heuristic optimisation outperforms the Centralised approach, as the Proposed one provides the minimum energy exchange, including energy surplus (to export) and shortage (to import). This best performance is attributed to the internal collaboration, continuous updating between agents and the proposed heuristic optimisation algorithm developed to assist in the optimisation process.

6. Conclusion and Future Work

The rapid development of renewable energy technology and continuous exploration of additional energy sources has led to an increase in the integration of these intermittent sources, moderating the uncertainty of energy supply/production to meet increased demand. As a result, a multi agent-based heuristics model was developed to achieve the best satisfaction of energy demand in different weather and seasonal changes. An improved heuristics algorithm was proposed to achieve sustainable energy storage levels at differently located devices in three major regions: North, Middle, and South. This sustainable level is required to avoid an energy shortage if weather conditions disrupt production. The exchange of energy in energy shortages via storage devices in different regions was also possible.

The application of the heuristics optimisation algorithm was also illustrated after designing and simulating historical data of three major regions of Iraq‘s electricity consumption and the simulation of renewable energy production of a German system, in order to test the behaviour of the proposed model in response to different weather and operational changes.

This approach was developed to achieve minimum production surplus and energy shortages while supplying consumers with energy and guaranteeing optimal and sustainable energy levels at storage devices located outside their regions. In addition, regional collaboration in exchanging energy stored in different devices has successfully reflected each region's support if a shortage is incurred in any of these regions/cities. It has been noted that the developed model attempted on many occasions to achieve the best balance between energy production and shortage. Surplus production is exported to any needy region, and in turn, energy is imported if a shortage occurs.

The model was compared with the Centralised approach, where a super agent was used to control the agents’ collaboration with no heuristics algorithm applied. The proposed model outperformed the Centralised agent-based model by providing more sustainable energy production and storage plans that achieved the minimum production surplus and shortage of energy per region.

As future work, larger scales of integrated renewable energy networks, including a higher number of regions, cities, distribution companies, and energy suppliers, along with a longer-term (operational time) profile, will be investigated and modelled for additional generalised scenarios. Also, the impact of weather profiles during the day or even longer than that will be investigated, modelled, and tested to identify optimal energy production level and the best allocation of sources for energy distribution sustainable plans.

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