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Genetic Algorithm for Energy Commitment in a Power System Supplied by Multiple Energy Carriers

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Abstract: In recent years, energy consumption has notably been increasing. This poses a challenge to the power grid operators due to the management and control of the energy supply and consumption. Here, energy commitment is an index criterion useful to specify the quality level and the development of human life. Henceforth, continuity of long-term access to resources and energy delivery requires an appropriate methodology that must consider energy scheduling such as an economic and strategic priority, in which primary energy carriers play an important role. The integrated energy networks such as power and gas systems lead the possibility to minimize the operating costs; this is based on the conversion of energy from one form to another and considering the starting energy in various types. Therefore, the studies toward multi-carrier energy systems are growing up taking into account the interconnection among various energy carriers and the penetration of energy storage technologies in such systems. In this paper, using dynamic programming and genetic algorithm, the energy commitment of an energy network that includes gas and electrical energy is carried out. The studied multi-carrier energy system has considered defending parties including transportation, industrial and agriculture sectors, residential, commercial, and industrial consumers. The proposed study is mathematically modeled and implemented on an energy grid with four power plants and different energy consumption sectors for a 24-h energy study period. In this simulation, an appropriate pattern of using energy carriers to supply energy demand is determined. Simulation results and analysis show that energy carriers can be used efficiently using the proposed energy commitment method.

Keywords: energy commitment; energy consumption; energy carrier; multi-carrier energy system; energy storage in various energy types; dynamic programing; genetic algorithm

1. Introduction

In recent years, the development of multi-carrier energy systems (MCE) has gained worldwide attention. This is a result of the rising global energy tensions, the interactions between gas, heat,
and electricity networks, and the penetration of various energy storage facilities such as power to

gas systems and fuel cells [1,2]. However, the environmental pollution and energy crisis are the most
critical issues. The improvement of energy efficiency has become an unavoidable option to overcome
these problems [3]. Therefore, the operation of energy carriers to supply the energy demand, called the
energy commitment (EC) problem, must be optimized to increase the efficacy of the energy system.

The power system operator applies unit commitment (UC) to assign the optimal generation
scheme of units for a weekly or daily period [4]. Several research works have studied the UC problem.
For instance, Morales-Espana and Tejada-Arango [5] proposed a formulation for clustered UC (CUC) in
order to accurately model the flexibility requirements such as reserves, ramping, and shutdown/startup
constraints; moreover, in [6]. A temporal decomposition strategy for computation time reduction of
security-constrained UC (SCUC) was proposed. In [7], Ning and You suggested a new data-driven
adaptive robust optimization model for the solution of UC with integration of wind power units into
smart grids. A variable reduction technique for large-scale UC is introduced in [8].

Energy hub (EH) is a unit providing the output and input of fundamental features, storage,
and conversion of various energy carriers. Thus, the EH expresses an extension or generalization of a
network node in an electric power system [9]. In [10], Moazeni et al. studied the optimal scheduling of
an EH with various energy resources for serving stochastic heat and electricity demands considering
uncertain prices and operational constraints, such as downtime requirements and minimum uptime.
Furthermore, an intelligent modeling and optimization method for EH is proposed in [11] by dividing
the complex EH into several simple EHs. Dolatabadi et al. [12] also evaluated the operation of an EH
consisting of combined heat and power units (CHP), wind turbine, boiler, and storage facilities based
on a hybrid stochastic/information gap decision theory model.

In recent years, networks such as natural gas, heating, and electrical networks are generally
considered as independent systems known as multi-carrier energy system (MES) [13,14]. In [15],
Wang et al. proposed a new optimal planning model for CHP in MES to benefit both networks by
reducing the use-of-system (UoS) charge for system users and deferring investment for network
owners. Moreover, a robust day-ahead operation technique for a MES that improves the power systems
flexibility with a large integration rate of variable wind turbines is proposed in [16]. Furthermore, in [17],
Kampouropoulos et al. presented a new technique for the energy optimization of MES, which combines
a genetic algorithm for optimizing its energy flow. Additionally, an adaptive neuro-fuzzy inference
network for modeling and forecasting the power load of a plant is proposed.

One of the important indicators of quality assessment of life and the level of progress in a society
or country is energy consumption; supplying this energy demand is the main challenge of energy
operation and planning. Particularly, energy planning makes and confirms scenarios in the energy
economy based on the World Energy Council definition that: “part of economics related to energy
problems, taking into account the analysis of energy supply and demand, as well as execution of the
means for ensuring coverage of energy needs in a national or international background” [18]. In general,
energy planning approaches are categorized in three groups: model-based planning, analogy-based
strategy, and inquiry-based one [19]. The energy planning based on models contains econometric and
optimization models. The econometric model depends on mathematical and statistical approaches
such as regression investigation [19,20]. Moreover, the optimization scheme makes the step from a
description by a model to an instruction by a model when the best possible solution method based
on a goal function is needed, as an optimization procedure will prove that any deviation from a
defined condition leads to a degraded one [21,22]. This is the extensive classification of tools for energy
planning. Particularly, the great relevance of this fact is related to the family of multi-period linear
programming schemes [23–25].

Regardless of the used method, energy planning issue requires a detailed study of the energy
system. In [26], Cormio has presented a linear programming optimization scheme based on the energy
flow adopted optimization framework. Moreover, as it is well-defined in [27], integrated planning
of energy resources is the process that includes “finding the optimum combination of supply and
consumption smoothing resources in order to meet energy needs in an area or country.” In this reference, a series of basic features planning for minimization of energy costs and social and industry costs is mentioned [28]. In addition, Hobbs has developed a linear programming integer in order to unify the consumption and production resources management programs. This model is based on mixed-integer linear program (MILP) and Linear Program (LP) [29] that includes the features of the demand side management (DSM) [30,31]. Hobbs and Contella have presented a model of integrated resource planning (IRP) considering the environmental impact of power generation [32]. Moreover, in [33], Hirst and Goldman have shown how environmental factors can impact the IRP program.

In the planning of such systems by the traditional method, all demand must be met by the supply of electrical energy, and shortage is not acceptable; however, in the IRP method, it is assumed that the production shortfall can be compensated through consumption management programs [34], so that in many processes of IRP, applying demand management programs can play an important role in meeting demand [29]. In order to remove large numbers of DSM options and determine which options are more feasible, usually the cost savings method is used that estimates the value of each management plan for system energy consumption [35].

Optimization of horizontal planning is performed for two times: once according to the predicted electrical load at baseline and again with the expected load curve. If consumption management programs run, energy cost savings are equal to the difference between production costs and production capacity in the two mentioned states [36]. Several studies have performed energy consumption management in developing countries [37] such as Cyprus, Nepal [38], and Sri Lanka [39,40]. Such management approaches include the effect of power factor correction, programs for improving the efficiency of lighting and air conditioning, energy audit, using engines with smart meters, etc., in final consumption.

Energy systems are based on fossil fuels (i.e., natural gas, oil, and coal), which represents the most important primary energy source worldwide [41–43]. Concerning the shortage of fossil fuels, high penetration of renewable sources with hydrogen as an energy carrier has been suggested in [44]. Moreover, in [45], a general structure has been developed for modeling energy systems, including various energy carriers such as power, gas, heat, and other forms of energy. Nevertheless, while renewable resources considered as primary energy carrier that follows its position in the energy system, the transportation industry is heavily dependent on oil energy carrier and there is no easy solution to meet the demand for renewable transport sector [46]. As an alternative to dependence of energy economy on oil energy carrier, hydrogen energy economy arises [47]. A comparison in terms of efficiency and operational capabilities between different energy carriers is performed in [48] in order to generate cheap power. Traditional primary resources (i.e., fossil fuels) have limited capacity, and an appropriate planning must be done considering the presence of renewable primary energy carriers [49].

In this research work, based on dynamic programming (DP) and genetic algorithm (GA) concepts, the solution of energy commitment (EC) in multi-carrier energy systems is proposed. Moreover, considering the required information from the final energy consumption, in the present study, a mathematical model is developed to estimate the amount of electrical energy demands in the country, the combination of input fuel to power plants, and the optimum combination of production with a view to satisfying the demand. Thus, it offers the best integration of primary energy carriers to supply energy consumption.

This work enables a better understanding for the following benefits:

- Determination of the most appropriate pattern of using energy carriers to satisfy energy consumption.
- Study of integrated energy network.
- Integrated optimization of energy carriers instead of independent optimization of each carrier separately.
- Mathematical modeling of energy network from bottom to up (from the lowest energy level to the highest energy level).
• Application of DP and GA in EC.
• Impact of crude oil refining and its products on EC.
• Distribution of electrical energy as a subset of EC study.

This paper is structured as follows: Section 2 presents the EC problem formulation. The steps and process of implementing the proposed study are described in Section 3. In Section 4, the simulation results of the solution of EC problem are studied. Finally, Section 5 discusses the conclusions.

2. EC Problem Formulation

There are several methods for establishing reference energy system. The easiest way is to do hand calculations, but since one of the reference energy system applications is to study effects of changes in the structure of demand on the supply side, and also in large networks the calculations are very heavy and time-consuming, it seems desirable to model the energy grids in a specific software.

A power system simulator in Brookhaven National Laboratory was developed based on the development and design of the idea of the reference system. The basic idea of matrix formulation is to create vertical incisions in the energy system [50].

The energy grid matrix model is simulated step by step from the lowest energy level as the final energy load to the highest energy level, which is the primary energy carrier.

In the first step, $V_1$ as final energy consumption matrix based on the various energy consumption sectors is defined by Equation (1).

$$V_2 = T_{1,2} \times V_1$$

where $V_2$ is the final various energy loads and $T_{1,2}$ is a transformation matrix for conversion of the consumption sectors to carriers.

Considering the losses in distribution and transmission sectors, energy consumption is determined by Equation (2).

$$V_3 = T_{2,3} \times V_2$$

where $V_3$ is the final energy consumption by different carriers considering losses and $T_{2,3}$ is transmission, distribution, and energy consumption efficiency matrix. It should be noted that due to the fact that mathematical modeling is considered from demand to production (down to up), the $T_{2,3}$ parameter (transmission, distribution, and consumption efficiency) has values of 1 or above.

In order to convert the electricity demand as a secondary energy carrier to primary energy carriers, first the production of each unit must be determined, then the required carriers to supply fuel of power plants are calculated. The participation rate of each power plant unit in supplying electricity demand is calculated by Equation (3). After allocating electrical energy to the units, the amount of energy input to different power plants considering the efficiency of power plants can be calculated by Equation (4).

$$V_{e1} = T_{e1,2} \times V_{e1}$$  \hspace{1cm} (3)

$$V_{e3} = T_{e2,3} \times V_{e2}$$  \hspace{1cm} (4)

where $V_{e1}$ is power generation of various plants, $V_{e1}$ is total produced power, $T_{e1,2}$ is the separation of power supply matrix by various plants, $T_{e2,3}$ is efficiency matrix of plants, and $V_{e3}$ is fuel of plants.

After determining the total amount of energy input to each power plant, the amount of different fuels according to the type of power plant is calculated by Equation (5).

$$V_{e4} = T_{e3,4} \times V_{e3}$$  \hspace{1cm} (5)

where $V_{e4}$ is the requirement energy carriers to generate electrical energy demand and $T_{e3,4}$ is separation of fuel of plants to matrix of various carriers.
After the model of power supply, the requirement for various carriers in regard to power supply is computed by Equation (6):

\[ V_4 = V_3 + V_{e_4} - V_e \] (6)

where \( V_4 \) is the requirement for various carriers concerning transmission, distribution, energy usage, and supply power losses, and \( V_e \) is produced power.

Up to this stage of modeling, energy grid losses have been calculated, as well as electrical energy, as one of the most important energy demands that is converted into energy carriers input to power plants. In fact, based on the energy conversion process in power plants, the number of energy carriers (which is used as fuel for power plants) with a certain amount is converted to electricity carriers.

Another conversion energy process considered in the proposed study is to simulate the process of refining crude oil in refineries and converting crude oil into various petroleum products. Refining of crude oil energy carrier as a primary energy carrier and conversion to obtained energy carriers from refining is simulated by Equation (7).

\[ V_{p_2} = T_p \times V_{p_1} \] (7)

where \( V_{p_1} \) is the upper bound of refineries capacity, \( T_p \) is the share of each product generated by crude oil refining, and \( V_{p_2} \) is the generated carriers by refining.

The requirement for energy carriers after simulating the crude oil refining process is specified by Equation (8).

\[ V_5 = V_4 - V_{p_2} + V_p \] (8)

where \( V_p \) is the refined crude oil, \( V_5 \) is the carriers need considering power loss in production and refinement steps.

After determining the amount of need for different energy carriers in order to supply energy demand, the amount of import and export of carriers based on the amount of domestic production is determined by Equation (9).

\[ V_6 = V_5 - P \] (9)

where \( P \) is the domestic supply of primary carriers and \( V_6 \) is carriers import and export. In \( V_6 \), positive/negative signs mean import/export of primary carriers.

The amount of production share of each power plant unit in supplying electricity demand in Equation (3) should be allocated optimally based on the economic dispatch. Genetic algorithms (GA) is used to achieve this purpose and optimally allocation electrical energy to power plants.

**Genetic Algorithm**

Genetic algorithm is a search algorithm that has arisen with inspiration from Darwin’s natural principle and the principles of genetics. This principle is based on choosing a random set of strings (i.e., potential solutions) and with regard to compatibility (i.e., criterion for measuring the performance) and applying genetic operators over successive generations, attains to adaptive strings (i.e., optimum solutions).

The general framework of genetic algorithm is as follows:

- **Coding parts of the search space:** In the genetic algorithm, a string should be assigned anywhere in the search space because the genetic algorithm works with strings.
- **Production of the initial population and calculation of the amount of people’s fitness:** After determining the kind of coding, the initial population should be determined. One of the important parameters in the genetic algorithm is to determine the number of the initial population. Usually, a score is given to each string of the search space that reflects the well-being or fitness score of that string. This score indicates how much chance that person has to participate in the production of children. Generally, the objective function value is considered as a fitness number anywhere.
Proliferation: At this stage, people are chosen from the initial population to produce children and sent to the pond coupling. People with higher fitness should have greater opportunities to produce children. There are several methods for making this choice. For example, using a roulette wheel is one of these methods.

Applying genetic operators on selected people in proliferation: By applying genetic operators on people, the children population is produced. Some of these operators are mentioned here:

(A) Displacement: The approach of performing displacement on two strings that have been selected from a pond coupling is shown in Figure 1. The result of this action is producing two children.

(B) Mutations: Random variation of a gene in each category is called mutation.

(C) The translation operator: At this stage, a part of the string is selected and after translation placed in its position.

(D) Selection: At the last stage, after generating children from the set of the initial population, children must be chosen for the next generation. For selection by the roulette wheel, race or elitism methods can be used.

![Figure 1. Displacement action.](image)

By applying proliferation, displacement, mutation, and selection on a new generation again, the third generation can be produced. This generation will continue to make a stop condition [51].

Genetic algorithm has been used as a widely used optimization technique in various studies such as UC [52], wind energy studies [53], and path planning for self-reconfigurable robots [54].

3. Simulation and Discussion

This section focuses on different parts including the simulation parts, results, and discussions. It provides a concise and precise description of the experimental results, the interpretation, as well as the experimental conclusions that can be drawn.

3.1. Case Study

To illustrate the energy planning of primary energy carriers, a multi-carrier energy system with four power plants is used. The selected network contains transportation, industrial, and agriculture sectors; residential, commercial, and industrial consumers. Such parties are selected in the studied multi-carrier system for investigating a realistic viewpoint of interconnection among different energy carriers. The diagram of this studied multi-carrier system as well as its energy flow is drawn in Figure 2. In other words, Figure 2 shows the flow of energy from primary energy carriers to energy demand. Part of the energy demand is met directly from the primary energy carriers, which is indicated by arrow 2. Part of the energy demand is related to secondary energy carriers that become available after the energy conversion process in refineries or power plants. This concept is indicated by arrow 1. For example, electrical energy is a secondary energy carrier that is generated based on the conversion process of energy carriers in power plants. Information on this system is shown in Tables 1–5. Some additional information is also provided in the Appendix A (Tables A1–A3). The profile of energy demand is displayed in Figure 3. This figure shows the energy demand for all energy carriers.
(and not just electrical energy). Part of this energy demand is related to electricity demand, which is supplied by power plant units. Specifically, according to the information provided in Tables 1 and 2, the peak demand for electricity in the seventh hour of the study is equal to 650.83122 MWh. This is while the maximum capacity of electricity production by the power plant units of this network is equal to 840 MWh. Therefore, the grid is able to supply the electricity demand.

**Figure 2.** Energy network flow.

| Table 1. Units data. |
|----------------------|
| **Power Plant** | **The Capacity of the Unit (MW)** | **Efficiency** | **Constant Cost ($)** | **Priority** |
| Thermal unit 1 | 75 | 400 | 0.368 | 700 | 1 |
| Thermal unit 2 | 60 | 300 | 0.368 | 600 | 2 |
| Combined Cycle unit | 25 | 80 | 0.455 | 500 | 3 |
| Gas unit | 20 | 60 | 0.278 | 400 | 4 |

| Table 2. Export and import of energy carriers. |
|-----------------------------------------------|
| **Energy Carrier** | **Exported Energy (BOE)** | **Imported Energy (BOE)** |
| Petroleum | 63,576 | 0 |
| Liquid gas | 0 | 390.097 |
| Fuel oil | 3470.37 | 0 |
| Gas oil | 849.214 | 0 |
| Kerosene | 47,809.2 | 0 |
| Gasoline | 0 | 3244.317 |
| Plane fuel | 0 | 467.2201 |
| Natural gas | 0 | 442.3143 |
| Coke gas | 5.76467 | 0 |
| Coal | 0 | 157.7139 |

| Table 3. Initial conditions and timing data of units (hour). |
|-------------------------------------------------------------|
| **Power Plant** | **Minimum Time of Running** | **Minimum Time of Shutting Down** | **Cold Start** | **Initial Conditions** |
| Thermal unit 1 | 4 | 3 | 5 | 4 |
| Thermal unit 2 | 4 | 2 | 4 | 4 |
| Combined Cycle unit | 3 | 1 | 3 | 4 |
| Gas unit | 2 | 1 | 2 | –5 |
**Table 4.** Startup costs (US dollar).

| Power Plant         | Hot Start | Cold Start |
|---------------------|-----------|------------|
| Thermal unit 1      | 500       | 1100       |
| Thermal unit 2      | 400       | 950        |
| Combined Cycle unit | 170       | 350        |
| Gas unit            | 150       | 300        |

**Table 5.** Energy consumption for 24 h period Barrels of Oil Equivalent (BOE).

| Hour | Residential, Commercial and Public | Industrial | Transportation | Agriculture | Other | Non-Energy |
|------|-----------------------------------|------------|----------------|-------------|-------|------------|
| 1    | 1300.973                          | 633.221    | 801.976        | 92.05099    | 6.734205 | 270.5027   |
| 2    | 1375.911                          | 669.6951   | 848.1706       | 97.35321    | 7.121101 | 286.0839   |
| 3    | 1478.626                          | 719.6897   | 911.489        | 104.6209    | 7.653766 | 307.4409   |
| 4    | 1617.767                          | 787.4134   | 997.2612       | 114.4659    | 8.374016 | 336.3714   |
| 5    | 1647.586                          | 801.9275   | 1015.643       | 116.5758    | 8.528372 | 342.5716   |
| 6    | 1748.432                          | 872.4802   | 1104.999       | 126.832     | 9.278688 | 372.7107   |
| 7    | 1792.539                          | 841.1231   | 1105.285       | 122.2736    | 8.914211 | 359.3154   |
| 8    | 1641.709                          | 799.067    | 1012.021       | 116.1599    | 8.497951 | 341.3497   |
| 9    | 1702.912                          | 828.8562   | 1049.749       | 120.4904    | 8.814754 | 354.0752   |
| 10   | 1440.681                          | 701.2208   | 888.098        | 101.9361    | 7.457372 | 299.5512   |
| 11   | 1327.732                          | 646.2451   | 818.4712       | 93.94429    | 6.872714 | 276.0664   |
| 12   | 1194.478                          | 581.3864   | 736.3275       | 84.51583    | 6.182953 | 248.3997   |
| 13   | 1075.463                          | 523.4585   | 662.9616       | 76.04888    | 5.566889 | 223.6138   |
| 14   | 970.6051                          | 472.4213   | 598.3229       | 68.67653    | 5.021426 | 201.8114   |
| 15   | 835.9294                          | 406.8708   | 515.3029       | 59.14658    | 4.327006 | 173.8092   |
| 16   | 845.3121                          | 411.4376   | 521.0869       | 59.81046    | 4.375574 | 175.7601   |
| 17   | 855.4559                          | 416.3749   | 527.3399       | 60.52819    | 4.428081 | 177.8692   |
| 18   | 867.4479                          | 422.2118   | 534.7323       | 61.37669    | 4.490155 | 180.3627   |
| 19   | 1113.965                          | 542.1985   | 686.6959       | 78.8191     | 5.766195 | 231.6192   |
| 20   | 1496.348                          | 659.2801   | 847.6451       | 97.29288    | 7.176888 | 285.9066   |
| 21   | 1496.348                          | 728.3153   | 922.4133       | 105.8748    | 7.745517 | 311.1256   |
| 22   | 1412.433                          | 687.4714   | 870.6844       | 99.93734    | 7.311149 | 293.6776   |
| 23   | 1496.348                          | 728.3153   | 922.4133       | 105.8748    | 7.745517 | 311.1256   |

**Figure 3.** Energy demand profile.
3.2. ED and UC Solving

In recent years, various optimization algorithms have been introduced by researchers [55–69] and have been applied by scientists in various fields such as energy [70], protection [71], electrical engineering [72–76], energy carriers [77,78], and energy management [79,80] to achieve the optimal solution. Optimization algorithms have been always a popular way to solve ED and UC problems. In this paper, the economic distribution of electrical energy is done using GA. The objective functions of economic distribution of electrical energy are presented in Equations (10)–(13).

\[
F_{\text{obj}} = \sum_{i=1}^{N_{FIU}} E_{FIU}^i C_{FIU}^i
\]  
\[
E_{FIU}^i = \sum_{l=1}^{N_{DU}} \sum_{k=1}^{N_{U}} e_{ij}^k E_{IU}^k \quad \& \quad i = 1 : N_{FIU}
\]  
\[
e_{ij} \in [ETF]_{N_{FIU} \times N_{DU}}
\]  
\[
E_{IU} = \frac{1}{n_U} E_{OU}
\]

where \(F_{\text{obj}}\) is the objective function, \(N_{FIU}\) is the set of input fuels to power plants, \(E_{FIU}^i\) is the whole energy input to power stations of fuel type \(i\), \(C_{FIU}^i\) is the fuel cost of plant type \(i\), \(N_{DU}\) is the set of different plants, \(N_{U}\) is the set of plants of type \(j\) in the studied network, \(e_{ij}\) is the fuel contribution factor \(i\) from the plant’s energy input type \(j\), \(ETF\) is the input energy to fuel conversion matrix proportional to the plants, \(E_{IU}\) is the input energy power plants matrix, \(n_{U}\) is the power plants efficiency vector, and \(E_{OU}\) is the output electrical energy of power plants.

3.3. Determination of Optimization Constraints

The constraints include:

1. Power balance
   \[
   \sum_{i=1}^{N} P_i(t) = D(t)
   \]  

2. Unit generation limits
   \[
   P_{\text{min}}^i \leq P_i \leq P_{\text{max}}^i
   \]

where \(N\) is the number of plants, \(P_i(t)\) is output power by the \(i\)th unit at time \(t\), \(D(t)\) is the electric power demand at time \(t\), \(P_{\text{min}}^i\) is the minimum power, \(P_i\) is output power, and \(P_{\text{max}}^i\) indicates the maximum output power of the \(i\)th plant.

3.4. Employment of Dynamic Programming

After the distribution of power at each time of planning, tailored to each energy division mode between power plants, the planning process continues and, therefore, an integration of energy carriers corresponding to the integration of plants is obtained. At this stage, energy strategy planning during the study period will be carried out using dynamic programming.

Recursive method for calculation of the least cost at hour \(K\) with the combination \(I\), is as:

\[
F_{\text{cost}}(K, I) = \min_{(L)} [P_{\text{cost}}(K, I) + S_{\text{cost}}(K-1, L : K, I) + F_{\text{cost}}(K-1, L)]
\]

In Equation (16), \(F_{\text{cost}}(K, I)\) is the minimum cost in order to achieve \((K, I)\) state, \(P_{\text{cost}}(K, I)\) is the cost of \((K, I)\) state, and \(S_{\text{cost}}(K-1, L : K, I)\) is the cost of transition from the state \((K-1, L)\) to \((K, I)\). The \((K, I)\) state is combination number \(I\) at hour \(K\).
3.5. EC Implementation Steps

The various steps of EC are specified in Algorithm 1. The process of implementing the EC problem using flowchart is also shown in Figure 4.

| Algorithm 1 Energy commitment (EC) implementation steps |
|---------------------------------------------------------|
| **START EC**                                           |
| 1: Problem information.                                |
| 2: Inputs data                                         |
| 3: **ITER = 1**: Study period (24 h)                   |
| 4: \( V_1 = V_{\text{study period}}^{\text{ITER,1}} \). |
| 5: \( V_2 \) calculation using Equation (1).           |
| 6: \( V_3 \) calculation using Equation (2).           |
| 7: \( V_e = V_3(ed,1) \) and \( ed \) = row number of electrical demand in \( V_3 \). |
| 8: **UC solving**                                      |
| 9: Determine possible combinations of power plants to supply electrical demand. |
| 10: **pc = 1**                                         |
| 11: **While** \( pc \leq PC \) (PC = number of possible combinations). |
| 12: Economic dispatch (ED) solving for selected possible combination. |
| 13: **End UC solving**                                 |
| 14: \( V_4 \) calculation using Equations (3)–(6).     |
| 15: Refinery simulation using Equation (7).             |
| 16: \( V_5 \) calculation using Equation (8).           |
| 17: \( V_6 \) calculation using Equation (9).           |
| 18: **DP: Storing strategy**                           |
| 19: **pc = pc + 1**                                    |
| 20: **END While**                                      |
| 21: **END ITER**                                       |
| 22: **EC outputs** (for every hour and whole period of study) |
| 23: Determining the most appropriate pattern of using energy carriers |
| 24: Import and export of energy carriers                |
| 25: Cost of energy supply                               |
| **END EC**                                             |

3.6. Experimental Setup

The proposed study is simulated on the mentioned energy network for a 24-h study period. Genetic algorithm has been used as the optimization technique to solve the objective function. The number of chromosomes (population size) of the algorithm is equal to 50, the length of each chromosome is equal to 8, and the number of iterations is 50. The objective function has 8 variables. The 4 variables are related to the on or off status of power plant units and the other 4 variables are related to the amount of production of each of these units. In GA, the length of each chromosome is selected based on the number of problem variables. Therefore, the length of each chromosome is considered to be equal to 8.
3.6. Experimental Setup

The proposed study is simulated on the mentioned energy network for a 24-h study period. Genetic algorithm has been used as the optimization technique to solve the objective function. The number of chromosomes (population size) of the algorithm is equal to 50, the length of each chromosome is equal to 8, and the number of iterations is 50. The objective function has 8 variables. In GA, the length of each chromosome is selected based on the number of problem variables. Therefore, the length of each chromosome is considered to be equal to 8.

Figure 4. Flowchart of energy commitment (EC) problem.

4. Simulation Results

DP is done by storing the paths to the maximum number of hours of study modes. The correct strategy is the third case of combined units during the study period. The economic dispatch of electrical energy between the power plants units is specified in Table 6. The need for energy carriers to provide final energy consumption over 24 h is given in Table 7. The need for energy carriers in the entire study period is given in Table 8. The export and import of energy carriers are shown in Table 2 with respect to the domestic production of energy carriers.

UC is one of the important outputs of EC study, which determines the on/off status and output of units for each hour of the study period. Table 6 presents the results of the UC. In this table, a power
plant with zero production is off. The power plant with a production rate that has been determined is on. In the last column of this table, the value of the objective function for each hour of the study is presented. Figure 5 shows the production profiles of the different units for the entire 24-h period. According to this figure, in the seventh hour of the study period, which is related to the highest peak of demand, the fourth unit turns on and then, with the decrease of demand, shut down in the 12th hour of the study period. The processes of achieving an optimal distribution of electrical energy between the units are shown in Figure 6 and Figure 7. Figure 6 is for the first to twelfth hours of the study period and Figure 7 is for the thirteenth to twenty-fourth hours of the study period. In these figures, the convergence curves of the performance of the GA in the optimization of the objective function are shown as the best solution in terms of the iteration of the algorithm. The “state” in these figures shows the number of power plants on.

Another important outcome of the energy commitment study is to determine the appropriate pattern of use of energy carriers, which is presented in Table 7. In this table, the amount of need for nine energy carriers for each hour of the study period is specified separately. In this table, negative numbers indicate the excess of energy carrier production and positive numbers indicate the remaining need for energy carrier, which is supplied based on its domestic production.

Based on the amount of need for energy carriers per hour of the study period, the total amount of need for energy carriers for the entire study period can be calculated, which is presented in Table 8. In fact, Table 8 identifies the need for each energy carrier for the entire 24-h study period. The meaning of negative and positive numbers in this table is similar to Table 7.

The need for energy carriers is identified in Tables 7 and 8, which must be supply using domestic products. But if domestic production is not enough to supply each of the energy carriers, that energy carrier must be supplied in the form of imports. Energy carriers that have surplus production also enter the export sector. Accordingly, the export and import volumes of different energy carriers as another output of the EC study are presented in Table 2.

### Table 6. Economic distribution of power between the units.

| Hour | Unit 1 Production (MW) | Unit 2 Production (MW) | Unit 3 Production (MW) | Unit 4 Production (MW) | Objective Function |
|------|------------------------|------------------------|------------------------|------------------------|-------------------|
| 1    | 170.6394               | 250                    | 80                     | 0                      | 25,196.44         |
| 2    | 190.665                | 250                    | 80                     | 0                      | 26,390.97         |
| 3    | 235.7225               | 250                    | 80                     | 0                      | 29,078.68         |
| 4    | 250.7417               | 250                    | 80                     | 0                      | 29,974.58         |
| 5    | 265.7609               | 250                    | 80                     | 0                      | 30,870.48         |
| 6    | 290.7929               | 250                    | 80                     | 0                      | 32,363.65         |
| 7    | 300                    | 250                    | 80                     | 20.83122               | 34,155.45         |
| 8    | 285.8122               | 249.9998               | 79.99999               | 20                     | 33,259.55         |
| 9    | 260.7801               | 250                    | 80                     | 20                     | 31,766.38         |
| 10   | 240.7545               | 250                    | 80                     | 20.00002               | 30,571.85         |
| 11   | 210.7161               | 250                    | 80                     | 20                     | 28,780.04         |
| 12   | 200.6778               | 250                    | 80                     | 0                      | 26,988.24         |
| 13   | 120.5755               | 250                    | 80                     | 0                      | 22,230.13         |
| 14   | 75                     | 245.5115               | 79.99998               | 0                      | 19,429.3          |
| 15   | 75                     | 195.4476               | 80                     | 0                      | 16,630.42         |
| 16   | 75.00002               | 175.422                | 80                     | 0                      | 15,513.47         |
| 17   | 75                     | 178.4259               | 79.99997               | 0                      | 15,684.18         |
| 18   | 75.00003               | 183.4322               | 80                     | 0                      | 15,963.03         |
| 19   | 75                     | 185.4348               | 80                     | 0                      | 16,067.62         |
| 20   | 75                     | 205.4604               | 79.99998               | 0                      | 17,188.08         |
| 21   | 80.52431               | 250                    | 80                     | 0                      | 19,988.01         |
| 22   | 120.5755               | 250                    | 80                     | 0                      | 22,228.1          |
| 23   | 170.6394               | 250                    | 80                     | 0                      | 25,196.44         |
| 24   | 220.7033               | 250                    | 80                     | 0                      | 28,182.78         |
Table 7. Need for energy carriers in the energy network with 4 units using genetic algorithm (GA) (BOE).

| Hour | Liquid Gas | Fuel Oil | Gas Oil | Kerosene | Gasoline | Plane Fuel | Natural Gas | Coke Gas | Coal |
|------|------------|----------|---------|----------|----------|------------|-------------|----------|------|
| 1    | 17.64232   | −138.509 | −26.9061| 1.145155 | 143.2188 | 19.8964    | 1621.539    | 9.975951 | 22.04914|
| 2    | 20.49007   | −123.933 | −9.56189| 7.580451 | 159.7088 | 20.78303   | 1694.771    | 10.41933 | 23.02911|
| 3    | 26.8975    | −91.1249 | 29.46262| 22.05987 | 196.8114 | 22.77289   | 1859.345    | 11.41692 | 25.23402|
| 4    | 29.03331   | −80.19   | 42.47079| 26.88634 | 209.1789 | 23.43618   | 1914.469    | 11.74945 | 25.96899|
| 5    | 31.16912   | −69.2552 | 55.47896| 31.71281 | 221.5464 | 24.09447   | 1969.394    | 12.08196 | 26.70396|
| 6    | 34.7288    | −51.3034 | 77.15924| 39.75693 | 242.1593 | 25.20495   | 2060.935    | 12.6362  | 27.92891|
| 7    | 39.0043    | −29.1606 | 103.1756| 49.40987 | 266.8949 | 26.53152   | 2170.784    | 13.30127 | 29.39886|
| 8    | 36.86462   | −40.0955 | 90.16741| 44.5834  | 254.5265 | 25.86823   | 2115.859    | 12.96874 | 28.66389|
| 9    | 33.30493   | −58.3203 | 68.48713| 23.9139  | 221.4739 | 24.76275   | 2024.318    | 12.41452 | 27.43893|
| 10   | 30.45718   | −72.9001 | 51.1429 | 30.10399 | 217.4239 | 23.87837   | 1951.086    | 11.97114 | 26.45897|
| 11   | 26.18556   | −94.7699 | 25.12656| 20.45104 | 192.6889 | 22.55179   | 1841.237    | 11.30608 | 24.98903|
| 12   | 21.91394   | −116.64  | −0.88977| 10.7981  | 167.9538 | 21.22522   | 1731.388    | 10.64101 | 23.51909|
| 13   | 10.5295    | −174.814 | −70.265 | −14.9431 | 101.9937 | 17.68768   | 1438.882    | 8.667512 | 19.59924|
| 14   | 3.403882   | −209.916 | −113.61 | −31.0313 | 60.76859 | 15.47672   | 1259.74     | 7.795073 | 17.14933|
| 15   | −3.71579   | −245.005 | −156.954| −47.1196 | 19.54351 | 13.26576   | 1080.64     | 6.650634 | 14.69943|
| 16   | −6.56353   | −290.022 | −174.292| −53.3549 | 3.053474 | 12.38138   | 1009.055    | 6.207258 | 13.71947|
| 17   | −6.13657   | −256.896 | −171.691| −52.5896 | 5.526979 | 12.51403   | 1019.86     | 6.273765 | 13.66646|
| 18   | −5.42444   | −253.395 | −167.356| −50.9807 | 9.649487 | 12.73513   | 1037.748    | 6.384699 | 14.11145|
| 19   | −5.13966   | −252.045 | −165.625| −50.3372 | 11.29849 | 12.83257   | 1044.756    | 6.428946 | 14.20945|
| 20   | −2.29191   | −238.003 | −148.285| −43.9019 | 27.78852 | 13.70795   | 1116.415    | 6.872322 | 15.18941|
| 21   | 4.82746    | −202.906 | −104.941| −27.8137 | 69.01361 | 15.91891   | 1295.538    | 7.908761 | 17.63931|
| 22   | 10.52295   | −174.828 | −70.265 | −14.9431 | 101.9937 | 17.68768   | 1438.839    | 8.667512 | 19.59924|
| 23   | 17.64232   | −138.509 | −26.9061| 1.145155 | 143.2188 | 19.8964    | 1621.539    | 9.975951 | 22.04914|
| 24   | 24.76169   | −102.06  | 16.45445| 17.23339 | 184.4438 | 22.1096    | 1804.62     | 11.08439 | 24.49905|

Table 8. Need for energy carriers in the entire study period in energy network.

| Energy Carrier | Energy Demand (BOE) |
|----------------|---------------------|
| Petroleum      | 34824               |
| Liquid gas     | 390.097             |
| Fuel oil       | −3470.37            |
| Gas oil        | −849.214            |
| Kerosene       | −47.8092            |
| Gasoline       | 3244.317            |
| Plane fuel     | 467.2201            |
| Natural gas    | 38122.31            |
| Coke gas       | 234.2353            |
| Coal           | 517.7139            |
Figure 5. The units productions on study period.

Figure 6. Cont.
Figure 6. The process of achieving optimal distribution of electrical energy. (a–l) means hours 1 to 12.
Figure 7. Cont.
5. Conclusions

Energy supply and demand in different types of energy carriers is one of the important challenges of the energy network. Operation of energy carriers in order to supply the energy demand of consumers at different energy levels requires accurate, technical, and economic planning. Therefore, in this paper, a new approach for energy studies is presented under the title of energy commitment (EC) in energy networks. In the proposed study, the energy network includes different parts of energy consumption that must be provided by appropriate energy carriers. The purpose of the EC study is to determine a technical and optimal pattern for the use of energy carriers in supply energy demand. The energy grid matrix model has been simulated step by step from the lowest energy level as the final energy consumption to the highest energy level, which is the primary energy carrier. Genetic algorithm (GA) has been used for the optimal allocation production share of each power plant unit in supplying electricity demand. At each hour of operation, different patterns of energy carriers are available to supply energy demand, and the best pattern must be selected. Dynamic planning (DP) method is used to determine the appropriate pattern of operation of energy carriers in the energy grid for the specified study period. The proposed EC study has been mathematically modeled and implemented on an energy grid with four power plants and different energy consumption sectors for a 24-h energy study period. In this simulation, an appropriate pattern of using energy carriers to supply energy demand has been determined. The presented results show clearly the proper strategy for economic scheduling of various units for energy production.

The authors express several items as suggestions and perspectives for future studies. Implementing the proposed study on different energy networks, using different optimization techniques to solve the EC problem, and considering different objective functions are study potentials for researchers. EC studies in the presence of newer generation sources such as photovoltaic and wind power plants also have a special potential for future studies.

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**Nomenclature**

- **MCE** Multi-Carrier Energy
- **EC** Energy Commitment
- **UC** Unit Commitment
- **CUC** Clustered Unit Commitment
- **SCUC** Security-Constrained Unit Commitment
- **EH** Energy Hub
- **CHP** Combined Heat and Power Units
- **UoS** Use of System
- **MILP** Mixed-Integer Linear Program
- **LP** Linear Program
- **DSM** Demand Side Management
- **IRP** Integrated Resource Planning
- **DP** Dynamic Programming
- **GA** Genetic Algorithm
- **ED** Economic Dispatch
- **BOE** Barrels of Oil Equivalent
- **MW** Mega Watts
- **V_1** Final energy consumption matrix
- **T_{1,2}** Transformation matrix for conversion of the consumption sectors to carriers
- **V_2** Final various energy loads
- **T_{2,3}** Transmission, distribution and energy consumption efficiency matrix
- **V_3** Final energy consumption by different carriers considering losses
- **T_{e1,2}** Separation of power supply matrix by various plants
- **V_{e1}** Total produced power
- **V_{e2}** Power generation of various plants
- **T_{e2,3}** Efficiency matrix of plants
- **V_{e3}** Fuel of plants
- **T_{e3,4}** Separation of fuel of plants to matrix of various carriers
- **V_{e4}** Requirement energy carriers to generate electrical energy demand
- **V_e** Produced power
- **V_4** Requirement for various carriers concerning transmission, distribution, energy usage and supply power losses
- **V_{P1}** Upper bound of refineries capacity
- **T_p** Share of each product generated by crude oil refining
- **V_{p2}** Generated carriers by refining
- **V_p** Refined crude oil
- **V_5** Carriers need considering power loss in production and refinement steps
- **P** Domestic supply of primary carriers
- **V_6** Carriers import and export
- **F_{obj}** Objective function
- **N_{FIU}** Set of input fuels to power plants
- **E_{FIU}** Energy input to power stations of fuel type i
- **C_{FIU}** Fuel cost of plant type i
- **N_{DU}** Set of different plants
Set of plants of type \( j \) in the studied network

Fuel contribution factor \( i \) from the plant’s energy input type \( j \)

Input energy to fuel conversion matrix proportional to the plants

Input energy power plants matrix

Power plants efficiency vector

Output electrical energy of power plants

Number of plants

Output power by the \( i \)th unit at time \( t \)

Electric power demand at time \( t \)

Minimum power

Output power

Maximum output power of the \( i \)th plant

Combination number \( I \) at hour \( K \)

Minimum cost in order to achieve \((K, I)\) state

Cost of \((K, I)\) state

Cost of transition from the state \((K-1, L)\) to \((K, I)\)

Number of possible combinations

Domestic production of energy carriers

Separation matrix of products created from refining crude oil

**Appendix A**

**Table A1.** Transmission matrix \( T_{1,2} \).

| Energy Carrier         | Residential, Commercial and Public | Industrial | Transportation | Agriculture | Other | Non-Energy |
|------------------------|------------------------------------|------------|---------------|-------------|-------|------------|
| Petroleum              | 0                                  | 0          | 0             | 0           | 0     | 0          |
| Liquid gas             | 0.051                              | 0.013      | 0.011         | 0           | 0     | 0          |
| Fuel oil               | 0.023                              | 0.212      | 0.014         | 0           | 0     | 0          |
| Gas oil                | 0.055                              | 0.087      | 0.363         | 0.689       | 0     | 0          |
| Kerosene               | 0.141                              | 0.002      | 0             | 0.018       | 0     | 0          |
| Gasoline               | 0.002                              | 0.002      | 0.573         | 0.003       | 0     | 0          |
| Plane fuel             | 0                                  | 0          | 0.031         | 0           | 0     | 0          |
| Other products         | 0                                  | 0          | 0             | 0           | 0.402| 0          |
| Natural gas            | 0.564                              | 0.521      | 0.007         | 0           | 0     | 0.497      |
| Coke gas               | 0                                  | 0.021      | 0             | 0           | 0     | 0          |
| Coal                   | 0.0003                             | 0          | 0             | 0           | 0     | 0.101      |
| Non-commercial fuels   | 0.064                              | 0          | 0             | 0           | 0     | 0          |
| Hydroelectric          | 0                                  | 0          | 0             | 0           | 0     | 0          |
| Wind and solar         | 0                                  | 0          | 0             | 0           | 0     | 0          |
| Electricity            | 0.102                              | 0.142      | 0.0004        | 0.29        | 1     | 0          |
| Nuclear                | 0                                  | 0          | 0             | 0           | 0     | 0          |

**Table A2.** \( T_p, T_{23}, P \).

| Energy Carrier         | \( T_p \) | \( T_{23} \) | \( P \) |
|------------------------|-----------|--------------|--------|
| Petroleum              | 0         | 1            | 5858.1 |
| Liquid gas             | 0.032     | 1            | 0      |
| Fuel oil               | 0.293     | 1            | 0      |
| Gas oil                | 0.293     | 1            | 0      |
| Kerosene               | 0.099     | 1            | 0      |
| Gasoline               | 0.157     | 1            | 0      |
| Plane fuel             | 0         | 1            | 0      |
| Other products         | 0.058     | 1            | 0      |
| Natural gas            | 0         | 1.1601       | 3814.2 |
| Coke gas               | 0         | 1            | 25.2   |
| Coal                   | 0         | 1            | 37.8   |
| Non-commercial fuels   | 0         | 1            | 152.4  |
| Hydroelectric          | 0         | 1            | 150.6  |
| Wind and solar         | 0         | 1            | 0.6    |
| Electricity (power)    | 0         | 1.3158       | 0      |
| Nuclear                | 0         | 1            | 0      |
Table A3. Input rate of energy for power plant.

| Unit          | Steam   | Steam   | Combined Cycle | Gas  |
|---------------|---------|---------|----------------|------|
| Fuel oil      | 0.254   | 0.254   | 0              | 0    |
| Gas oil       | 0.003   | 0.003   | 0.082          | 0.166|
| Natural gas   | 0.743   | 0.743   | 0.918          | 0.834|

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