# Availability Analysis of a Loop Structured System - Application of the GO-FLOW methodology to a distributed energy system consisting of a solar panel, a rechargeable battery and a fuel cell -

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**Abstract:** Availability analysis has been conducted for a distributed energy system consisting of a solar panel, a rechargeable battery, and a fuel cell. This is an attempt at availability analysis of a loop structured engineering system. The operational schedule of a distributed energy system has been set based on each subsystems' functional capability. The fuel cell repeatedly starts and stops the operation of the loop structure. The solution of Boolean expression for the availability of the fuel cell has been explained. Availability analysis has been performed by the GO-FLOW methodology. The system has been modeled into a GO-FLOW chart. The loop structured part has been modeled by utilizing the phased mission operator which is prepared in the GO-FLOW analysis framework. The chart shows how to model logical loop relations even without any loop structure in the chart. The availability of the system has been obtained by one GO-FLOW chart with a single calculation. The proposed modeling method of logical loop structure is applicable to any engineering systems that contain loop structure(s). This method is particularly useful for evaluating the reliability and/or availability of any kinds of complex engineering systems.

**Keywords:** Distributed energy system, Availability analysis, Loop structured system, GO-FLOW methodology.

## 1. INTRODUCTION

Renewable energy and its technologies are the foundation for climate action and for a sustainable world. Effective use of solar energy is important for the realization of a sustainable society. The goal of the society is to reduce the consumption of finite resources and to make a low-carbon and environmentally friendly society [1]. Introducing a distributed energy system consisting of a solar panel, a rechargeable battery and a fuel cell as a household system can greatly contribute to reducing $CO_2$ emissions, realizing energy conservation, and improving the energy self-sufficiency.

The stable power supply by the system is essential, so it is necessary to evaluate the (instantaneous) availability of this distributed energy system. Since the fuel cell system performs an operation having a loop structure that feeds back and uses the electric power generated by itself, it is necessary to carry out an availability analysis that correctly evaluates the logical loop structure.

Many of engineering systems, such as nuclear power plants or aerospace systems, have loop structures in their system. With the loop structure, systems establish high reliability or robustness. A loop structed system can operate without support from outside of the system.

In this paper, the availability analysis considering a loop structure has been carried out using the GO-FLOW methodology [2]. The remainder of this paper is organized as follows. In Section 2, explain the structure and function of the distributed energy system. Its operational schedule has been set based on each subsystems' functional capability. In section 3, explain a solution of Boolean expression for a loop structured system. In section 4, brief explanations have been given for the GO-FLOW methodology and phased mission operator. The target system has been modeled into GO-FLOW chart. Modeling technique has been explained for a loop structured system. In section 5, analysis results are shown, and discussions are given. Finally, conclusion is given in section 6.

## 2. SYSTEM DESCRIPTION

Figure 1 shows a system configuration consisting of a solar panel, a rechargeable battery, and a fuel cell. A solar panel makes electricity, and it is used for household consumption and for battery charge. There will be extra electricity instantaneously. In this case, the electricity is sold to an electric company through power grid.

The solar panel sometimes stops to make electricity during nighttime and when there is no sunshine.

A rechargeable battery can supply electricity to household consumption when the solar panel cannot supply enough energy. The battery has an upper limit of the storage capacity and there is a limit of the power supply duration by itself. The battery is also used for the start of a fuel cell system.

Once a fuel cell starts its operation, it can continue to make electricity without the support of battery. The fuel cell system has a loop structured configuration. The fuel cell can supply enough electricity to household consumption when both the solar panel and the battery cannot supply electricity. It can supply electric power until the hydrogen that is the fuel is exhausted, but the power generation efficiency and load followability are low, and it is better to use it as an auxiliary in the three technologies in order to reduce the running cost.

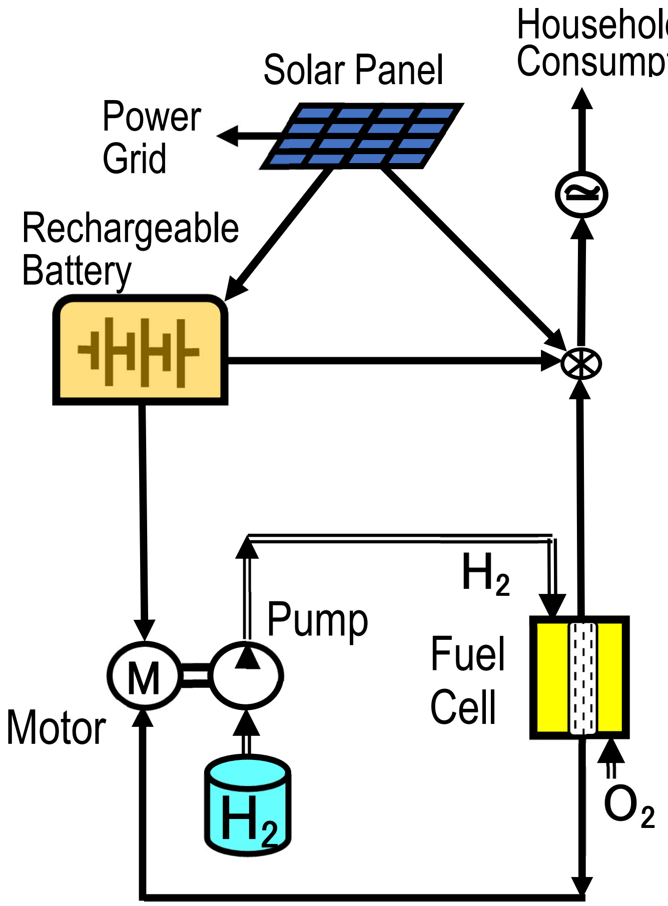


Figure 1. A system consisting of a solar panel, a rechargeable battery, and a fuel cell

In the present analysis, the specifications for the components are set as shown in table 1. Failure rates are set based on the data shown in the reference [3].

The household consumption is set as average 10kwh/day. The solar panel can supply household consumption and battery charge at the same time during shine daytime. Two days are required for the battery to be fully charged by the solar panel. The fuel cell can cover the needs of household consumption.

Intermittent availability of the solar panel is assumed and set the operational schedule of this system as shown in Fig. 2. In this figure “N” means nighttime and “D” means daytime. The relations between actual time and “Dawn”, “Sunrise”, “Sunset” and “Dusk” can be seen in Table. 2 (analysis results).

Table 1. Specifications of components

| Components | capacity | lifetime | Failure rates | |
|---|---|---|---|---|
| Solar panel | maximum 20kWh/day | 30years | 3.8E-6/h | Failure |
| Rechargeable battery | 20kWh | 10years | 1.14E-5/h | Failure |
| Fuel cell | 10kWh/day | 60,000h | 1.67E-5/h | Failure |
| Motor | | 50,000h | 2E-5/h<br>1.1E-4/D | Failure to run<br>Failure to start |
| Pump | | 50,000h | 2E-5/h | Failure to run |
| $H_2$ tank | | | 1.2E-7/h | Leak & Plug |
| $O_2$ flow | | | 1E-8/h | Plug |
| DC-AC inverter | | | 2.8E-7/h | Failure |

In Fig. 2., the orange region means the solar panel makes electricity in some specific daytime. The gray region means that the battery is being charged and cannot be used for household consumption. After the battery is fully charged, it can supply electricity to household consumption for almost full two days. This situation is indicated by purple color in Fig.2.

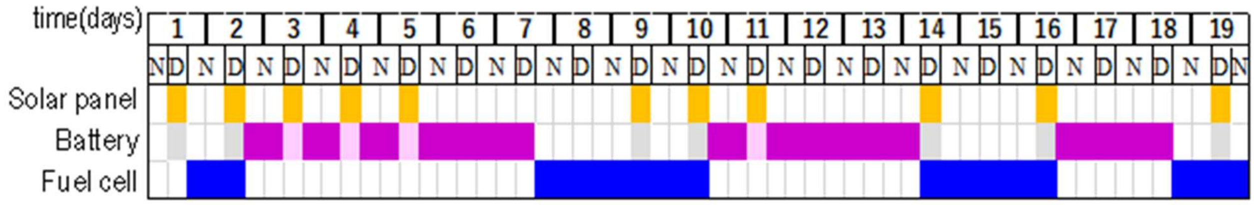


Figure 2. Schedule for operation

Generation of electricity by the solar panel changes even during daytime depending on the weather condition. Therefore, the solar panel requires parallel operation with the battery or fuel cell. The light purple color means that the battery is operating parallel with the solar panel and occasionally supplies the electricity, and it is assumed that charged electricity during daytime can cover the needs in that nighttime. The battery always takes priority over the fuel cell.

The electricity from fuel cell is indicated by blue color. If the battery is not available, the fuel cell provides the electricity parallel with the solar panel. For example, the daytime of 2nd day is in this situation. If both the solar panel and battery cannot supply the electricity, the fuel cell alone provides the electricity. In the schedule of Fig.2, fuel cell repeatedly starts and stops the operation of the loop structure.

## 3. SOLUTION OF BOOLEAN EXPRESSION FOR A LOOP STRUCTURED SYSTEM

Reliability analysts have been long suffered to solve a problem of logical loops in reliability and/or availability analysis. Many attempts [4-6] have been made as breaking the logical loops at the points where the dependencies among the support systems are relatively weak and developing new logic without loops. Recursive methods [7,8] have been presented for finding the solution of logical loops. But these methods give us approximate solutions and there exists contra-example for the result [9].

For a system which has logical loop structure(s), the Boolean relations which express system logical relations, is described with unknown variable(s). If we try to solve the Boolean equation(s) with unknown variable(s), we encounter infinite circulation of the unknown variable(s). An exact method [10] has been proposed for solving this problem in reliability analysis. It has been shown that Boolean equations are mathematically solvable with arbitrary sets [11].

This arbitrary sets can be determined by the concept of "Takeover phenomenon" [12]. Then, it has been shown for abstract model systems that a loop structured system can be basically solved. Analyses have been applied to rather abstract conceptual system models [13,14]. In this paper, availability of loop structured system has been solved for a concrete engineering system; a distributed energy system consisting of a solar panel, a rechargeable battery and a fuel cell.

The fuel cell is required to start 4 times during the operational schedule shown in Fig.2. The procedure to start the fuel cell is as follows. First, motor is started to rotate by the electricity from the battery, then pump begins to run and hydrogen from $H_2$ tank is supplied to a fuel cell. Oxygen taken from air reacts to hydrogen at the cell and electricity is produced. This electricity can be used as the power source to the motor, and to continue the fuel cell operation without the support of battery. A loop structured operation is established.

The relation is expressed as follows in Boolean equation.

$$x(t) = H_2(t) \cdot Mo(t) \cdot Pu(t) \cdot O_2(t) \cdot Fu(t) \cdot x(t) \qquad (1).$$

Where $x(t)$ expresses an instantaneous (or point) availability of the electricity from fuel cell at time $t$. The availabilities of hydrogen and oxygen are denoted as $H_2(t)$ and $O_2(t)$, respectively. The soundness of motor operation, pump operation and fuel cell operation are denoted as $Mo(t)$, $Pu(t)$ and $Fu(t)$, respectively. These variables are "sets" which represent availabilities or the sound condition of components. The solution of equation (1) becomes as follows [10].

$$x(t) = H_2(t) \cdot Mo(t) \cdot Pu(t) \cdot O_2(t) \cdot Fu(t) \cdot m \qquad (2).$$

Where, $m$ is an arbitrary set. The arbitrary set $m$ is determined as $Ba(t_0)$ in the present configuration by considering takeover phenomenon [12]. The set "$Ba(t_0)$" is an availability of the battery at time $t_0$ ($t_0$ is the time when loop structured operation of fuel cell is established), and it is a fixed value.

An instantaneous availability of the electricity $E(t)$ supplied by this system is expressed in the following equation.

$$E(t) = So(t) + Ba(t) + Ba(t_0) \ \cdot H_2(t) \cdot Mo(t) \cdot Pu(t) \cdot O_2(t) \cdot Fu(t) \qquad (3).$$

Where $So(t)$ is an availability of the solar panel.

## 4. ANALYSIS BY THE GO-FLOW METHODOLOGY

### 4.1. OVERVIEW OF THE GO-FLOW METHODOLOGY

GO-FLOW [2] is a success-oriented system analysis technique that is capable to evaluate reliability and/or availability of the systems with complex time-sequence and phased-mission problems. The GO-FLOW method can also deal with common cause failure (CCF) analysis with uncertainty [15]. The modeling technique produces a chart which consists of signal lines and operators and represents the engineering function of the components/subsystems/system [16].

The GOFLOW operators model function or failure of the physical equipment, logical gates, and signal transmissions. Generally, three types of signals are connected to an operator: main input signal(s) S, sub input signal(s) P, and an output signal R. Each operator has a logic for combining the inputs properly and producing the output. Specific probability (point estimates) of component operation or failure are given to operators as input data. Currently 14 operators are defined, and their type numbers and shapes are summarized in Fig. 3.

Signals represent some physical quantities or information. A signal line between two operators transmits a physical quantity or information in the direction of the arrow of the signal line. A quantity called "intensity" is associated with a signal. In general, the intensity indicates the probability that a signal is present. The existence of a signal is interpreted as the actual or potential existence of a signal. "Potential existence" means that a signal is present when all downstream resistances are eliminated. When a signal is used as a sub-input signal of the type-35, -37 and -38 operators, the intensity represents the time interval between successive time points.

A finite number of discrete time values (points) are required to express the system operational sequence. The value does not necessarily represent real time but corresponds to it and represents an ordering [2].

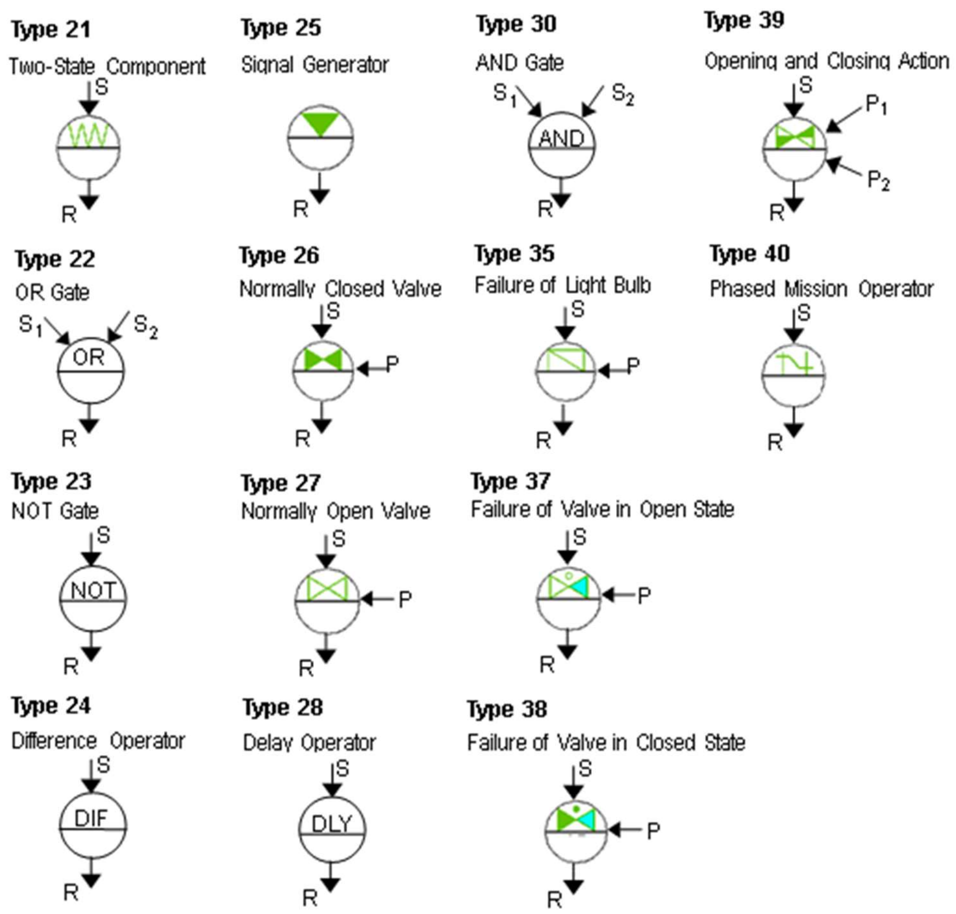


Figure 3. GO-FLOW operators.

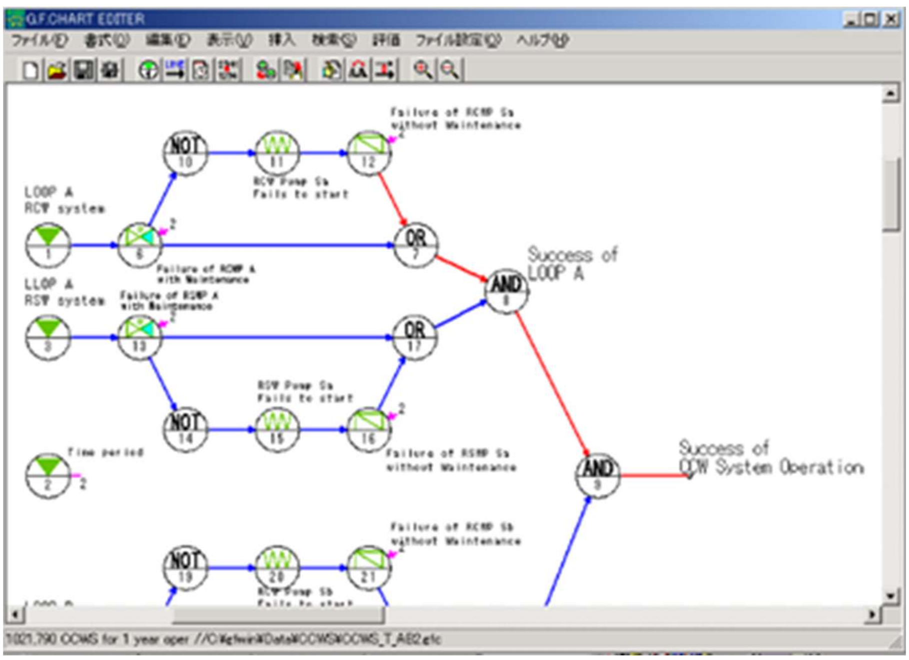


Figure 4. GO-FLOW chart editor.

The first step of the analysis is to construct a GO-FLOW chart, which is the model of the engineering system under consideration. An analyst interactively constructs a chart on a PC display with the support of the GO-FLOW chart editor as shown in Fig. 4.

During the construction of a chart, component failure data and analysis conditions are given. The GO-FLOW model analysis is performed from upstream to downstream along the signal lines. In most cases, only one or a few defined signals are of interest. These signal lines are called “final signals” and indicated by red color as seen in Fig. 4. An analysis is performed by one GO-FLOW chart with a single calculation on the GO-FLOW chart editor.

### 4.2. Type 40 Operator (Phased Mission Operator)

The type 40 operator is prepared for the analysis of phased mission problem [17] in the GO-FLOW methodology. The detailed procedure to analyze phased mission problem has been shown in reference [16].

The type 40 operator freezes signal intensity except during specific period (phase) as shown in Fig. 5. In this figure *S(t)* and *R(t)* are the intensities of input and output signals, respectively. A specific period (phase) is from time $t_i$ to $t_j$. Before this phase, output *R(t)* is always 1.0, and after this phase *R(t)* holds the intensity of $S(t_j)$, that is, the input at the end of the specific phase.

The availability of loop structured operation of fuel cell is obtained as shown in Eq. (3). The solution contains a fixed value of the Battery availability when the loop operation is established ($Ba(t_0)$). The type 40 operator is used for obtaining this fixed value in the GO-FLOW modeling.

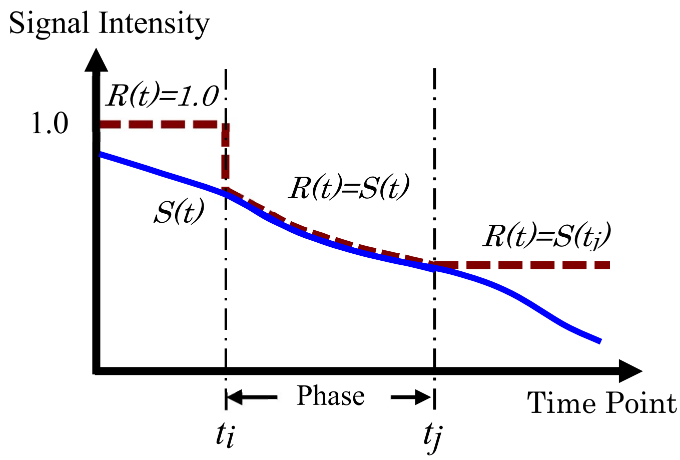


Figure 5. Function of type 40 operator (Phased Mission Operator).

### 4.3. GO-FLOW chart

The system is modeled into a GO-FLOW chart as shown in Fig. 6. Followings are detailed explanations of this chart. Although the content is somewhat complicated, it will help to understand how to model the analytical solution of a loop structure with a GO-FLOW chart.

In this chart, operator No.1 is a signal generator and gives signal intensity of 1.0 at all the time points. This is the starting point of this system model.

The solar panel is modeled by the No.23, type 37 operator: “Failure of valve open state”. By this operator, failure progression due to aging of solar panel is modeled. A constant failure rate 3.8E-6/h is given. Signal 4 gives time duration after the start of the system and used as a sub input signal to No.23 operator. Output signal of No.23 operator gives the soundness of solar panel over time progress. Non-reparable model for failure is used in the present analysis.

Operator No.24 is type 39: “Open/Close action operator” and it models the available period of the solar panel, it corresponds to the orange part in Fig.2. Operator No.5, signal generator, gives start signals of solar panel operation and is given to No.24 operator as sub input signal P1(t). Operator No.6 gives stop signals for the solar panel operation and is given to No.24 operator as sub input signal P2(t). Intermittent availability of the solar panel is modeled by the set of operators No.4, No.5, No.6, No.23 and No.24.

The solar panel supplies electricity to the rechargeable battery for charging up. For operator No.48, type 40 (phased mission operator), a specific period (phase) is defined as from "Start of 1st day" to "5th day sunset". This operator freezes input signal after "5th day sunset". The output of operator No. 48 gives the probability of the soundness of solar panel and the soundness is fixed after "5th day sunset". The operator No.49, type 39 opens a window for signal passing from "2nd day dusk" to "7th day sunset" by receiving the signals from operators No.15 and No.16. Signal 49 (output of operator No. 49) represents the possibility of the role of solar panels in enabling storage battery from "2nd day dusk" to "7th day sunset". As seen in Fig.2, the battery is fully charged up at "2nd day sunset" and starts the operation at "2nd day dusk". During the discharging period from "5th day dusk" to "7th day sunset", soundness of the solar panel at the "5th day dusk" contributes to the battery availability. Therefore, the fixed value of the probability of soundness of the solar panel at "5th day sunset" (This is modeled by using the No.48, type 40 operator.) is used for the discharging period.

Aged deterioration of battery is modeled by No.46, type 37 operator, with failure rate of 1.14E-5/h. Combination of No.48, No.49 and No.46 operators give availability of battery operation during "2nd day dusk" to "7th day sunset".

Other 2 periods (from "10th day dusk" to "14th day sunrise", and from "16th day dusk" to "18th day sunset") for the battery operation are modeled in the same way, by the combination of No.51, No.52, No.46 operators, and No.53, No.54, No.46 operators, respectively.

The fuel cell starts its operation by receiving the electricity of the battery. As seen in Eq. (3), the availability of fuel cell is governed by a fixed value of battery availability at the time the fuel cell starts. For example, for the fuel cell operation from "1st day dusk" to "2nd day sunset", the fuel cell availability consists of the battery availability Ba($t_{1st\ day\ sunset}$)) and fuel cell components' soundness and availabilities of hydrogen and oxygen.

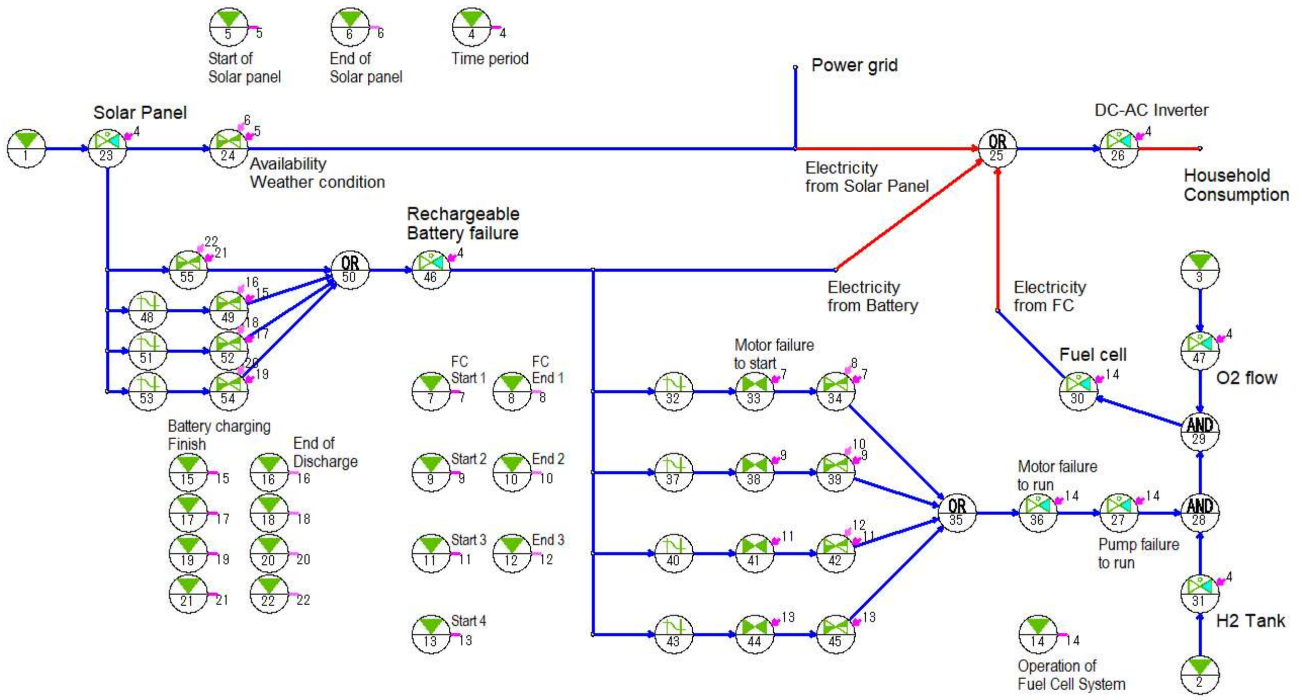


Figure 6. GO-FLOW chart for the system consisting of a solar panel, a rechargeable battery, and a fuel cell.

Operator No.32, type 40, freezes the availability of battery after the time "1st day dusk". The actual time of "$t_{1st\ day\ sunset}$" and "$t_{1st\ day\ dusk}$" are the same time. The electricity from the battery charged during daytime on the first day is just used for the start of motor operation. Operator No.55 models the supply of electricity to the start of motor at $t_{1st\ day\ dusk}$. Operator No.34, type 39, specifies the fuel cell operation period from "1st day dusk" to "2nd day sunset", in the same way of the operator No.24's modeling for solar panel operation.

Operators Nos.33, 36, 27, 31, 47 and 30 model “motor failure to start”, “motor failure to run”, “pump failure to run”, “$H_2$ tank failure”, “$O_2$ flow failure” and “fuel cell failure”, respectively. Aged deteriorations and “failure to start” are considered for components’ failure.

A series of operators from No.32 to No.30 along the signal line direction can give the availability of loop structured operation (fuel cell operation) for the period from “1st day dusk” to “2nd day sunset”. It corresponds to the third term in Eq. (3). Other 3 periods for the fuel cell operation are modeled in the same way by the series of operators from No.37 to No.30, and so on.

The total system availability is obtained by “OR” combinations of the three availabilities, “the electricity from solar panel”, “the electricity from battery” and “the electricity from fuel cell”. After considering the soundness of DC-AC invertor (No.26, type37 operator, failure rate of 2.8E-7/h), the final availability is obtained by the No. 26 signal (output of the No.26 operator).

## 4. ANALYSIS RESULTS

Fig. 7. and Table 2. show the analysis results by the GO-FLOW methodology. Total availability, which means availability of any electric source, is indicated by gray color line in Fig. 7.

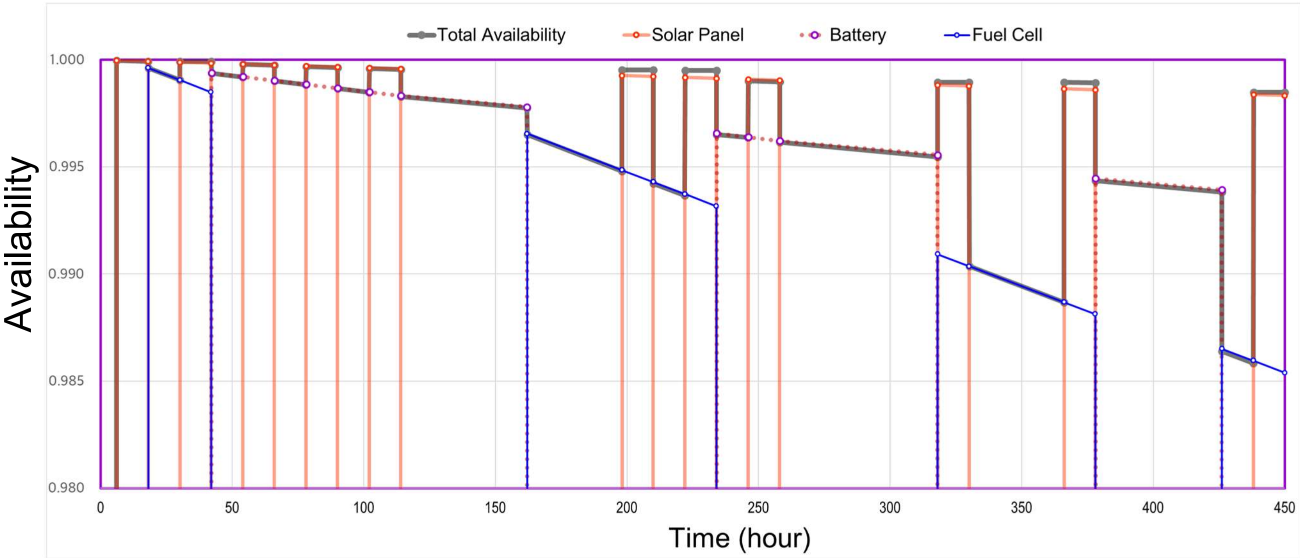


Figure 7. Availability of the system consisting of a solar panel, a rechargeable battery and a fuel cell.

Availability of the solar panel, the rechargeable battery and the fuel cell are indicated by orang line, purple dotted line, and blue line, respectively. Corresponding to the operational schedule (Fig. 2.), availability of the solar panel intermittently drops and backup system, the battery or the fuel cell, is put in operational states. All the components are affected by aged deterioration and availabilities decrease with time, as seen in Fig. 7. The deterioration of the fuel cell is assumed to proceed only during operation.

When the solar panel is backed up by the fuel cell, the total availability is greater than the availability of solar panel. For example, from the sunrise to sunset of 9th day (198h to 210h), the fuel cell operation is started at 7th day dusk (162h) and the availability of battery at 7th day sunset ($Ba(t_{7\text{th day sunset}})$) contributes to the fuel cell availability as seen in Eq.(3). Moreover, the battery is charged up at 5th day sunset (114h) by the solar panel. The availability of the fuel cell from the sunrise to sunset of 9th day is a subset of the availability of the solar panel at 5th day sunset (114h), not from the sunrise to sunset of 9th day (198h to 210h).

A loop structured operation is isolated from outside of the loop structure after the establishment of loop operation. Any component failure of outside of a loop structure does not affect the availability of loop operation. This is a distinguished feature of a loop operation.

The availability of the system is obtained by one GO-FLOW chart with a single calculation. The loop structured part (the fuel cell) is properly modeled in the GO-FLOW chart and its availability can be obtained.

Table 2. Analysis results (availability, numerical values)

| Day | Time (hours) | Solar Panel | Rechargeable Battery | Fuel cell | to Household consumption |
|---|---|---|---|---|---|
| 1st day | 0 | 0.0 | 0.0 | 0.0 | 0.000000 |
| Dawn | 6 | 0.0 | 0.0 | 0.0 | 0.000000 |
| Sunrise | 6 | 0.999978 | 0.0 | 0.0 | 0.999976 |
| Sunset | 18 | 0.999933 | 0.0 | 0.0 | 0.999928 |
| Dusk | 18 | 0.0 | 0.0 | 0.999623 | 0.999618 |
| 2nd day Dawn | 30 | 0.0 | 0.0 | 0.999058 | 0.999050 |
| Sunrise | 30 | 0.999889 | 0.0 | 0.999058 | 0.999925 |
| Sunset | 42 | 0.999845 | 0.0 | 0.998493 | 0.999921 |
| Dusk | 42 | 0.0 | 0.999383 | 0.0 | 0.999371 |
| 3rd day Dawn | 54 | 0.0 | 0.999207 | 0.0 | 0.999191 |
| Sunrise | 54 | 0.999800 | 0.999207 | 0.0 | 0.999785 |
| Sunset | 66 | 0.999756 | 0.999030 | 0.0 | 0.999737 |
| Dusk | 66 | 0.0 | 0.999030 | 0.0 | 0.999012 |
| 4th day Dawn | 78 | 0.0 | 0.998854 | 0.0 | 0.998832 |
| Sunrise | 78 | 0.999711 | 0.998854 | 0.0 | 0.999690 |
| Sunset | 90 | 0.999667 | 0.998678 | 0.0 | 0.999642 |
| Dusk | 90 | 0.0 | 0.998678 | 0.0 | 0.998653 |
| 5th day Dawn | 102 | 0.0 | 0.998502 | 0.0 | 0.998473 |
| Sunrise | 102 | 0.999623 | 0.998502 | 0.0 | 0.999594 |
| Sunset | 114 | 0.999578 | 0.998326 | 0.0 | 0.999546 |
| Dusk | 114 | 0.0 | 0.998326 | 0.0 | 0.998294 |
| 7th day Sunset | 162 | 0.0 | 0.997799 | 0.0 | 0.997753 |
| Dusk | 162 | 0.0 | 0.0 | 0.996543 | 0.996498 |
| 9th day Dawn | 198 | 0.0 | 0.0 | 0.994854 | 0.994799 |
| Sunrise | 198 | 0.999268 | 0.0 | 0.994854 | 0.999521 |
| Sunset | 210 | 0.999223 | 0.0 | 0.994291 | 0.999517 |
| Dusk | 210 | 0.0 | 0.0 | 0.994291 | 0.994233 |
| 10th day Dawn | 222 | 0.0 | 0.0 | 0.993729 | 0.993667 |
| Sunrise | 222 | 0.999179 | 0.0 | 0.993729 | 0.999513 |
| Sunset | 234 | 0.999135 | 0.0 | 0.993167 | 0.999510 |
| Dusk | 234 | 0.0 | 0.996566 | 0.0 | 0.996501 |
| 11th day Dawn | 246 | 0.0 | 0.996390 | 0.0 | 0.996366 |
| Sunrise | 246 | 0.999090 | 0.996390 | 0.0 | 0.999021 |
| Sunset | 258 | 0.999046 | 0.996215 | 0.0 | 0.998974 |
| Dusk | 258 | 0.0 | 0.996215 | 0.0 | 0.996143 |
| 14th day Dawn | 318 | 0.0 | 0.995557 | 0.0 | 0.995469 |
| Sunrise | 318 | 0.998824 | 0.0 | 0.990925 | 0.998955 |
| Sunset | 330 | 0.998780 | 0.0 | 0.990365 | 0.998951 |
| Dusk | 330 | 0.0 | 0.0 | 0.990365 | 0.990362 |
| 16th day Dawn | 366 | 0.0 | 0.0 | 0.988686 | 0.988673 |
| Sunrise | 366 | 0.998647 | 0.0 | 0.988686 | 0.998939 |
| Sunset | 378 | 0.998602 | 0.0 | 0.988127 | 0.998935 |
| Dusk | 378 | 0.0 | 0.994459 | 0.0 | 0.994354 |
| 18th day Sunset | 426 | 0.0 | 0.993934 | 0.0 | 0.993815 |
| Dusk | 426 | 0.0 | 0.0 | 0.986510 | 0.986392 |
| 19th day Dawn | 438 | 0.0 | 0.0 | 0.985952 | 0.985831 |
| Sunrise | 438 | 0.998381 | 0.0 | 0.985952 | 0.998477 |
| Sunset | 450 | 0.998336 | 0.0 | 0.985395 | 0.998473 |

## 5. CONCLUSIONS

In this paper, we have presented an availability analysis for a distributed energy system consisting of a solar panel, a rechargeable battery, and a fuel cell which includes logical loop structure. This is an attempt at availability analysis of a loop structured engineering system.

Take up a distributed energy system as an example of concrete engineering system. The operational schedule of this system has been set based on each subsystems' functional capability. The fuel cell part has a loop structured operation. The fuel cell repeatedly starts and stops the operation of the loop structure. The solution of Boolean expression for an availability of fuel cell has been briefly explained.

Availability analysis has been performed by the GO-FLOW methodology. Brief explanations have been given for the GO-FLOW methodology and phased mission operator. The system has been modeled into a GO-FLOW chart. The detailed explanations have been given for the construction of the chart, in which loop structured part is modeled by utilizing the type 40 operator (phased mission operator) corresponding to the solution of the Boolean expression. The chart shows how to model logical loop relations even without any loop structure in the chart.

The availability of the system has been obtained by one GO-FLOW chart with a single calculation. The availability of loop structured part (the fuel cell) can be also obtained. The proposed modelling method for logical loop structure is applicable to any engineering systems that contain loop structure(s). This method is particularly useful for evaluating the reliability and/or availability of any kinds of complex engineering systems.

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