Exploring Hybrid Energy Systems for Demand-Responsive Coordination Between Solar and Conventional Power Sources

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Abstract. Ensuring a continuous power supply that adapts to real-time demand remains a central challenge in modern energy systems, particularly when integrating renewable sources alongside conventional energy generation systems. Sudden and unpredictable fluctuations in electrical load, such as the unexpected activation of high-power equipment, can momentarily disturb the balance between supply and demand. In conventional setups, such situations are typically managed effectively through established automated and human-supervised control mechanisms, which have ensured reliable and stable operation over time. However, the introduction of solar photovoltaic systems brings additional complexity due to their dependence on environmental factors such as solar irradiance, temperature, and cloud conditions. These factors lead to inherent variability in power output that traditional control frameworks were not originally designed to accommodate. This study examines hybrid energy systems developed to enable demand-responsive coordination between solar and conventional power sources. The focus is placed on adaptive control concepts capable of sustaining operational stability and maintaining a continuous energy supply despite unpredictable solar behavior and varying demand conditions. Although primarily conceptual at this stage, the work provides the foundation for future simulation-based investigations employing interactive control interfaces and advanced coordination strategies. The ultimate aim is to contribute to the development of intelligent and resilient hybrid systems capable of delivering consistent performance under dynamic and uncertain environmental circumstances.

Keywords: Hybrid Energy Systems, Solar Power Variability, Demand-Responsive Coordination, Conventional Generation Control, Renewable Integration Challenges

1 Introduction

Modern energy generation systems must maintain high reliability by continuously balancing supply and demand as consumption fluctuates throughout the day [1]. Conventional generators such as gas turbines, hydro units, and steam plants exhibit well-

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established and predictable response characteristics and have historically relied on structured load shedding practices ranging from priority-based schemes [2, 3] to rotational [4] and manual strategies [5] to manage contingencies and protect critical loads. More technical optimal load shedding approaches have also emerged, including methods based on swarm intelligence and metaheuristics [6, 7], although such techniques can increase the complexity of power system controllers [8-10].

The growing integration of solar photovoltaic generation introduces a fundamentally different behavior into this traditionally stable landscape [11]. Unlike conventional generators, solar output depends directly on environmental conditions such as irradiance, cloud movement, and temperature, all of which can change rapidly and cannot be controlled [12]. This variability creates uncertainty in generation and complicates efforts to maintain instantaneous power balance [13]. Coordinating a predictable generator with an inherently fluctuating source, therefore, becomes a central challenge, particularly when demand must be met without deviation [14]. A demand-responsive approach is needed to compensate for solar fluctuations while ensuring overall system stability [15].

This paper presents a conceptual framework for demand-responsive coordination between solar and conventional power sources, building on earlier efforts in simplified load-shedding logic. Reference [16] proposed a streamlined binary search–based approach, while [17] introduced a script-based automation method developed in a different context. By combining these ideas, the proposed method provides an automated and scalable algorithm for handling any number of loads. The remainder of the paper is structured as follows: Section 2 presents the algorithm, Section 3 outlines the validation scenarios, Section 4 offers a discussion, and Section 5 concludes the work.

2 Materials and Methods

This section establishes the computational approach used to evaluate load–generation coordination in a hybrid power system. Rather than implementing a full control architecture, the focus is on designing a flexible algorithmic process that can test all feasible combinations of optional loads under varying solar output and conventional generator availability. The method operates with an arbitrary number of loads, each represented by its rated power demand. Generator capacity and solar PV output are treated as separate inputs so the system can evaluate how different solar conditions influence which load subsets remain active.

To evaluate all feasible load combinations, the script employs binary counting as a straightforward and scalable method for generating configurations for N loads [16]. The full binary range naturally represents every possible arrangement, where a bit value of one corresponds to an active load and zero to a shed load. Incrementing the binary sequence ensures that the entire configuration space is covered in an orderly and non-repetitive manner.

For each configuration, the script calculates the total demand and excludes any case that exceeds the currently available supply. This step becomes particularly relevant under varying solar conditions, where fluctuations in irradiance or temperature can alter the available power over short intervals. By treating solar output as a time-dependent input, the script can reassess the admissibility of each configuration as conditions change. Throughout this process, the script also keeps track of the configuration whose demand lies closest to the maximum available generation, ensuring that the most suitable option is retained for further analysis, as shown in Listing 1.

```
  void FindOptimalLoadCombo(int P_Gen, int P_Solar, int[] P_Loads)
  {
      int iteration = 0;
      int n = P_Loads.Length;
      string bestBinary = "";
      string currentBinary = "0";
      double optimalScore = double.MaxValue;

      while (true)
      {
          if (currentBinary.Length > n)
              break;

          int sum = 0;
          string filledNumber = new string('0', n -
currentBinary.Length) + currentBinary;
          for (int i = 0; i < filledNumber.Length; i++)
              if (filledNumber[i] == '1')
                  sum += P_Loads[i];

          int difference = P_Gen + P_Solar - sum;
          if (optimalScore > difference && difference >= 0)
          {
              optimalScore = difference;
              bestBinary = currentBinary;
              iteration = Convert.ToInt32(currentBinary, 2);
          }

          currentBinary = IncrementBinaryString(currentBinary);
          Console.WriteLine($"{filledNumber} -> F:" + difference +
(difference >= 0 ? "" : " Ignored!"));
      }
      Console.WriteLine("\n===== Best Combination =====");
      Console.WriteLine($"Best Decimal: {optimalScore}");
      Console.WriteLine($"Best Binary: {new string('0', n -
bestBinary.Length) + bestBinary}");
      Console.WriteLine($"Best iteration: {iteration}");
  }
```

Listing 1 Dynamic search function for identifying the optimal load combination in a hybrid solar–conventional generation system

A dedicated function is used to increment the binary sequence, and the binary state is represented as a string rather than an integer [16]. This design avoids the overhead of repeatedly converting between numeric and binary formats, which would introduce additional parsing, padding, and range-checking operations. Because the goal is simply to advance the binary pattern by one step, operating directly on the character sequence provides a lightweight and predictable mechanism, as shown in Listing 2.

```
string IncrementBinaryString(string binaryNumber)
{
    char[] bits = binaryNumber.ToCharArray();
    int i = bits.Length - 1;

    while (i >= 0)
    {
        if (bits[i] == '0')
        {
            bits[i] = '1';
            return new string(bits);
        }
        else
        {
            bits[i] = '0';
            i--;
        }
    }

    return "1" + new string(bits);
}
```

Listing 2 Binary-increment function for advancing a string-based binary counter

The function processes the bits from right to left, flipping a '0' to '1' at the first admissible position and resetting any trailing '1' values to '0', thus producing the next valid configuration. This mirrors how binary counting naturally progresses and allows the enumeration to proceed cleanly and predictably, which is helpful when navigating large sets of possible configurations.

3 Experimental Results

The proposed method is validated through a sequence of progressively more demanding scenarios. The first validation step reproduces a data set used in earlier work, referred to as Case 1, to ensure that the present implementation is consistent with previously established results [16]. Once this baseline is confirmed, additional scenarios are introduced to test whether increasing the number of loads, adding solar generation, or altering the demand profile affects the accuracy of the method.

Validation was conducted across ten distinct cases, varying the number of loads, the level of solar generation, and the arrangement of load values, including unsorted sequences, as shown in Listing 3.

```
FindOptimalLoadCombo(950, 0, new int[] {650, 350, 260, 50});
FindOptimalLoadCombo(950, 0, new int[] {260, 650, 350, 50});
FindOptimalLoadCombo(950, 100, new int[] {650, 350, 260, 50 });
FindOptimalLoadCombo(950, 100, new int[] {650, 350, 160, 100, 50});
FindOptimalLoadCombo(950, 200, new int[] {650, 350, 160, 100, 50});
FindOptimalLoadCombo(950, 220, new int[] {450, 350, 200, 160, 100, 50});
FindOptimalLoadCombo(950, 220, new int[] {160, 450, 50, 100, 350, 200});
FindOptimalLoadCombo(950, 180, new int[] {450, 350, 200, 160, 100, 50});
FindOptimalLoadCombo(950, 240, new int[] {450, 350, 200, 160, 100, 50});
FindOptimalLoadCombo(950, 75, new int[] {450, 350, 200, 160, 100, 50});
```

Listing 3 Input configuration used for validation of the proposed method

Table 1 summarizes the results for each case, reporting the input parameters for the conventional generator, the solar panels, and the load set. For each scenario, the table also indicates the binary configuration selected, the iteration at which it was identified, and the total power utilized by the active loads.

Table 1. Validation results for ten cases.

Case	P Gen	P Solar	P Loads as Array	Best Case Found		
				Binary	Result	Iteration
1	950 W	0	[650, 350, 260, 50]	1010	910 W	10
2	950 W	0	[260, 650, 350, 50]	1100	910 W	12
3	950 W	100 W	[650, 350, 260, 50]	1101	1050 W	13
4	950 W	100 W	[650, 350, 160, 100, 50]	11001	1050 W	25
5	950 W	200 W	[650, 350, 160, 100, 50]	11011	1150 W	27
6	950 W	220 W	[450, 350, 200, 160, 100, 50]	111100	1160 W	60
7	950 W	220 W	[160, 450, 50, 100, 350, 200]	110011	1160 W	51
8	950 W	180 W	[450, 350, 200, 160, 100, 50]	110111	1110 W	55
9	950 W	240 W	[450, 350, 200, 160, 100, 50]	111100	1160 W	60
10	950 W	75 W	[450, 350, 200, 160, 100, 50]	110101	1010 W	53

Figure 1 illustrates the results, providing a visual comparison of performance across these cases. For clarity, the figure shows four lines corresponding to “Load Total”, “Just Gen”, “With Solar”, and “Load Used”. “Load Total” represents the overall demand considered in each case. “Just Gen” indicates the contribution from conventional generators alone for reference. “With Solar” adds the fluctuating solar panel input to the generator output. “Load Used” shows the total load actually fulfilled according to the optimal configuration determined by the proposed algorithm. This breakdown highlights how solar integration affects load fulfillment and system performance.

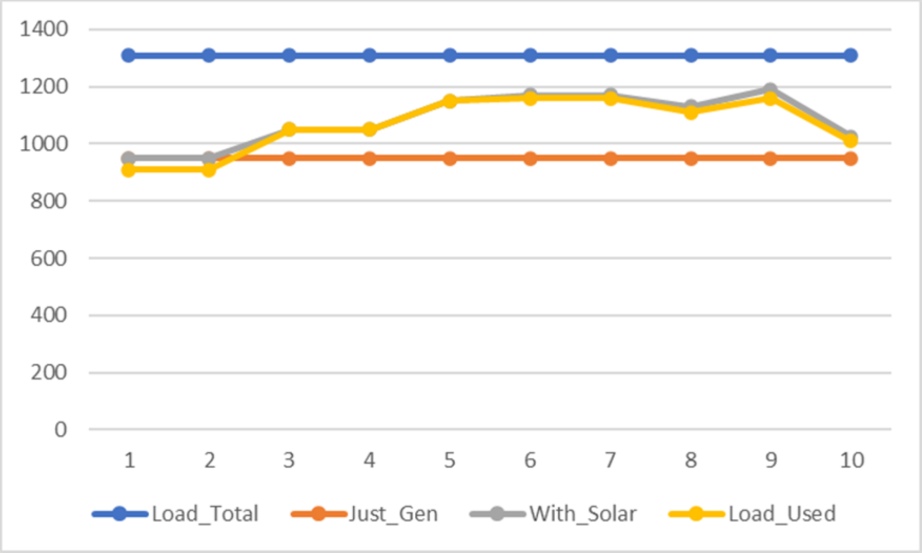

Fig. 1. Graphical view of results across ten cases.

For all cases, the "Load Total" was maintained at 1310 W, with the power distributed differently among the individual loads in each scenario, while the generator's maximum capacity "Just Gen" remained fixed at 950 W. Figure 1 illustrates how the additional, fluctuating contribution from the solar panel affects the system and shows that in some cases the "Load Used" remains below the combined available generation.

4 Discussion and Analysis

A key challenge in hybrid energy systems is the inherent unpredictability of solar output compared to conventional generators, which makes it difficult to maintain a perfectly balanced supply at all times. Even with buffers or reserve capacity, fluctuations can create situations that require careful management, especially at larger scales where deviations may be significant. At this early stage, the approach is conceptual, but it highlights opportunities for further development, such as coordinating multiple generation stations through successive rounds of load evaluation to distribute power more efficiently. Similarly, linking solar panel capacity to environmental conditions like temperature and irradiance, rather than fixed power values, could enable a more predictive and flexible strategy for hybrid energy management.

5 Conclusion

The results presented in Table 1 and illustrated in Figure 1 demonstrate that integrating solar panel generation into a hybrid system can enable a greater number of load configurations to be fulfilled, enhancing overall utilization of available capacity. At the same time, the inherent variability of solar output introduces unpredictability, and Figure 1 also shows that in some cases the “Load Used” remains below the maximum capability of the hybrid power generation system “With Solar”, indicating potential areas for further investigation. The binary configurations obtained for all cases in Table 1 were manually verified by summing the corresponding loads to confirm the accuracy of the method, reinforcing confidence in its validity.

Overall, these findings highlight that hybrid coordination is essential to maintain stability when solar sources are included and that understanding solar fluctuation patterns is important for integrating them with conventional load distribution systems. In future works, the method can be applied within a simulation environment with interactive controls, allowing researchers and practitioners to explore hybrid coordination strategies and evaluate how different approaches perform under varying operating conditions.

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