Increasing Use of Renewable Energy by Coalition Formation of Renewable Generators and Energy Stores

Pavel Janovsky and Scott A. DeLoach

Kansas State University, Department of Computer Science, KS 66506, USA,
{janovsky,sdeloach}@ksu.edu

Abstract. Renewable sources are not used to their full potential for electricity generation. Unpredictability of solar and wind power forces renewable generators to bid conservative generation amounts in a day-ahead market in order to avoid fees for failure to provide generation. In this paper we propose an approach to increase the use of renewable sources, which allows renewable generators to hedge against generation unpredictability by forming coalitions with energy stores. Inside these coalitions renewable generators purchase availability of energy stores to generate power when needed. Renewable generators use this availability to avoid fees for failure to provide committed generation whenever the current generation is lower than the committed value. We experimentally show that our approach allows renewable generators to commit to 100% of the predicted generation, thus increasing the use of renewable sources. We also show that our approach generates profit incentives for both renewable generators and energy stores to form coalitions.

Keywords: renewable sources, large-scale coalition formation, multi-agent simulation

1 Introduction

Weather-related unpredictability of power generation by renewable resources forces renewable generators to produce conservative amounts of power. Electricity is traded ahead of time in a day-ahead energy market. In this market generators bid amounts of energy that they will be able to generate at given time slots. Since in the electricity market the supply must always match the demand, a failure to deliver the committed amount of energy can have major negative consequences, and it is therefore penalized. Consequently, the renewable generators, due to weather unpredictability, are forced to bid amounts that are lower than the predicted generation, thus decreasing the use of renewable resources [2].

In this paper we propose an approach that can be used to increase the use of renewable resources by forming coalitions between renewable generators and a high number of energy stores. We are not concerned with the type of energy stores, however we require them to be able to provide energy at a time that they commit to. This capability can be viewed as a commodity for which there is demand among the renewable generators. A renewable generator can buy coverage of some portion of the generation that it commits to. If the renewable generator is able to produce the entire amount of committed energy, it only pays the store owners for the coverage it ordered. On the other hand, if the renewable generator is not able to generate the committed energy, it can use part of the ordered coverage in order to avoid fees for failure to provide energy. A store owner is paid for the uncertainty coverage as well as for the amount of energy provided to the grid.

Specifically, this paper provides the following contributions:

1. An approach to increase use of renewable energy sources using coalition formation of renewable generators and energy store owners. We show our model of renewable sources and energy stores in Section 2, and we describe how to use multi-agent simulation for coalition formation of renewable generators and energy store owners in Section 3.
2. Experimental evaluation of the coalition formation process between renewable generators and energy store owners. We show that our approach increases use of renewable resources by increasing profit of renewable generators in Section 4.

2 Model

We model the renewable generators and energy store owners as agents in a multi-agent system. We describe all variables used in our model in Table 1. Renewable generators are modeled using a triplet $(g_c(t), g_r(t), u_r)$ for time t corresponding to the time slots. This triplet represents the generation committed and actually generated by the renewable generator, and a coverage uncertainty that the generator is willing to pay for. The energy store owners are modeled as a triplet (s_b, s_e, m) which represents the beginning and end of a time interval within which the store can provide power, and the maximum total amount of provided power.

2.1 Renewable Generators

In order to increase the use of renewable resources, an incentive has to be given to renewable generators to bid higher energy amounts in the day-ahead market. In this section we derive this incentive in a form of a profit function. We assume this profit function to be of the following form:

$$p_r = \sum_t p_r(t) = \sum_t (p_g \cdot \min(g_c(t), g_r(t)) - c_c(t) - c_f(t)), \tag{1}$$

representing the fact that the renewable generator is paid for its generation, but has to pay for uncertainty coverage and failure to provide committed generation.

Table 1: Description of model variables

$p_r(t)$	profit of a renewable generator r that participates in coalition formation
$p_{r0}(t)$	profit of a renewable generator r that does not participate in coalition formation
$g_c(t)$	generation committed by a renewable generator
$g_e(t)$	estimated generation of a renewable generator
$g_r(t)$	real generation achievable by a renewable generator, not observable
$g_{sc}(t)$	generation committed by an energy store
$g_{sr}(t)$	real generation provided by an energy store
$u_r[\%]$	percentage of g_c to be requested as coverage for uncertainty
$u(t)[\%]$	percentage of $g_c(t)$ granted by energy stores as coverage for uncertainty
m	maximum total amount of power to be distributed by an energy store
s_b, s_e	energy store availability begin, end
p_g	price for generation
p_c	price for uncertainty coverage
p_f	price for failure to provide committed generation
$c_c(t)$	cost of uncertainty coverage
$c_f(t)$	cost of failure to provide committed generation
$c_0[\%]$	commitment of a renewable generator that does not participate in coalition formation
t	time

This profit function assumes that $\forall t : g_c(t) = g_e(t)$, i.e. that the renewable generator will always commit to generate the estimated amount of energy.

The cost of uncertainty coverage $c_c(t)$ depends on the uncertainty coverage parameter $u(t)$ as follows: $c_c(t) = p_c \cdot u(t) \cdot g_c(t)$. The uncertainty cost is independent of the real generation $g_r(t)$, since the uncertainty coverage is paid for before the value of $g_r(t)$ is known. The uncertainty cost is calculated using the percentage of the coverage actually provided $u(t)$, for which it holds that $\forall t : u(t) \leq u_r$, since the store owners can commit less than the value requested by a renewable generator.

The cost of failure to provide committed generation $c_f(t)$ is determined using a difference between amounts of generation committed and actually provided as follows:

$$c_f(t) = p_f \cdot \max\left(g_c(t) - (g_r(t) + u(t) \cdot g_c(t)), 0\right). \tag{2}$$

Profit of a renewable generator in the coalition formation setting is therefore expressed as

$$p_r = \sum_t p_r(t) = \sum_t \Big(p_g \cdot \min(g_c(t), g_r(t)) - p_c \cdot u(t) \cdot g_c(t) - p_f \cdot \max\left(g_c(t) - (g_r(t) + u(t) \cdot g_c(t)), 0\right) \Big). \tag{3}$$

Without coalition formation the renewable generator is forced to bid a lower amount to prevent paying the cost for failure to provide committed energy. On the other hand, the uncertainty coverage cost does not apply to this renewable generator. The profit of a renewable generator that does not participate in coalition formation with energy store owners is therefore

$$p_{r0} = \sum_t p_{r0}(t) = \sum_t \Big(p_g \cdot \min(c_0 \cdot g_e(t), g_r(t)) - p_f \cdot \max(c_0 \cdot g_e(t) - g_r(t), 0)\Big). \quad (4)$$

2.2 Energy Stores

In order to simplify the problem we assume that energy stores are always able to sell their stored energy, either to renewable generators through the coalition formation process, or to some other party. We also assume that stores are always able to provide the committed amounts of energy. This assumption eliminates factors such as different types of stores, or whether stores buy the power from other subjects.

Following is the profit function of an energy store owner:

$$p = \sum_{t=s_b}^{s_e} (p_g \cdot g_{sr}(t) + p_c \cdot g_{sc}(t)). \quad (5)$$

This profit function must satisfy the following constraints: $0 \leq \sum_{t=s_b}^{s_e} g_{sc}(t) \leq m$ and $\forall t : g_{sr}(t) \leq g_{sc}(t)$, which limits the total amounts of energy committed and provided by the store. An energy store is incentivized to participate in coalition formation with renewable generators if $\sum_{t=s_b}^{s_e} p_c \cdot g_{sc}(t)$ is positive, which happens when a renewable generator purchases the uncertainty coverage from this store.

3 Coalition Formation using Multi-agent Simulation

To simulate coalition formation of renewable generators and store owners we use the multi-agent simulation approach proposed in [4]. There a simulator is proposed in which agents leave and join coalitions in an iterative manner. This coalition formation process is used to search the state space of coalition structures, which are sets of coalitions, in order to find coalition structures with high social welfare. During the simulation agents use strategies to decide whether to leave their coalitions and which coalition to join. The strategy that achieves best results combines agent's best response, in which an agent searches for a coalition to which it can bring most benefit, with random jumps whenever a local optimum is reached. In this work we will therefore base the agents' strategy on that strategy. The coalitions are assigned values by a specified valuation function. Quality of solutions is represented in [4] by a social welfare, which is a sum of values of all coalitions in a coalition structure. The simulation generates a pool of coalition structures, from which a coalition structure with the highest social welfare is selected as the solution.

There are several differences between the approach in [4] and coalition formation of renewable generators with energy store owners. First, unlike in [4], coalition formation between renewable generators and energy store owners is not concerned with social welfare. Both renewable generators and energy store owners are self-interested agents, which seek only to maximize their own profit. This difference can be implemented by changing agents' strategies to find best fitting coalitions based on agents' profit instead of coalition value. Second, each coalition in our setting must always contain exactly one renewable generator. In terms of coalition formation we call these agents coalition leaders. Coalition leaders do not leave or join coalitions. On the other hand coalition leaders affect the profit of agents joining the coalitions, which consequently affects the behavior of the other agents. Finally, since the iterative coalition formation process yields a pool of coalition structures, a single coalition structure must be selected as the solution. Unlike in [4], in which the solution is selected based on social welfare, in our setting we select a solution with the highest profit of renewable generators gained from participation in coalition formation.

Algorithm 1 Simulation of coalition formation between renewable generators and store owners

```
    Input: number of energy stores, number of renewable generators, number of iterations N, number of time slots.
    Output: coalition structure with highest profit of renewable generators.
 1: initiate energy stores and renewable generators
 2: create a coalition for each renewable generator
 3: for iteration in 1 : N do
 4:     for all energy stores in random order do
 5:         if energy_store.strategy.leave then
 6:             energy_store.coalition.recompute profit of energy stores after energy_store
 7:             energy_store.coalition ← energy_store.strategy.pick_coalition
 8:             calculate energy_store.profit
 9:         end if
10:     end for
11:     save current coalition structure
12: end for
13: choose coalition structure with highest profit of renewable generators
```

The simulator for coalition formation of renewable generators and energy store owners is shown in Algorithm 1, and it works as follows. First, renewable generators are created and assigned estimated generation values for each time slot. Then energy stores are created and assigned the beginning and end of availability s_b and s_e, and maximum total amount of power m (line 1). Then we create coalitions, each containing one renewable generator (line 2). After this initialization step the simulation begins. In the simulation energy stores are deciding whether they should leave their coalitions and which coalitions they should join. When an energy store joins a coalition, its profit is increased, and the coalition is updated (lines 5-8). If an energy store leaves a coalition, profit of all stores that joined the coalition after this store is recalculated, since the distribution of their power might have changed after the removal (line 6). Finally, we select the coalition structure with highest profit of renewable generators (line 13).

4 Experimental Analysis

We experimentally evaluate the coalition formation algorithm in the renewable domain in order to show that our approach creates profit incentives for renewable generators to participate in coalition formation. We will also show that our coalition formation approach increases use of renewable resources.

The experiments were performed using the following setup. We tested our approach in scenarios with 50 renewable generators. Generation amounts for 24 time slots corresponding to one day were generated for each renewable generator at random from a uniform distribution $\mathcal{U}(0, 100)$, and the generators were given estimates of these amounts drawn from a normal distribution with standard deviation $\sigma = 20$. Parameters of the stores s_b, s_e, and m were generated randomly from uniform distributions $\mathcal{U}(0, 23)$ and $\mathcal{U}(0, 100)$ respectively. We set prices as follows: $p_g = 50$, $p_c = 10$, and $p_f = 100$. As a baseline we use a scenario in which renewable generators do not participate in coalition formation, in which case renewable generators only bid commitment percentage $c_0 = 80\%$ of predicted generation $g_e(t)$ to hedge against uncertainty. We let the simulation run for 10 iterations and then selected a coalition structure with highest sum of profit of renewable generators. All results were averaged over 10 random runs.

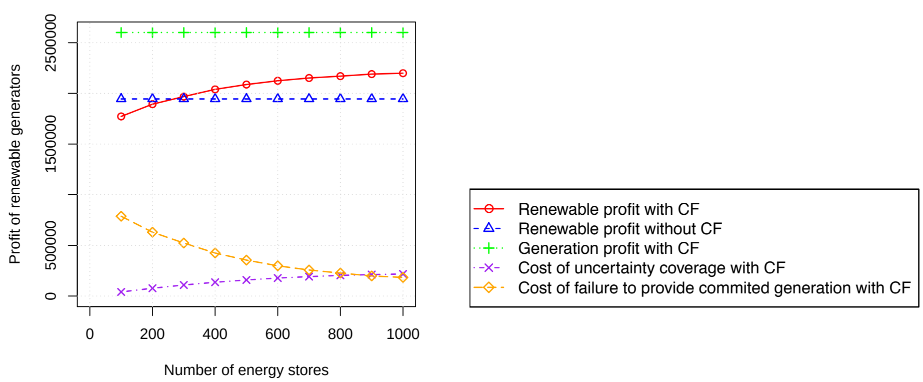

Fig. 1: Summarized profit of 50 renewable generators with 100 to 1000 energy stores

Figure 1 compares summarized profit of renewable generators that participate in coalition formation p_r with their profit in case they did not participate p_{r0}. Generation profit is constant, since it is independent of the number of energy stores. On the other hand, with increasing number of energy stores the cost for failure to provide committed generation decreases and the cost of uncertainty coverage increases because the generators can cover more uncertainty. Since the decrease in the cost of failure to provide committed generation is larger than the increase in the cost of uncertainty coverage, the resulting profit is increasing. In scenarios with over 300 energy stores the profit of 50 renewable generators is greater if they participate in coalition formation.

Over all, the amount of renewable generation is increased because the generators are able to bid higher values. In Figure 1 the generators not participating in coalition formation only bid 80% of the predicted generation $g_e(t)$, while generators utilizing coalition formation bid 100% of $g_e(t)$. Table 2 shows amounts of renewable generation with and without coalition formation as well as energy store use and total generation. Our approach yields a 13.5% increase in total renewable generation. Total generation of renewable generators and energy stores is increased by 30.4% due to coalition formation.

Table 2: Increase in renewable generation caused by coalition formation (CF) of 50 renewable generators and 1000 energy stores

Generation type	**Generation amount**	**Increase in generation**
Renewable generation without CF	45,837	–
Renewable generation with CF	52,012	**13.5%**
Energy store generation	7,780	–
Total generation with CF	59,792	**30.4%**

5 Related Work

Coalition formation has been proposed in literature to increase the integration of renewable resources. [8] uses law of large numbers to show that coalitions of renewable generators can benefit from their spacial distribution, since the adverse effects of prediction uncertainty are mitigated. Coalitions of renewable generators are also studied in [5]. There a profit sharing mechanism is proposed that is used to distribute profit after coalitions of renewable generators are formed. Even though the goals of [5] and [8] are similar to our goals, their approaches are different since they study homogeneous coalitions of renewable generators.

Coalition formation has been studied extensively. First approach for finding optimal coalition structures used dynamic programming [7]. This approach was further improved in [6]. Hierarchical clustering algorithm for large-scale coalition formation was proposed in [1]. Their algorithm finds high-quality sub-optimal coalition structures. The algorithm is however not suitable for coalition formation of self-interested agents, as was shown in [3]. Finally, [4] proposes a simulation framework for large-scale coalition formation. This framework is best suited for our scenario, since it is easily extensible to model self-interested agents, and it can be used to model renewable generators as well as energy stores.

6 Conclusion

In this paper we proposed an approach to increase use of renewable sources by allowing renewable generators to hedge against uncertainty by forming coalitions with energy stores. In these coalitions energy stores offer to cover generation that renewable generators committed to, but are unable to deliver due to prediction uncertainty. We model renewable generators and energy stores as self-interested agents, and we use multi-agent simulation to create coalition structures by allowing energy stores to leave and join coalitions based on their preference.

We experimentally show that our approach increases use of renewable resources. With the support of coalition formation with energy stores, renewable generators can afford to bid higher amounts of generation in the day-ahead market. In our experiments we show that renewable generators can bid 100% of the predicted generation and still gain profit, even when facing high fees for failure to provide committed generation. In our experimental setting our approach increased the use of renewable resources by 13.5%. We also show that forming coalitions with energy stores increases profit of renewable generators, which incentivizes them to increase renewable generation.

Acknowledgments: This work was supported by the US National Science Foundation via Award No. CNS-1544705.

References

[1] Farinelli A, Bicego M, Ramchurn S, Zucchelli M (2013) C-link: A hierarchical clustering approach to large-scale near-optimal coalition formation. Twenty-Third International Joint Conference on Artificial Intelligence

[2] Holttinen H, Meibom P, Orths A, Lange B, Mark O, Olav J, Estanqueiro A, Gomez E, Sder L, Strbac G, Smith JC, van Hulle F (2009) Impacts of large amounts of wind power on design and operation of power systems , results of iea collaboration. 8th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks of Offshore Wind Farms

[3] Janovsky P, DeLoach SA (2016) Forming stable coalitions in large systems with self-interested agents. 14th European Conference on Multi-agent Systems EUMAS 2016

[4] Janovsky P, DeLoach SA (2016) Multi-agent simulation framework for large-scale coalition formation. 2016 IEEE/WIC/ACM International Conference on Web Intelligence

[5] Nayyar A, Poolla K, Varaiya P (2013) A statistically robust payment sharing mechanism for an aggregate of renewable energy producers. 2013 European Control Conference (ECC)

[6] Rahwan T, Jennings NR (2008) An improved dynamic programming algorithm for coalition structure generation. 7th International Conference on Autonomous Agents and Multiagent Systems

[7] Yun Yeh D (1986) A dynamic programming approach to the complete set partitioning problem. BIT Numerical Mathematics

[8] Zhang B, Johari R, Rajagopal R (2015) Competition and coalition formation of renewable power producers. IEEE Transactions on Power Systems