Paper ID APEN-MIT-2019_xxx
Applied Energy Symposium: MIT A+B
May 22-24, 2019 • Boston, USA

Developing a PV and Energy Storage Sizing Methodology for Off-Grid Transactive Microgrids

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Abstract— A simulation tool was developed through MATLAB for comparing Centralized Energy Sharing (CES) and Interconnected Energy Sharing (IES) operating strategies with a standard Stand-Alone Photovoltaic System (SAPV). The tool can be used to investigate the effect of several variables on cost and trading behavior including: initial charge of Energy Storage System (ESS), amount of load variability, starting month, number of stand-alone systems, geographic location, and required reliability.

It was found that the CES strategy improves initial cost by 7% to 10% compared to a standard SAPV in every simulation. The IES case consistently saved money compared to the baseline, just by a very small amount (less than 1%). The number of systems did not have a demonstrable effect, giving the same cost per system whether there were 2 systems or 50 involved in the trading strategies. Geographic locations studied (Indianapolis, Indiana; Phoenix, Arizona; Little Rock, Arkansas; and Erie, Pennsylvania) showed a large variation on the total installed cost with Phoenix being the least expensive and Erie being the most expensive location. Required reliability showed a consistent and predictable effect with cost going down as the requirement relaxed and more hours of outage were allowed.

Keywords—Community Energy Sharing, Off Grid PV, PV Sizing, Energy Storage Sizing, Transactive Microgrid, Blockchain

I. INTRODUCTION

Communities can employ photovoltaic (PV) energy through Grid-Connected Photovoltaic (GCPV) systems, Stand-Alone Photovoltaic (SAPV) systems, or by creating a transactive microgrid. A GCPV system is an independent decentralized power system that is connected to an electricity transmission and distribution system (the electricity grid). An SAPV produces power independently from the utility grid and uses energy storage to fulfill their load requirements [1]. A transactive microgrid is two or more SAPV systems connected so that they can trade their energy generation and storage.

GCPV systems offer a distinct advantage in having energy back up to meet the load demand whenever the system fails. GCPV systems do not require energy storage and are easier to design when compared to SAPV systems because the reliability of electricity supply is not an issue [2]. SAPV systems are becoming increasingly viable and cost-effective in remote locations with very high yearly solar radiation where there is no readily available utility grid network or a very high electricity cost. [2]–[5].

Optimizing solar and storage for off-grid residential applications is not currently economical [6]–[9]. Making and storing your own electricity is expensive, and maintenance and troubleshooting will be serious, ongoing problems. The SAPV strategy requires that any excess generation is wasted and no back up energy is available if you fail to meet demand.

Transactive microgrids have been enabled with the advent of ’Blockchain’ [10]. Reference [11] demonstrates how transactive energy exchanges could be implemented on the Ethereum blockchain. Blockchain enables the transactive microgrid but is not explored in this research. Implementing a transactive microgrid can help alleviate both major problems associated with SAPV systems. Specifically, a transactive microgrid enables systems to sell power when their batteries are full and buy power when their batteries are empty. This can reduce the total cost per home depending on the cost to implement the energy infrastructure and the specific energy generation and load scenarios.

Methods for establishing transactive microgrids include either Centralized Energy Sharing (CES) where both PV and ESS are centrally stored, or Interconnected Energy Sharing (IES) where PV and ESS are distributed throughout the community.

A schematic for the CES operating strategy is shown in Figure 1. Battery storage and solar generation is centralized and Blockchain technology is used to ensure that everyone receives power and only pays for the power they receive. This system is modeled by summing all loads into one, not

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This is the author's manuscript of the article published in final edited form as:

Vance, B., Razban, A., Schubert, P., Weissbach, R. (2019). Developing a PV and Energy Storage Sizing Methodology for Off-Grid Transactive Microgrids. Proceedings of Applied Energy Symposium: MIT A+B.

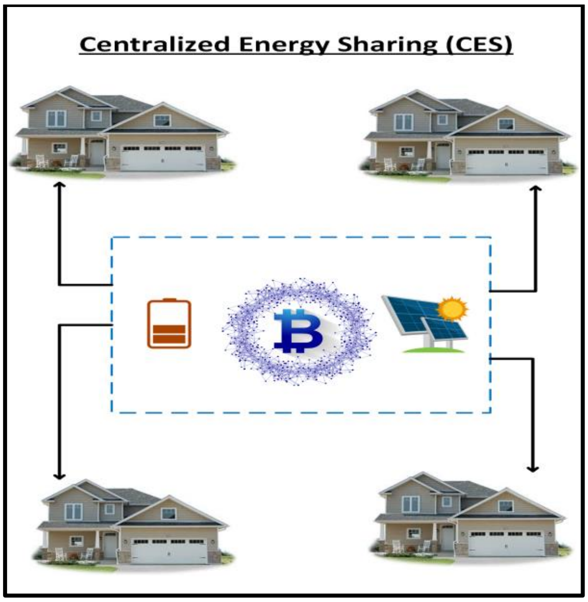

Fig. 1. Schematic of a CES operating strategy for transactive microgrids

considering internal trades, and considering that every customer is without power if energy storage is depleted.

In the IES operating strategy, shown in Figure 2, each system has their own energy storage and PV generation. Blockchain technology allows customers to automatically buy and sell energy while ensuring that everyone pays for and receives their share. Habib [12] proposed an 'interconnected sharing mode' where residential customers can exchange PV power to supply their electrical loads in the case that the micro-grid switches to islanded mode due to a large scale power outage or blackout. In a study of 10 houses the inter-connected sharing case supplied the most load for 5 out of the 10 houses, 3 houses preferred isolated self-consumption, and 2 houses achieved the same load met under either operating mode. The study concluded that "the interconnected energy sharing case produces only slightly better individual results than the isolated case. However, most importantly, it also led to a 44% reduction in the total size of ESS required." In another study [13] Habib indicated that most stand-alone houses cannot meet their load demand in the winter without requiring significant PV generation. Habib's proposal focuses on grid-connected customers who are disconnected from the grid due to isolation or blackout, while this research proposes allowing islanded systems to share their stored energy with each other year-round without connecting to a main grid.

The idea of a 'transactive or connected neighborhood' for a residential micro-grid has been investigated analytically by several sources, none of which use conventional SAPV sizing strategies or consider off-grid operation [13]–[18]. The gap in literature this research fills is to propose a sizing methodology for off-grid transactive microgrids that allows operating strategies (SAPV, CES, and IES) to be compared. A MATLAB program will be developed for comparing the costs of each operating strategy.

II. METHODOLOGY

This model was developed considering the following variables' effect on total cost, component sizing, and trade behavior: initial charge, amount of load variation, number of SAPV systems, geographic location, required reliability, and starting month. The variables 'number of SAPV systems' and 'amount of load variation' were added because they were deemed important when considering transactive microgrids. Amount of load variation was thought to be important because this is what makes energy trading worthwhile. If every system has the exact same load profile and PV generation then it will not be beneficial for them to trade. The number of SAPV systems was chosen because it was thought that more systems would yield more trades and the benefit of establishing a transactive microgrid would increase.

The model runs through MATLAB files which are explained and made available on a public GitHub page [19].

Inputs to the model are divided into project specifications and component specifications. Project specifications include number of SAPV systems, number of trials, number of acceptable outage hours, number of years of simulation, solar and load data, initial charge of battery and starting month of simulation. Component specifications include solar panel rating, solar panel unit cost, PV de-rating factor, battery capacity, battery efficiency, battery unit cost, battery hardware cost, battery installation cost, and initial number of batteries to test.

Outputs from the model are three Excel files with results for the baseline, IES, and CES case including an optimized number of batteries for each solar panel configuration, associated total and component cost for each configuration, amount of PV generation wasted and loss of power supply probability. For the IES case, it also outputs how many times each system buys or sell and the total number of trades among all systems. Pivot tables are automatically produced which takes the average from all trials for these outputs.

A. *Simulating Solar Irradiation*

Solar irradiation data is simulated using Weissbach's Markov model [6]. This approach creates results that are typical and realistic, though not useful for site specific sizing. There is another method given by [20] that improves

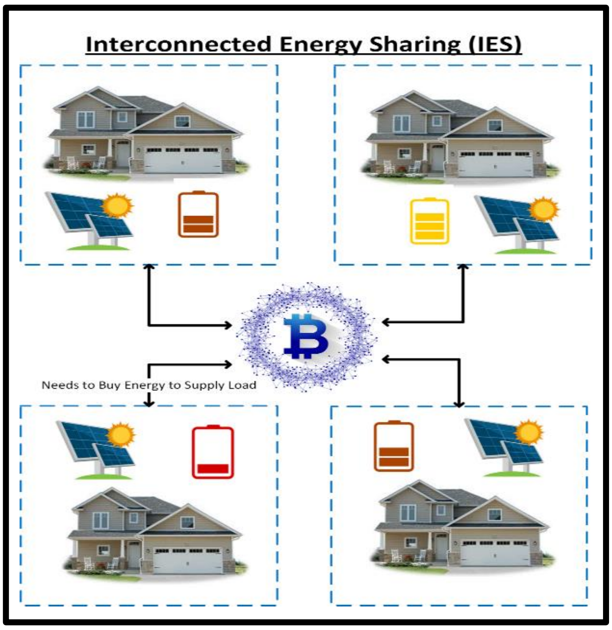

Fig. 2. Schematic of an IES operating strategy for transactive microgrids

Weissbach's Markov model, but it is for dimensioning high-reliability systems and was not easily accessible.

This model was developed for use with files that contain hourly data for the year and can account for leap years. Ideally, the dataset would come from a high-quality site-specific solar monitoring station that is well maintained and the measurements taken over 30 years or longer. However, very few data sets of that duration exist, and the need for short-term profitability places severe constraints on the practicality of undertaking any new and comprehensive studies before seeking funding for a project at any given site.

A good type of data file for this purpose is a Typical Meteorological Year (TMY) data file, created from long-term data files to help with the analysis of building performance at a time when computers were much slower and had smaller memory banks than today. A set of TMY files were created to represent typical meteorological years and not typical solar years. Although not designed to investigate meteorological extremes, TMY data have natural diurnal and seasonal variations and represent a year of typical climatic conditions for a location [21].

B. *Simulating Residential Load*

The reason for selecting TMY solar irradiation data is because there are usually associated residential load data for these datasets, and they will be in the same favorable format. These datasets might not be useful for investigating a specific case, but they do usually contain high, low, normal, early-bird, and night-owl typical residential load profiles.

Simulated residential load is taken straight from the residential load data. Variability is introduced by adding or subtracting hours, creating the effect that residential customers are on different schedules.

C. *Technical Considerations*

The technical parameter chosen for this model is Loss of Power Supply Probability (LPSP). LPSP is a tried and true method for sizing SAPV systems with a standard value of 0.001 or 9 hours/year. The LPSP is given by the ratio of number of hours of outage to the total number of hours considered in the period [22], [23]. The expression used for LPSP is:

$$LPSP = \frac{N_{outage}}{N_{total}}; \quad 0 \leq LPSP \leq 1 \tag{1}$$

In this calculation it is important to notice that we are considering the time sensitivity of the variables and not the quantity of energy produced. It would be incorrect, for instance, to say that over a large time interval more energy is generated than consumed so LPSP must be equal to 0 without conducting time simulation to show if there is any moment where energy demand is greater than energy available.

Because it is expected that the utilization of solar energy will be improved due to the proposed energy infrastructure, "% PV Generation Utilization" will be calculated by the tool but will not be used in the optimization model. The purpose of including this feature is to compare different cases and determine if a higher percentage of PV Generation is utilized using the proposed energy infrastructure. '% PV Generation' is given as the ratio of the PV generation that is utilized by the system over the total PV generated by the solar panels in that time period.

$$\%PVGenerationUtilization = \frac{\sum_{t=0}^{t=T} PVGenerationUtilized}{\sum_{t=0}^{t=T} TotalPVGeneration} \tag{2}$$

The model also has a system for tallying the number of trades each system performs, the total number of trades, the number of outage hours, and the battery storage, PV generation and load for each hour of the simulation. These results can be used in the future to determine ideal trading conditions.

D. *Economic Considerations*

For the purposes of sizing our proposed energy infrastructure, capital cost will be the main consideration. Capital cost is given as the total cost of the system including the cost for all solar panels, all batteries, their installation and hardware, and the cost of interconnection. Although lifecycle cost, net present value, and levelized cost of energy are useful economic parameters, they are not given directly by the model and require extra analysis such as determining operation and maintenance costs.

III. RESULTS

A. *Validation*

Functions were validated by choosing inputs that allowed for verifying the expected output. The approaches for these validation tests are available at [24].

HOMER [25] was chosen as the validation source because it is recognized as the world's leading microgrid modeling software company and it performs a similar analysis to the proposed model (hourly numerical analysis). No existing commercial software to our knowledge allows for transactive microgrid modeling or simulation of trading between systems. Because HOMER cannot simulate an energy trading system or more than one residential system, it can only be used to verify the Baseline (SAPV) case.

HOMER was setup according to the following specifications:

- Tesla Powerwall 2.0 from complete energy storage catalog. Changed Capital Cost to $ 8,100, the search space to integers from 1 - 30, and changed the initial state of charge to match the different cases. Included a 'Large free Converter' component to model the integrated inverter.
- Imported the same load and solar data used in this model. Noted that the load data is somewhat larger than HOMER's initial estimate for the same location, but our data includes electric heating.
- Used the 'Generic flat plate PV' component for the PV generation. Changed the PV capacity to 3 kW, capital cost to $8,377, Derating Factor to %73.1, and edited the search space to only give answers our model would look at. Did not consider the effect of temperature.
- HOMER does not consider the effect of starting month, so June was taken as the starting month for

TABLE I. VALIDATION OF BASELINE SIZING MODEL USING HOMER SOFTWARE

Method	Location	Required Reliability (%)	Initial Charge (%)	Solar Panels (#)	Batteries (#)	Capital Cost ($)
HOMER	Phoenix,AZ	0.1	10	6	3	$ 74,562
Baseline	Phoenix,AZ	0.1	10	5	3.2	$ 67,805
HOMER	Phoenix,AZ	0.1	20	6	3	$ 74,562
Baseline	Phoenix,AZ	0.1	20	5	3.1	$ 67,319
HOMER	Phoenix,AZ	0.1	100	6	3	$ 74,562
Baseline	Phoenix,AZ	0.1	100	5	3	$ 66,995
HOMER	Phoenix,AZ	1	10	5	3	$ 66,185
Baseline	Phoenix,AZ	1	10	4	3	$ 58,051
HOMER	Phoenix,AZ	1	20	5	3	$ 66,185
Baseline	Phoenix,AZ	1	20	3	3	$ 57,970
HOMER	Phoenix,AZ	1	100	5	3	$ 66,185
Baseline	Phoenix,AZ	1	100	4	3	$ 57,808
HOMER	Erie,PA	0.1	10	13	3	$ 133,201
Baseline	Erie,PA	0.1	10	13	3.1	$ 134,011
HOMER	Erie,PA	0.1	20	12	3	$ 124,824
Baseline	Erie,PA	0.1	20	13	3	$ 133,444
HOMER	Erie,PA	0.1	100	12	3	$ 124,824
Baseline	Erie,PA	0.1	100	13	3.1	$ 133,768
HOMER	Erie,PA	1	10	12	2	$ 116,724
Baseline	Erie,PA	1	10	12	2.3	$ 118,992
HOMER	Erie,PA	1	20	12	2	$ 116,724
Baseline	Erie,PA	1	20	12	2.2	$ 118,020
HOMER	Erie,PA	1	100	12	2	$ 116,724
Baseline	Erie,PA	1	100	12	2.2	$ 118,263

our baseline model based on preliminary results. June was one of several months that showed typical results.

- Case studies considered:
    - Geographic Locations = (Phoenix, Arizona; Little Rock, Arkansas; Indianapolis, Indiana; Erie, Pennsylvania)
    - Required Reliability = (0.1%, 1% LPSP)
    - Initial Charge = (10%, 20%, 100%)

These case studies make up only a small portion of the possible baseline cases but were chosen to validate whether the developed model matches up with HOMER. The geographic locations were chosen because they all have Class 1 (lowest uncertainty) data from TMY3, they represent a spectrum of different yearly Global Horizontal Irradiance (GHI) values, and they provide examples from each climate zone in the US. The validation results for Phoenix and Erie are included in Table I. Results for Indianapolis and Little Rock can be found on the GitHub page [19]. The average percent difference for each location are approximated as follows: 11% for Erie, 3% for Phoenix, 21% for Indianapolis, and 5% for Little Rock.

Some reasons for discrepancies between the two models are that HOMER calculates reliability through capacity shortage (capacity loss / total capacity demanded) while we are looking at hours (hours where capacity is lost/ 8760). It also may be due to the simulation model, battery model, and better optimization model of HOMER. HOMER also selects an optimum integer value for the number of batteries while the proposed model takes an average of all the trials.

B. *Results*

Some sample results are included (Figures 3 to 5) to show the type of analysis being doing with the model. Each graph has a similar shape with an optimum solution found and then

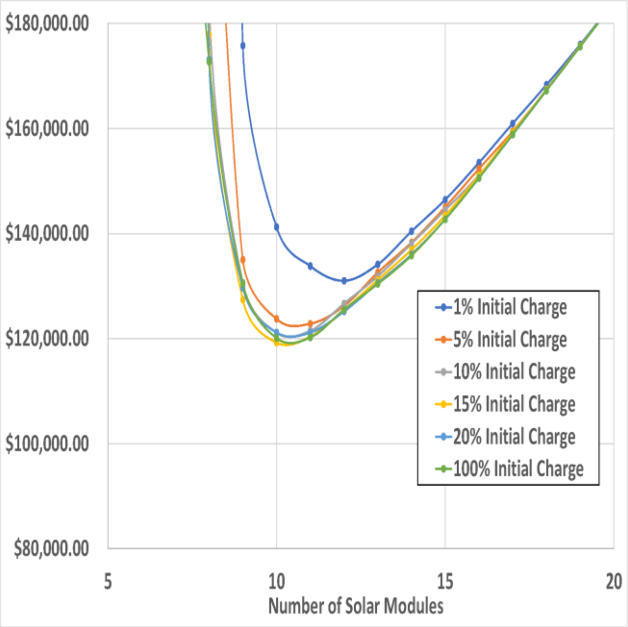

Fig. 3. Results for IES case with varying initial charge given November, 5 systems, Indianapolis, and 0.1% LPSP.

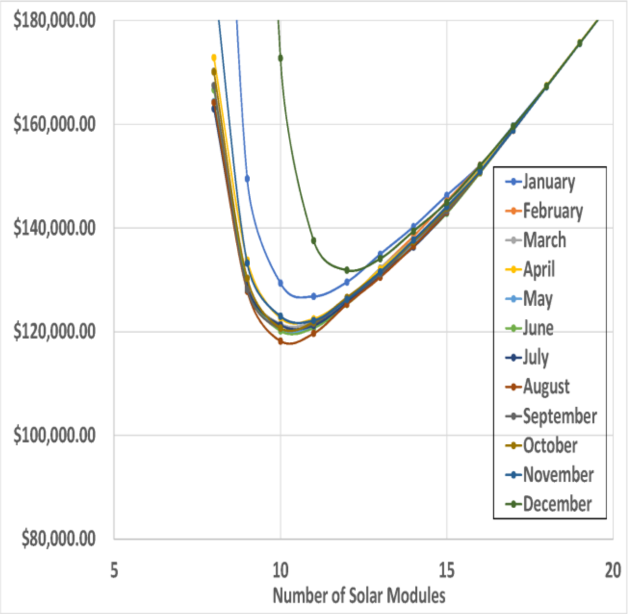

Fig. 4. Results for IES case with varying starting month given 10% initial charge, 5 systems, Indianapolis, and 0.1% LPSP.

the cost increasing as solar panels are added. Figure 3 shows results for the IES case given differing initial charge of the battery, starting month of November, 5 systems, Indianapolis, and 0.1% LPSP. Figure 4 shows results for IES case with varying starting month given 10% initial charge, 5 systems, Indianapolis, and 0.1% LPSP. Figure 5 shows results for varying LPSP required given June, 10% initial charge, 5 systems, and Indianapolis. The optimal solutions found for 100 trials of different cases in Indianapolis are included in Table II to show typical results.

IV. CONCLUSIONS

In conclusion, the purpose of this research was to develop a sizing methodology for off-grid transactive microgrids to compare the conventional isolated system (SAPV), with centralized energy sharing (CES), and interconnected energy sharing (IES) operating strategies. A MATLAB program was developed which directly compares the three operating strategies. Although existing software such as HOMER do not include transactive microgrid modeling, the CES operating strategy could be included by allowing for more than one system's load and solar generation to be simulated at a time and combining the results.

The initial results from this model are as follows. The CES strategy improved initial cost by 7% to 10% compared to the baseline and IES cases. The IES case saved less than 1% compared to the baseline but did show a consistent savings considering that an interconnection cost was included. The number of systems involved in a transactive microgrid did not seem to affect the initial cost for the CES or IES case. This may be due to the load simulation method but it may also indicate that only one other system is necessary to receive the benefits from an energy sharing operating strategy. Geographic locations studied showed a large effect on total cost with Phoenix being considerably cheaper than other locations studied, Erie having the highest cost, and Little Rock and Indianapolis following closely behind Erie. This result was expected due to the associated load and solar radiation profiles of each geographic location. When the reliability requirement was relaxed, allowing for more hours of outage per system in a year, the cost went down predictably.

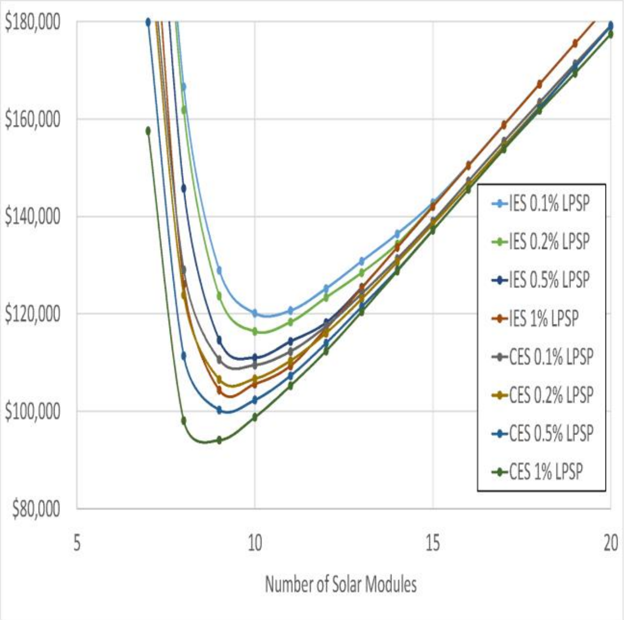

Fig. 5. Results for varying LPSP required given June, 10% initial charge, 5 systems, and Indianapolis.

Some other strategies for simulating residential load should be included in the future: synthetic loads with more variability, high and low use load profiles, specific end uses (TV, heating, air conditioning, stove, microwave, etc.), electric vehicle energy storage, hot water heater energy storage, and smart load control.

Future work underway:

- Investigating the effect of initial charge of the battery, starting month of the simulation, and amount of variability between loads of the systems on the total cost.
- Improving load simulation by adding peak shifting
- Researching typical residential load variability, no study was found which determines the typical variation between residential loads
- Considering wind energy generation for transactive microgrids. Wind complements solar nicely by producing more consistent power during the winter, but a high capital cost usually hinders residential applications

Initial results need to be expanded to draw substantiated conclusions which will be included in a future paper, but a MATLAB tool is now available to advance this research. Although existing software such as HOMER do not include off-grid transactive microgrid modeling, the CES operating strategy could be included by allowing for more than one system's load and solar generation to be simulated at a time and combining the results. The CES model shows promising potential for improving the baseline and furthering research in this field while the IES model can be used to investigate resident behavior and trading scenarios.

TABLE II. Optimum configurations found for selected case studies in Indianapolis

Summary Table for Indianapolis					
Operating Strategy	**LPSP (%)**	**Number of Systems**	**Optimum # of Solar Panels**	**# of Batteries (Average)**	**Capital Cost (Average)**
Baseline	0.1	-	10	4.5	$ 120,301
Baseline	0.2	-	10	4.2	$ 117,709
Baseline	0.5	-	10	3.3	$ 110,662
Baseline	1	-	9	3.5	$ 103,338
IES	0.1	2	10	4.4	$ 119,691
IES	0.1	5	10	4.5	$ 120,161
IES	0.1	10	10	4.3	$ 119,035
IES	0.1	20	10	4.1	$ 117,188
IES	0.1	50	10	4.2	$ 117,630
IES	0.2	2	10	4	$ 116,532
IES	0.2	5	10	4	$ 116,435
IES	0.2	10	10	4.1	$ 117,059
IES	0.2	20	10	3.9	$ 115,884
IES	0.2	50	10	4	$ 116,540
IES	0.5	2	10	3.2	$ 109,931
IES	0.5	5	10	3.3	$ 111,056
IES	0.5	10	10	3.2	$ 109,769
IES	0.5	20	10	3.1	$ 109,426
IES	0.5	50	10	3.1	$ 109,048
IES	1	2	9	3.6	$ 104,713
IES	1	5	9	3.6	$ 104,397
IES	1	10	9	3.2	$ 101,116
IES	1	20	9	3.3	$ 102,319
IES	1	50	9	3.2	$ 101,703
CES	0.1	2	10	3.3	$ 110,903
CES	0.1	5	10	3.2	$ 109,517
CES	0.1	10	10	3.1	$ 108,716
CES	0.1	20	9	3.9	$ 107,337
CES	0.1	50	10	2.9	$ 108,168
CES	0.2	2	9	4	$ 107,912
CES	0.2	5	9	3.8	$ 106,567
CES	0.2	10	9	3.8	$ 106,584
CES	0.2	20	10	2.7	$ 106,067
CES	0.2	50	10	2.8	$ 106,519
CES	0.5	2	9	3	$ 99,974
CES	0.5	5	9	3.1	$ 100,314
CES	0.5	10	9	2.8	$ 98,411
CES	0.5	20	9	2.8	$ 97,917
CES	0.5	50	9	2.8	$ 98,352
CES	1	2	9	2.4	$ 95,317
CES	1	5	9	2.3	$ 94,110
CES	1	10	9	2.1	$ 92,611
CES	1	20	9	2.1	$ 92,814
CES	1	50	9	2.1	$ 92,739

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