CSIRO CLUSTER PROJECT #3

Optimized control constraints and costs for wind, fuel cells, combustion generation

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Contents

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1. Introduction

This report presents optimisation techniques that can be adopt for optimal DG sitting and dispatch, control constraints that is common for DG connected power systems, general constraints with wind, fuel cells, and combustion generation, and cost of installation and energy of selected DG technologies. As cost of each technology varies depending on the type, location and the year of installation, manufacturer, size, and technological advances, there may be inconsistencies in costs compared to a particular installation site. However, the report can be used as a general document that covers the published work. In particular the report presents a realistic costing data of wind installations carried out by Curtin University of technology.

2. Optimisation and control constraints (Momoh, 2009, Brown, 2002)

Power system optimisation is typically performed for the purpose of active power cost minimisation, active power loss minimisation, minimum control shift, or to calculate minimum number of controls scheduled. It requires solving a set of non-linear equations, describing optimal and secure operation, which are typically expressed as:

$$\begin{aligned} &\textit{Minimise} && F(x,u) \\ &\text{Subject to} && g(x,u) = 0 \\ &&& h(x,u) \leq 0 \end{aligned}$$

Where, g(x, u) represents a set of non-linear equality constraints (typically power flow equations), h(x, u) represents a set of inequality constraints of vector arguments x and u, x represents vector of dependant variables consisting of bus voltage magnitude and phase angles, reactive power loads, fixed bus voltages, line parameters etc., and u represents vector of control variables that includes:

- Real and reactive power generation
- Phase shifter angles (if applicable)
- Net interchange (if applicable)
- Load MW and MVAr (load shedding)
- DC transmission line flows (if applicable)

- Control voltage settings
- On Load tap changing (OLTC) settings

In a power system optimisation, the equality and inequality constraints include:

- Limits on all control variables
- Power flow equations
- Generation/ load balance
- Branch power flow limits
- Bus voltage limits
- Active and reactive reserve limits (if applicable)
- Generator MVAr limits
- Corridor (transmission interface) limits (if applicable)
- Specific constraints applied to distributed generation (DG) technologies (if applicable)
- DG operating constraints (if applicable)

There is variety of optimisation techniques specifically developed to address particular problems in a power system domain. They include:

- Linear programming based methods (LP)
- Non liner programming based methods (NLP)
- Integer programming based methods
- Separable programming methods

In LP, the objectives and constraints are linear. LP has extensions including simple method, revised simplex method, and interior point technique. Interior point techniques are based on the Karmarkar algorithm and encompass variants such as the projection scaling method, duel affine method, primal affine method, and barrier algorithm. NLP optimisation methods encompass following techniques within the formulation.

- Sequential quadratic programming (SEQ)
- Augmented Lagrangian methods
- Generalised reduced gradient method
- Projected augmented lagrangian

- Successive LP
- Interior point methods

In an optimisation problem, the basic formulation is extended to include security and environmental constraints in particular concerning with global warming aspects and energy security.

Special decomposition strategies are necessary for solving large-scale problems in order to improve the solution. These strategies are addressed through Benders decomposition, Lagrangian relaxation, and Talukdar-Giras optimisation techniques.

Further, the Optimisation can be described in terms of continuous or discrete variables. Although the continuous variable optimisation is benefitted for conceptual purposes, the vast majority of distribution network optimisation problems consist of discrete choices rather than continuum of choices. For examples, a distribution network has integer number of fuses and switches. The devices can be placed at specific pole locations and they can be purchased with specific ratings. The feeder sections can be either overhead or underground. Switches are only automated or not. Considering these facts, there are two main category of optimisation programming. The one that address the discrete choices fall into integer programming. The other falls into mixed integer programming. However, the discrete optimisation suffers from a problem called combinatorial explosion, which means that the number of possible solutions grows exponentially with the problem size.

The discrete optimisation problem, wherever possible, is solved by restricting domain space to avoid unsustainable issues. Such problem can be limited by applying divide-and-conquer approach that break a large problem into several sub problems which can be solved independent of one another. However, it is important to insure that each sub problem is sufficiently independent of other sub-problems.

Increased complexity of power system optimisation problem incorporated specialised techniques to solve large scale problems. These techniques include dynamic programming, Lagrange multiplier methods, and evolutionary computation methods such as genetic algorithms. These techniques are often applied through artificial neural networks, expert systems, and Tabu-search algorithm, and fuzzy logic. There are other techniques in published domain however, the maturity of them are yet to be achieved.

3. Planned optimisation techniques for the proposed project

(Talbi and Batouche, 2004, Vadivoo and Slochanal, 2009, Optimatics, 2009, Krueasuk and Ongsakul, 2006, Momoh, 2009, Wikipedia, 2009)

The investigators of the proposed project plan to apply particle swarm optimisation (PSO) and Genetic algorithms (GA) for realisation of tasks.

PSO is a stochastic optimisation technique originated from patterns of social behaviour. The common analogy of the technique is a flock (swarm) of birds (particles), flying over a field with varying densities of food. Each bird has a memory of the best food source it has found so far (this is called the local best), as well as the best food source that the flock has found (this is called the global best). Each bird tends to fly toward a randomly weighted average of the local best and the global best. After a number of iterations, most of the flock is converging on the best available food source in the area. In applying PSO, the system is initialised with a population of random solutions and searches for optima by updating potential solutions. Each particle keeps track of its coordinates in the problem space which are associated with the best solution it has achieved. Another best value that is tracked by the particle swarm optimiser is the best value obtained so far by any particle in the neighbourhood of the particle. In this way the process repeats for identifying the global solution.

GA is a stochastic optimisation technique that is based on the Darwinian thinking of natural selection and genetics. GA starts with an initial set of random solutions that lie in the feasible solution space. The random cluster of solution is called population. Each solution in the population represents a possible solution to the optimisation problem and is therefore called chromosome. The chromosome is a string of symbols based on the uniqueness of two-state machines. They are commonly binary bit strings; however, other encodings are also possible. The evolution commonly starts from a population of randomly generated individuals (candidate solutions) and happens in generations. In each generation, the fitness of every individual in the population is evaluated, multiple individuals are stochastically selected from the current population (based on their fitness), and modified (recombined and possibly randomly mutated) to form a new population. The new population is then used in the next iteration of the algorithm. Commonly, the algorithm terminates when either a maximum number of generations has been produced, or a satisfactory fitness level has been reached for the population. If the algorithm has terminated due to a maximum number of generations, a satisfactory solution may or may not have been reached.

4. General constraints with DG technologies

In general wind technologies have constraints to compete with other generating technologies that have already been established. Some of them include (Chandrasenal et al., 2006, Nelson)

- Intermittency of Wind Power
- Network constraints
- Logistical constraints
- Installation and unit costs
- Policy and regulatory constraints
- Maturity of technology

Other DG technologies also have barriers in competing with matured generating technologies. For examples fuel cell technology has barriers including:

- Maturity of technology for large scale power generation
- Capacity constraints
- Unit cost and cost of generation

The combustion generation has also constraints including:

- Dependency on fossil fuel
- Environmental pollution
- Geometrical constraints
- Installation, running, and maintenance cost
- Regulatory incentives

5. Cost of wind and Photovoltaics (PV)

Wind turbines come in many shapes and sizes and total costs for installing a commercial-scale wind turbine depending on the cost of financing, construction contracts, the type of machine, the location of the project, and other factors. Cost components for wind projects include wind resource assessment and site analysis expenses; the price and freight of the turbine and tower; construction expenses; permitting and interconnection studies; utility system upgrades, transformers, protection, and metering equipment; insurance; operations, warranty, maintenance, and repair; legal and consultation fees.

The costs for a commercial scale wind turbine in 2007 ranged from $1.2 million to $2.6 million, per MW of nameplate capacity installed. Most of the commercial-scale turbines installed today are 2 MW in size and cost roughly $3.5 million installed. Smaller farm or residential scale turbines cost less overall, but are more expensive per kilowatt of energy producing capacity. Wind turbines under 100 kilowatts cost roughly $3,000 to $5,000 per kilowatt of capacity.

Wind turbines have significant economies of scale. A number of factors determine the economics of utility-scale wind energy and its competitiveness in the energy market. These include wind speed, turbine design, installed capacity of wind farm, cost of financing, transmission and distribution tax, environmental concerns, regulatory incentives. Figs. 1 and 2 show the cost of electricity with different wind speeds and the installed capacity for a particular installation (American Wind Energy Association, 2005)

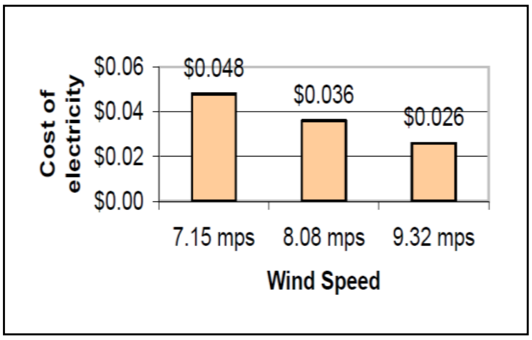

Fig. 1: Cost of energy and wind speed. Three examples above are for costs per kilowatt-hour for a 51 MW wind farm at three different average wind speeds expressed in meters per

second. Cost figures include the current wind production tax credit [Source: (American Wind Energy Association, 2005)]

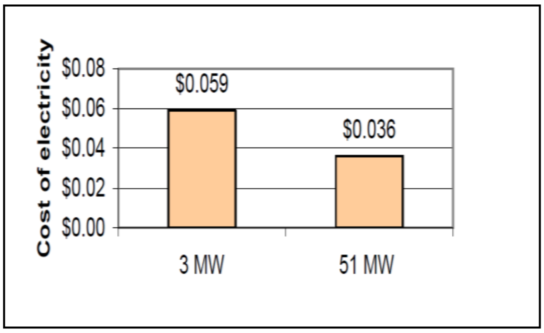

Fig. 2: Cost of energy – large wind farm vs. small. Cost figures include the current wind production tax credit [Source: (American Wind Energy Association, 2005)]

Eestimated cost of low power wind turbines and PV arrays gained through a survey in Australia suggest that the costs can be within the ranges of (1$/W to 13$/W) and (5$/W to 14$/W) respectively (WINDUSTRY, 2009, Derbyshire, 2009).

6. Cost of distributed generation technologies

Table 1 shows a comparison of cost components of different DG technologies. The table includes capacity cost, capital cost, fuel cost, and operation and maintenance cost. It also provides the information on heat rate and service life of the technology used for cost calculation.

Table 1: A comparison of selected electricity generation technologies [Source: (The Congress of the United States - Congressional Budget Office, 2003)]

	Capacity (kW)	Capital Cost[a] ($/kW)	Fuel Cost ($/kWh)	O&M Cost ($/kWh)	Service Life (Years)	Heat Rate[b] (Btu/kWh)
Microturbine—Power Only	100	1,485	0.075	0.015	12.5	13,127
Microturbine—CHP	100	1,765	0.035	0.015	12.5	6,166
Gas ICE—Power Only	100	1,030	0.067	0.018	12.5	11,780
Gas ICE—CHP	100	1,491	0.027	0.018	12.5	4,717
Fuel Cell—CHP	200	3,674	0.029	0.010	12.5	5,106
Solar Photovoltaic	100	6,675	0	0.005	20	n.a.
Small Wind Turbine	10	3,866	0	0.005	20	n.a.
Large Wind Turbine	1,000	1,500	0	0.005	20	n.a.
Combustion Turbine—Power Only	10,000	715	0.067	0.006	20	11,765
Combustion Turbine—CHP	10,000	921	0.032	0.006	20	5,562
Combined-Cycle System[c]	100,000	690	0.032	0.006	20	5,642

Fig. 3 shows the levelised energy cost of each DG technology shown in table 1. It is evidenced from this figure that the solar photovoltaic and combined heat and power technologies have the highest and lowest cost of energy respectively.

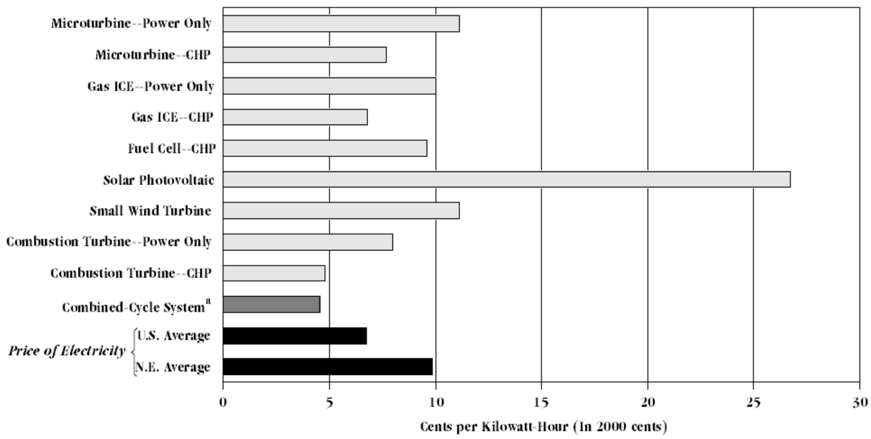

Fig. 3: Levelised cost of selected technologies suitable for distributed generation [source: (The Congress of the United States - Congressional Budget Office, 2003)]

7. Installation costs of selected DG technologies

(The California Energy Commision, 2008, Derbyshire, 2009)

6(i) Wind

Large-scale wind farms can be installed for the cost of $1,000/kW. The cost of electricity produced from wind farms typically range from 3 to 6 cents/kWh. These costs include the wind production federal tax credits of 1.7 cents/kWh for the first ten years of operation. The cost for small-scale wind turbines is higher. A typical 10 kilowatt home wind turbine system will cost $25,000 - $35,000 to install. If placed in windy areas, it will produce between 10,000 to 18,000 kWh per year. Such a turbine has a blade diameter of about 20-25 feet and needs to sit on a tower about 100 feet tall.

Curtin University of technology performed a survey on real cost of different types of wind turbine generators and their auxiliaries. They are tabulated in Appendix –A under Tables 3-5. These tabulated data show a complete breakdown of cost components that involve for a wind generator installation. (Derbyshire, 2009)

6(ii) Fuel Cell

The first cost of fuel cells is very high compared to those of other distributed energy technologies. The cost of the unit of a fuel cell is approximately $4,000/kW. The installed cost of the unit approaches $1.1 million. At a rated output of 200kW, this translates to about $5,500/kW, installed. Fuel cell technologies are still to be technically matured. Only a limited number of units are available in the market and further research and development are underway in this technological area.

Price projections of fuel cells vary among fuel cell developers, but most are targeting costs below $1,500/kW based on volume production. Maintenance costs of a fuel cell are expected to be ranging from $0.005-$0.010/kWh (based on an annual inspection visit to the unit). Currently, UTC Power manufactures 200-kW phosphoric acid fuel cell units at a cost of approximately $4000/kW. Table 2 shows the projected cost figures of fuel cell technologies.

Table 2: Emerging fuel cell technologies (The California Energy Commision, 2008)

Technology	Projected Cost (Long-term, Uninstalled)
MCFC	$1,200-1,500/kW
SOFC	$1,000-1,500/kW
PEMFC	Initially $5,000/kW, Long term $1,000/kW

6(iii) Reciprocating piston engine

Reciprocating internal combustion engines have the lowest first costs among distributed energy technologies. The capital cost of a basic gas-fuelled generator set package ranges from $300-$900/kW. Depending on size, fuel type, and engine type, Overall engine cost ($/kW) increases. The total installed cost can be 50%-100% more than the engine itself. Additional costs may arise from balance of plant equipment, installation fees, engineering fees, and other owner costs. The pie chart in Fig. 4 shows an example of breakdown of the total installed cost of a 550 kW natural gas internal combustion engine.

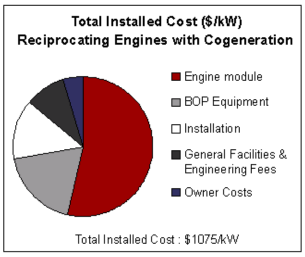

Fig. 4: An example of breakdown of installed cost of 550kW gas internal combustion engine(The California Energy Commision, 2008)

Maintenance costs of gas and diesel IC engines range between $0.007-$0.015/kWh and $0.005-$0.010/kWh respectively.

6(iv) Stirling engine

Capital costs of Stirling engines are relatively high ($2,000-$50,000/kW), and are generally not cost competitive with other distributed energy technologies. Stirling engines are manufactured in very low quantities which results in the high capital cost.

8. Cost of selected DG technologies in Australia

Fig. 5 shows an estimated cost of energy of selected generation technologies in Australia in 2006. It is obvious from this figure that the highest cost of energy arises from solar powered DG technology.

The reference (Alternative Energy Press, 2007) claims that a 1GW wind farm is to be installed in NSW, Australia for the cost of 2 billion A$. In other words, the installation costs of this wind power plant can be estimated at a rate of 2000A$/ kW. The reference (BlueGen, 2009) predicts that 2kW fuel cell units will be produced for the market price of A$ 8000, which suggests that cost of this type of fuel cells can be estimated at a rate of 4000 A$/kW. Further, the reference (BlueGen, 2009) estimates that the cost of energy could even reach 0.11 $/kWh with this type of fuel cell deployment, however, it is based on some assumptions given in (BlueGen, 2009).

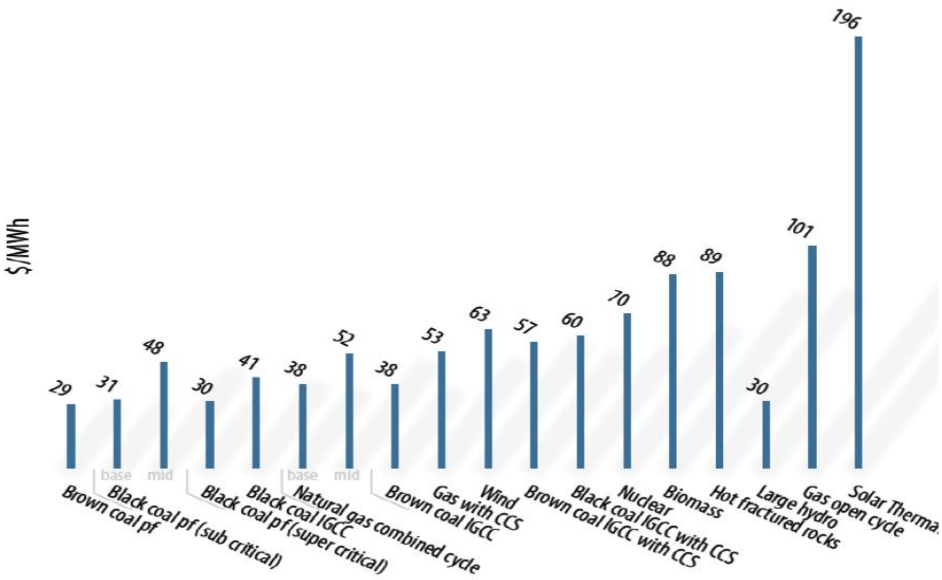

Fig. 5: CSIRO estimated costs of electricity generation technologies in A$(CSIRO, 2006)

9. True cost of DG

Costs of DG technology presented in above sections are based on cost of DG technology itself. However, these cost figures should be incorporated with cost factors that de-rate or up-rate the cost of DG technology that directly or indirectly related to network constraints, operational constraints, maintenance constraints, network access and licensing cost in order to properly reflect the cost of DG technology at a particular installation. In addition, it is necessary to calculate the life cycle cost of DG technology considering those attributes to compare the true benefit of DG technology. These techniques are not yet being well established, however, some references including (Khan et al., 2004, Flecka and Huot, 2009, Ahmadigorji et al., 2009) are attempting to calculate the cost of DG with some of those attributes.

10. Summary

This report presents the optimisation methods used in conventional and modern power systems and costs details of various DG technologies.

The presented optimisation routine can be adopted and further developed in order to investigate optimal DG sitting and dispatch in the current economical and technological climate. The existing optimisation routines are not concentrated on ICT (Information and Communication Technologies) infrastructure to the problem formulation; however, they must be incorporated in order to address modern optimisation aspects including the DG sitting and dispatch. Thus, it is obvious that the robustness of the ICT infrastructure will be a new constraint for DG technology related optimisations.

There are limited publications available in the area of cost of DG technologies. However, report presents the cost of energy, installation cost of selected DG technologies. There are many attributes that affect the DG technology. Therefore, the ranking of DG technology based on cost does not always feasible and consistent. However, it is obvious that the cost of wind is neither highest nor the lowest compared to other DG technologies. Among the selected DG technologies, the cost of reciprocating engine power generation has the lowest installation cost. Cost of fuel cell powered generation shows a relatively higher cost of installation. In the case of cost of energy, the wind energy neither the highest nor the lowest. The combined cycle gas turbine shows the lowest cost of energy where as the cost of photo-voltaic shows the highest. However, the cost figures should be because the DG technology maturity is yet to be achieved and they are still in the evolutionary stage.

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Appendix – A

Table 3: Cost components of permanent magnet horizontal axis wind turbine

Component List	Detail	Qty	Unit Cost	Total
PM Wind Turbine				
Wind Turbine Controller	Leonics WTC	1	$800	$800
Dump Load	5kW with fan	1	$2,000	$2,000
Grid connected inverter	KACO Powerdor 4501x1	1	$3,950	$3,950
MPPT charger	Unknown	1	$5,000	$5,000
Power meter	3 phase AC modbus	1	$507	$507
Power meter	DC with Modbus	1	$355	$355
Power meter	DC with Modbus	1	$355	$355
Power meter	AC with Modbus, single phase	1	$290	$290
Power meter	DC with Modbus	1	$355	$355
DC transfer switch	2 positional, 2 pole	1	$60	$60
AC transfer switch	3 positional, 2 pole	1	$100	$100
DC transfer switch	2 positional, 2 pole	1	$60	$60
Main WT CB		1	$150	$150
Saftery WT CB		1	$150	$150
WTC CB		1	$150	$150
AC GCI CB	2 pole, lockout type	3	$150	$450
DC Bus CB	2 pole, 16A	2	$150	$300
Installation extras	Cable, lugs, terminal strips, switches, relays	1	$2,500	$2,500
Wireless monitoring equipment	Netgear wireless equipment	1	$600	$600
Civil works for WT		1	$4,000	$4,000
Main installation cabinet		1	$1,500	$2,500
Screen print front		1	$500	$500
Labour for cabinet		80	$80	$6,400
Commissioning/Testing		1	$1,000	$1,000
Sub total				$32,532
Tower				
Company	Manufacturer	Rated Power	Tower	Price
Navitas	Windchina	5200	15m	15560
Total				$48,092

Table 4: Cost components of permanent magnet vertical axis wind turbine installation

Component List	Detail	Qty	Unit Cost	Total
PM Wind Turbine	3.2kW	1	$21,600	$21,600
Wind Turbine Controller	Leonics WTC	1	$800	$800
Dump Load	5kW with fan	1	$2,000	$2,000
Grid connected inverter	Fronius IG30	1	$4,070	$4,070
MPPT charger	Unknown	1	$5,000	$5,000
Power meter	3 phase AC modbus	1	$507	$507
Power meter	DC with Modbus	1	$355	$355
Power meter	DC with Modbus	1	$355	$355
Power meter	AC with Modbus, single phase	1	$290	$290
Power meter	DC with Modbus	1	$355	$355
DC transfer switch	2 positional, 2 pole	1	$60	$60
AC transfer switch	3 positional, 2 pole	1	$100	$100

DC transfer switch	2 positional, 2 pole	1	$60	$60
Main WT CB	3 phase	1	$150	$150
Saftery WT CB	3 phase	1	$150	$150
WTC CB	3 phase	1	$150	$150
AC GCI CB	2 pole, lockout type	3	$150	$450
DC Bus CB	2 pole, 16A	2	$150	$300
12m Tower	12m Free Standing	1	$2,106	$2,106
Installation extras	Cable, lugs, terminal strips, switches, relays	1	$2,500	$2,500
Wireless monitoring equipment	Netgear wireless equipment	1	$600	$600
Civil works for WT		1	$4,000	$4,000
Main installation cabinet		1	$1,500	$1,500
Screen print front		1	$500	$500
Labour for cabinet		80	$80	$6,400
Commissioning/Testing		1	$1,000	$1,000
Total				$55,358

Table 5: Cost components of 3-phase induction motor wind turbine installation

Component List	Detail	Qty	Unit Cost	Total
IM Wind Turbine	Aerogenesis inc tower	1	21500	21500
DC Controller	Aerogenesis	1	5000	5000
Power meter	3 phase AC modbus	1	507	507
Power meter	3 phase AC modbus	1	507	507
Power meter	DC with Modbus	1	355	355
DC transfer switch		1	60	60
Main WT CB	3 phase	1	$150	$150
Saftery WT CB	3 phase	1	$150	$150
WTC CB	3 phase	1	$150	$150
DC Bus CB	2 pole, 16A	2	$150	$300
Installation extras	Cable, lugs, terminal strips, switches, relays	1	$2,500	$2,500
Wireless monitoring equipment	Netgear wireless equipment	1	$600	$600
Civil works for WT		1	$4,000	$4,000
Main installation cabinet		1	$1,500	$1,500
Screen print front		1	$500	$500
Labour for cabinet		80	$80	$6,400
Commissioning/Testing		1	$1,000	$1,000
Total				$45,179