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A Systems Approach to Model a Micro-Grid Cyber-Physical System in Urban Cities

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Motivation

- The growth outlook of alternative energy in the US increases day after day and accounts for 32 percent of the overall growth in electricity generation from 2011 to 2040
- Dynamic micro-grid platforms will operate connected to the power grid while maintaining the ability to stand alone to increase efficiency and local reliability
- operations research approach taken to understand the cost-effectiveness of using renewable energy based micro-grids for power generation

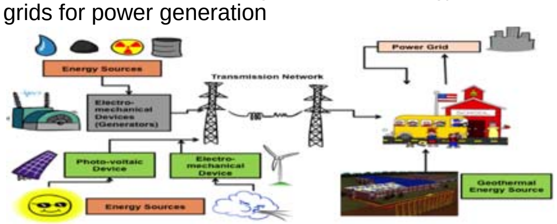

Figure 1: Power Network Flow Model

Operations Research Formulation

- The overall goal of this formulation is to select a set of renewable energy sources to build with minimum cost such that maintenance and startup costs fall within the budget, and that we are not purchasing an abundant amount from the grid, while still satisfying the power demand.

Objective Function: Minimize total cost:

$$\sum_j C_j X_j + \sum_r M_r P_r + p_e P_e + p_b B - p_s S$$

Constraints:

$$\sum_j C_j X_j + \sum_r M_r P_r + p_e P_e + p_b B - p_s S \leq \textbf{Budget}$$

$$\sum_r P_r + P_e + B - S \geq \textbf{Demand}$$

Environmental & Weather

$$P_w + P_s \leq 10{,}000$$
$$P_e + P_t + P_g \leq 5{,}000$$

Minimum Ren. Energy sources

$$X_g + X_t + X_s + X_w \geq 2$$

Maximum Energy source selection (size limitation)

$$X_g + X_t + X_s + X_w + X_e \leq 4$$

Capacity

$$600 \leq P_e \leq 3100$$
$$P_w \leq 6272$$
$$P_s \leq 6609.38$$
$$P_g \leq 7856.68$$
$$P_t \leq 8110.65$$
$$P_g \leq 7856.68$$

Build Requirement

$$6272\, X_w - P_w \geq 0$$
$$6609.38\, X_s - P_s \geq 0$$
$$7856.68\, X_g - P_g \geq 0$$
$$8110.75 X_t - P_t \geq 0$$
$$3100 X_e - P_e \geq 0$$

Either Horizontal or Vertical

$$X_g + X_t \leq 1$$

		w	s	g	t	e	Pe	Pw	Ps	Pt	Pg	Pbuy	Psell			
BUDGET		1910.4	1050.35	1546.83	1527.61	600	0.08	0.012	0.013	0.021	0.019	0.11	-0.07	3545.189	<=	6000
DEMAND							1	1	1	1	1	1	-1	18200	>=	18,200.00
POWER CAPACITY	Max generator output						1							600	<=	3100
	Max wind output							1						2869.503	<=	6272
	Max geothermal vertical									1				4400	<=	8110.75
	Max solar output								1					6609.375	<=	6609.375
	Max geothermal horizontal										1			0	<=	7856.68
	Min generator output						1							600	>=	600
WEATHER								1	1					9478.878	<=	10,000
ENVIRONMENT							1			1	1			5000	<=	5,000
BUILD REQUIREMENT	wind	6272						-1						0	>=	0
	solar		6609.375						-1					0	>=	0
	geothermal horizontal			7856.68							-1			0	>=	0
	geothermal vertical				8110.75					-1				0	>=	0
	generator					3100	-1							0	>=	0
if - then	vertical or horizontal			1	1									0.54249	<=	1
min energy sources required		1	1	1	1									2	>=	2
max energy sources		1	1	1	1	1								2.193548	<=	4
Linear Programming Relaxation Binary Integer Constraint		1												0.45751	<=	1
			1											1	<=	1
				1										0	<=	1
					1									0.54249	<=	1
						1								0.193548	<=	1
Objective Function		1910.4	1050.35	1546.83	1527.61	600	0.09	0.012	0.013	0.021	0.019	0.11	-0.07			
Optimal Solution		0.45751	1	0	0.54249	0.193548	600	2869.503	6609.375	4400	0	3720.122	0			
Optimal Values		874.0273	1050.35	0	828.713	116.129	54	34.43404	85.92188	92.4	0	409.2134	0		3545.19	

Figure 2: Excel Solver Simulation

Optimization

- Linear Relaxation of binary constraints was implemented to apply the Branch & Bound technique. The optimal solution is at node [14] where *w=g=0* and *s=t=e=1* at a value of 4135.1
- Genetic Algorithm is selected as the meta-heuristic for this problem. There are seven steps in this heuristic: Initialization, Crossover, Mutation, Evaluation, Selection and Evolution.

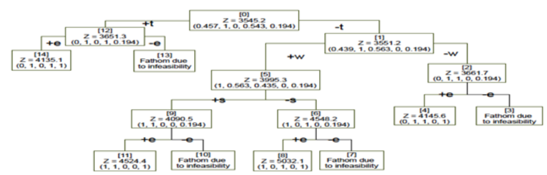

Figure 3: Branch & Bound Analysis

Component-Based Modeling

- In this project, our goal has been to provide systems engineering models of the structure and behavior of a micro-grid. Systems Engineering models have been created with respect to three viewpoints: a function-based analysis, a behavior model, and lastly a cyber-physical based decomposition.
  - Functionally, the Micro-Grid has been divided into many subsystems.

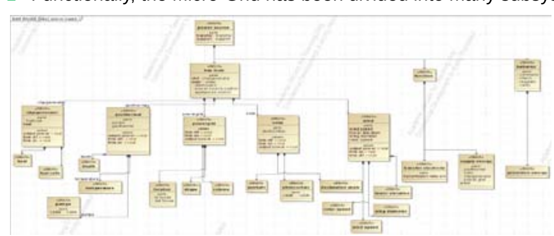

Figure 4: Micro Grid Architecture Model

Behavior modeling

- A systems engineer's perspective through an economist's model can be taken as such:
  - **Stackelberg** (1934) proposed a dynamic model of duopoly in which a dominant or leader firm moves first and a subordinate or follower firm moves second
  - **Nash's** equilibrium is reached when many individuals (players) make the best personal decisions they can, while also taking into account the decisions made by everyone else

Figure 5: Stackelberg's model of duopoly

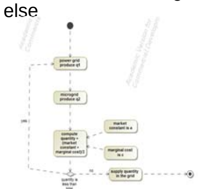

Figure 6: Nash's Equilibrium

Cyber-Physical System Model

- To promote a sustainable smart city, the smart grid must take into account the collaborating computational elements that control the physical entities.
- These CPS aspects of the system are modeled below including the obstacles and threats we see possible in implementing a micro-grid.

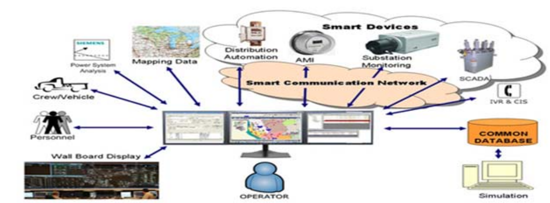

Figure 7: The Operations Center

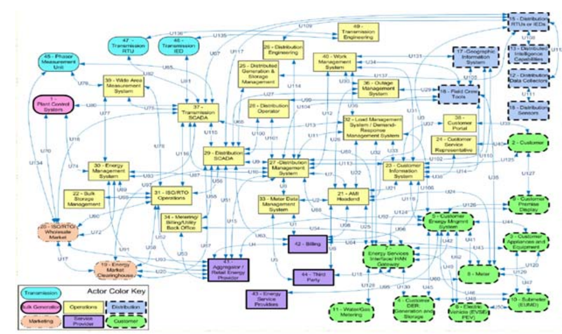

Figure 8: Logical Interface Categories in the Smart Grid Architecture Model

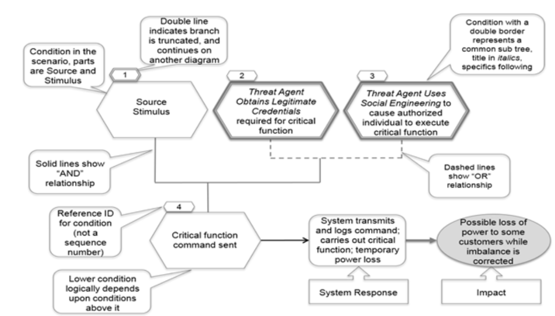

Figure 9: Attack trees for Smart Grids