Electric Distribution Network Planning

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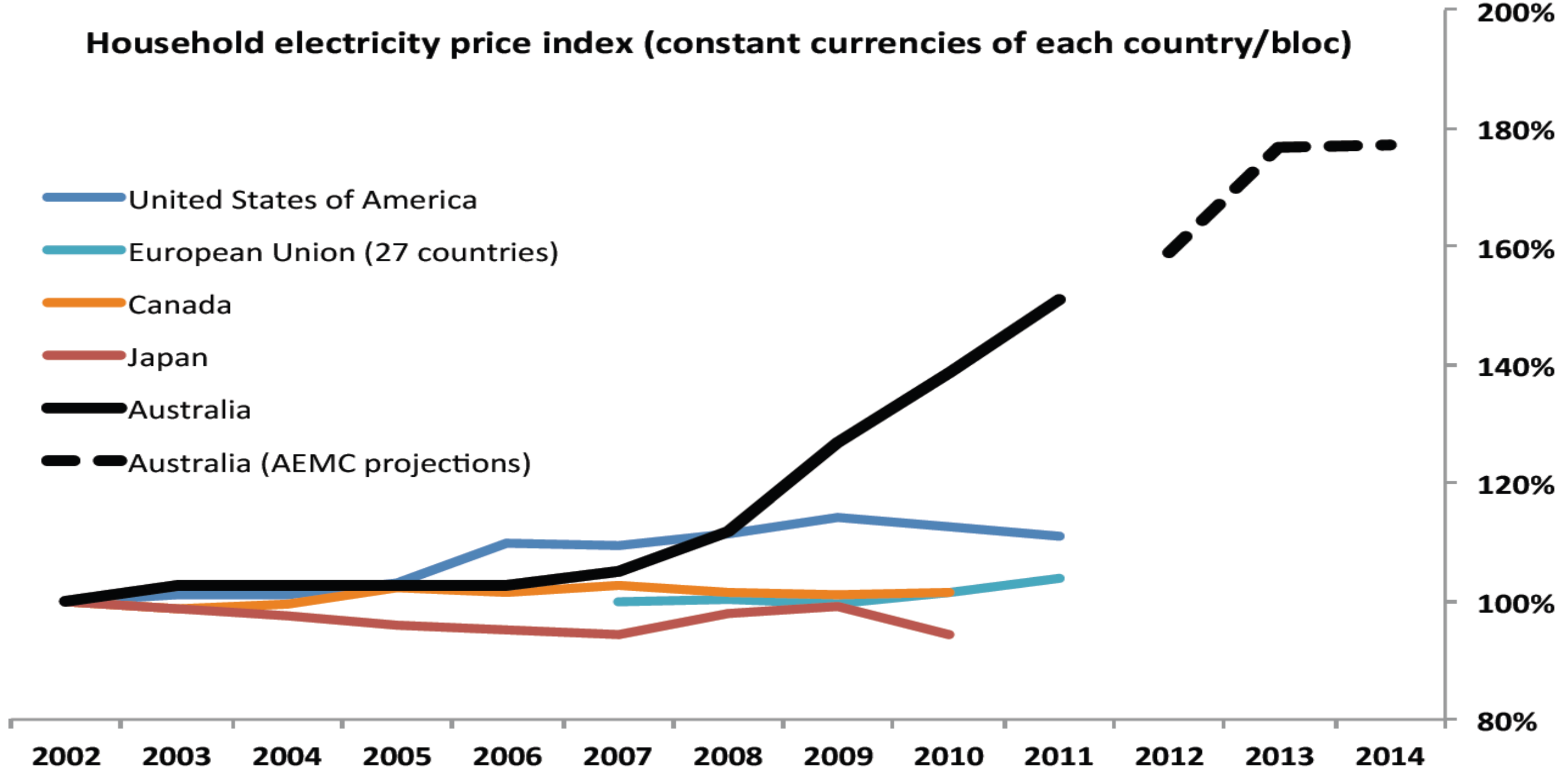
Outline

- Risk-Managed electric network planning
- Ageing effect on distribution network planning
- Value of condition monitoring in electric distribution network planning

Current Situation

Australian electricity price have risen around 80% in 7 years from 2007 to 2014

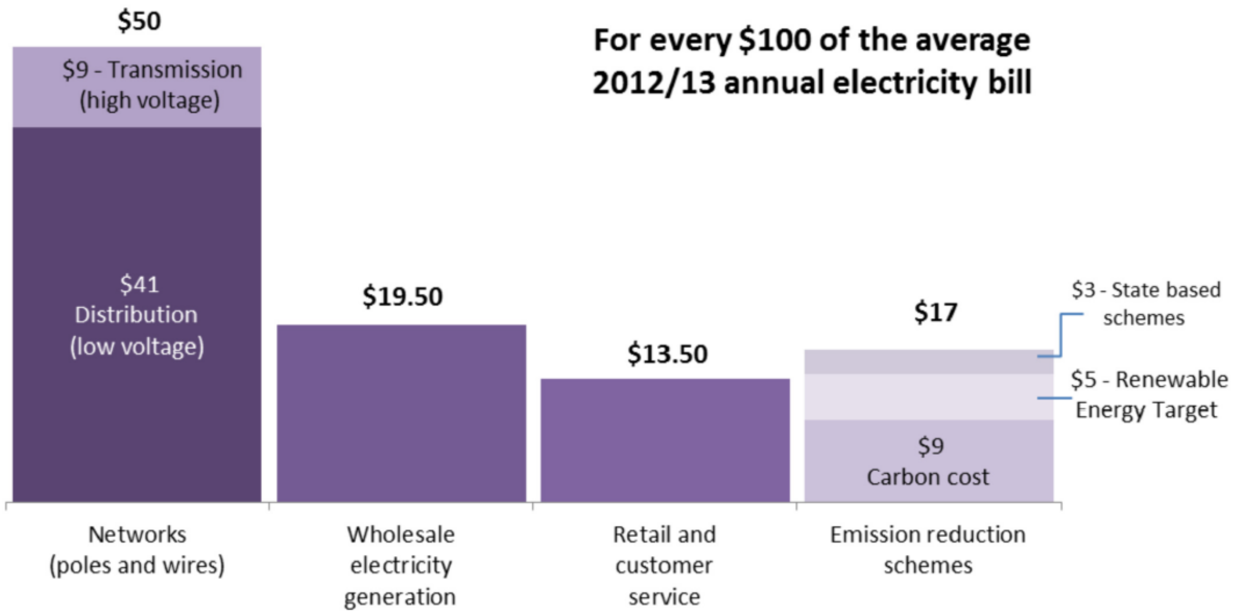


Ref.: Electricity Prices in Australia: An International Comparison, CME, March 2012.

Risk-Managed Planning

- Cost of electric networks is a large portion of customer electricity bills.

- Caused by the capital cost of increasing the capacity of the electricity distribution network to consider uncertainties associated with load and distributed generations (DGs).



Ref.: The facts on electricity prices, Australian Government, Department of Industry.

Question: How to reduce cost of network maintaining service quality and technical constraints?

Approach: Long-term optimization of electric distribution network upgrade taking into account Non-Network Solutions (NNSs) along with conventional network solution to:

- Reduce long-run cost
- Manage the risks associated with uncertainties and equipment failure.

Developing a tool for Multi-Stage Distribution Expansion Planning (MSDEP)

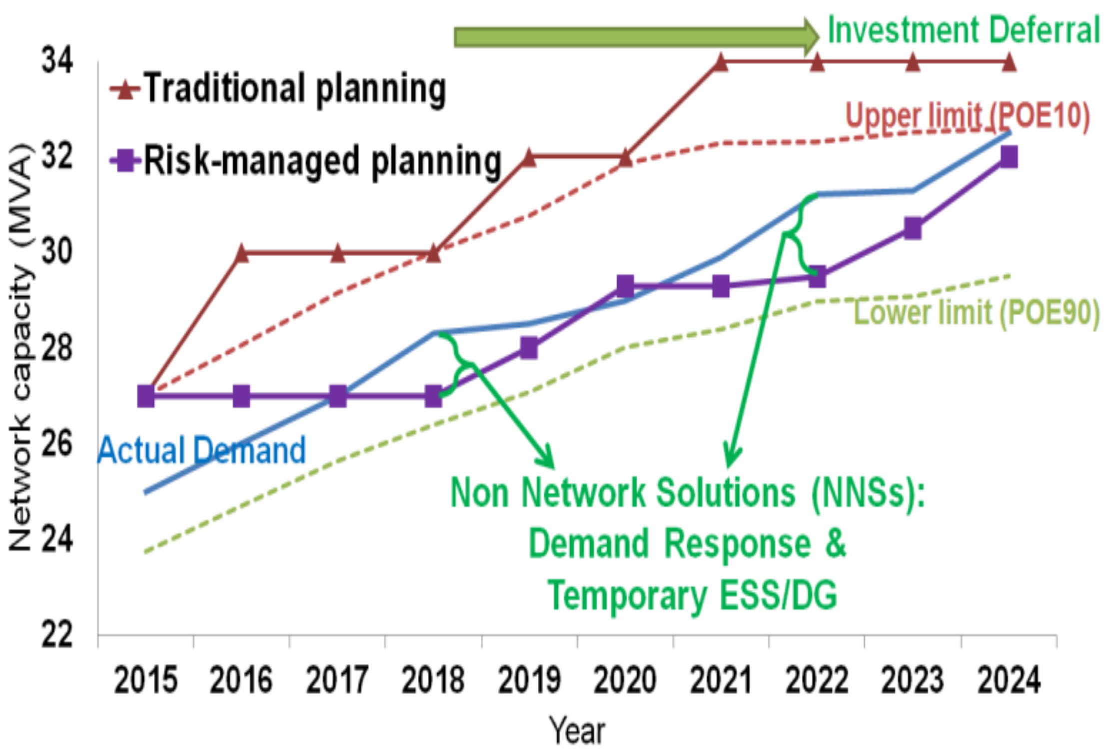
- Providing a cost-effective approach to manage the risk associated with uncertainties of load and renewable generation
- Using temporary Non-Network Solutions (NNSs) including:
  1) short-term customer engagement programs in demand response (DR)
  2) Temporary energy storage system (ESS)/distributed generation (DG)
- Using these solutions rather than investing on high level of a network capacity to meet uncertainties.

Existing planning approach:

- Designing a network for given demand forecast:
  - Considering a high reserve margin to take into account uncertainties of the forecasts.
  - Results in building extra network capacity to tackle increased uncertainties.

New planning approach:

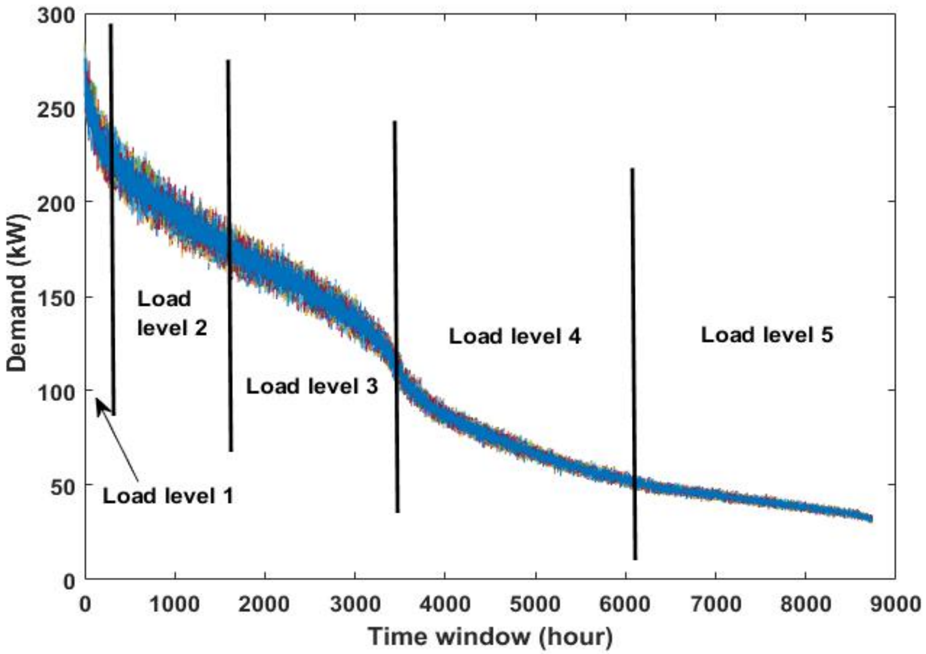
- Finding optimal level of demand:
  - Using network solutions (NSs)
  - Procuring NNSs to manage the risk of exceeding demand above this level.



Risk-managed planning concept

Uncertainty Modelling

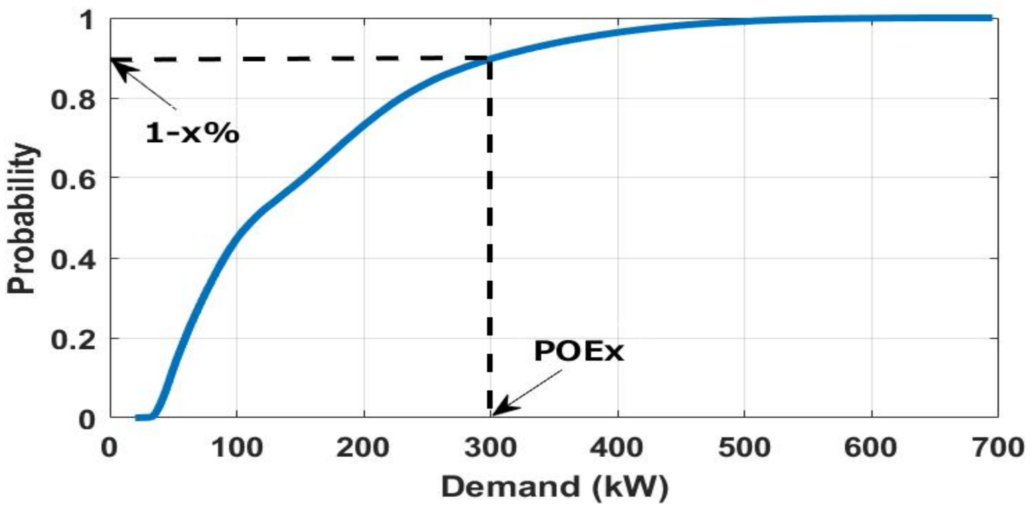
- Uncertainty levels: standard deviations of forecasts at each time window
- Considering Solar PV as the renewable energy source that is connected to distribution network as DGs
- Associating a level of uncertainty to demand and PV generation forecasts
- Obtaining effective load duration curves (LDCs)



Effective LDCs at a node with determined 5 load levels

Uncertainty of peak load forecast

- Peak load is the main driver of capacity augmentation in a distribution network
- Obtaining cumulative distribution functions (CDF) of effective load at each node using load duration curves
- Probability of exceedance (POE) extracted from CDF of peak load at each node is used to model the uncertainties of peak load forecast.



The CDF of effective load over 10 years of planning for a node.

Risk-managed Cost (RMC)

- Risk-managed cost (RMC) or C_{RMC}^{y} for year y is the expected value of solution costs for managing the risk.

$$C_{Prob,NNS}^{y} = C_{RMC}^{y} = \sum_{i=1}^{m} C_{NNS}^{y,i}\left(kWh^{y,i}, kVA^{y,i}\right) \times p_i = \sum_{i=1}^{m} C_{NNS}^{y,i}\left(kWh^{y,i}, kVA^{y,i}\right) \times (x_{i+1}\% - x_i\%)$$

(i is the level of load and m is total number of load levels)

Problem Formulation

The goal of proposed planning is to supply the demand by optimum selection of network solution and NNAs.

$$Minimisation\ of\ \sum_{y=1}^{H} C_{Prob}^{y}$$

NPV of total probabilistic cost at year y

$$subject\ to: \begin{cases} P(0.95 \leq |v_i^y| \leq 1.05) \geq 0.95 \\ P(|I_i^y| \leq 1.1) \geq 0.95\ , \quad \begin{matrix} i = 1 \ldots n \\ y = 1 \ldots H \end{matrix} \\ meet\ demand\ at\ each\ transformer \end{cases}$$

$$C_{Prob}^{y} = \sum_{i=1}^{m} C_{Total\,,i}^{y} \times P_i^y =$$
$$= \sum_{i=1}^{m} \{C_{NNA}^{y}(POEx_i) + C_{NS}^{y}\} \times (x_{i+1}\% - x_i\%) =$$
$$= C_{NS}^{y} + \sum_{i=1}^{m} C_{NNA}^{y}(POEx_i) \times (x_{i+1}\% - x_i\%) =$$
$$= C_{NS}^{y} + C_{Risk}^{y}$$

NPV of Network solution cost

Problem Formulation

Network cost includes NPV of fixed and variable investment cost of network solutions, operation and maintenance cost and the salvage value.

$$C_{NS}^{y} = C_{NS,fix}^{y} + C_{NS,var}^{y} + C_{O\&M}^{y} - C_{salvage}^{y}$$

Operation and maintenance cost includes the costs of energy and power loss as well as reliability cost.

$$C_{O\&M}^{y} = C_{O\&M,NS}^{y} + E_{Loss}^{y} \times C_{ELoss}^{y} + P_{Loss}^{y} \times C_{PLoss}^{y} + SAIDI^{y} \times C_{SAIDI}^{y} + SAIFI^{y} \times C_{SAIFI}^{y}$$

System average interruption duration index (SAIDI)

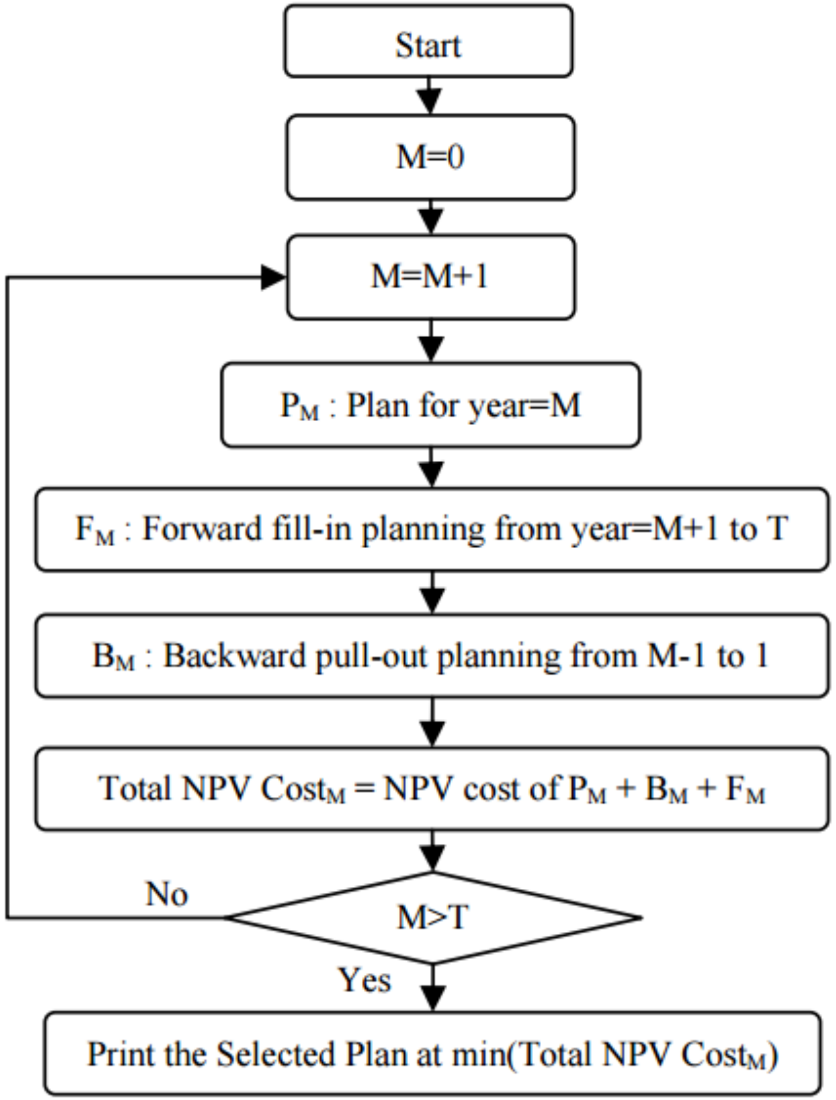
System average interruption frequency index (SAIFI)

Proposed Optimization Approach for real-sized networks

- MSDEP problem:
  - A complex combinatorial problem and hence the exact mathematical solution can only be applied to solve the MSDEP problem for small scale networks.
- Large-sized networks:
  - Even with heuristic optimization, achieving good solutions remains a time consuming operation
- Forward-backward pseudo-dynamic algorithm:
  - Decompose the multistage problem into a sequence of single stage problems and to solve each stage independently.
- Increase the accuracy of the solution:
  - A modified version of PSO (MPSO) can be applied by adding the idea of mutation from genetic algorithm (GA) as in into standard PSO particle update rules to avoids local minima.

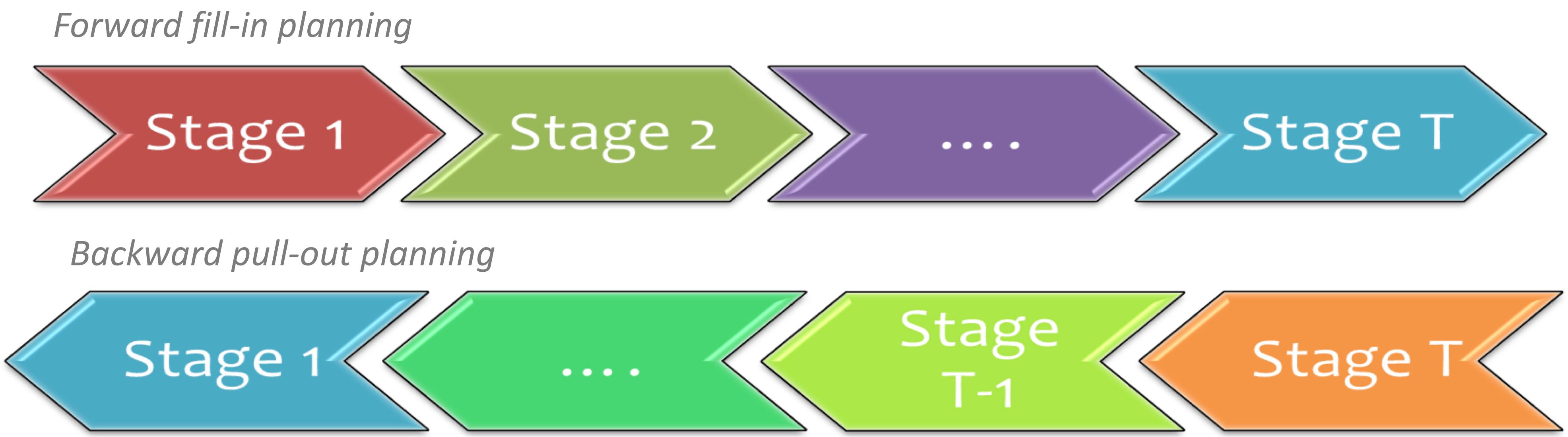
Optimization steps

1) Decomposition of MSDEP problem into single-stage problems.
2) Solving single stage problems using a heuristic optimization approach.
3) Applying forward-backward strategy to coordinate the single-stage solutions to find the optimal plan.



Risk-managed Planning

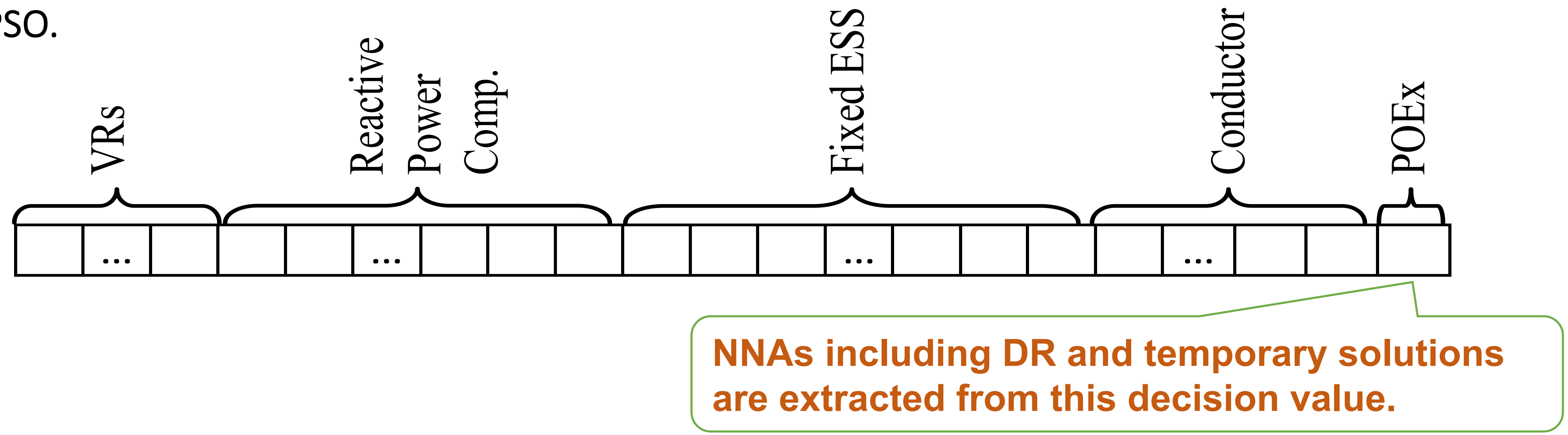
Decompose multi-stage planning into a sequence of single-stage (one-year) problems to be solved independently to reduce computational time and complexity.



What is proposed in risk-managed planning: Forward-backward Approach

Risk-managed Planning

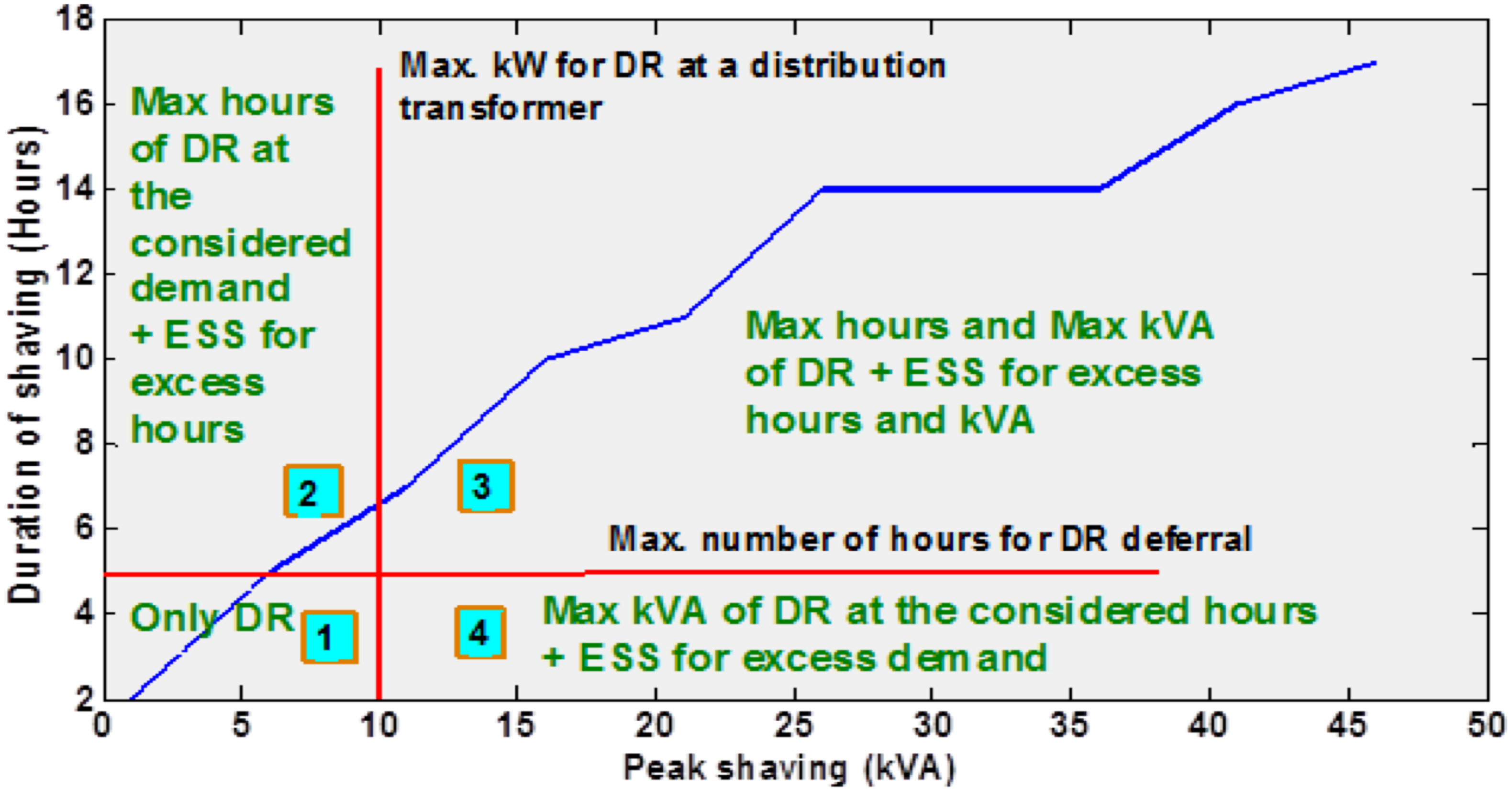
The one-year planning is carried out using a modified version of PSO by adding mutation into standard PSO.



- These variables are considered as particles of PSO
  - Tap setting of voltage regulators (VRs)
  - The location and the size of reactive power compensators such as capacitors
  - The location and the size of fixed ESS
  - The number of conductor upgrades
  - The level of demand supplied by the NSs (DSNS index)

Demand Response and Energy Storage

Type of NNA	k_1	k_2 (\$/kWh)	k_3 (\$/kW)
Temporary ESS/DG	Preparation cost	Battery/Delivered energy cost	Inverter/DG purchased cost
DR	Availability cost [14]	Deferred energy cost [15, 16]	Deferred demand cost [16, 17]



$$C_{NNA}^{y} = k_1 + k_2 \times kWh_{max}^{y} + k_3 \times kW_{peak}^{y}$$

MSDEP parameters

- The MPSO parameters used in the simulations:

  Particle population=50

  Maximum iterations=100

  ψ_{max}=4.05

  K=0.99

  Mutation probability=80%

  The mutation operator is applied to 10% of particle population.

THE PARAMETERS FOR MSDEP

Parameter	Value
Interest rate (%)	5
SAIDI cost ($/min-customer)	1.14
SAIFI cost ($/failure-customer)	88
Cost of power loss ($/kW-year)	235
Cost of energy loss ($/kWh)	0.04
Failure rate of OH/UG line. (f/km-yr)	0.14/0.05
Failure rate of OH/PM Trans. (f/yr)	0.02/0.005
Repair time OH/UG line. (min)	180/300
Repair time of OH/PM Trans. (min)	900
Switching time (min)	60

Simulation Results: Input Parameters

Parameter	Value
Interest rate (%)	**5**
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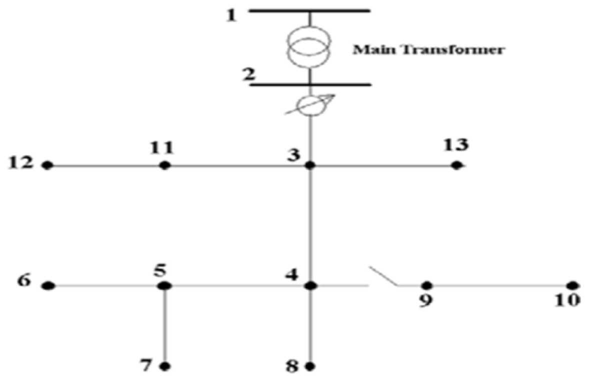
The MPSO parameters:
particle population = 50,
maximum iterations = 100,
ψ_{max} = 4.05,
K = 0.99,
mutation probability = 80%.
The mutation is applied to 10% of particles.

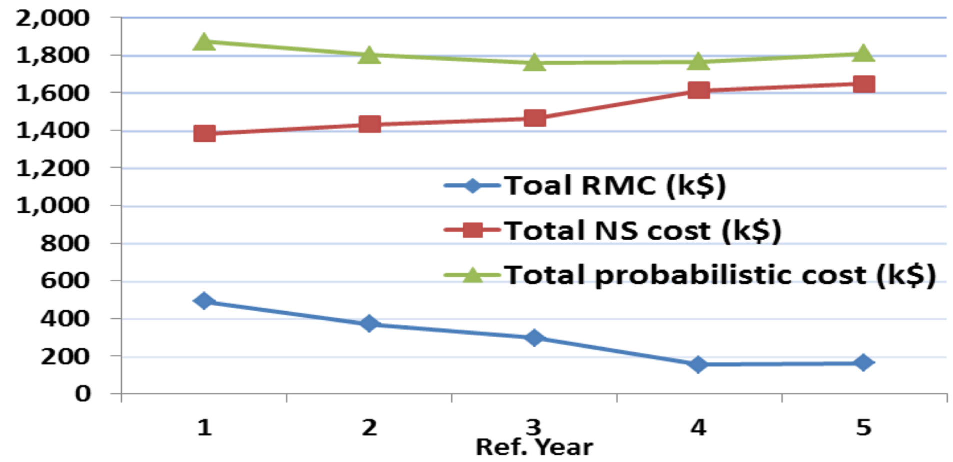


The cost of DR program: $0.382/kWh with the maximum of 20 kVA and 6 hours per distribution transformer.

The load growth and the renewable penetration are 4% and 10%, respectively.

The load and renewable uncertainty, as a Gaussian distribution, at the first year is 3% and increases by 3% each year.

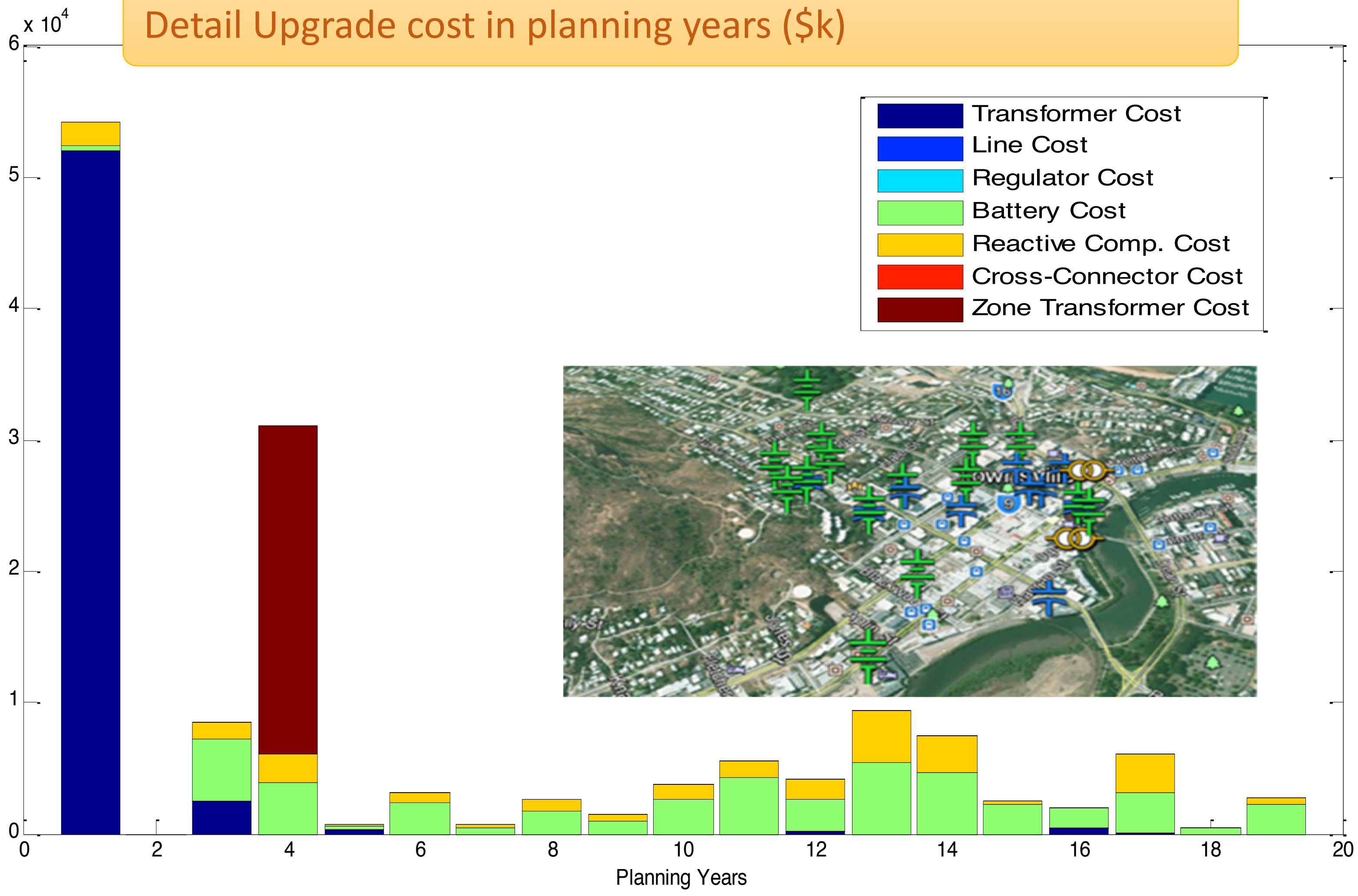
- Lowest total network expansion cost ($\sum C^{y}_{Prob}$):
  - Obtained from forward-backward approach for Ref. Year 3.
  - It is cost-effective to utilize fixed ESSs and capacitors to meet the forecast demand to a certain level and procure temporary NNSs such as DR and ESS to meet the demand rather than investing in costly transformers.



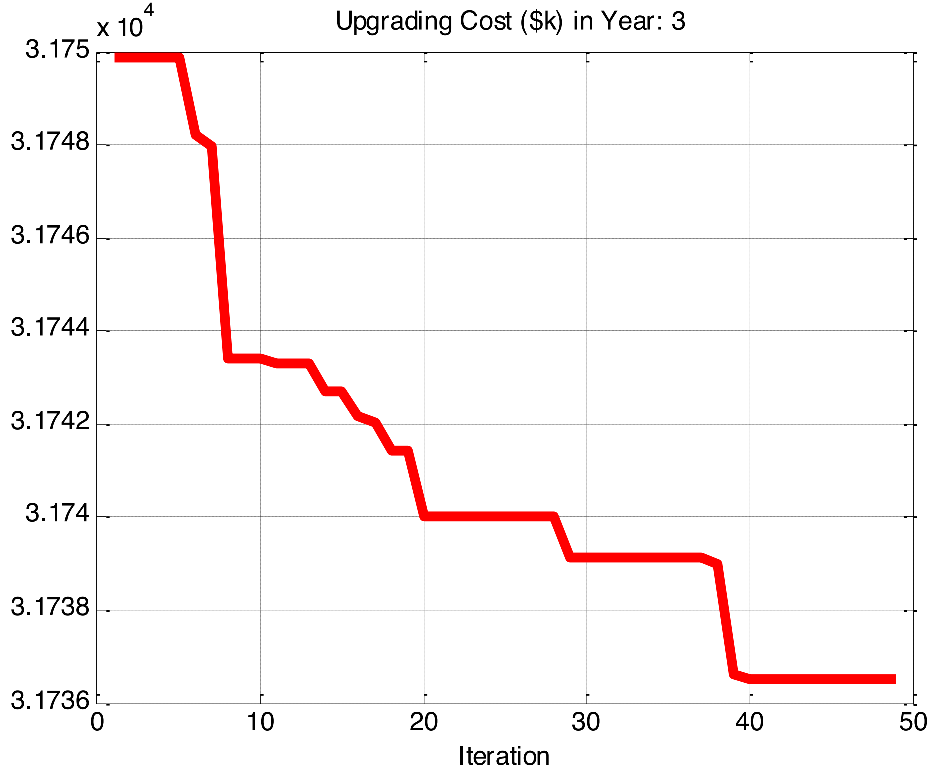
Ref. Year	Upgrades	Planning years					Total
		1	2	3	4	5	
1	Trans.(kVA)	0	0	0	25	0	25
	Fix ESS (kVA)	0	5	5	335	445	789
	Cap.(kVAR)	375	900	0	275	25	1,575
	DSNS^y	POE10	POE30	POE80	POE50	POE30	-----
	C^{y}_{RMC}(k$)	0	7	314	122	46	489
	C^{y}_{Prob}(k$)	194	204	439	644	392	1,872
2	Trans.(kVA)	0	0	0	0	0	0
	Fix ESS (kVA)	0	0	20	325	710	1,055
	Cap.(kVAR)	300	750	275	200	0	1,525
	DSNS^y	POE20	POE30	POE70	POE50	POE30	-----
	C^{y}_{RMC}(k$)	0.5	2	192	128	48	369
	C^{y}_{Prob}(k$)	191	189	366	553	502	1,800
3	Trans. (kVA)	0	0	0	0	0	0
	Fix ESS (kVA)	0	0	10	335	550	895
	Cap.(kVAR)	300	925	250	50	25	1,550
	DSNS^y	POE20	POE20	POE80	POE50	POE30	-----
	C^{y}_{RMC} (k$)	0.5	0.4	124	123	47	295
	C^{y}_{Prob} (k$)	191	283	293	558	434	1,759
4	Trans.(kVA)	0	0	25	0	0	25
	Fix ESS (kVA)	0	0	40	340	520	900
	Cap.(kVAR)	300	750	175	0	350	1,575
	DSNS^y	POE20	POE30	POE70	POE50	POE20	-----
	C^{y}_{RMC}(k$)	0.5	1	76	64	13	154
	C^{y}_{Prob}(k$)	191	283	379	514	398	1,765
5	Trans.(kVA)	200	0	0	0	0	200
	Fix ESS (kVA)	0	0	30	345	435	810
	Cap.(kVAR)	300	925	50	0	0	1,275
	DSNS^y	POE20	POE20	POE70	POE50	POE30	-----
	C^{y}_{RMC}(k$)	0.5	0.4	72	63	25	161
	C^{y}_{Prob}(k$)	297	188	276	680	368	1,808

Simulation output: Investment plan

Detail Upgrade cost in planning years ($k)

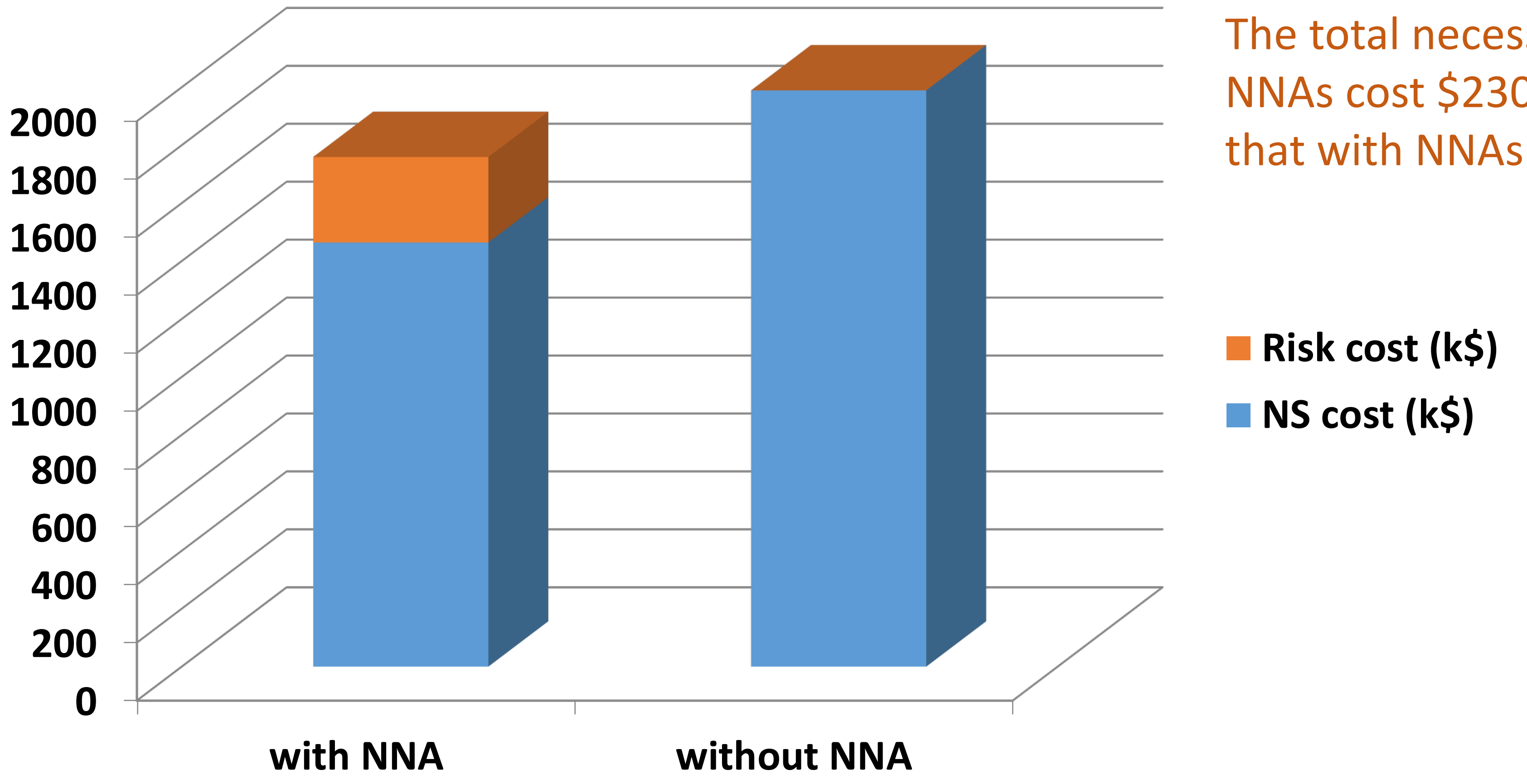


Upgrade cost ($k) minimization in a specific year



Simulation and Discussion

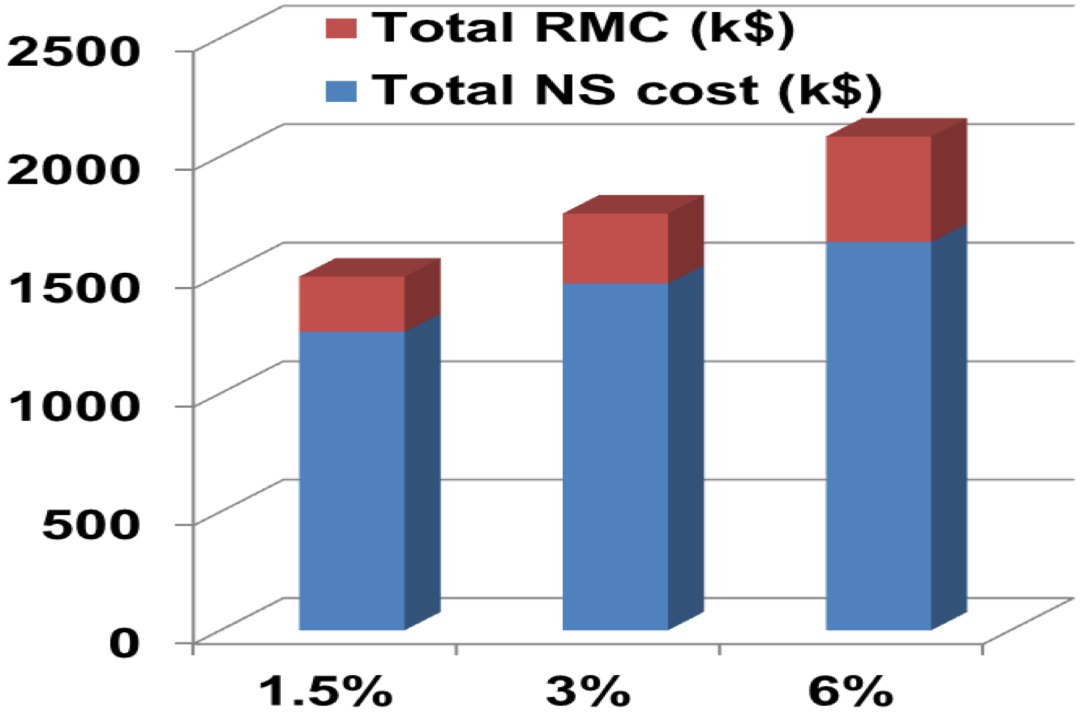
The Effect of NNAs on total cost:



The total necessary upgrades without NNAs cost $230k (13%) more than that with NNAs.

The effect of uncertainty level

- Two MSDEPs are developed with different level of uncertainties:
  1) Decreasing the uncertainty level to half from the base case (3% in first year and increases 3% each year)
  2) Doubling the uncertainty from base case.
- As expected, both RMC and total cost increase with level of uncertainty



The total RMC and NS cost for different level of uncertainties.

Outputs of Risk-Managed Planning Aid

Transformer and conductor sizing

Selection of Non Network Alternatives:

- DM targeted to particular communities
- Mobile Gen. / Storage / Renewables
- Reactive Compensation

Cross connector sizing & siting

Voltage regulator placement

Energy Storage sizing & siting

Zone substation siting and upgrading

Evaluation by Network Planners

Considering the effect of Transformer ageing on planning decisions

- IEEE 13 Bus Network is used as the test system
- Random ages are provided for transformers
- Weibull parameters are used to calculate failure rate of transformers

Bus No.	Total No. of Customers	Bus_kVA	Installed trans	Allocation of customers for each transformer	Age
3	1000	123	1) 63 kVA 2) 100 kVA	: 385 : 615	: 6 : 28
4	1250	1502	3) 500 kVA 4) 500 kVA 5) 500 kVA 6) 315 kVA	: 345 : 345 : 345 : 215	: 31 : 38 : 36 : 23
6	150	178	7) 200 kVA	: 150	: 29
7	150	160	8) 315 kVA*	: 150	: 30
9	450	236	9) 200 kVA 10) 100 kVA	: 300 : 150	: 11 : 5
10	625	889	11) 1000 kVA*	: 625	: 33
11	150	223	12) 200 kVA 13) 100 kVA	: 100 : 50	: 38 : 24
12	375	280	14) 315 kVA	: 375	: 29
13	250	523	15) 500 kVA 16) 315 kVA	: 155 : 95	: 21 : 10

Total NPV cost of the network for a 10 year planning

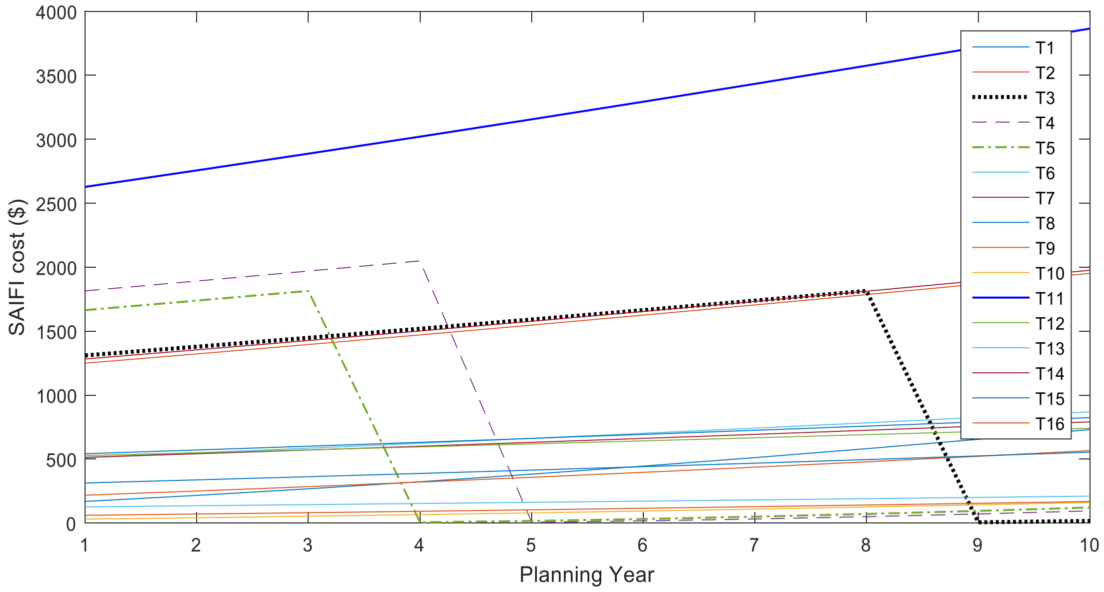
- Considering Transformer Replacement
  - Three transformers have replaced which according to their age and their allocated number of customers are correct choices for replacement.

Planning Year	0	1	2	3	4	5	6	7	8	9	10	Total NPV cost (k$)
Year NPV cost (k$)	0	1046	1014	983	948	735	654	633	612	586	524	7738
Replaced Trans. No.	-	-	-	-	5	4		-	-	3	-	-

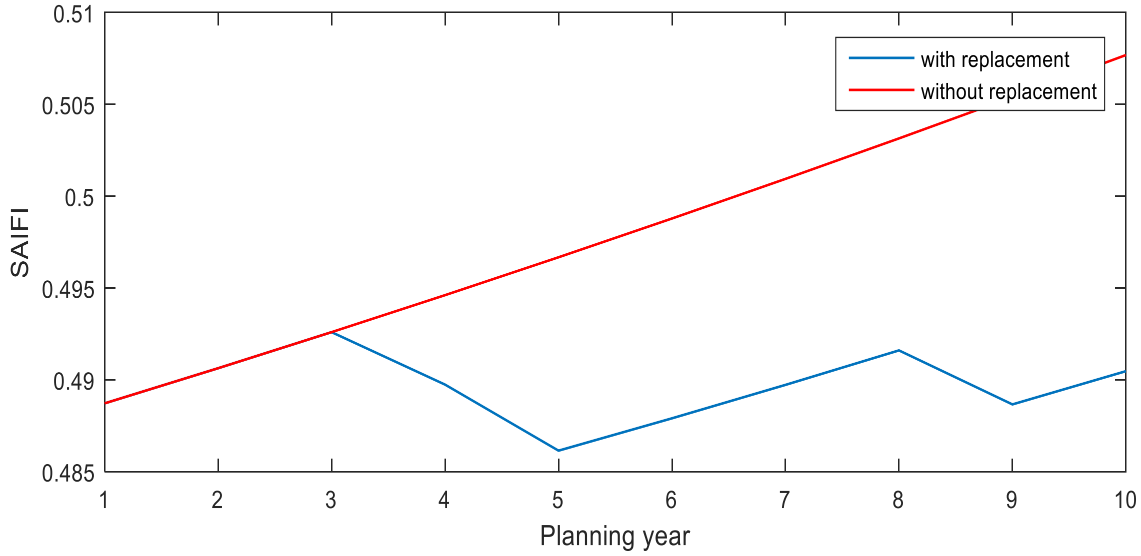
- Without Considering Transformer replacement
  - The total NPV cost of the network is higher than the previous case.

Planning Year	0	1	2	3	4	5	6	7	8	9	10	Total NPV cost (k$)
Year NPV cost (k$)	0	1046	1014	983	949	808	784	760	737	714	693	8491

Simulation results



SAIFI cost associated to each transformer for each year

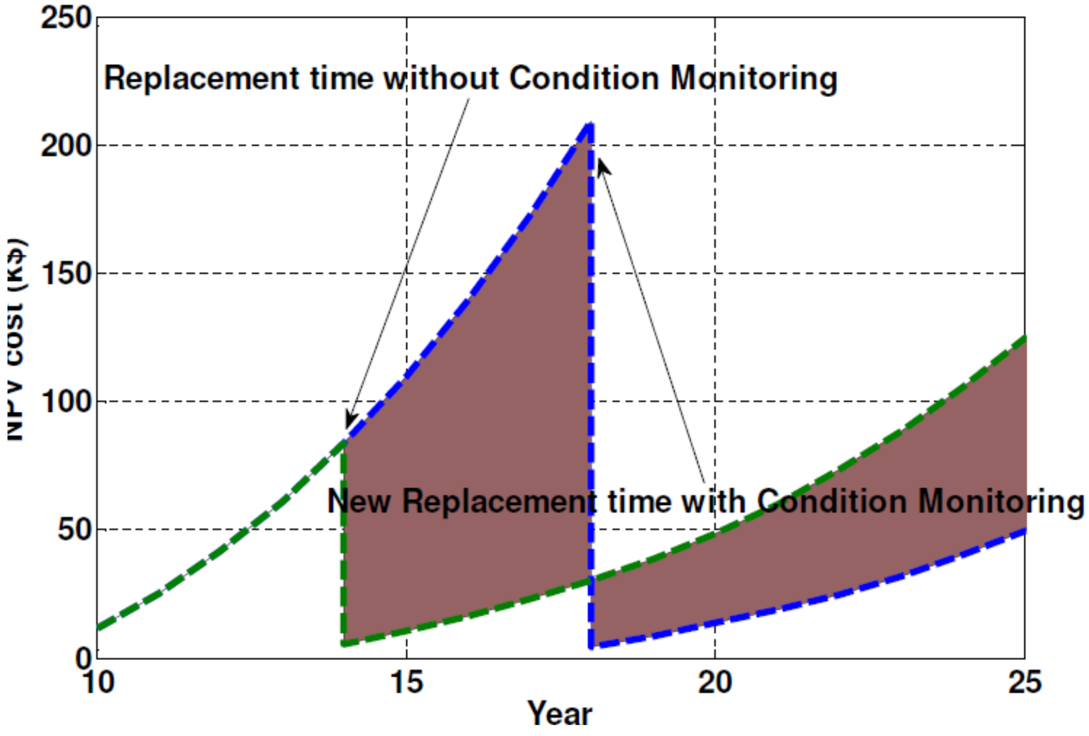


Total SAIFI value of the network with and without Transformer replacement

- At replacement years SAIFI cost decreases significantly.
- Total SAIFI value of the network is decreased due to transformer replacement

Value of Condition Monitoring

Cases when transformer is younger than expected	Cost (k$)
Replacement at normal time (without condition monitoring)	455
Replacement later than planned (using condition monitoring)	399



Cases when transformer is Older than expected	Cost (k$)
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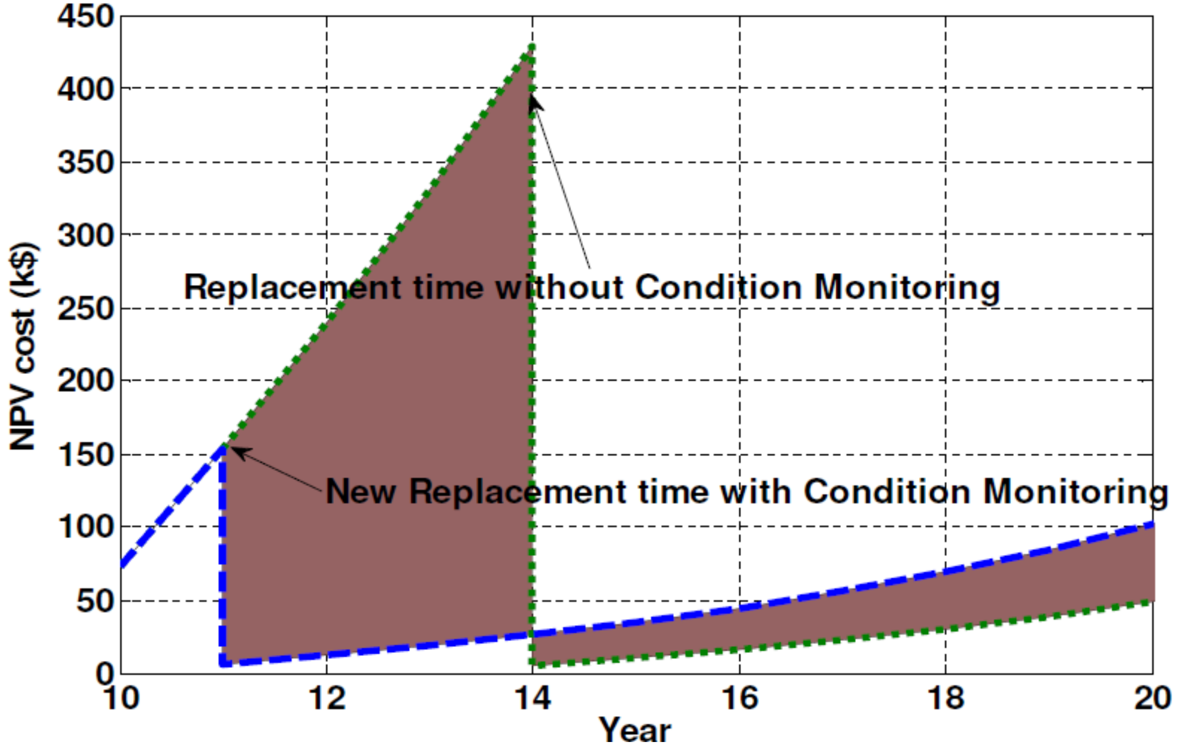

Value of Condition Monitoring

Age	Probability
5 years younger than expected	0.3
The same age as expected	0.4
5 years older than expected	0.3

Case	Value of Condition Monitoring (k$)
5 years younger than expected	0.3*(455-399) = 17
The same age as expected	0
5 years older than expected	0.3*(796-725) = 21
Total Probabilistic Benefit (k$)	38

The innovations to increase the efficiency of planning tool to be applicable to real network are as:

1) Efficient Forward-backward Approach:

   Decompose multi-stage planning into a sequence of single-stage (one-year) problems, in average 10% lower cost.

2) *Fast reliability assessment:*

   Developing a fast direct method for reliability calculation, at least 1000 times faster.

3) *Pre-processing algorithm:*

   Developing an algorithm to identify more attractive candidates before optimization at each stage.

4) *Fast probabilistic distribution load flow:*

   Using a direct method without any matrix inversion in one step, at least 2 times faster.

Questions?