Andrea Scalfati

Tutor: Diego Iannuzzi – Maurizio Fantauzzi

XXX Cycle – 3rd year presentation

Optimal Sizing of Distributed Energy Resources in DC Microgrids

Università degli Studi di Napoli
Federico II

Personal Background

M.Sc. in Electrical Engineering (cum laude), march 1997

DIETI groups:

ING-IND/32: Power electronic converters, electrical machines and drives

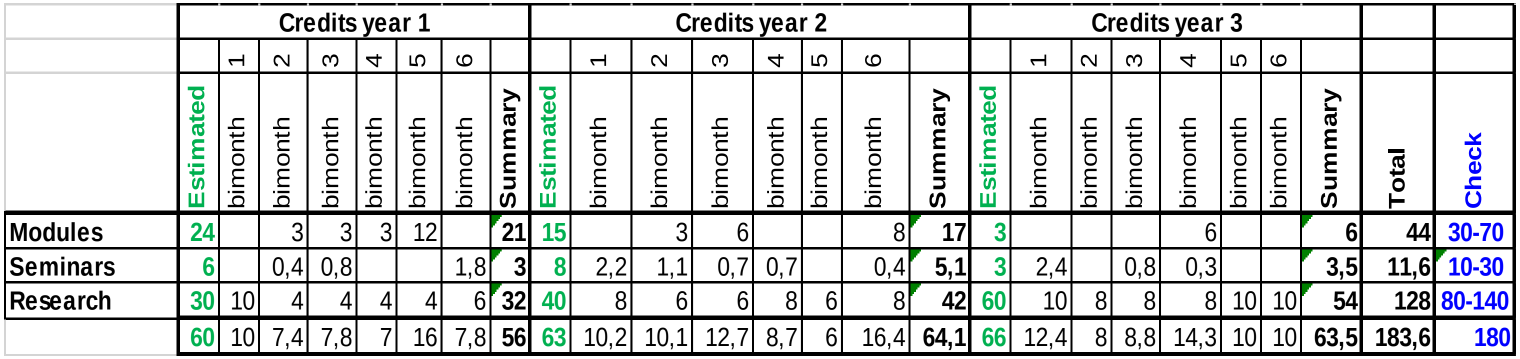
ING-IND/33: Electrical power systems

No Fellowship

Full time worker for the Italian Ministry of Education as High School teacher in electrical engineering from 2008

Professional Engineer since 1998

Credit Summary



	Credits year 1								Credits year 2								Credits year 3									
		1	2	3	4	5	6			1	2	3	4	5	6			1	2	3	4	5	6			
	Estimated	bimonth	bimonth	bimonth	bimonth	bimonth	bimonth	**Summary**	**Estimated**	bimonth	bimonth	bimonth	bimonth	bimonth	bimonth	**Summary**	**Estimated**	bimonth	bimonth	bimonth	bimonth	bimonth	bimonth	**Summary**	**Total**	**Check**
Modules	24		3	3	3	12		**21**	15		3	6			8	**17**	3				6			**6**	**44**	**30-70**
Seminars	6		0,4	0,8			1,8	**3**	8	2,2	1,1	0,7	0,7		0,4	**5,1**	3	2,4		0,8	0,3			**3,5**	**11,6**	**10-30**
Research	30	10	4	4	4	4	6	**32**	40	8	6	6	8	6	8	**42**	60	10	8	8	8	10	10	**54**	**128**	**80-140**
	60	10	7,4	7,8	7	16	7,8	**56**	63	10,2	10,1	12,7	8,7	6	16,4	**64,1**	66	12,4	8	8,8	14,3	10	10	**63,5**	**183,6**	**180**

MODULES:

1st year

- Project Management per la Ricerca
- The Entrepreneurial Analysis of Engineering Research Projects
- 16th Edition of the European PhD School, Power Electronics, Electrical Machines, Energy Control, Power Systems, 2015
- Dinamica e controllo delle macchine e degli azionamenti elettrici

2nd year

- Game theory and analysis of competitive dynamics for industrial systems
- Introduzione a Matlab
- Communicating and Disseminating your Research Activity
- Modelli, metodi e software per l'Ottimizzazione

3rd year

- Cambridge Advanced English
- Global Optimization and Uncertainty Quantification

Outline

OPTIMAL SIZING OF DISTRIBUTED ENERGY RESOURCES IN DC MICROGRIDS

- **CONTEXT AND MOTIVATIONS**
- **PROBLEM – RESEARCH TOPIC**
- **RESEARCH ACTIVITY 1:** **Analytical Approach for the Optimal Sizing of Energy Storage Systems in DC Microgrids to Minimize Power Losses**
- **RESEARCH ACTIVITY 2:** **Mixed Integer Linear Programming and Robust Optimization Approaches for the Optimal Sizing of DERs in Smart DC Microgrids to minimize total cost of ownership**
- **PUBLICATIONS**
- **CONCLUSIONS**

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Context and Motivations

MICROGRIDS

- a fundamental building block of the future smart grid
- expected to play a key role in allowing better **integration of Distributed Energy Resources**, increasing **energy efficiency** and **reliability** of the whole system, and providing the possibility to improve **power quality** and to achieve **grid-independence** to individual end-user sites

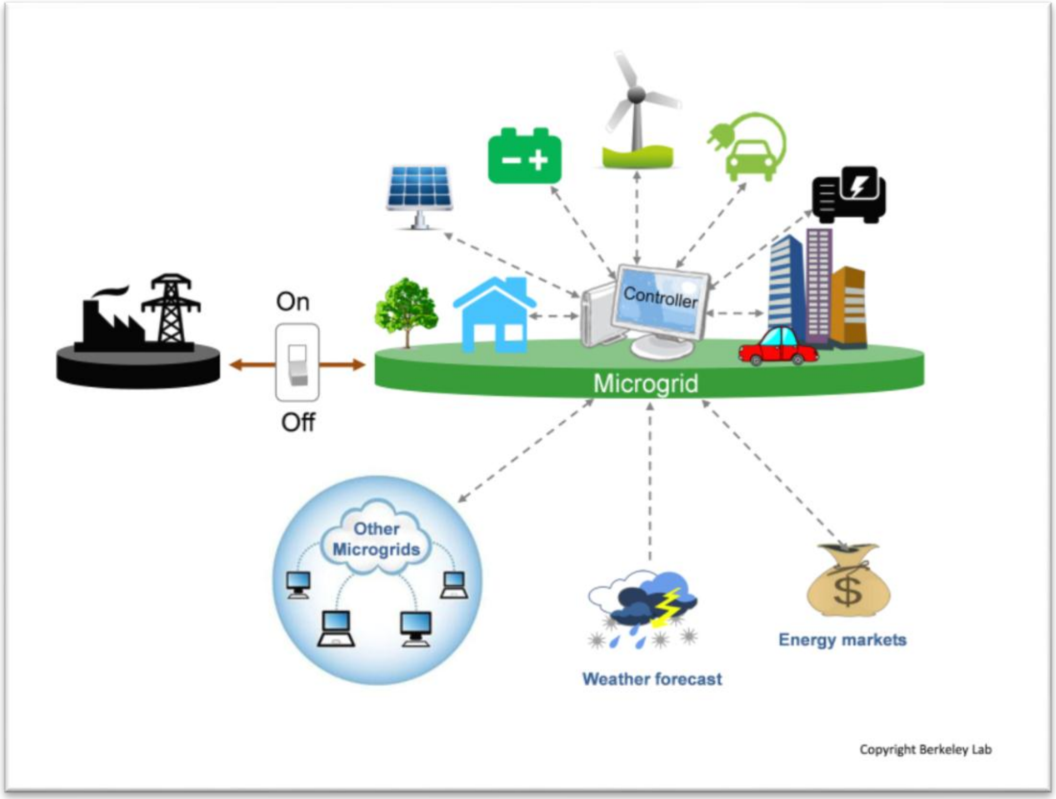
Microgrid (μG)

"… group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid, and that can connect and disconnect from the grid to enable it to operate in both grid-connected and island mode"

Distributed Energy Resources (DERs)

Generation and Storage Resources located on the customer's side of the distribution system

- Distributed Generation (DG)
- Distributed Energy Storage (DES)



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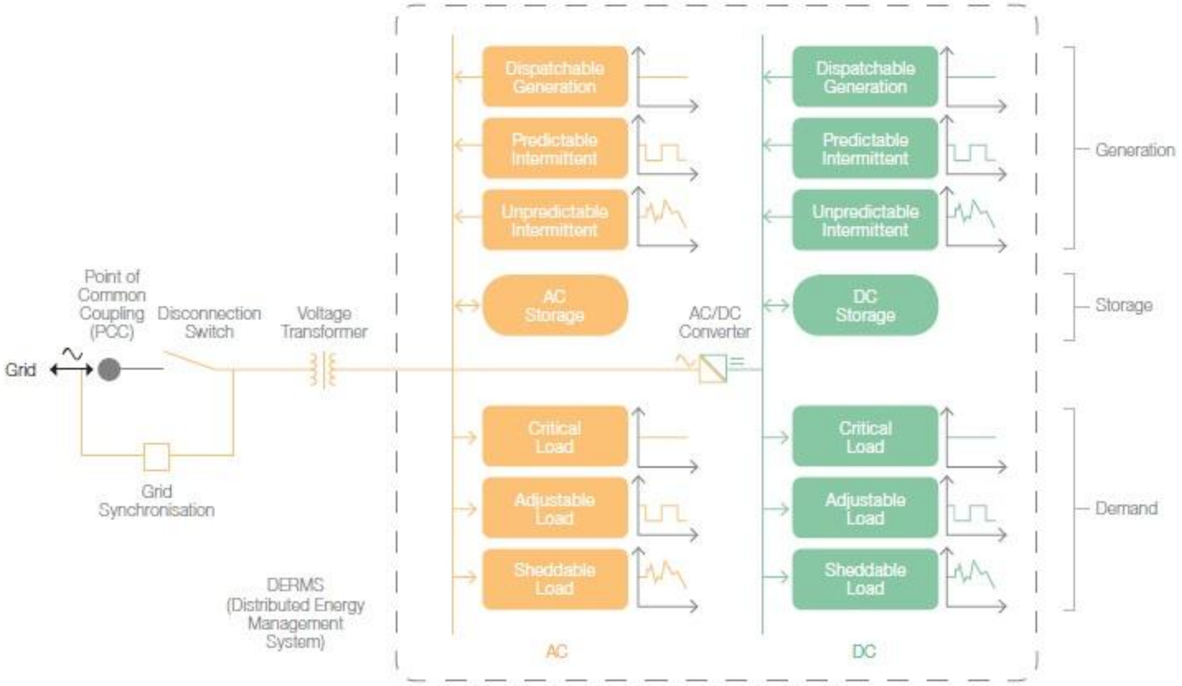
Context and Motivations

MICROGRID ARCHITECTURE

"… group of interconnected loads and distributed energy resources (DERs) within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid, and that can connect and disconnect from the grid to enable it to operate in both grid-connected and 'island' mode"



Context and Motivations

MICROGRIDS BENEFITS

- secure and reliable supply
- sustainable and low carbon supply
- affordable and profitable supply

MICROGRIDS CHALLENGES

- Technical challenges

Synchronization

Protection

Control

- Economic and regulatory issues

Medium term investment

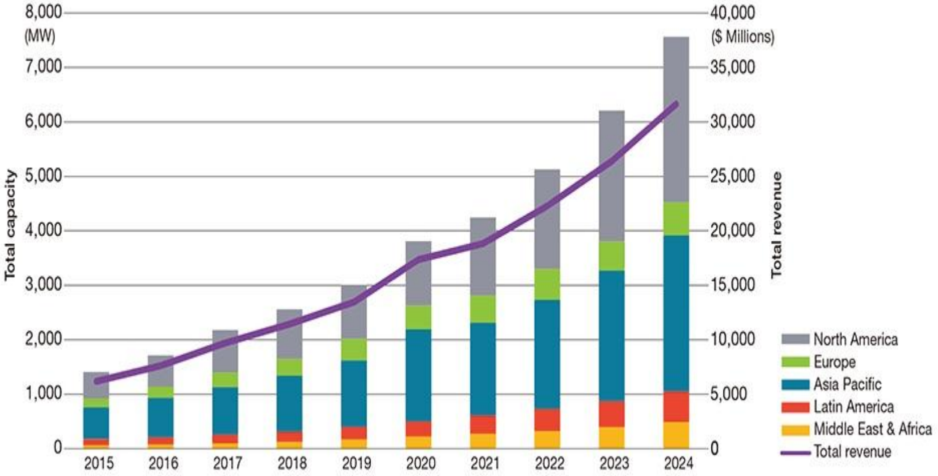
Regulatory and market uncertainties

Costs and benefits difficult to monetize

Evolving standards and rules

FUTURE PROSPECTS

Total Microgrid Capacity and Revenue, World Markets: 2015-2024



Source: Navigant Research

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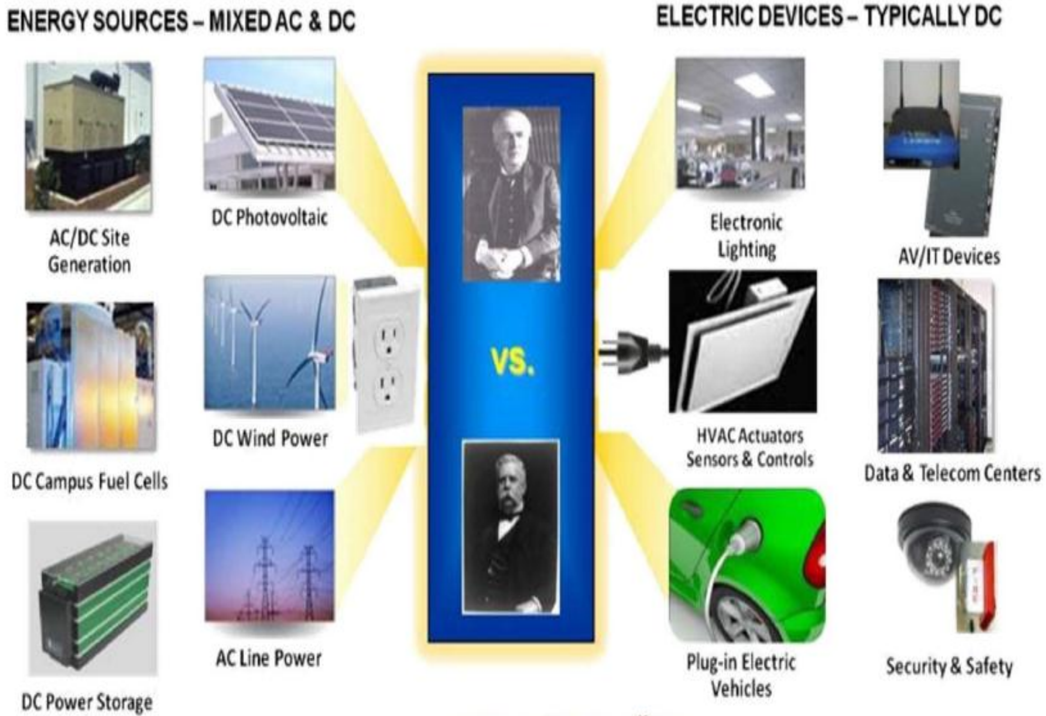
Problem – Research Topic

OPTIMAL SIZING OF DISTRIBUTED ENERGY RESOURCES IN DC MICROGRIDS



source: eMerge Alliance

DC Technology Pros

Many DGs, DESs and electrical devices are DC based, then DC LV distribution systems allow:

- Lower conversion requirements, with reduction in number of devices required
- Capital savings
- Energy savings (around 5-15%)
- Improvement in reliability

… and Cons

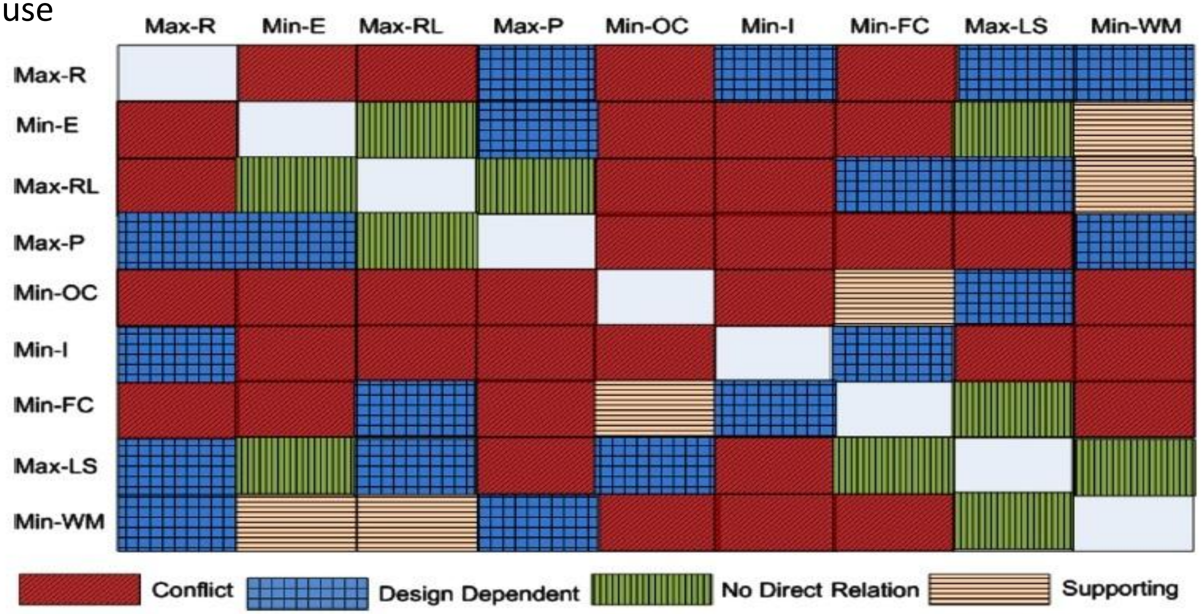
- Lack of existing applications for DC LV distribution systems
- Current lack of approved codes, standards and products
- Lack of familiarity with design of DC LV distribution systems
- Different safety and protection practices compared with AC

Problem – Research Topic

OPTIMAL SIZING OF DISTRIBUTED ENERGY RESOURCES IN DC MICROGRIDS

Despite the strong consensus among researchers and stakeholders on the variety and importance of the advantages deriving from the implementation of the Microgrid paradigm in modern electrical distribution systems, t**heir widespread diffusion is hindered from cost considerations and from the difficulties in conducting a comprehensive cost-benefit analysis** and in identifying qualified modalities for system design and management.

The Microgrid Planning problem is generally a **multi-objective constrained optimization problem**, which can be hard to solve because typically different objectives come in conflict with each other.



	Max-R	Min-E	Max-RL	Max-P	Min-OC	Min-I	Min-FC	Max-LS	Min-WM
Max-R		🟥	🟥	🟦	🟥	🟦	🟥	🟦	🟦
Min-E	🟥		🟩	🟦	🟥	🟥	🟥	🟩	🟧
Max-RL	🟥	🟩		🟩	🟥	🟥	🟦	🟦	🟧
Max-P	🟦	🟦	🟩		🟥	🟥	🟥	🟥	🟦
Min-OC	🟥	🟥	🟥	🟥		🟥	🟧	🟦	🟥
Min-I	🟦	🟥	🟥	🟥	🟥		🟦	🟥	🟥
Min-FC	🟥	🟥	🟦	🟥	🟧	🟦		🟩	🟥
Max-LS	🟦	🟩	🟦	🟥	🟦	🟥	🟩		🟩
Min-WM	🟦	🟧	🟧	🟦	🟥	🟥	🟥	🟩	

🟥 Conflict 🟦 Design Dependent 🟩 No Direct Relation 🟧 Supporting

Relation between conflicting objectives. Max-R: maximize revenue, Min-E: minimize emissions, Max-RL: maximize reliability, Max-P: maximize production, Min-OC: minimize operating cost, Min-I: minimize investment, Min-FC: minimize fuel cost, Max-LS: maximize life span, Min-WM: minimize waste.

Problem – Research Topic

OPTIMAL SIZING OF DISTRIBUTED ENERGY RESOURCES IN DC MICROGRIDS

The Microgrid planning problem has also to cope with **different sources of uncertainty**.

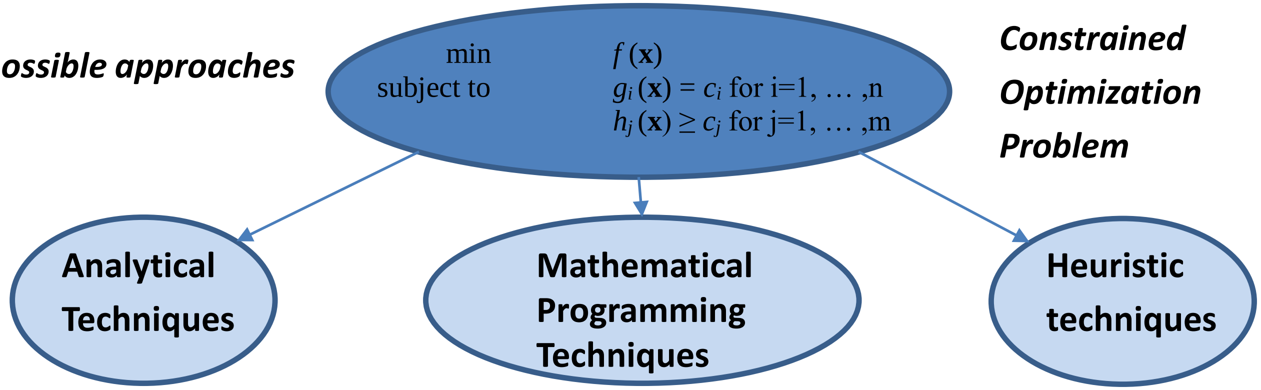
SOURCES OF UNCERTAINTY

- LONG-TERM MICROGRID LOAD FORECASTING
  depending on variations in hourly prices, weather conditions, and consumers’ decisions
- RENEWABLE GENERATION FORECASTING
  depending on site and weather conditions
- MARKET PRICE FORECASTING
  depending on site and weather conditions
- UNINTENTIONAL ISLANDING EVENTS

Problem – Research Topic

OPTIMAL SIZING OF DISTRIBUTED ENERGY RESOURCES IN DC MICROGRIDS

Different possible approaches



$$\begin{array}{ll} \min & f(\mathbf{x}) \\ \text{subject to} & g_i(\mathbf{x}) = c_i \text{ for } i=1, \ldots, n \\ & h_j(\mathbf{x}) \geq c_j \text{ for } j=1, \ldots, m \end{array}$$

Constrained Optimization Problem

Analytical Techniques

- **Calculus of variations**
- **Lagrange multipliers method** (equality constraints)
- Karush-Kuhn-Tucker conditions (inequality constraints)

Mathematical Programming Techniques

- Linear Programming
- Quadratic Programming
- Non-linear Programming
- **Mixed Integer Programming**

Heuristic techniques

- Genetic Algorithm
- Simulated Annealing
- Ant Colony Search Algorithm
- Particle Swarm Optimization

Dealing with uncertainties: Stochastic Optimization & SAA, **Robust Optimization**, Decision Theory

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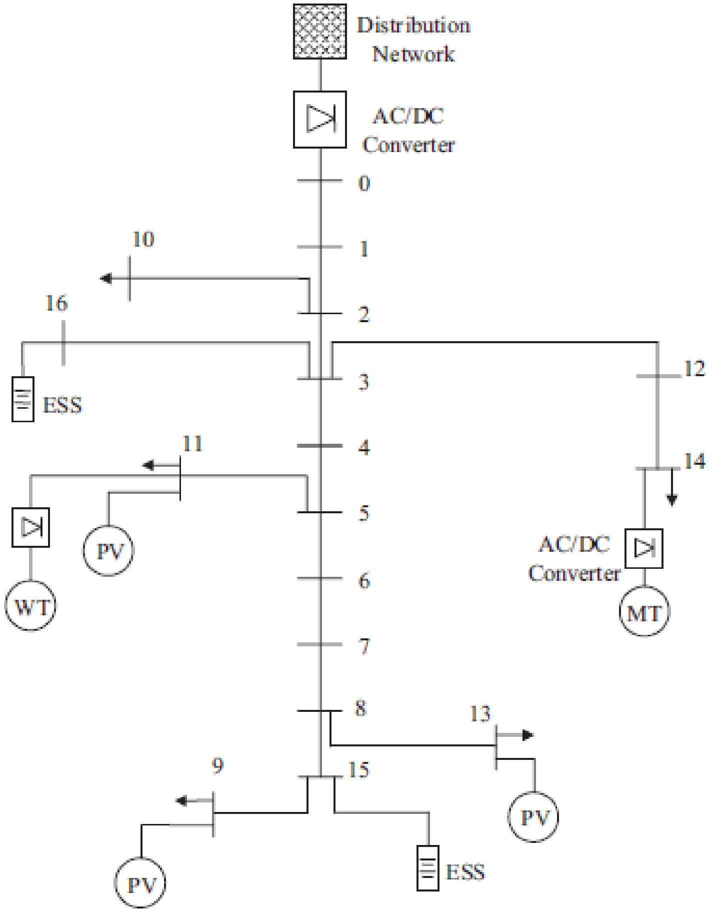
Research Activity 1

APPLICATION OF AN ANALYTICAL APPROACH FOR THE OPTIMAL SIZING OF ENERGY STORAGE SYSTEMS IN DC MICROGRIDS TO MINIMIZE POWER LOSSES



IDEA

Optimal sizing and control of Energy Storage Systems (ESSs) installed in a DC microgrid with the aim of minimizing power losses in presence of periodic loads

METHODOLOGY

- Analytical approach
- Closed form solution (suitable for sensitivity analyses and probabilistic studies)
- Numerical Applications
- Sensitivity Analyses
- Validation through comparison with full load-flow calculations

Research Activity 1

APPLICATION OF AN ANALYTICAL APPROACH FOR THE OPTIMAL SIZING OF ENERGY STORAGE SYSTEMS IN DC MICROGRIDS TO MINIMIZE POWER LOSSES

DETAILS, General Modeling of a DC Network

$$\left[\begin{array}{c} J_0 \\ \hline \mathbf{J} \end{array}\right] = \mathbf{G}\left[\begin{array}{c} E \\ \hline \mathbf{V} \end{array}\right] \Rightarrow \left[\begin{array}{c} J_0 \\ \hline \mathbf{J} \end{array}\right] = \left[\begin{array}{c|c} G_{00} & \mathbf{G}_{0E} \\ \hline \mathbf{G}_{E0} & \mathbf{G}_{EE} \end{array}\right]\left[\begin{array}{c} E \\ \hline \mathbf{V} \end{array}\right]$$

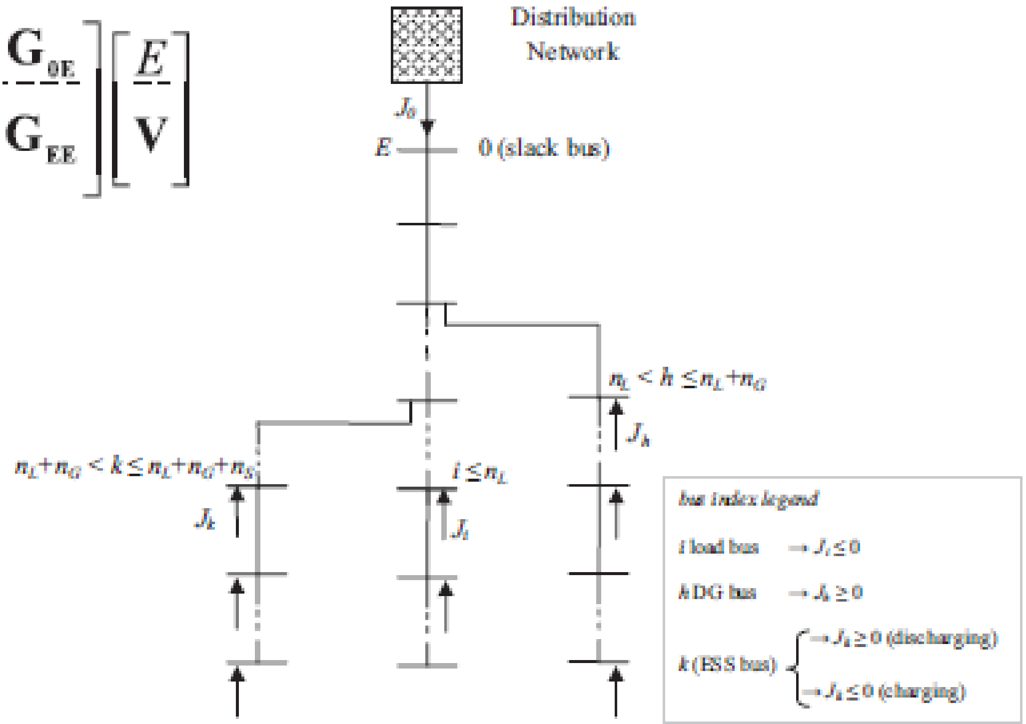
By defining: $\mathbf{R} = \mathbf{G}_{EE}^{-1}$

$$\mathbf{V} = E\mathbf{1} + \mathbf{R}\mathbf{J}$$

$$\mathbf{V}^{T}\mathbf{J} = E\mathbf{1}^{T}\mathbf{J} + \mathbf{J}^{T}\mathbf{R}\mathbf{J} = E\sum_{k=1}^{n} J_k + \mathbf{J}^{T}\mathbf{R}\mathbf{J}$$

$$EJ_0 + \mathbf{V}^{T}\mathbf{J} = \mathbf{J}^{T}\mathbf{R}\mathbf{J}$$

$$P_{loss} = \mathbf{J}^{T}\mathbf{R}\mathbf{J}$$



Research Activity 1

APPLICATION OF AN ANALYTICAL APPROACH FOR THE OPTIMAL SIZING OF ENERGY STORAGE SYSTEMS IN DC MICROGRIDS TO MINIMIZE POWER LOSSES

DETAILS, Matrix formulation of power losses minimization problem with isoperimetric constraint

$$\min \int_0^T \mathbf{J}^T \mathbf{R} \mathbf{J} dt \quad \text{subject to:}$$

$$\int_0^T diag(\mathbf{E}_{\text{sto}}) \mathbf{J}_{\text{sto}} dt = 0$$

$$\frac{d}{d\mathbf{J}_{\text{sto}}} (\mathbf{J}^T \mathbf{R} \mathbf{J} + \lambda^T \mathbf{J}_{\text{sto}}) = \mathbf{0} \quad \text{subject to:}$$

$$\int_0^T diag(\mathbf{E}_{\text{sto}}) \mathbf{J}_{\text{sto}} dt = 0$$

$$\mathbf{V} = E\mathbf{1}$$

$$\mathbf{V} = E\mathbf{1} + \frac{\mathbf{RP}}{E}$$

constant voltages at ESS busses

$$\mathbf{J}_{\text{sto}} = \mathbf{R}_2^{-1} \mathbf{R}_1 \left[\frac{1}{T} \int_0^T \mathbf{J}^* \text{dt} - \mathbf{J}^* \right]$$

$$\mathbf{R}_{1i,j} = R_{(n_L+n_G+i,j)}$$

$$i = 1, \ldots, n_S, \; j = 1, \ldots, n_L + n_G$$

$$\mathbf{R}_{2i,j} = R_{(n_L+n_G+i, n_L+n_G+j)}$$

$$i = 1, \ldots, n_S, \; j = 1, \ldots, n_S$$

$$\mathbf{J}_{\text{sto}} = -\mathbf{B}_1 \cdot \mathbf{K}_1 + \mathbf{B}_2 \left[\int_0^T \mathbf{B}_2 \text{dt} \right]^{-1} \int_0^T \mathbf{B}_1 \cdot \mathbf{K}_1 \text{dt}$$

$$\mathbf{B}_1 = [\mathbf{A}_1 \mathbf{K}_2 + \mathbf{A}_2]^{-1} \mathbf{A}_1, \; \mathbf{B}_2 = \frac{1}{2} [\mathbf{A}_1 \mathbf{K}_2 + \mathbf{A}_2]^{-1}$$

$$\mathbf{A}_1 = \mathbf{K}_2^T \mathbf{R}_{11} + \mathbf{R}_{21}, \qquad \mathbf{A}_2 = \mathbf{K}_2^T \mathbf{R}_{12} + \mathbf{R}_{22}$$

$$\begin{bmatrix} \mathbf{J}_{\text{load}} \\ \mathbf{J}_{\text{gen}} \end{bmatrix} = \mathbf{K}_1 + \mathbf{K}_2 \mathbf{J}_{\text{sto}}$$

K_1 and K_2 are time-variant matrices depending on E and on the powers injected at load and generator busses

Research Activity 1

APPLICATION OF AN ANALYTICAL APPROACH FOR THE OPTIMAL SIZING OF ENERGY STORAGE SYSTEMS IN DC MICROGRIDS TO MINIMIZE POWER LOSSES

DETAILS, Application to the sizing of energy storage systems

Multi-objective optimization to consider both cost of energy and cost of the ESSs

$$\min \gamma_1 \int_0^T \mathbf{J}^{\mathrm{T}}\mathbf{R}\mathbf{J}\,dt + \gamma_2^{\mathrm{T}} \int_0^T \frac{1}{2}\, diag\left(\mathbf{E}_{\mathrm{sto,rtd}}\right) |\mathbf{J}_{\mathrm{sto}}|\,dt \qquad \text{subject to:} \quad \int_0^T diag(\mathbf{E}_{\mathrm{sto}})\mathbf{J}_{\mathrm{sto}}\,dt = 0$$

$$\Downarrow$$

$$\mathbf{J}_{\mathrm{sto}} = -\mathbf{B}_1' \cdot \mathbf{K}_1 + \mathbf{B}_2' \left[\int_0^T \mathbf{B}_2' \mathrm{d}t\right]^{-1} \int_0^T \mathbf{B}_1' \cdot \mathbf{K}_1 \mathrm{d}t$$

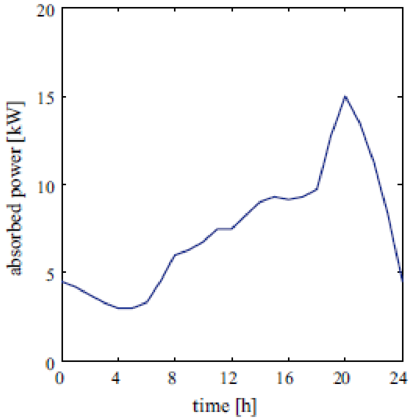
Research Activity 1

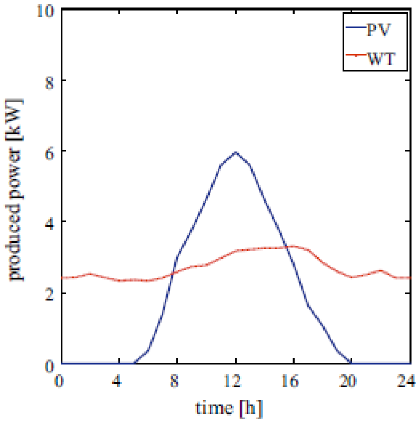
APPLICATION OF AN ANALYTICAL APPROACH FOR THE OPTIMAL SIZING OF ENERGY STORAGE SYSTEMS IN DC MICROGRIDS TO MINIMIZE POWER LOSSES

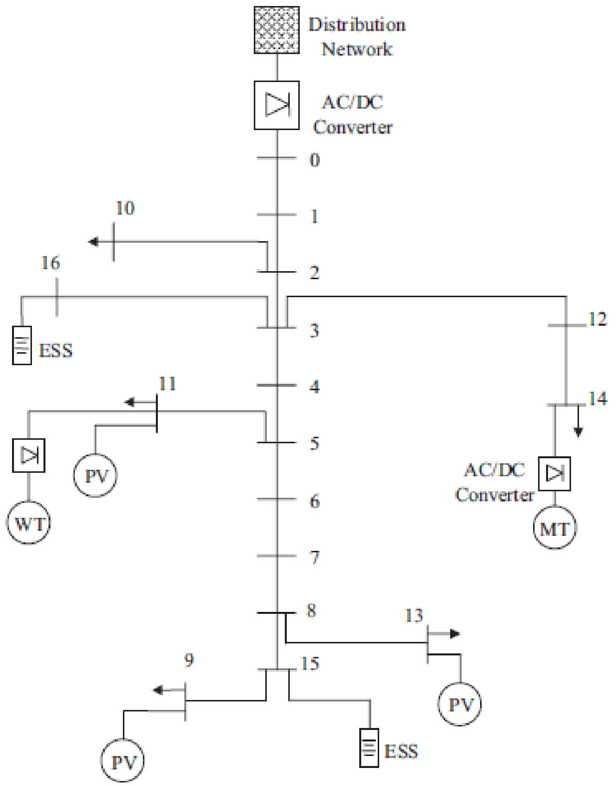
NUMERICAL APPLICATIONS, INPUTS

Rated powers of the DGs and loads.

DGs			Loads	
Bus #	Type	Rated power [kW]	Bus #	Rated power [kW]
9	PV	10	9	47
11	PV	10	10	15
11	WT	10	11	50
13	PV	3	13	15
14	MT	30	14	72







Research Activity 1

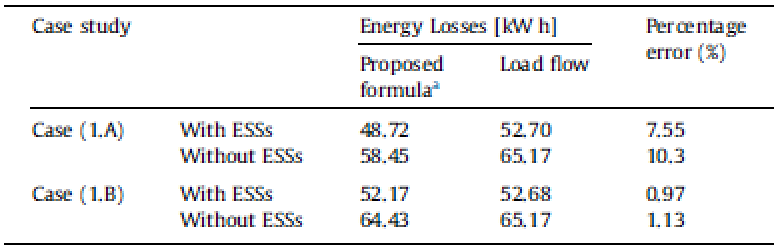
APPLICATION OF AN ANALYTICAL APPROACH FOR THE OPTIMAL SIZING OF ENERGY STORAGE SYSTEMS IN DC MICROGRIDS TO MINIMIZE POWER LOSSES

NUMERICAL APPLICATIONS, RESULTS

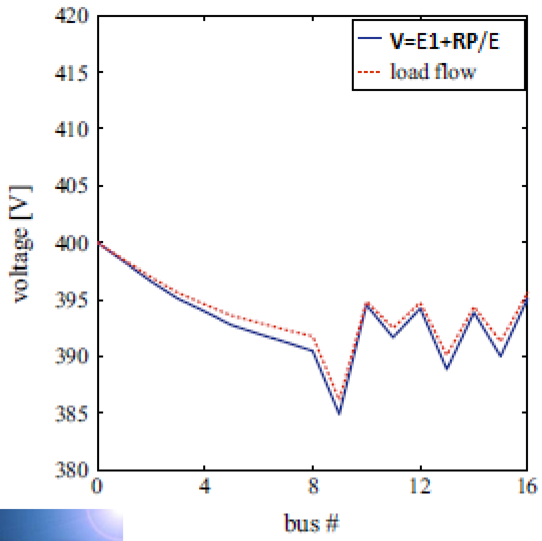
Case 1.A: constant voltage approximation $\mathbf{V} = E\mathbf{1}$

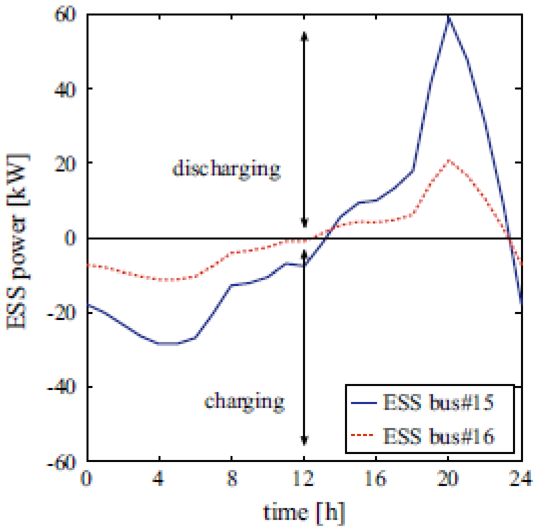
Case 1.B: first order approximation $\mathbf{V} = E\mathbf{1} + \frac{\mathbf{RP}}{E}$

Accuracy of the proposed approaches.



Case study		Energy Losses [kW h]		Percentage error (%)
		Proposed formula[a]	Load flow	
Case (1.A)	With ESSs	48.72	52.70	7.55
	Without ESSs	58.45	65.17	10.3
Case (1.B)	With ESSs	52.17	52.68	0.97
	Without ESSs	64.43	65.17	1.13





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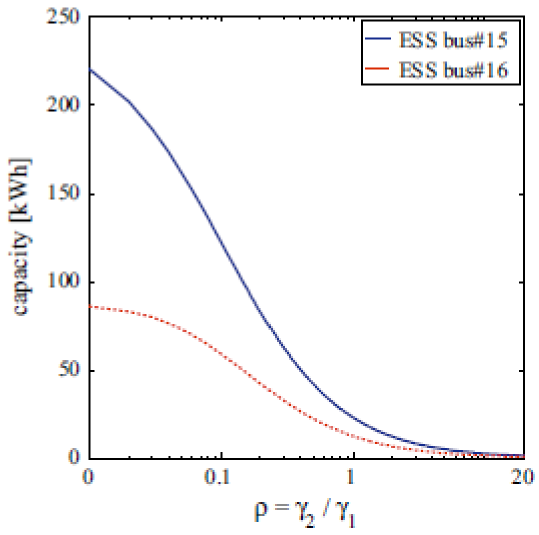
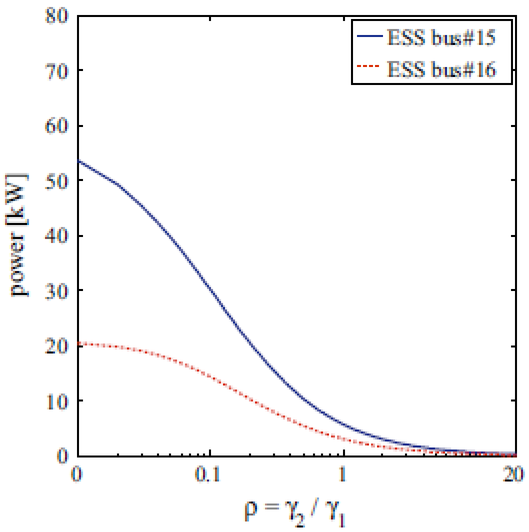
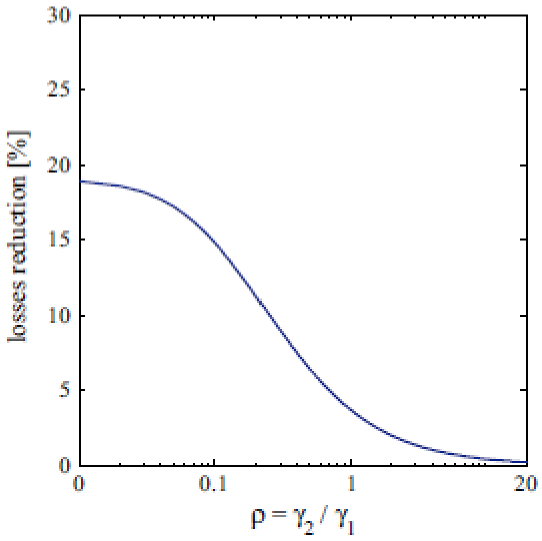
NUMERICAL APPLICATIONS, RESULTS



Parametric evaluation of the optimal capacities of the ESSs.



Parametric evaluation of the optimal power of the ESSs.



Parametric evaluation of the reduction in power losses.

Research Activity 1

APPLICATION OF AN ANALYTICAL APPROACH FOR THE OPTIMAL SIZING OF ENERGY STORAGE SYSTEMS IN DC MICROGRIDS TO MINIMIZE POWER LOSSES

CONCLUDING REMARKS

The closed forms obtained by means of the analytical approach guarantee high accuracy and velocity of calculation, thus allowing sensitivity analyses and probabilistic studies.

The main limitation is in the hypothesis of periodic behavior of microgrid loads and generators, which restricts the practicality of the methodology to some specific applications.

Future work could be focused on:

1. analyses of the performances of optimal sizing results against loads and generators power profiles changes;
2. application of Stochastic Optimization / Sample Average Approximation techniques to include uncertainties in the design process;
3. development of the analytical formulation to expand its practical applicability.

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- **RESEARCH ACTIVITY 2: Mixed Integer Linear Programming and Robust Optimization Approaches for the Optimal Sizing of DERs in Smart DC Microgrids to minimize total cost of ownership**
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Research Activity 2

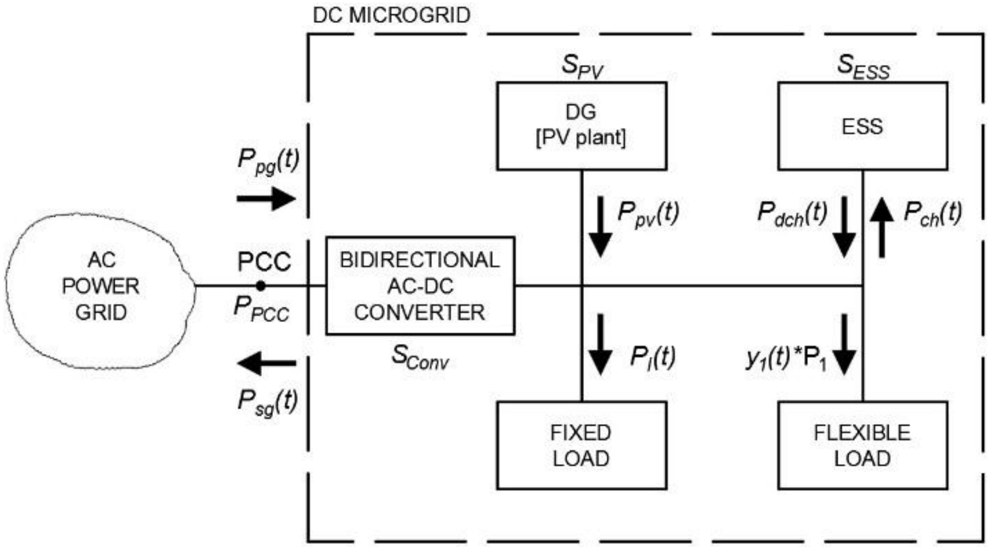
APPLICATIONS OF MIXED INTEGER LINEAR PROGRAMMING AND ROBUST OPTIMIZATION APPROACHES FOR THE OPTIMAL SIZING OF DERS IN SMART DC MICROGRIDS TO MINIMIZE TOTAL COST OF OWNERSHIP

IDEA

The aim is to optimize the sizes of DGs, DESs and of the AC-DC bidirectional converter to minimize the Total Cost of Ownership (TCO) over a prefixed time horizon

METHODOLOGY

- Mixed Integer Linear Programming model (efficient off-the-shelf sw)
- Numerical Applications
- Sensitivity Analyses
- Monte Carlo Method
- Robust Optimization



Research Activity 2

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DETAILS, linear objective function and constraints

Objective function to be minimized: TCO (Total Cost of Ownership)

$$\mathrm{TCO} = S_{PV}\left(PV_{acq} + PV_{o\&m}Act\right) + S_{ESS}\left(ESS_{acq} + ESS_{o\&m}Act\right) + S_{Conv}\left(Conv_{acq} + Conv_{o\&m}Act\right) + P_{PCC}GR_{ysc}Act + \sum_{t=1}^{NT}\left(C_p(t)P_{pg}(t) - C_s(t)P_{sg}(t)\right)Act_{en} + \sum_{t=1}^{NT}\left(C_{CU}P_{CU}(t)\right)Act$$

Power Balance Constraint

$$\eta_{Conv}P_{pg}(t) + S_{PV}P_{PV1}(t) + P_{dch}(t) = \left(\frac{1}{\eta_{Conv}}\right)P_{sg}(t) + P_{ch}(t) + P_l(t) + \sum_{i=1}^{N_{SL}}(y_i(t)P_i)$$

Constraints on charging and discharging power of ESSs

$$P_{ch}(t) \le P_{ESS,max}S_{ESS} \qquad P_{dch}(t) \le P_{ESS,max}S_{ESS} \qquad \forall t$$

Constraints on energy stored in ESSs

$$W_{ESS}(1) = SoC_{in}S_{ESS} + \left(\eta_r P_{ch}(\mathbf{1}) - P_{dch}(\mathbf{1})\right)\Delta t$$

$$W_{ESS}(t) = W_{ESS}(t-1) + \left(\eta_r P_{ch}(t) - P_{dch}(t)\right)\Delta t \qquad \forall t$$

$$W_{ESS}(t) \ge SoC_{min}S_{ESS} \qquad W_{ESS}(t) \le SoC_{max}S_{ESS} \qquad \forall t$$

Constraints on size of sub-systems

$$S_{PV} \le S_{PV,max} \qquad S_{Conv} \le S_{Conv,max} \qquad S_{ESS} \le S_{ESS,max} \qquad P_{PCC} \le P_{PCC,max}$$

Constraints on power exchanged with the grid

$$P_{pg}(t) \le \mathrm{Max}(S_{Conv,p}(t), P_{PCC}) \qquad P_{sg}(t) \le \mathrm{Max}(S_{Conv,s}(t), P_{PCC}) \qquad \forall t$$

Constraints on initial investment cost

$$S_{PV}PV_{acq} + S_{ESS}ESS_{acq} + S_{Conv}\,Conv_{acq} \le Inv_{in,max}$$

Constraints on load curtailment

$$P_{CU}(t) \le (1 - CL_{ratio})P_l(t) \qquad \forall t$$

Research Activity 2

APPLICATIONS OF MIXED INTEGER LINEAR PROGRAMMING AND ROBUST OPTIMIZATION APPROACHES FOR THE OPTIMAL SIZING OF DERS IN SMART DC MICROGRIDS TO MINIMIZE TOTAL COST OF OWNERSHIP

DETAILS, using integer variables to control flexible loads

Constraints on controllable loads

for each day of the considered time horizon and for all *i* in (1 .. N_{SL})

$\sum_{t=t_{in,i}}^{t_{fin,i}} y_i(t) = N_i Nw_i Dw_i$

$\sum_{t=t_{in,i}}^{t_{fin,i}-Dw_i} k_i(t) = N_i Nw_i$

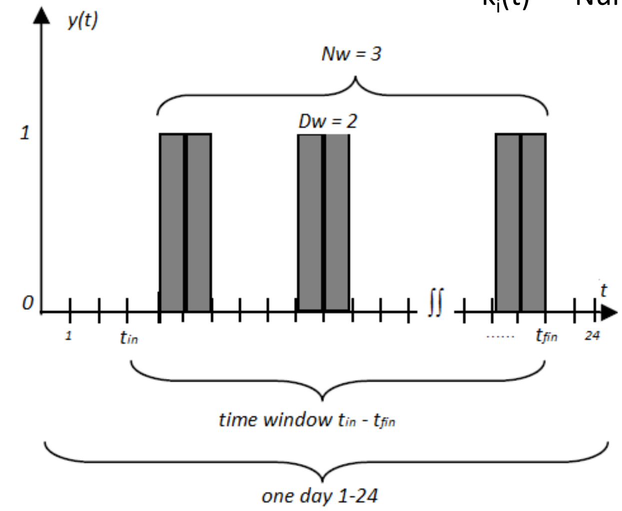
$y_i(t_{in,i}) = k_i(t_{in,i})$

$y_i(t) = y_i(t-1) + k_i(t)$ *for all t in* ($t_{in,i}+1 .. t_{in,i}+Dw_i-1$)

$y_i(t) = y_i(t-1) + k_i(t) - k_i(t-Dw_i)$ *for all t in* ($t_{in,i}+Dw_i .. t_{fin,i}$)

$y_i(t) \le N_i$ *for all t in* ($t_{in,i} .. t_{fin,i}$)

N_{SL}	Number of types of shiftable loads
N_i	Number of appliances type I (i=1..SL)
N_{wi}	Number of work-cycles for shiftable load *i*
D_{wi}	Duration of each work-cycle for shiftable load *i*
P_i	Constant power of shiftable load *i*
$t_{in,i}$	Start of the time-window for shiftable load *i*
$t_{fin,i}$	End of the time-window for shiftable load *I*
$y_i(t)$	Number of appliances type "i" running at time t
$k_i(t)$	Number of appliances type "i" starting at time t



Research Activity 2

APPLICATIONS OF MIXED INTEGER LINEAR PROGRAMMING AND ROBUST OPTIMIZATION APPROACHES FOR THE OPTIMAL SIZING OF DERS IN SMART DC MICROGRIDS TO MINIMIZE TOTAL COST OF OWNERSHIP

DETAILS, linearizing the product of decision variables

To prevent solutions where energy is sold to the grid and bought from the grid at the same time (which is physically impossible on a single PCC), 3 auxiliary variables were used:

- u(t): binary variable which is 1 when energy is purchased and 0 when energy is sold to the grid
- $S_{Conv,p}$ (t): real variable which is equal to S_{Conv} when u(t)=1 and is 0 when u(t)=0
- $S_{Conv,s}$ (t): real variable which is equal to S_{Conv} when u(t)=0 and is 0 when u(t)=1

The link among values of $S_{Conv,p}$ (t), $S_{Conv,s}$ (t) and u(t) can be expressed as:

$$\mathrm{S_{Conv,p}(t) = S_{Conv}\, u(t)}, \qquad \mathrm{S_{Conv,p}\,(t) = S_{Conv}\,(1 - u(t))}$$

These equations contain products of decision variables, therefore, to preserve the desired linear formulation of the problem, we resort to the BigM technique through the following set of linear inequalities (to be applied at each time t):

a) $\mathrm{S_{Conv,p}(t) \leq BigM\, u(t)}$ b) $\mathrm{S_{Conv,p}(t) \leq S_{Conv}}$ c) $\mathrm{S_{Conv,p}(t) \geq S_{Conv} - BigM\,(1 - u(t))}$

d) $\mathrm{S_{Conv,s}(t) \leq BigM\,(1 - u(t))}$ e) $\mathrm{S_{Conv,s}(t) \leq S_{Conv}}$ f) $\mathrm{S_{Conv,s}(t) \geq S_{Conv} - BigM\, u(t)}$

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APPLICATIONS OF MIXED INTEGER LINEAR PROGRAMMING AND ROBUST OPTIMIZATION APPROACHES FOR THE OPTIMAL SIZING OF DERS IN SMART DC MICROGRIDS TO MINIMIZE TOTAL COST OF OWNERSHIP

DETAILS, Robust Optimization approach, introduction

Robust optimization is a modelling framework that can be used in optimization problems when the uncertainty in the input data is assumed to be bounded in a known set of values U (described by linear constraints, convex quadratic constraints, or as a discrete set of vectors of uncertain data).

The RO paradigm rests on three implicit assumptions on the underlying decision-making environment:

1. All entries in the decision vector represent “here and now” decisions: they should get specific numerical values as a result of solving the problem before the actual data reveals itself.
2. The decision maker is fully responsible for consequences of the decisions to be made when, and only when, the actual data is within a prespecified uncertainty set U.
3. The constraints of the uncertain optimization problem in question are “hard”, i.e. the decision maker cannot tolerate violations of constraints when the data is in U.

- Solutions must remain feasible for whatever realization of the uncertains in U (robust feasible sol.)
- The “worst-case-oriented” philosophy underlying the RO paradigm makes it natural to quantify the quality of a robust feasible solution by the guaranteed value of the original objective, that is, by its largest value

Research Activity 2

APPLICATIONS OF MIXED INTEGER LINEAR PROGRAMMING AND ROBUST OPTIMIZATION APPROACHES FOR THE OPTIMAL SIZING OF DERS IN SMART DC MICROGRIDS TO MINIMIZE TOTAL COST OF OWNERSHIP

DETAILS, Robust Optimization approach, basic formulation for linear programs

A generic LP can be written as: $\min_x \{c^T x: Ax \leq b\}$

In Robust optimization, an uncertain LP is defined as a collection of LP programs with a common structure and actual values of parameters (c, A, B) varying in a given uncertainty set *U*:

$$\{\min_x \{c^T x: Ax \leq b\}: (c, A, B) \in U\}$$

Thus, the best possible robust feasible solution is the one that solves the optimization problem:

$$\min_x \left\{ \sup_{(c,A,b)\in\mathcal{U}} c^T x : Ax \leq b \ \forall (c, A, b) \in \mathcal{U} \right\}$$

or, which is the same, the optimization problem:

$$\min_{x,t} \{t : c^T x \leq t, \ Ax \leq b \ \forall (c, A, b) \in \mathcal{U}\}$$

which is called the Robust Counterpart (RC) of the original uncertain problem.

Research Activity 2

APPLICATIONS OF MIXED INTEGER LINEAR PROGRAMMING AND ROBUST OPTIMIZATION APPROACHES FOR THE OPTIMAL SIZING OF DERS IN SMART DC MICROGRIDS TO MINIMIZE TOTAL COST OF OWNERSHIP

DETAILS, Robust Optimization approach, application to the DERs optimal sizing problem

Modifications of the MILP formulation to achieve scenario-based robustness against load variations

We assume to know hourly realizations of the non-controllable load $P_l(t)$ for a certain number of years in the past, and intend to achieve robustness of sizing results against realizations of the non-controllable load within this historical database (scenario-based robustness).
We introduce the uncertain variable UD(t), which represent the possible deviation of the actual non-controllable load at time t, say $P_{lact}(t)$, from its forecasted value $P_l(t)$, and, following the rules of the scenario based approach, can take values in the set of all available past realizations of $P_{lact}(t)-P_l(t)$.
The power balance constraint must be reformulated as follow:

$$P_l(t) + UD(t) \leq \eta_{Conv}\, P_{pg}(t) + P_{PV}(t) + P_{dch}(t) - \left(\frac{1}{\eta_{Conv}}\right) P_{sg}(t) - P_{ch}(t) - \sum_{i=1}^{N_{SL}} (y_i(t) P_i) + P_{cu}(t).$$

No other relation of the original formulation needs to be modified, if only uncertainties on the demand from non-controllable loads are considered.

Research Activity 2

APPLICATIONS OF MIXED INTEGER LINEAR PROGRAMMING AND ROBUST OPTIMIZATION APPROACHES FOR THE OPTIMAL SIZING OF DERS IN SMART DC MICROGRIDS TO MINIMIZE TOTAL COST OF OWNERSHIP

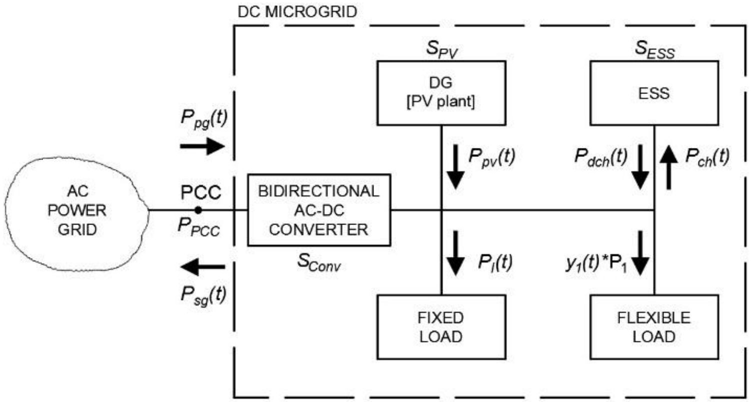
NUMERICAL APPLICATIONS – INPUTS, PARAMETERS

General parameters

Parameter	Value	Parameter	Value
NT	8760	η_{Conv}	0.93
NY	25	η_r	0.86
Δt	1 h	SoC_{min}	0.2
$P_{ESS,max}$	0,5 kW/kWh	SOC_{max}	0.95
N_{SL}	1	SoC_{in}	0.5
N_1	10	$S_{PV,max}$, $S_{Conv,max}$, $P_{PCC,max}$	1 MW
Nw_1	2	$S_{ESS,max}$	1 MWh
Dw_1	2 h	e	0.025
P_1	5 kW	v	0.015
$t_{in,1}$	10:00	i	0.020
$t_{fin,1}$	23:00		

Cost parameters

Parameter	Value
PV_{acq}	1.500 €/kW
$PV_{o\&m}$	20 €/kW
ESS_{acq}	500 €/kWh
$ESS_{o\&m}$	10 €/kWh
INV_{acq}	500 €/kW
$INV_{o\&m}$	10 €/kW
GR_{ysc}	20 €/kW
$C_p(t)$	0.120 €/kWh from 0:00 to 6:00 and from 23:00 to 24:00 0.233 €/kWh from 7:00 to 23:00
$C_s(t)$	0.039 €/kWh
C_{CU}	15 €/kWh
$Inv_{in,max}$	10,000,000 €



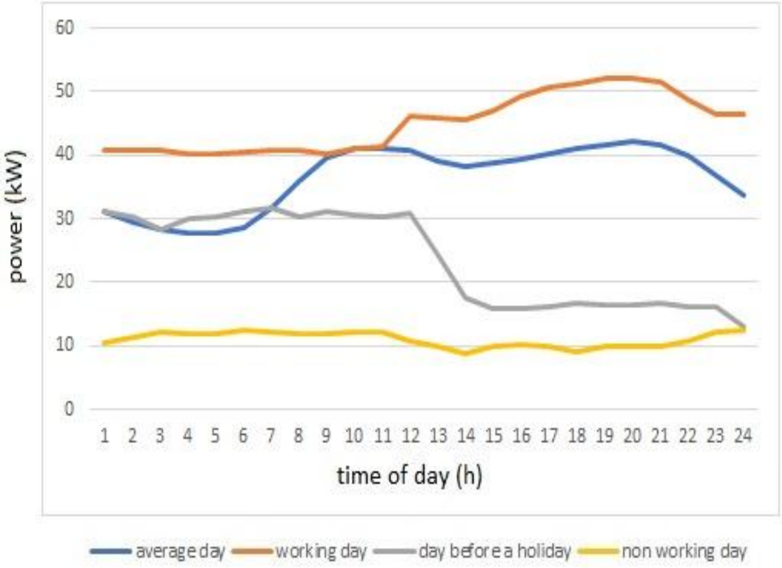
Research Activity 2

APPLICATIONS OF MIXED INTEGER LINEAR PROGRAMMING AND ROBUST OPTIMIZATION APPROACHES FOR THE OPTIMAL SIZING OF DERS IN SMART DC MICROGRIDS TO MINIMIZE TOTAL COST OF OWNERSHIP

NUMERICAL APPLICATIONS – INPUTS, LOAD DEMAND

Yearly energy demands (2007-2016) (kWh/kW).

Year	Energy demand non-controllable load (kWh)	Energy demand controllable load (kWh)	Energy demand total load (kWh)
2007	307.200	73.000	380.200
2008	332.800	73.000	405.800
2009	310.400	73.000	383.400
2010	313.600	73.000	386.600
2011	320.000	73.000	393.000
2012	307.200	73.000	380.200
2013	352.000	73.000	425.000
2014	310.400	73.000	383.400
2015	324.800	73.000	397.800
2016	321.600	73.000	394.600



Andrea Scalfati

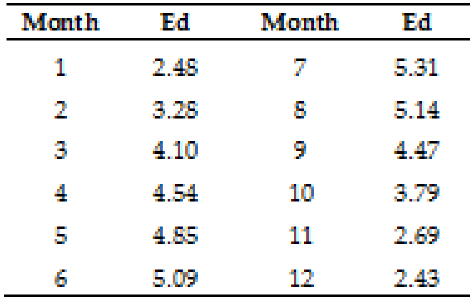
Research Activity 2

APPLICATIONS OF MIXED INTEGER LINEAR PROGRAMMING AND ROBUST OPTIMIZATION APPROACHES FOR THE OPTIMAL SIZING OF DERS IN SMART DC MICROGRIDS TO MINIMIZE TOTAL COST OF OWNERSHIP

NUMERICAL APPLICATIONS – INPUTS, PV SYSTEM PRODUCTIVITY

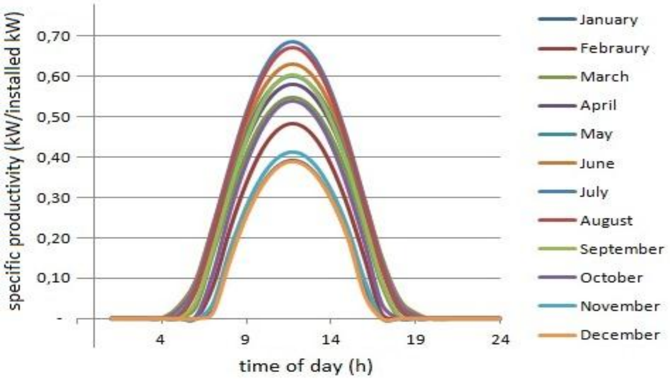
Photovoltaic Geographical Information System of the European Community

- crystalline silicon PV technology
- Naples, Latitude: 40°51'6" North Longitude: 14°16'5" East
- Inclination of modules (tilt): 34 deg Orientation (azimuth) of modules: -1 deg
- Forecasted productivity (yearly specific production): 1464 kWh/kW.



Month	Ed	Month	Ed
1	2.48	7	5.31
2	3.28	8	5.14
3	4.10	9	4.47
4	4.54	10	3.79
5	4.85	11	2.69
6	5.09	12	2.43

Average daily electricity production in each month - Ed (kWh/kW)

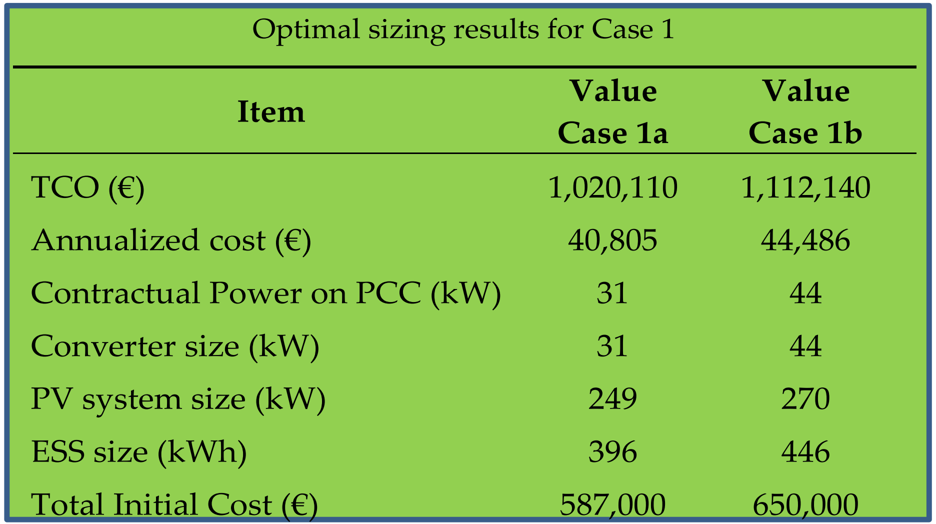


Power produced by 1 kW of PV in the average day of each month

Research Activity 2

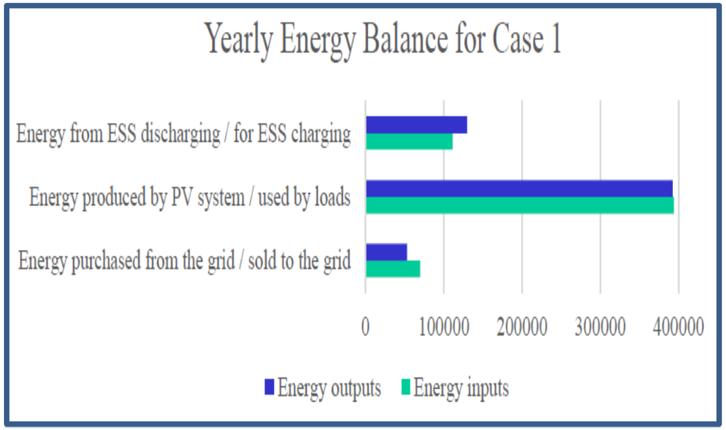
APPLICATIONS OF MIXED INTEGER LINEAR PROGRAMMING AND ROBUST OPTIMIZATION APPROACHES FOR THE OPTIMAL SIZING OF DERS IN SMART DC MICROGRIDS TO MINIMIZE TOTAL COST OF OWNERSHIP

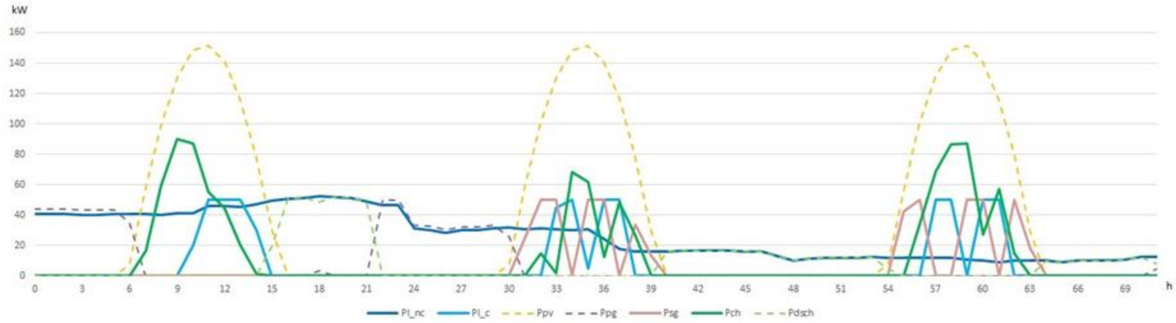
NUMERICAL APPLICATIONS – RESULTS, case 1, base Case



Optimal sizing results for Case 1

Item	Value Case 1a	Value Case 1b
TCO (€)	1,020,110	1,112,140
Annualized cost (€)	40,805	44,486
Contractual Power on PCC (kW)	31	44
Converter size (kW)	31	44
PV system size (kW)	249	270
ESS size (kWh)	396	446
Total Initial Cost (€)	587,000	650,000

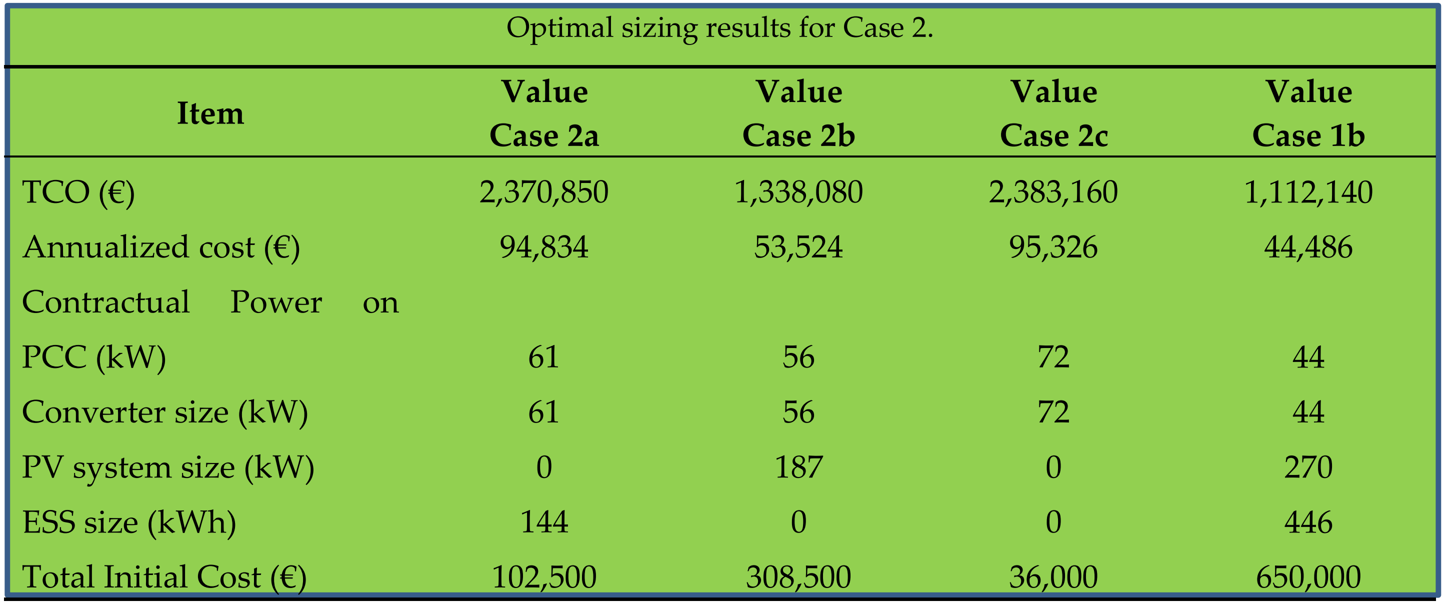




Research Activity 2

APPLICATIONS OF MIXED INTEGER LINEAR PROGRAMMING AND ROBUST OPTIMIZATION APPROACHES FOR THE OPTIMAL SIZING OF DERS IN SMART DC MICROGRIDS TO MINIMIZE TOTAL COST OF OWNERSHIP

NUMERICAL APPLICATIONS – RESULTS, case 2, a priori exclusion of DERs installation



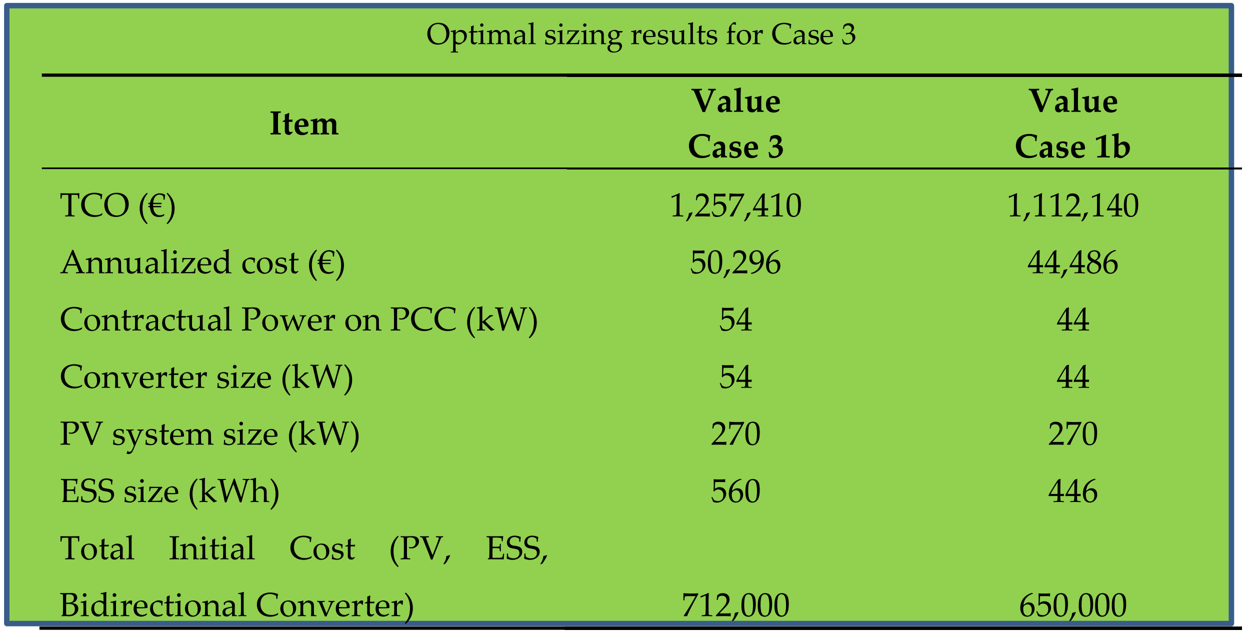
Optimal sizing results for Case 2.

Item	Value Case 2a	Value Case 2b	Value Case 2c	Value Case 1b
TCO (€)	2,370,850	1,338,080	2,383,160	1,112,140
Annualized cost (€)	94,834	53,524	95,326	44,486
Contractual Power on PCC (kW)	61	56	72	44
Converter size (kW)	61	56	72	44
PV system size (kW)	0	187	0	270
ESS size (kWh)	144	0	0	446
Total Initial Cost (€)	102,500	308,500	36,000	650,000

Research Activity 2

APPLICATIONS OF MIXED INTEGER LINEAR PROGRAMMING AND ROBUST OPTIMIZATION APPROACHES FOR THE OPTIMAL SIZING OF DERS IN SMART DC MICROGRIDS TO MINIMIZE TOTAL COST OF OWNERSHIP

NUMERICAL APPLICATIONS – RESULTS, case 3, No control of flexible loads



Optimal sizing results for Case 3

Item	Value Case 3	Value Case 1b
TCO (€)	1,257,410	1,112,140
Annualized cost (€)	50,296	44,486
Contractual Power on PCC (kW)	54	44
Converter size (kW)	54	44
PV system size (kW)	270	270
ESS size (kWh)	560	446
Total Initial Cost (PV, ESS, Bidirectional Converter)	712,000	650,000

Research Activity 2

APPLICATIONS OF MIXED INTEGER LINEAR PROGRAMMING AND ROBUST OPTIMIZATION APPROACHES FOR THE OPTIMAL SIZING OF DERS IN SMART DC MICROGRIDS TO MINIMIZE TOTAL COST OF OWNERSHIP

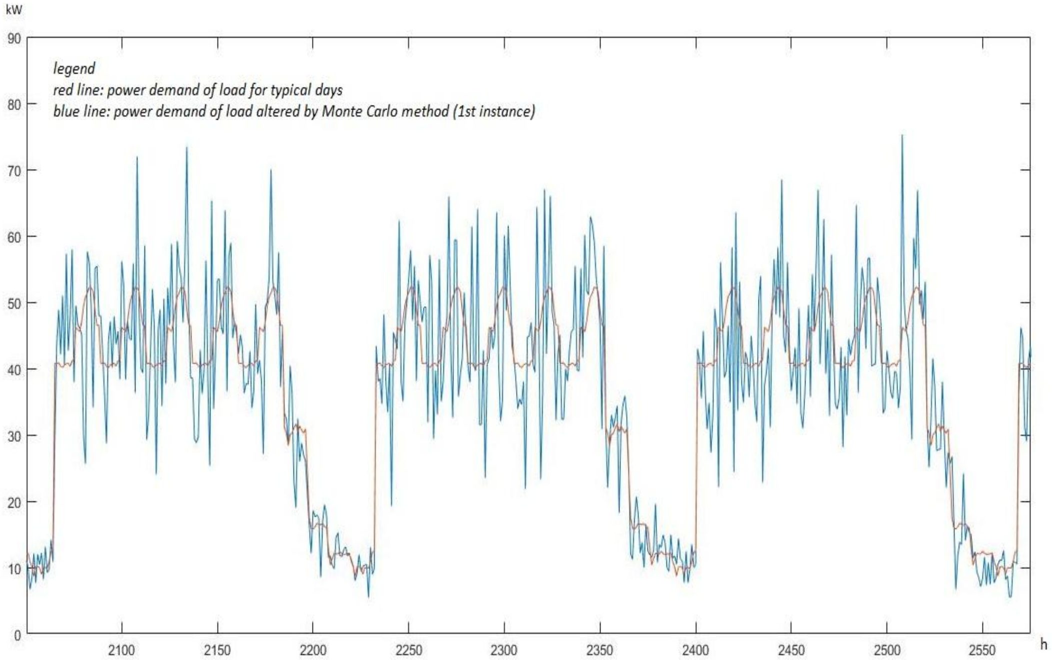
NUMERICAL APPLICATIONS – Results, case 4, Monte Carlo Tests (1)

Case 4a: DERs sized as in case 1a
σ = 0,10

Case 4b: DERs sized as in case 1b
σ = 0,10

Case 4c: DERs sized as in case 1b
σ = 0,20

Case 4d: DERs sized as in case 1b
σ = 0,20
Total load demand +20%



Research Activity 2

APPLICATIONS OF MIXED INTEGER LINEAR PROGRAMMING AND ROBUST OPTIMIZATION APPROACHES FOR THE OPTIMAL SIZING OF DERS IN SMART DC MICROGRIDS TO MINIMIZE TOTAL COST OF OWNERSHIP

NUMERICAL APPLICATIONS – RESULTS, case 4, Monte Carlo Tests (2)

TCOs for Case 4

Case	TCO (€)
Case 4a (sizing based on average day, σ=0.10)	
mean	1,175,800
ratio to TCO of case 1a (€ 1,020,110)	+15.3%
Case 4b (sizing based on typical days, σ=0.10)	
mean	1,120,066
ratio to TCO of case 1b (€ 1,059,380)	+0.7%
Case 4c (sizing based on typical days, σ=0.20)	
mean	1,136,671
ratio to TCO of case 1b (€ 1,059,380)	+2.2%
Case 4d (sizing based on typical days, σ=0.20, load x1.2)	
mean	1,417,342
ratio to TCO of case 1b (€ 1,059,380)	+27.4%

Research Activity 2

APPLICATIONS OF MIXED INTEGER LINEAR PROGRAMMING AND ROBUST OPTIMIZATION APPROACHES FOR THE OPTIMAL SIZING OF DERS IN SMART DC MICROGRIDS TO MINIMIZE TOTAL COST OF OWNERSHIP

NUMERICAL APPLICATIONS – Results, case 5, Scenario-based Robust Optimization (1)

Cases 5a÷5e: 10 years of hourly values of power demand artificially created:

$P_l'(t) = P_l(t) * (1+rnd_{[0-1]} * ul)$, with ul = 0% (deterministic), 10%, 20%, 30%, 40%

Case 5f: real historical data used (10 years of power demand hourly registrations)

Optimal sizing results for Case 5.

Uncertainty Level (*ul*)	**Case 5a** **0%**	**Case 5b** **10%**	**Case 5c** **20%**	**Case 5d** **30%**	**Case 5e** **40%**	**Case 5f** **n.a. (real historical data used)**
Converter size (kW)	44	48	52	56	60	64
PV system size (kW)	270	290	310	330	350	361
ESS size (kWh)	446	489	527	569	610	616
Total Initial Cost (€)	650,000 *100%*	703,500 *108%*	754,500 *116%*	807,500 *124%*	860,000 *132%*	881,500 *136%*

! Increasing *ul* causes DERs sizes and Initial Cost to increase, but the operation costs decrease !

Research Activity 2

APPLICATIONS OF MIXED INTEGER LINEAR PROGRAMMING AND ROBUST OPTIMIZATION APPROACHES FOR THE OPTIMAL SIZING OF DERS IN SMART DC MICROGRIDS TO MINIMIZE TOTAL COST OF OWNERSHIP

NUMERICAL APPLICATIONS – Results, case 5, Scenario-based Robust Optimization (2)

Mean TCOs (€) of Monte Carlo tests with DERs optimal sizes from results of Case 5.

Load scaling factor (*lsf*)	**Case 5a**	**Case 5b**	**Case 5c**	**Case 5d**	**Case 5e**	**Case 5f**
1.0	**1,136,671** *100% - 100%*	1,137,997 *100% - 100%*	1,156,122 *102% - 100%*	1,180,254 *104% - 100%*	1,206,222 *106% - 100%*	1,206,222 *106% - 100%*
1.1	1,269,337 *102% - 113%*	1,243,602 *100% - 109%*	**1,241,253** *100% - 107%*	1,255,863 *101% - 106%*	1,279,179 *103% - 106%*	1,290,648 *104% - 106%*
1.2	1,417,342 *105% - 126%*	1,375,228 *102% - 121%*	1,349,135 *100% - 117%*	**1,343,637** *100% - 114%*	1,356,302 *101% - 112%*	1,366,568 *102% - 112%*
1.3	1,627,709 *112% - 146%*	1,525,183 *105% - 134%*	1,482,342 *102% - 128%*	1,453,466 *100% - 123%*	**1,446,997** *100% - 120%*	1,453,510 *100% - 119%*
1.4	2,523,879 *162% - 234%*	1,715,910 *110% - 151%*	1,631,221 *104% - 141%*	1,589,662 *102% - 135%*	1,561,079 *100% - 129%*	**1,557,913** *100% - 128%*

Research Activity 2

APPLICATIONS OF MIXED INTEGER LINEAR PROGRAMMING AND ROBUST OPTIMIZATION APPROACHES FOR THE OPTIMAL SIZING OF DERS IN SMART DC MICROGRIDS TO MINIMIZE TOTAL COST OF OWNERSHIP

CONCLUDING REMARKS

A simple and tight formulation has been developed allowing to apply MILP to the optimal sizing problem, thus benefiting from its advantages as compared to other optimization methods (e.g.: guaranteed convergence to optimality, availability of efficient off-the-shelf software).

The Robust Optimization approach offers a straightforward way to cope with the uncertainties affecting the optimization problem.

Future work could be focused on:

1. model refinement and expansion to include and characterize other DG and ESS technologies and/or market and operating conditions, as well as different objectives through a multi-objective optimization approach;
2. further investigation on the variation of performances of optimal sizing results against loads and generators power profiles changes and variations of other design parameters;
3. implementation of different approaches dealing with uncertainty, such as Stochastic Optimization and Decision Theory.

Outline

OPTIMAL SIZING OF DISTRIBUTED ENERGY RESOURCES IN DC MICROGRIDS

- CONTEXT AND MOTIVATIONS
- PROBLEM – RESEARCH TOPIC
- RESEARCH ACTIVITY 1: Analytical Approach for the Optimal Sizing of Energy Storage Systems in DC Microgrids to Minimize Power Losses
- RESEARCH ACTIVITY 2: Mixed Integer Linear Programming and Robust Optimization Approaches for the Optimal Sizing of DERs in Smart DC Microgrids to minimize total cost of ownership
- **PUBLICATIONS**
- CONCLUSIONS

Publications

Journal papers:

1. M. Fantauzzi, D. Lauria, F. Mottola, **A. Scalfati**. Sizing energy storage systems in DC networks: A general methodology based upon power losses minimization. Applied Energy, Volume 187, 1 February 2017, pp. 862-872, https://doi.org/10.1016/j.apenergy.2016.11.044

Conference papers:

1. M. Fantauzzi, D. Iannuzzi, M. Pagano, **A. Scalfati**, M. Roscia “Building DC microgrids: Planning of an experimental platform with power hardware in the loop features”, IEEE International Conference on Renewable Energy Research and Applications, 2015, Palermo, Italy
2. **A. Scalfati**, D. Iannuzzi, M. Fantauzzi, M. Roscia “Optimal Sizing of Distributed Energy Resources in Smart Microgrids: a Mixed Integer Linear Programming Formulation”, IEEE International Conference on Renewable Energy Research and Applications, 2017, San Diego, USA

Papers in preparation:

1. **A. Scalfati**, D. Iannuzzi, M. Fantauzzi, “Optimal Sizing of Distributed Energy Resources in Smart Microgrids: Deterministic and Robust Optimization Approaches based on a Mixed Integer Linear Programming Formulation”

Outline

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- **CONCLUSIONS**

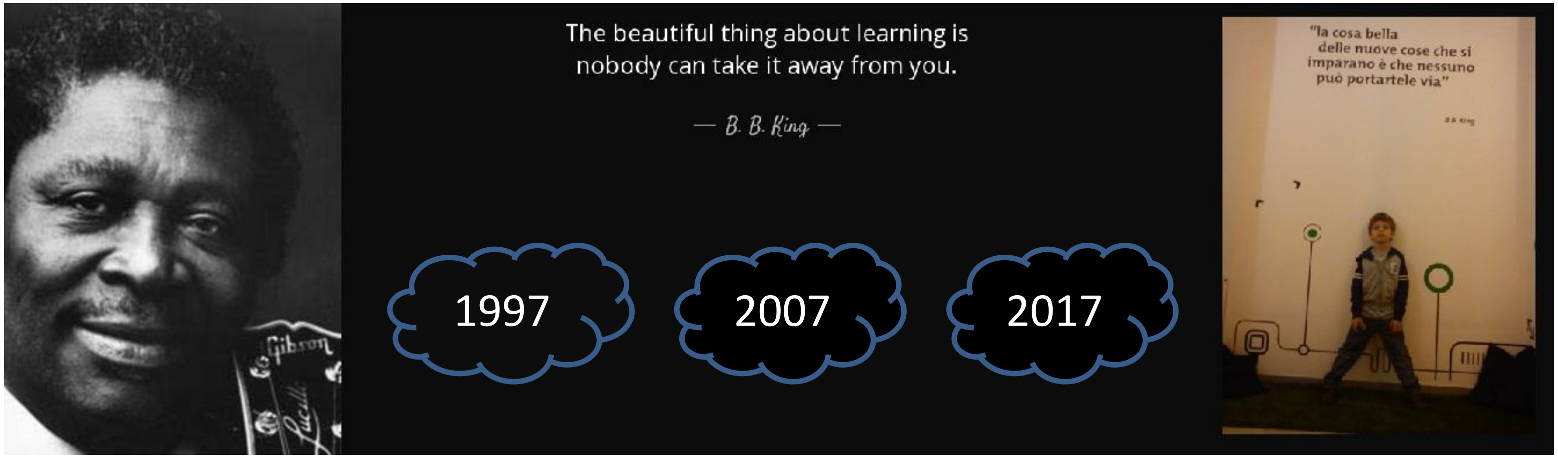
Conclusions

- 3 years of Ph.D. course have offered to me the chance to study current trends and future perspectives of electrical systems, particularly focusing on main trends in distribution systems (microgrids, smartgrids, DC distribution systems) and DERs technologies (ESSs, EVs, DGs), attending several modules, focused both on general aspects (Program Management; Entrepreneurship of Research Projects; Communication and Dissemination of Research Activities) and on specific topics (Dynamics and Control of Electrical Machines and Drives, Game Theory; Matlab; Models, Methods and Software for Optimization; Global Optimization and Uncertainty Quantification)

- My research activity has been focused on the application of optimization techniques to the microgrid planning problem

- Two research applications have been developed using analytical techniques, Mixed Integer Programming and Robust Optimization; results can be considered satisfactory, but only a part of the possible approaches have been exploited

- There's plenty of room for further work focused on the refinement of the developed models and on the study and application of other optimization techniques, especially Stochastic Optimization and Heurystics



The beautiful thing about learning is nobody can take it away from you.

— B. B. King —

"la cosa bella delle nuove cose che si imparano è che nessuno può portartele via"

B.B. King

Thank you for your attention!