Energy Scheduling of a Smart District Microgrid with Shared Photovoltaic Panels and Storage: the case of the Ballen marina in Samsø

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Outline

Energy Scheduling of a Smart District Microgrid with Shared Photovoltaic Panels and Storage: the case of the Ballen marina in Samsø

- **Motivation and objectives**
- **Contribution and positioning wrt literature**
- **Problem statement**
- **Energy scheduling algorithms**
- **Simulation results and analysis**
- **Conclusions**

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Motivation and objectives

Energy efficiency and environmental sustainability...

… requires efficient energy behaviors of all involved actors

- **need of development of energy optimization algorithms to obtain responsive and proficient behaviors of microgrids**

This motivates the effort in designing and developing ICT-based energy management tools

Objective

- **Presenting a real-time strategy based on Model Predictive Control (MPC) for the energy scheduling of a grid-connected smart microgrid where consumers share energy production and storage**
  - **aiming at minimization of energy costs and maximization of the self-supply with renewable energy**
  - **using an iterative finite horizon on-line optimization based on MPC**
    - **taking into account time-varying buying/selling pricing of energy**
    - **formulating an optimal planning of shared resources, (i.e., storage system charge/discharge and renewable energy usage) and of energy exchange with grid**

Acknowledgements

- **The present work is developed in the framework of the «Smart Islands Energy System (SMILE)» H2020 project**

- **The end goal of the project is to foster the market introduction of smart grid technologies and demonstrate them in three islands**

- **Specific objective for the marina of Ballen, Samsø (Denmark):**
  - **To install a battery system to level out fluctuations in supply and demand, and to test it.**
  - **To install a photovoltaic power generation system covering 50% of heating demand in harbour master's office using renewable energy and new heat pump**
  - **To develop and test an overall control system, which allows for variable market prices (hourly spot prices).**

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Contribution and positioning wrt literature

- **Typically the works on energy scheduling deal with traditional users, i.e., houses equipped <u>only with passive loads</u>**
- **The simultaneous presence of loads, generators and storage systems has never been considered in the integrated energy scheduling of a group of interconnected users (microgrid).**

- **The progress of this paper with respect to the cited literature:**
  1. **Optimal sharing by microgrid users of energy generation / storage resources to jointly take advantage of the collective locally produced / stored energy.**
  2. **Developing a comprehensive technique that simultaneously pursues the cost-optimal planning of usage of shared *<u>storage system</u>* and production by the shared *<u>energy generator</u>***
  3. **Presenting a case study on a real microgrid: a comparison of our proposed method with a naïve scheduling method is provided to validate the effectiveness of the approach considering the minimization of energy costs and/or maximization of the self-supply with renewable energy**

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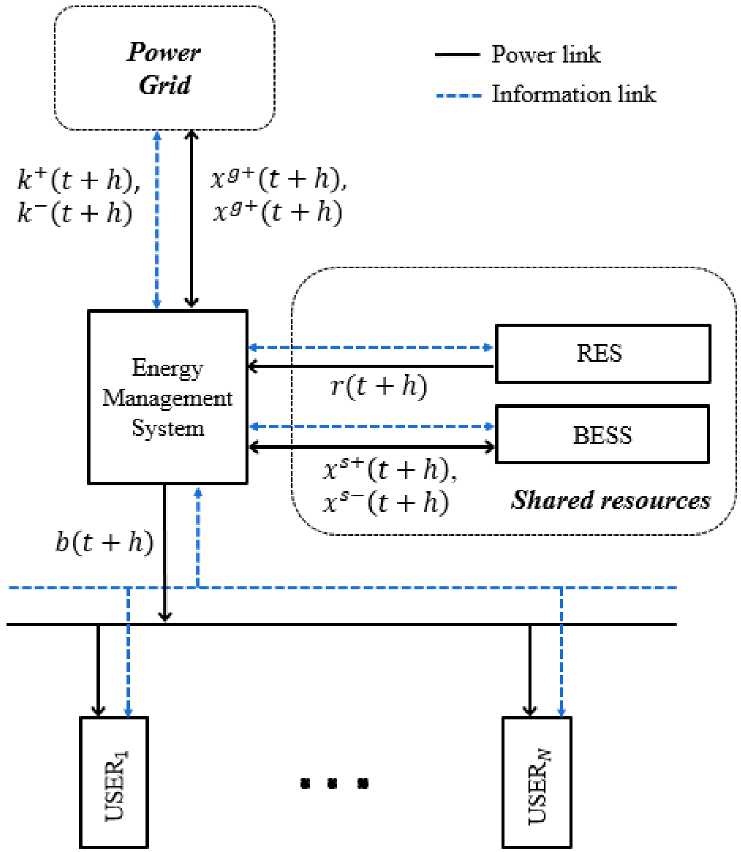
System model

- **Control inputs:**
  - **Forecast data of RES (Renewable Energy Source) production**
  - **Forecast of loads consumption**
  - **Initial charge of BESS (Battery Energy Storage System)**
- **Control outputs:**
  - **Charging/discharging strategies of BESS**
  - **Profiles of energy to be bought/sold from/to the grid**
- **Scheduling time horizon:**

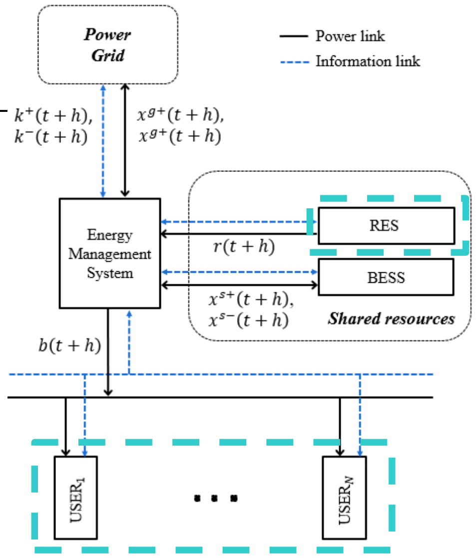
$$\mathcal{H}(t) = [t+1, t+H].$$

- **Energy Management System**
  - **Controls the demand response of the microgrid**
  - **Allows the optimal and autonomous interaction between users, RES, BESS and distribution network**



Scheme of energy flow and links

Problem statement



Loads consumption

- **The cumulative consumption of loads is an *input parameter* of the scheduling problem:**

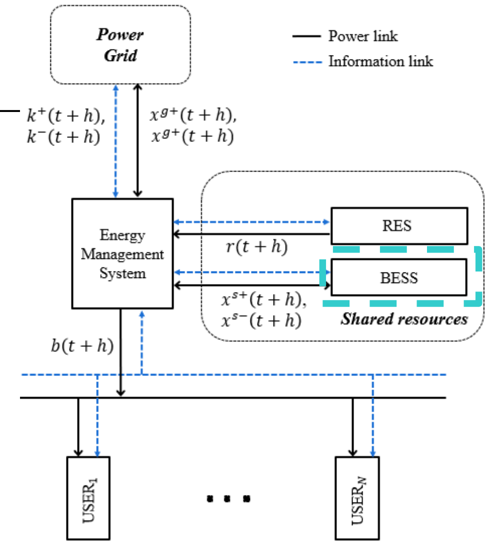
$$\boldsymbol{b}(t) = (b(t+1) \ldots b(t+h) \ldots b(t+H))$$

Renewable energy source

- **The cumulative production of the renewable energy source is an *input parameter* of the scheduling problem:**

$$\boldsymbol{r}(t) = (r(t+1), \ldots, r(t+h), \ldots, r(t+H))$$

Problem statement



Battery Energy Storage System

- **A finite capacity energy buffer which may either supply or accumulate adaptable packets of energy in each time slot**
- **Charge and discharge energy profile:**

decision variables

$$\boxed{x^{s+}(t+h)}, h \in \mathcal{H}(t)$$

$$\boxed{x^{s-}(t+h)}, h \in \mathcal{H}(t)$$

η^+ and η^-: BESS charging and discharging efficiencies

constraints

State equation (state of charge)

$$s(t+h) = s(t+h-1) + \eta^+ x^{s+}(t+h) - x^{s-}(t+h)/\eta^-, h \in \mathcal{H}(t)$$

Charge/discharge are limited by maximum/minimum storage capacity ($\overline{S}$, $\underline{S}$)

$$\underline{S} - s(t+h-1) \leq \eta^+ x^{s+}(t+h) - x^{s-}(t+h)/\eta^- \leq \overline{S} - s(t+h-1), \; h \in \mathcal{H}(t)$$

supporting binary decision variables

$$\boxed{\delta^{s+}(t+h)} \in \{0,1\}, \boxed{\delta^{s-}(t+h)} \in \{0,1\}, h \in \mathcal{H}(t)$$

BESS cannot be simultaneously charged and discharged

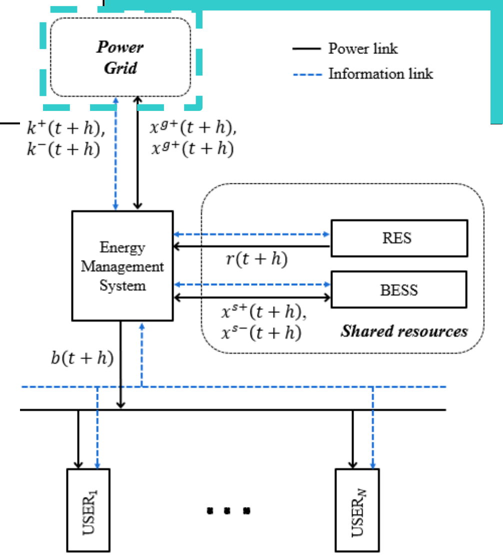
$$\delta^{s+}(t+h) + \delta^{s-}(t+h) \leq 1, h \in \mathcal{H}(t)$$

Charge/discharge are limited by charging/discharging rate ($\overline{s}$, $\underline{s}$)

$$0 \leq x^{s+}(t+h) \leq \delta^{s+}(t+h)\overline{s}, \quad h \in \mathcal{H}(t)$$

$$0 \leq x^{s-}(t+h) \leq \delta^{s-}(t+h)\underline{s}, \; h \in \mathcal{H}(t)$$

Problem statement



- **Grid energy flows**
  - **energy balance**

constraint
$$\begin{cases} b(t+h) - r(t+h) + x^{s+}(t+h) - x^{s-}(t+h) = \\ \qquad \boxed{x^{g+}(t+h)} - \boxed{x^{g-}(t+h)},\ h \in \mathcal{H}(t) \end{cases}$$

decision variables representing bought/sold energy

  - **constraints in buying/selling energy, microgrid cannot simultaneously buy and sell energy**

supporting binary decision variables

constraints
$$\begin{cases} \boxed{\delta^{g+}(t+h)} \in \{0,1\}, \boxed{\delta^{g-}(t+h)} \in \{0,1\}, h \in \mathcal{H}(t) \\ 0 \le x^{g+}(t+h) \le \delta^{g+}(t+h)\overline{g}, \quad h \in \mathcal{H}(t) \\ 0 \le x^{g-}(t+h) \le \delta^{g-}(t+h)\underline{g}\ ,\ h \in \mathcal{H}(t) \\ \delta^{g+}(t+h) + \delta^{g-}(t+h) \le 1,\ h \in \mathcal{H}(t) \end{cases}$$

$\overline{g}$ and $\underline{g}$: maximum purchasable and salable energy profile imposed by the energy provider

  - **microgrid is not allowed to sell energy directly from battery to grid, but can only sell the RES surplus**

constraint
$$\{\ 0 \le x^{g-}(t+h) \le \max(r(t+h) - b(t+h), 0)\ ,\ h \in \mathcal{H}(t)$$

- **Energy cost**
  - **cost per time slot**

buying/selling time-varying cost coefficients

$$c\big(x^{g+}(t+h), x^{g-}(t+h)\big) = \overbrace{k^{+}(t+h)}x^{g+}(t+h) - \overbrace{k^{-}(t+h)}x^{g-}(t+h), h \in \mathcal{H}(\mathrm{t})$$

Problem statement

- **Optimization problem for microgrid energy scheduling**

  a. **minimizing operational costs:**

$$\underbrace{\min_{\substack{\boldsymbol{x}^{s+}(t),\boldsymbol{x}^{s-}(t),\boldsymbol{x}^{g+}(t),\boldsymbol{x}^{g-}(t),\\ \boldsymbol{\delta}^{s+}(t),\boldsymbol{\delta}^{s-}(t),\boldsymbol{\delta}^{g+}(t),\boldsymbol{\delta}^{g-}(t)}} \sum_{h=1}^{H} \left(k^{+}(t+h)x^{g+}(t+h) - k^{-}(t+h)x^{g-}(t+h)\right)} \qquad \text{(Pa)}$$

subject to:
all the previously defined constraints

the objective function is the sum of the energy cost per slot

  b. **maximizing energy self-reliance, i.e., minimizing exchanges with grid (microgrid operates in islanded mode when possible, i.e., using only the internal energy produced by the microgrid and receiving the least power from the main grid)**

$$\min_{\substack{\boldsymbol{x}^{s+}(t),\boldsymbol{x}^{s-}(t),\boldsymbol{x}^{g+}(t),\boldsymbol{x}^{g-}(t),\\ \boldsymbol{\delta}^{s+}(t),\boldsymbol{\delta}^{s-}(t),\boldsymbol{\delta}^{g+}(t),\boldsymbol{\delta}^{g-}(t)}} \underbrace{\sum_{h=1}^{H} \left|x^{g+}(t+h) - x^{g-}(t+h)\right|} \qquad \text{(Pb)}$$

subject to:
all the previously defined constraints

the objective function is the sum of unsigned flows from/to main grid

$$\left|x^{g+}(t+h) - x^{g-}(t+h)\right| = x^{g+}(t+h) + x^{g-}(t+h)$$

mixed integer linear programming (MILP) problems

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Energy Scheduling Algorithm

Naïve Scheduling Algorithm (Algorithm 1)

Repeat at each time step:

IF RES production ≥ loads demand THEN

IF BESS is not full THEN charge BESS

ELSE sell to the grid END

ELSE

IF BESS is not empty THEN discharge BESS

ELSE buy from the grid END

END

Simplest approach for determining time slot-by-time slot energy bought/sold from/to the grid and energy from/to the BESS

- **selling to the grid is to be avoided, because the selling price is generally low, and it is better to use the RES to maximize the self-supply**
- **buying from the grid is unavoidable, because the RES production is too small to cover the total demand**

Algorithm 1 – Naïve energy scheduling algorithm

Inputs: $\{b(\tau)\}$, $\{r(\tau)\}$, $\{k^+(\tau)\}$, $\{k^-(\tau)\}$, $s(0)$

Procedure:

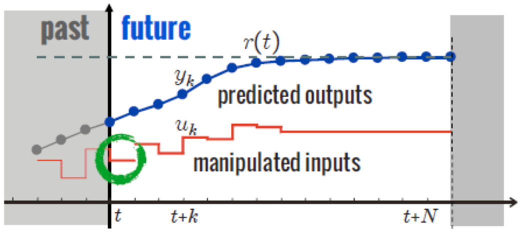
Set $\tau \leftarrow 1$
iterate
  if $r(\tau) \geq b(\tau)$
    $x^{s-}(\tau) = 0$
    $x^{g+}(\tau) = 0$
    if $s(\tau-1) < \overline{S}$
      $x^{s+}(\tau) = \min\left(r(\tau) - b(\tau), (\overline{S} - s(\tau-1))/\eta^+\right)$
      $x^{g-}(\tau) = r(\tau) - b(\tau) - x^{s+}(\tau)$
    else
      $x^{s+}(\tau) = 0$
      $x^{g-}(\tau) = r(\tau) - b(\tau)$
    end
  else
    $x^{s+}(\tau) = 0$
    $x^{g-}(\tau) = 0$
    if $s(\tau-1) > \underline{S}$
      $x^{s-}(\tau) = \min\left(b(\tau) - r(\tau), \eta^-(s(\tau-1) - \underline{S})\right)$
      $x^{g+}(\tau) = b(\tau) - r(\tau) - x^{s-}(\tau)$
    else
      $x^{s-}(\tau) = 0$
      $x^{g+}(\tau) = b(\tau) - r(\tau)$
    end
  end
  $s(\tau) = s(\tau-1) + \eta^+ x^{s+}(\tau) - x^{s-}(\tau)/\eta^-$
  set $\tau \leftarrow \tau + 1$

Outputs: $\{x^{g+}(\tau)\}, \{x^{g-}(\tau)\}, \{x^{s+}(\tau)\}, \{x^{s-}(\tau)\}$

Baseline strategy

MPC-based Scheduling Algorithm (Algorithm 2)

- **Main ingredients:**
- **1 model;**
- **2 (predictive) optimization problem;**
- **3 receding horizon control policy**



- **Copes well with:**
  - **constraints on decision variables and internal variables**
  - **uncertainties (robustness with respect to a wide class of external disturbances)**

- **The control law is determined by resolving at each time step MILPs Pa or Pb for a finite horizon H**
  - **Objective function is iteratively updated and recomputed at each time slot by shifting the horizon in the future until the simulation end time**
  - **The decision variables of the first time slot are extracted from the MILP solution (whose results are given for H slots) and implemented with the receding horizon concept by repeating the MILP for the next horizon iteratively**

Algorithm 2a and 2b – Energy scheduling MPC algorithm

Inputs: $\{b(t)\}, \{r(t)\}, \{k^+(t)\}, \{k^-(t)\}, s(0)$
Procedure:
1 Set $t \leftarrow 0$
2 **iterate**
3 Get forecast data $\boldsymbol{b}(t)$ and $\boldsymbol{r}(t)$
4 Solve the optimization problem (Pa) or (Pb) (**Algorithm 2a** or **2b**)
5 Apply only $x^{g+}(t+1), x^{g-}(t+1), x^{s+}(t+1), x^{s-}(t+1)$
6 Set $t \leftarrow t+1$
Outputs: $\{x^{g+}(t)\}, \{x^{g-}(t)\}, \{x^{s+}(t)\}, \{x^{s-}(t)\}$

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Ballen Marina Case Study

Scenario

- **Results by the MPC-based algorithm are compared with the naïve method**
- **Period of analysis**
  - **one leap year (i.e., $t \in [0, T-1]$, where $T = 24 \cdot 366 = 8{,}784$)**
- **Scheduling horizon:**
  - **1 day with *H* = 24 time slots (equal to 1 hour)**
- **Cost coefficients:**
  - **selling pricing -> the spot price on the Nord Pool electricity market (DK1 market)**
    https://www.nordpoolgroup.com/Market-data1/Dayahead/Area-Prices/ALL1/Hourly/?view=table
  - **buying pricing -> the spot price plus taxes and fees (estimated equal to 0.03 €/kWh or 0.07€/kWh)**

Storage parameters

- **3 Lithium Ion battery racks:**

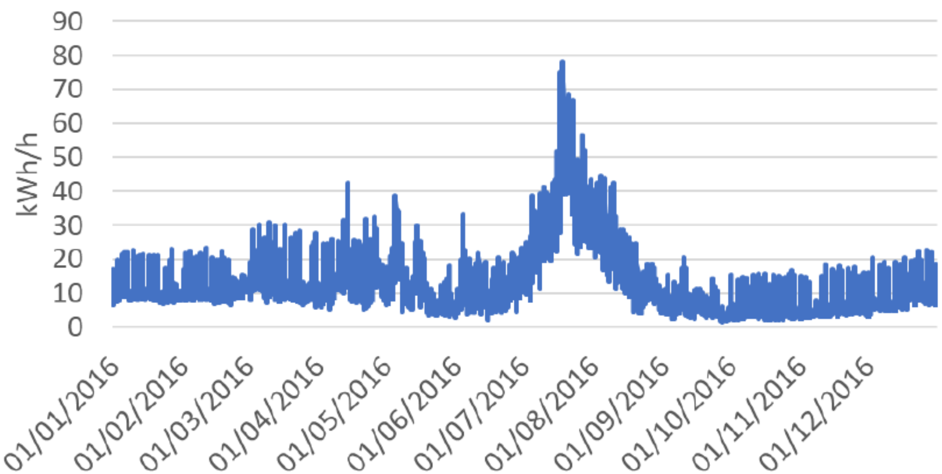
TECHNICAL PROPERTIES OF SINGLE BATTERY RACK	
Battery chemistry	Li-ion NMC
Power (charge/discharge)	30 kW standard, but can be up to 1C/70 kW
Energy	79kWh
Max. power (32 racks)	1.6 [MW]
Max. energy (32 racks)	2.5 [MWh]
Nominal capacity	106Ah
Nominal voltage	700VDC
Voltage range	610-806.4V DC
Grid connection voltage	3 x 400V AC
Charge/discharge temperature (cell)	0°C – 45°C
Recommended ambient temperature	15°C -25°C
Maximum parallel racks	32
Battery system efficiency (typical/minimum)	97%/94%
System Power density (gravimetric)	83W/kg
System Energy density (gravimetric)	125Wh/kg
System Energy density (volumetric)	11Wh/l
Weight	800kg
Dimensions indoor version	D655mm x W660mm x H1895mm
Dimensions outdoor version	D705mm x W845cm x H2025mm
Cooling	Forced air passive parallel cooling
Developed according to standards for stationary energy storage systems: (To be certified)	CE UN38.3 EN 62619 61439-1 EMC Immunity: 61000-6-2 EMC Emissions: 61000-6-4
Protection class	IP 21 indoor version (To be confirmed)
	IP 55 Outdoor version (To be confirmed)

Rack 1 of the Samso BESS system

Simulation results and analysis

Loads consumption

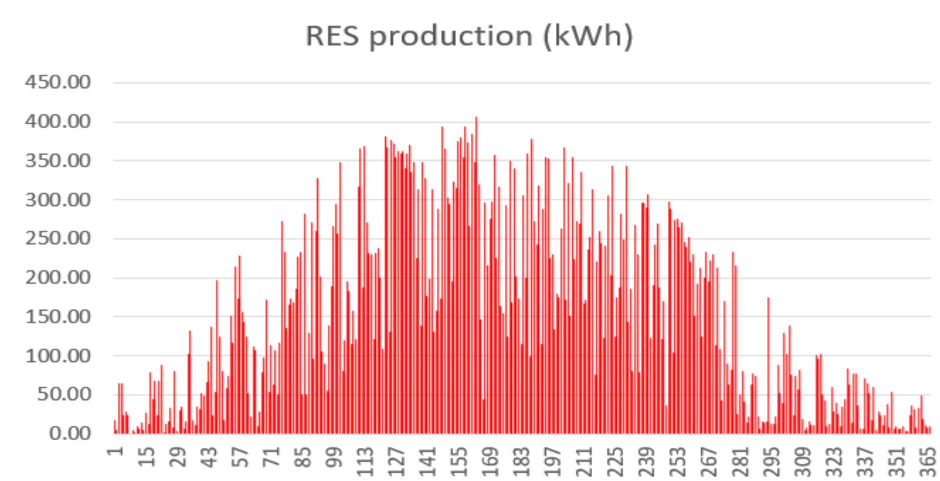
- consumption of the marina, (onshore + offshore) - 2016
- 106,000 kWh over a year



https://plangreatly.com/dashboards/ballen/lweek.php

RES production

- measurements come from a Photovoltaic plant at 3 km from the Ballen marina - 2016
- 56,000 kWh over a year



http://arkiv.energiinstituttet.dk/643/

Simulation results and analysis

- **3 metrics analyzed over the year (nr. of hours T in the year):**
  - **Energy cost (index to minimize)**

$$EC_T = \sum_{\tau=1}^{T} \left(k^+(\tau)x^{g+}(\tau) - k^-(\tau)x^{g-}(\tau)\right)$$

business economy (cost saving)

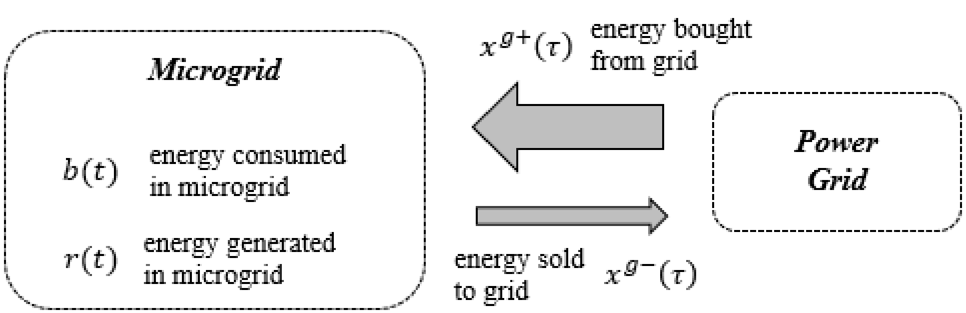
  - **Self-supply (index to maximize), in [0, 1] range**

$$SS_T = 1 - \sum_{\tau=1}^{T} x^{g-}(\tau) \Big/ \sum_{\tau=1}^{T} r(\tau)$$

  - **Energy independence (index to maximize), in [0, 1] range**

$$EI_T = 1 - \sum_{\tau=1}^{T} x^{g+}(\tau) \Big/ \sum_{t=1}^{T} b(t)$$

energy self-reliance (microgrid operates in islanded mode, i.e., it is operated with only the internal energy produced by the island itself, without receiving the power from the main grid)



Simulation results and analysis

- **Results**

- lower cost, worse self-reliance
- (buying – selling price) ⇧ -> cost saving ⇩

(yearly cost, self supply and energy independence)

Selling price = spot price; buying price = spot price + 0.03 €/kWh

		Algorithm 1 – naïve	Algorithm 2a - cost minimization	Algorithm 2b – self-supply maximization
Energy cost	EC_T	€3,022.52	€2,816.12 (-6.83%)	€3,022.52 (+0.00%)
Self-supply	SS_T	89.89%	88.04% (-1.85%)	89.89% (+0.00%)
Energy-independence	EI_T	46.02%	45.97% (-0.05%)	46.02% (+0.00%)

Selling price = spot price; buying price = spot price + 0.07 €/kWh

		Algorithm 1 – naïve	Algorithm 2a - cost minimization	Algorithm 2b – self-supply maximization
Energy cost	EC_T	€5,321.45	€5,191.78 (-2.44%)	€5,321.45 (+0.00%)
Self-supply	SS_T	89.89%	88.26% (-1.63%)	89.89% (+0.00%)
Energy-independence	EI_T	46.02%	44.44% (-1.58%)	46.02% (+0.00%)

- identical performance of Pb with naïve algorithm
- no advantages in further charging storage with energy from grid

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Conclusions

Contribution

- **MPC-based energy scheduling approach for a grid-connected microgrid with RES and BESS**
  - **Framework: loads consumption, renewable energy generation and storage systems sharing**
  - **Simulations (based on a public real dataset) indicate approach allows ~90% exploitation of potential of local production and ~ 2÷7% cost saving wrt naïve scheduling**

Outlooks

- **Enhancing the scheduling considering:**
  - **Controllable loads (e.g. , heat pumps can preheat or precool rooms in convenient time slots, sauna heater can preheat room at times when battery can afford it, and wastewater pump can be started at night)**
  - **Uncertainty (e.g. on renewable energy due to unreliable weather forecast) via stochastic or robust techniques**
  - **Integration of other terms into the objective function (e.g., a penalty term to capture user comfort, battery degradation costs) or trading-off between Alg. 2a and 2b in a multi-objective optimization**
- **Work in progress:**

R. Carli, M. Dotoli, J. Jantzen, M. Kristensen "Energy Scheduling of a Smart District Microgrid with Shared Photovoltaic Panels and Storage: the case of the Ballen marina in Samsø", to be submitted to "ESAAU 2019" Special Issue of *Energy – The International Journal*, Oct. 2019.

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