Pv-battery power supply for next-generation cellular telecommunication networks

Javidsharifi, Mahshid

DOI (link to publication from Publisher):
10.54337/aau528213502

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Javidsharifi, M. (2023). *Pv-battery power supply for next-generation cellular telecommunication networks*. Aalborg Universitetsforlag. Ph.d.-serien for Det Ingeniør- og Naturvidenskabelige Fakultet, Aalborg Universitet
https://doi.org/10.54337/aau528213502

PV-BATTERY POWER SUPPLY FOR NEXT-GENERATION CELLULAR TELECOMMUNICATION NETWORKS

BY
MAHSHID JAVIDSHARIFI

DISSERTATION SUBMITTED 2023

AALBORG UNIVERSITY
DENMARK

PV-BATTERY POWER SUPPLY FOR NEXT-GENERATION CELLULAR TELECOMMUNICATION NETWORKS

by

Mahshid Javidsharifi

AALBORG UNIVERSITY
DENMARK

Dissertation submitted

Dissertation submitted: February 2023

PhD supervisor: Associate Prof. Tamas Kerekes
Aalborg University, Denmark

Assistant PhD supervisors: Associate Prof. Dezso Sera
Queensland University of Technology,
Brisbane, QLD, Australia

Associate Prof. Sergiu Viorel Spataru
Technical University of Denmark, DTU, Denmark

Prof. Josep M. Guerrero
Aalborg University, Denmark

PhD committee: Associate Professor Jayakrishnan Radhakrishna Pillai
Aalborg University, Denmark

Professor Maryam Saeedifard
Georgia Institute of Technology, USA

Professor Olav Bjarte Fosso
Norwegian University of Science and Technology, Norway

PhD Series: Faculty of Engineering and Science, Aalborg University

Department: AAU Energy

ISSN (online): 2446-1636
ISBN (online): 978-87-7573-760-4

Published by:
Aalborg University Press
Kroghstræde 3
DK – 9220 Aalborg Ø
Phone: +45 99407140
aauf@forlag.aau.dk
forlag.aau.dk

Printed in Denmark by Stibo Complete, 2023

ENGLISH SUMMARY

Next-generation cellular telecommunication networks require a higher density of base stations to satisfy the required latency and quality of service. Mobile network operators (MNOs) must urgently reduce their carbon footprint and energy demand. From the perspective of MNOs, this poses serious concerns about the future sustainability and energy consumption of cellular telecommunication networks. Currently, efforts are being made to decrease the electricity bills and carbon footprints of MNOs, such as powering base stations with photovoltaic (PV)-battery systems as a green and sustainable solution for next-generation cellular telecommunication networks. Although using PV-battery systems reduces OPEX, it may increase CAPEX.

The Ph.D. project focuses on a systematic approach to choosing the power rating of the PVs and battery capacity considering technical and economical viewpoints for minimizing investment cost and operational expenditures and maximizing the power autonomy of the PV-battery system. In this regard, the power consumption profile of the base stations and the PV generation profile at the location of the base stations are identified in the first step. An optimal power dispatch strategy is then adopted to satisfy the power balance between PV generation, power consumption of base stations, and battery charging and discharging power.

The second phase of the Ph.D. research consists of developing PV-battery-powered UAV recharging stations for next-generation cellular telecommunication networks. As a result of the different consumption profiles of UAVs and their mission planning, the power supply systems of UAV-based cellular telecommunication networks are sized differently compared to conventional systems. Accordingly, the next step in this thesis is to derive the power consumption profile of a UAV-based cellular telecommunication network based on the mission planning of UAVs. Afterward, an optimal framework for dimensioning the PV-battery power supply for UAV-based telecommunication networks in rural and urban regions is proposed to minimize the total cost.

A systematic approach is developed for each case study to achieve a self-sufficient and cost-effective PV-battery system: in the first step, the optimal size and installation angle of PV panels and battery capacity will be determined to maximize the usage of PV generations and power autonomy, minimize the lifetime capital cost and payback period while meeting power balance constraints.

At the final phase an optimal energy-efficient management strategy for a multi-renewable hybrid energy system (RHES) is proposed: after determining the battery capacity and the size of PV panels as well as solving the optimal operation problem for each single RHES, an optimization framework for power management is extended

to minimize OPEX and achieve coordinated operation of the cooperative multi-RHES considering the technical constraints.

.

DANSK RESUME

Næste generations cellulære telekommunikationsnetværk kræver en højere tæthed af basestationer for at tilfredsstille den påkrævede latenstid og servicekvalitet. Mobilnetværksoperatører (MNO'er) skal omgående reducere deres CO2-fodaftryk og energiforbrug. Set fra MNO'ers perspektiv giver dette anledning til alvorlige bekymringer om bæredygtigheden og energiforbruget af cellulære telekommunikationsnetværk i fremtiden. I øjeblikket bliver der gjort en indsats for at reducere elregningerne og CO2-fodsporene fra MNO'er, såsom at drive basestationer med fotovoltaiske (PV)-batterisystemer som en grøn og bæredygtig løsning til næste generations cellulære telekommunikationsnetværk. Selvom brug af PV-batterisystemer reducerer OPEX, kan det øge CAPEX.

Ph.D. Projektet fokuserer på en systematisk tilgang til at bestemme PV'ernes og batterikapacitetens nominelle effekt ud fra tekniske og økonomiske synspunkter for at minimere investeringsomkostninger samt driftsudgifter, mens PV-batterisystemets effektautonomi maksimeres i en multi-objektiv optimeringsramme. I denne henseende identificeres strømforbrugsprofilen for basestationerne og PV-genereringsprofilen ved placeringen af basestationerne i det første trin. En optimal strømafsendelsesstrategi vedtages derefter for at tilfredsstille strømbalancen mellem PV-generering, strømforbrug af basestationer og batteriopladning og -afladning.

Anden fase af ph.d. er dedikeret til de batteridrevne UAV-baserede basestationer i næste generations cellulære telekommunikationsnetværk, hvor UAV-opladningssteder drives af PV-batterisystemer. På grund af UAV'ernes forskellige strømforbrugsprofil og deres missionsplanlægning er bestemmelsen af den optimale dimensionering af strømforsyningssystemet for de UAV-baserede cellulære telekommunikationsnetværk helt anderledes end de konventionelle systemer. Følgelig er næste trin i denne afhandling at udlede strømforbrugsprofilen for et UAV-baseret cellulært telekommunikationsnetværk baseret på missionsplanlægningen af UAV'er. Derefter foreslås en optimal tilgang til dimensionering af PV-batteriets strømforsyning til UAV-baserede cellulære netværk i land- og byområder for at minimere de samlede omkostninger, herunder kapital- og driftsudgifter.

For hvert casestudie udvikles en systematisk tilgang til at opnå et selvforsynende og omkostningseffektivt PV-batterisystem: i det første trin, gennem den foreslåede tilgang, vil den optimale størrelse og installationsvinkel for PV-paneler og batterikapacitet blive bestemt til at maksimere brugen af PV-generationer og strømautonomi, minimere levetidskapitalomkostninger og tilbagebetalingsperiode, mens strømbalancebegrænsningen er opfyldt.

I den afsluttende fase foreslås en optimal energieffektiv styringsstrategi for et multi-renewable hybridt energisystem (RHES): efter bestemmelse af batterikapaciteten og

størrelsen af PV paneler samt løsning af det optimale driftsproblem for hver enkelt RHES, en optimeringsramme for strømstyring er udvidet for at minimere OPEX og opnå koordineret drift af det kooperative multi-RHES under hensyntagen til de tekniske begrænsninger.

ACKNOWLEDGMENTS

This dissertation summarizes the results of the Ph.D. project "PV-battery power supply for next-generation cellular telecommunication networks" conducted at AAU Energy, Aalborg University, Denmark. This Ph.D. project is funded by the European Union’s Horizon 2020 research and innovation program under the Marie Sklodowska-Curie grant agreement No 812991 and the PAINLESS project.

I would like to extend my gratitude towards my supervisor Associate Professor Tamas Kerekes for his valuable guidance, and patience during the study. I would also like to thank my co-supervisors Professor Josep M. Guerrero, Associate Professor Dezso Sera, and Associate Professor Sergiu Spataru for their guidance and help during the Ph.D. project. Thanks for giving me the opportunity to work under your supervision. I also appreciate all the support I received from Professor Claus Leth Bak and Professor Juan C. Vasquez during my stay at Aalborg.

I would also like to thank all my colleagues and secretaries at AAU Energy, and my friends for their support and kindness.

I would like to thank my husband Hamoun for his endless love all the way. Without his support, this project would not be possible.

Finally, I would like to express my gratitude to my parents and my siblings. Their encouragement has been the greatest support in many ways.

Mahshid Javidsharifi

Aalborg University, January 15, 2023,

TABLE OF CONTENTS

TABLE OF FIGURES

CHAPTER 1. INTRODUCTION

This chapter is devoted to the background, the motivations, research questions, objectives, and the limitations of the Ph.D. thesis. A list of main contributions as well as a concise presentation of the thesis outline is presented at the end.

1.1. BACKGROUND

As energy demand grows, renewable energy sources (RESs) are becoming more widely deployed to meet the demand and reduce the environmental impact of fossil fuels. While most renewable sources are advantageous, their intermittent nature remains a challenge that can be addressed through hybridization. Renewable-hybrid energy systems (RHES) combine batteries for the storage of energy, RESs, and the main grid for power generation [1]. The telecommunication network is one of the most important RHES in residential and commercial applications. Due to the high energy demand of the ICT industry (it is 3% of global annual energy demand and is even growing annually at a rate of 15%-20%) it is predicted that the carbon footprint from this industry will surpass 14% of the global footprint by 2040 [2].

Telecom providers, researchers, and government agencies face new challenges in providing next-generation cellular telecommunication network services to districts that do not have access to a reliable electricity grid. A promising solution is to apply solar-powered base stations in cellular telecommunication networks, especially in areas rich in solar resources but deficient in grid connectivity [3]. Applying solar-powered energy supply for base stations in telecommunication networks can both reduce carbon emission and operation costs compared to power from the main electricity grid or conventional energy sources [4].

The prospect of supplying base stations in telecommunication networks with photovoltaic (PV)-battery systems has been studied in the literature [5-14]. Some papers focused on the networks that were solely powered by RESs [5] while others studied grid-connected networks where there is an exchange link between the main electricity grid and the RES [6].

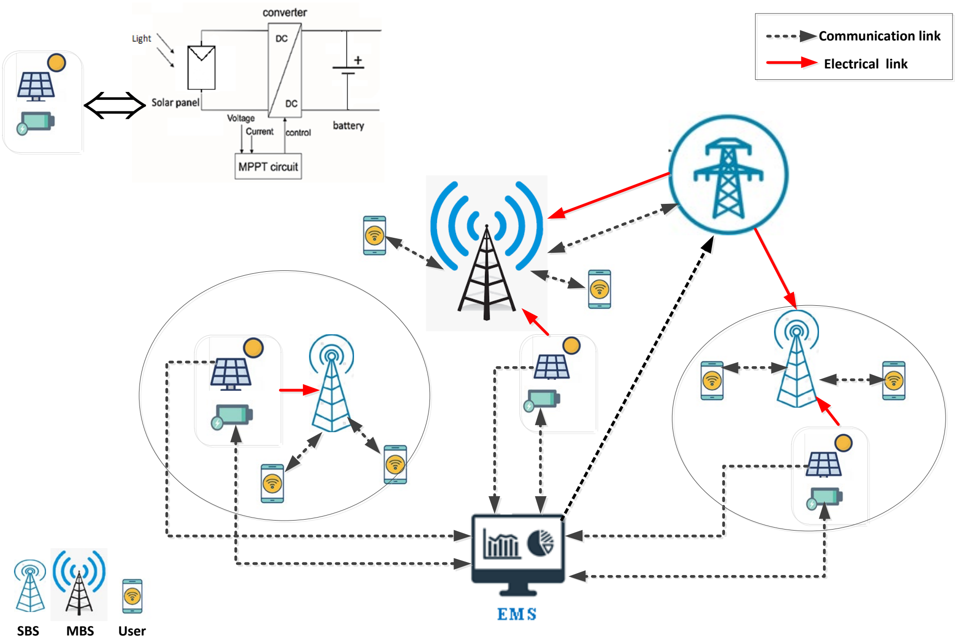


Fig. 1. 1. Configuration of a PV-battery powered next-generation cellular telecommunication network [J1].

A solar-powered base station is equipped mainly with PV panels, batteries, and converters. Consequently, determining the size of the PV-battery system is a crucial issue of research interest since under-dimensioning leads to frequent power outages. This is while over-dimensioning results in unnecessarily high capital costs [27]. Applying probabilistic models which consider the amount of energy produced by a PV panel, the amount of energy consumed by the base station, and the energy storage capacity is necessary for dimensioning the PV-battery power system of the base station [3].

On the other hand, with its quick and dynamic deployment, a drone (UAV)-based base station (DBS) can serve as a flying base station in a variety of situations. In public safety communication, for instance, where the ground infrastructure is subject to damage by natural disasters, an alternative solution is DBSs to provide coverage and connectivity. Due to their mobility, DBSs are more robust against sudden environmental changes [15, 41]. DBSs are also useful for temporary/unexpected high-traffic demand cases where infrastructures that have already been deployed become overloaded and require additional communication equipment to maintain the high quality-of-service (QoS) level. For example, in such big events as football games, Olympic Games, or concerts, it is unfeasible from an economical viewpoint to invest in the ground infrastructure for an approximately short duration [15, 41].

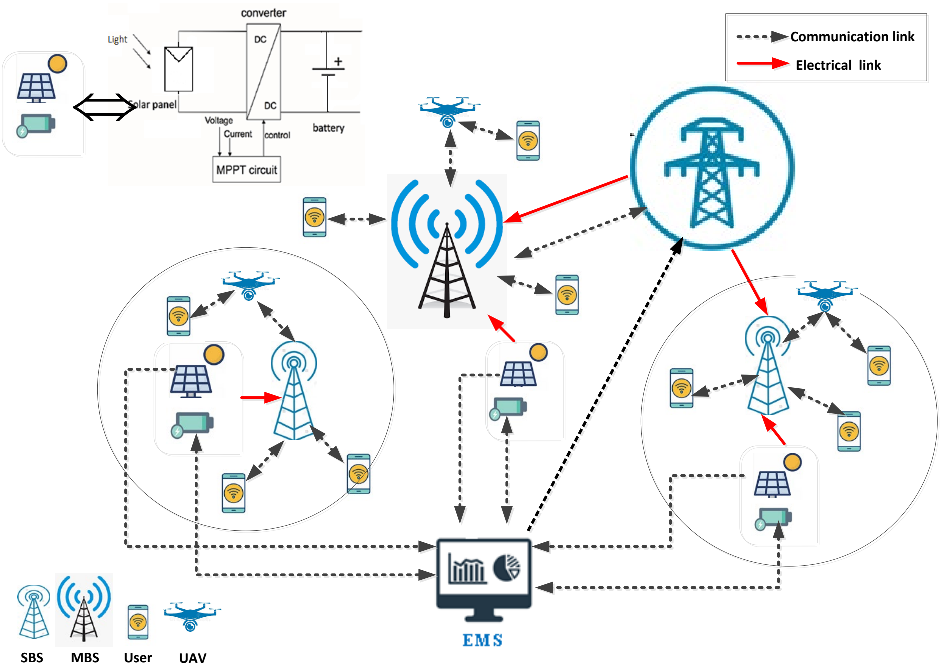


Fig. 1.2. Configuration of a UAV-assisted cellular telecommunication network powered by PV-battery systems [C3].

UAVs may improve the performance of telecommunication networks, but may also increase power demand, system costs, and carbon footprints. PV-battery power systems provide a sustainable solution for these problems. In addition to reducing dependency on the electricity grid, this approach can reduce carbon footprints resulting from increased load demand of telecommunication networks [16].

1.2. PROJECT MOTIVATION

An overview of the main studies related to solar-powered next-generation cellular telecommunication networks is provided in Table 1.1. Almost all the provided references in Table 1 focused on the PV-battery systems without investigating realistic, detailed, and scenario-specific energy modeling. Additionally, the ambient temperature effect, battery degradation, and feed-in tariff are not considered in their suggested models of power management. Therefore, to assess the power generation capability and energy storage capacity of PV-battery-powered base stations the Ph.D. project first defines realistic and case-specific scenarios combined with models of PV power generation and batteries. Afterward, an optimization scheme is suggested for determining the power rating of PV panels and battery capacity while the technical and economical constraints are satisfied to minimize both CAPEX and OPEX.

Moreover, a power autonomy factor is defined for the PV-battery system and is maximized as the second objective function.

The second phase of the Ph.D. is devoted to the UAV-based base stations in the next-generation cellular telecommunication networks which are powered by PV-battery systems. The power demand of the drones and their mission planning caused the determination of optimal sizing of the power supply system of the drone-based telecommunication networks be completely different from conventional structure [17]. Accordingly, the next step in this thesis is to derive the power demand profile of a drone-based cellular telecommunication network based on the mission planning of UAVs of [15]. Afterward, an optimal framework for determining the size of the PV-battery power supply for drone-based telecommunication networks in rural and urban regions is proposed to minimize the total cost, including capital and operational expenditures.

Table 1.1. Overview of some publications related to solar-powered next-generation cellular telecommunication networks - main discussed themes.

Ref.	**PV angle optimization**	**Temperature effect**	**Storage**	**Battery degradation**	**CAPEX**	**OPEX**	**Feed-in tariff**
[20&21]	✓		✓				
[22]			✓		✓		
[23]					✓	✓	
[24]			✓				
[25]			✓		✓		
[26-31]			✓		✓	✓	
[16&18]			✓			✓	
[19]						✓	

1.3. PROJECT OBJECTIVES AND LIMITATIONS

1.3.1. RESEARCH QUESTION AND OBJECTIVES

The general research question for this project is "How to establish an optimal energy-aware planning of RHESs for supplying next-generation cellular telecommunication networks?" Starting from the general question, the following sub-questions will be addressed in the study:

i. What is the optimal sizing method for the PV-battery power supply system to maximize the power autonomy factor and minimize the payback period of the studied RHES?
ii. What is the most suitable coordinated energy-efficient management strategy in a system consisting of cooperative multi-RHES?

To answer the selected research questions, the objectives can be summarized as follows:

i. Propose a systematic approach to achieve a self-sufficient and cost-effective PV-battery system to power the studied RHES: in the first step, through the suggested approach the optimal size and installation angle of PV panels and battery capacity will be determined to maximize the usage of PV generations and power autonomy, minimize the lifetime capital cost and payback period while the power balance constraint is satisfied. Afterward, based on the obtained results the techno-economical assessment of the studied RHES will be done.
ii. Propose an optimal energy-efficient management strategy for multi-RHES: after determining the battery capacity and the size of PV panels as well as solving the optimal operation problem for each single RHES, an optimization framework for power management will be developed to minimize OPEX and achieve coordinated operation of the cooperative multi-RHES considering the technical constraints.

1.3.2. PROJECT LIMITATIONS

- The first limitation regarding sizing PV-battery systems for base stations in a next-generation cellular telecommunication network is accessing the exact consumption profile of base stations. It will be more difficult when the UAVs are used as base stations. In the literature, there is no experimental power consumption of base stations in 5G mobile networks. Furthermore, all decisions regarding PV-battery configuration are based on the assumed power consumption profile in the rural and urban case studies.
- Regarding the current technology of UAVs, the maximum covering duration for telecom users by a UAV-based base station is about 30 minutes and after that, the UAV's battery must be recharged. So, for providing services there are multiple UAVs and the mission planning of these UAVs is needed. The quantification of the duration of each time slot in mission planning is a challenging question because it also defines the time slot in the power consumption profile. Moreover, the available time resolution for irradiation data to estimate PV generation and the 4G mobile network's base station is mostly equal to one hour.
- The assuming power consumption profile of a UAV-based base station is established based on optimal mission planning in [15] and it is considered as the input of our research. However, the dimensioning of the PV-battery system and the mission planning of the UAVs must be investigated in a united optimization framework based on the power-supplying system and telecom network indices and the technical constraints, simultaneously.

1.4. THESIS CONTRIBUTIONS AND OUTCOMES

1. Since powering base stations in cellular telecommunication networks with renewable energy sources can reduce the emission and cost and increase the power autonomy of the system, an optimal method for designing a PV-battery system to supply base stations in telecommunication networks is suggested in **Chapter 2**. To analyze the effect of solar availability on the optimal dimensioning of PV-battery system, the results are compared in three different locations.
2. In **Chapter 3**, sizing the PV-battery power supply system for droned-based base stations is investigated for two cases, namely, off-grid (in a rural area) and grid-connected (in an urban area) cellular telecommunication networks. The objective in both cases is to suggest an optimal approach to minimize the total cost, including capital and operational expenditures while the techno-economic constraints are satisfied.
3. **Chapter 4** extends the PV-battery-powered cellular telecommunication network to a multi-renewable hybrid energy system (RHES). An optimal power management framework and an efficient power dispatch strategy are proposed for the studied multi-RHES. The techno-economic and environmental indices are optimized through the considered optimization approach. To quantify the impact of different parameters on the optimal operation of the studied system, sensitivity analysis is done.

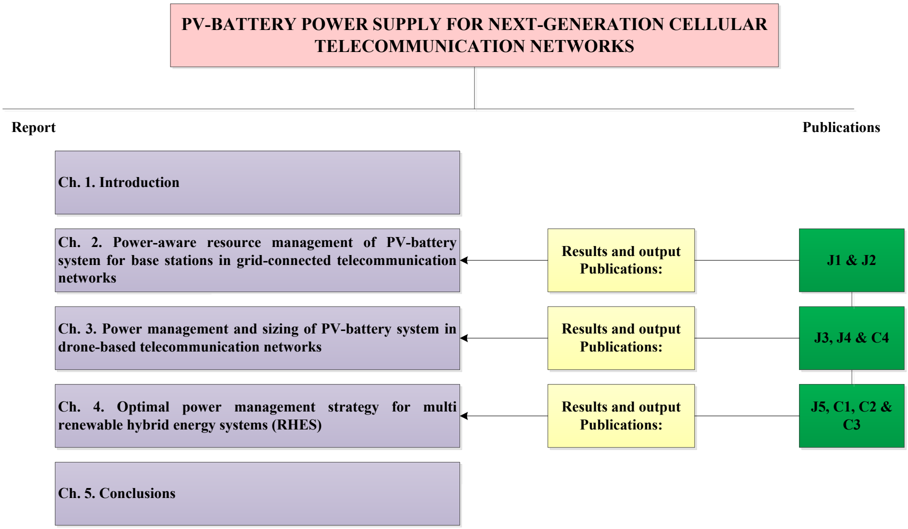


Fig. 1. 3. Thesis structure and related publications of each section.

1.5. THESIS OUTLINE

Since the Ph.D. thesis is written as a collection of papers, the thesis summary is followed by the PhD-related publications that are done during the period of the Ph.D. The thesis is organized into two major parts: “Report” and “Selected Publications.” A guideline of the connection of the content of the thesis to the selected papers is shown in Fig. 1.3. A summary of the managed research during the Ph.D. study is displayed in the report section, the main results of which are based on the selected publications. The report is structured into 5 chapters. The introduction, the background of the research, the motivation, and the objectives of the Ph.D. study are discussed in Chapter 1. Power management and sizing of PV-battery power supply systems for ground-based base stations in grid-connected telecommunication networks are studied in Chapter 2 where a power dispatch strategy is suggested to optimally size the PV-battery system. In Chapter 3, power management and sizing of PV-battery systems in drone-based telecommunication networks are investigated in two different case studies, namely, urban, and rural areas. Chapter 4 deals with the optimal power management strategy for multi-renewable hybrid energy systems (RHES). An efficient power dispatch strategy is proposed for optimal power management of RHESs, and a sensitivity analysis is done afterward to quantify the impact of different parameters on the optimal operation of multi-RHES. The main outcomes of the Ph.D. study, concluding remarks and potential future research works are finally summarized in Chapter 5.

1.6. LIST OF PUBLICATIONS

The dissemination of the Ph.D. study is some conference and journal papers as listed in the following.

1.6.1. PUBLICATIONS IN JOURNALS

J1. **Javidsharifi, M.**, Pourroshanfekr, H., Kerekes, T., Sera, D., Spataru, S., & Guerrero, J. M. (2021). Optimum sizing of photovoltaic and energy storage systems for powering green base stations in cellular networks. Energies, 14(7), 1895.

J2. **Javidsharifi, M.**, Pourroshanfekr Arabani, H., Kerekes, T., Sera, D., Spataru, S., & Guerrero, J. M. (2022). Effect of battery degradation on the probabilistic optimal operation of renewable-based microgrids. Electricity, 3(1), 53-74.

J3. **Javidsharifi, M.**, Pourroshanfekr Arabani, H., Kerekes, T., Sera, D., Spataru, S. V., & Guerrero, J. M. (2021). Optimum sizing of photovoltaic-battery power supply for drone-based cellular networks. Drones, 5(4), 138.

J4. Virgili, M., Babu, N., **Javidsharifi, M.**, Valiulahi, I., Masouros, C., J. Forsyth, A., Kerekes, T. & B. Papadias, C. (2022). Cost-Efficient Design of an Energy-Neutral UAV-Based Mobile Network. IEEE Transactions on Communications.

J5. **Javidsharifi, M.**, Pourroshanfekr Arabani, H., Kerekes, T., Sera, D., & Guerrero, J. M. (2022). Stochastic optimal strategy for power management in interconnected multi-microgrid systems. Electronics, 11(9), 1424.

1.6.2. PUBLICATIONS IN CONFERENCES

C1. **Javidsharifi, M.**, Pourroshanfekr Arabani, H., Kerekes, T., Sera, D., & Guerrero, J. M. Demand response planning for day-ahead energy management of CHP-equipped consumers, IEEE 4th GPECOM, 2022.

C2. **Javidsharifi, M.**, Arabani, H. P., Kerekes, T., Sera, D., & Guerrero, J. M. (2022, August), Quantifying the Impact of Different Parameters on Optimal Operation of Multi-Microgrid Systems. IEEE 7th Forum on Research and Technologies for Society and Industry, IEEE 7th RTSI, 2022.

C3. **Javidsharifi, M.**, Arabani, H. P., Kerekes, T., Sera, D., & Guerrero, J. M. (2022, October), Optimal Day-Ahead Power Management of AC-DC Microgrids. ICMECE 2022 2nd Interdisciplinary Conference on Mechanics, Computers, and Electrics.

C4. **Javidsharifi, M.**, Arabani, H. P., Kerekes, T., Sera, D., & Guerrero, J. M. (2022, September), PV-powered Base Stations Equipped by UAVs in Urban Areas. VTC2022-Fall IEEE 96th Vehicular Technology Conference.

CHAPTER 2. POWER-AWARE RESOURCE MANAGEMENT OF PV-BATTERY SYSTEMS FOR BASE STATIONS IN GRID-CONNECTED TELECOMMUNICATION NETWORKS

This chapter presents an optimum approach for sizing the PV-battery power supply systems for powering ground-based base stations in cellular telecommunication networks. Additionally, an efficient power dispatch strategy is suggested by applying which the dependency of the telecommunication network on the power grid will reduce and this results in the increase of the reliability of the system. The suggested approach is described briefly in this chapter and a detailed investigation is presented in publications J1 and J2.

2.1. INTRODUCTION

An optimal approach to designing a photovoltaic (PV)-battery system for supplying ground-based base stations in cellular networks is presented in J1. An efficient method is suggested to decide on the power rating of the PV generator and battery capacity while considering technical and economic aspects. Accordingly, two objective functions, namely the total cost and the power autonomy are defined and optimized. To verify the effectiveness of the suggested method, it is tested for sizing a PV-battery system in three different locations. The following sections focus on the details.

2.2. POWER MANAGEMENT AND SIZING OF PV-BATTERY SYSTEM IN GRID-CONNECTED TELECOMMUNICATION NETWORKS

The considered system in this chapter is the grid-connected cellular telecommunication network of Fig. 1.1, the base stations of which are also powered with PV-battery systems. First, the considered models for PV generation and battery energy storage are presented, and afterward, the problem formulation and the suggested approach for solving the optimal power management of PV-battery-powered base stations in the grid-connected cellular telecommunication network are introduced.

The suggested mathematical model for PV generation is as (2-1). It is worth mentioning that this model is more realistic compared to other models in the literature since the cell temperature and installation angles of the PV panels are also considered [J1].

$$\boldsymbol{P_{PV}^{t}} = \frac{\boldsymbol{I^{t}(\theta,\gamma) \times P_{PV}^{Peak} \times (1 + dp(T_{C}^{t} - 25))}}{\boldsymbol{1000}} \tag{2-1}$$

where P_{PV}^{t} is the hourly generated PV power, P_{PV}^{Peak} is the PV system rated power, $I^{t}(\theta,\gamma)$ is the received solar irradiance by the PV system, dp (%/°C) is the temperature coefficient considered equal to -0.4, and T_{C}^{t} is the cell temperature.

Since the RESs have intermittent nature, storage devices are integrated with these sources. To power the base stations in green cellular telecommunication networks the solar energy is first used, and the surplus energy is stored in the associated battery to be used during the hours that the PV panels cannot provide enough energy to supply the base stations. The considered constraints related to the battery are summarized as follows [J1, J2]:

$$SOC_{Batt,min} \leq SOC_{Batt}^{t} \leq SOC_{Batt,max} \tag{2-2}$$

$$SOC_{Batt}^{t} = SOC_{Batt}^{t-1} + \frac{\eta_{Ch}.P_{Ch}^{t}.\Delta t}{B_{cap}} + \frac{P_{Dch}^{t}.\Delta t}{\eta_{Dch}.B_{cap}} \tag{2-3}$$

$$P_{Ch,min} \leq P_{Ch}^{t} \leq P_{Ch,max} \tag{2-4}$$

$$P_{Dch,min} \leq P_{Dch}^{t} \leq P_{Dch,max} \tag{2-5}$$

where $SOC_{Batt,min}$, $SOC_{Batt,max}$, and SOC_{Batt}^{t} are the battery minimum and maximum *SOC* and the battery *SOC* at time *t*, respectively. P_{Ch}^{t}, P_{Dch}^{t}, B_{cap}, η_{Ch} and η_{Dch} are, respectively, the battery charge and discharge rates at time *t*, the battery capacity, and the battery charge and discharge efficiencies. $P_{Ch,min}$, $P_{Ch,max}$, $P_{Dch,min}$ and $P_{Dch,max}$ are the battery minimum and maximum charge and discharge rates, respectively.

To optimally benefit from the PV-battery power supply system of the base stations in the telecommunication network, two objective functions, namely the total cost and the power autonomy factor are defined as follows [J1]:

$$OF_{1} = \min\,(CAPEX + OPEX) \tag{2-6}$$

$$OF_{2} = max\left\{\left[\frac{1}{H}\sum_{t=1}^{H}\left(\frac{P_{PV2Load}^{t} + P_{Batt2Load}^{t}}{P_{Load}^{t}}\right)\right] \times 100\right\} \tag{2-7}$$

where $P_{PV2Load}^{t}$, $P_{Batt2Load}^{t}$ and P_{Load}^{t} are the hourly power share of PV and battery for supplying the base stations, and the hourly demand of the base stations, respectively. The main considered technical constraint is the following power balance constraint:

$$\boldsymbol{P_{PV}^{t} + P_{Batt}^{t} + P_{grid}^{t} = P_{Load}^{t}} \tag{2-8}$$

where P_{Batt}^{t} is the hourly power of the battery.

The suggested power dispatch strategy of Fig. 2.1. is applied to reduce the dependency of the telecommunication network on the main electricity grid. The multi-objective JAYA algorithm is then used to optimally decide on the dimension of PV-battery systems of the base stations while the total cost is minimized, and the power autonomy factor is maximized.

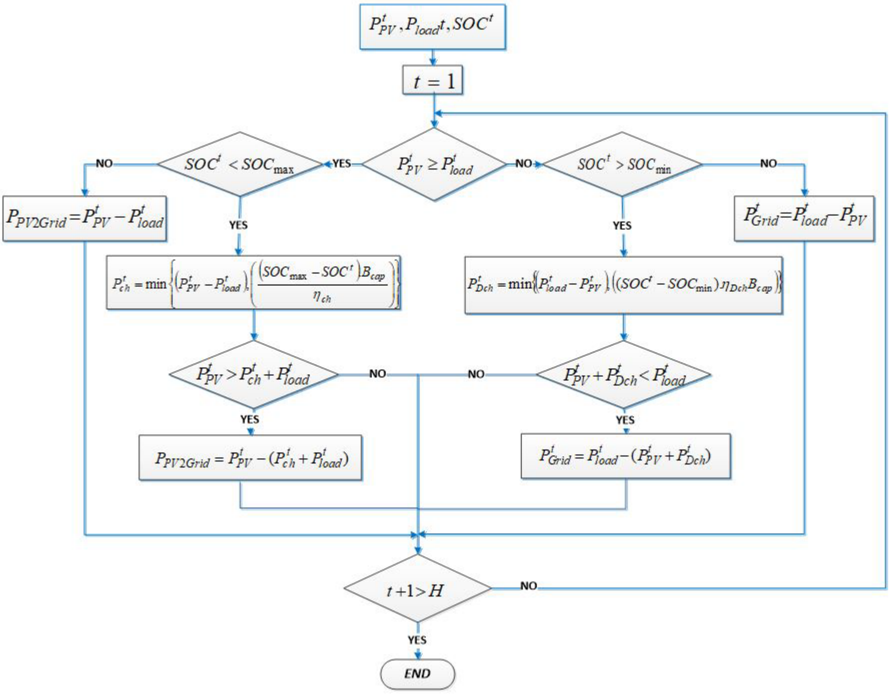


Fig. 2.1. Flowchart of the suggested power dispatch strategy [J1].

2.3. SIMULATION RESULTS AND DISCUSSION

Three different geographical locations (with different available solar irradiation,) Aalborg, Denmark, Malaga, Spain, and Boujdour, Morocco are considered as the case studies, and the efficiency of the suggested approach is verified by applying it to these case studies. The horizon of study is one year, and the time slot (one hour) and the hourly power consumption (kW) of base stations are considered the same as in [32]. The electricity tariffs, the yearly rental costs of the sites, and the ranges of the system variables are available in Tables 2.1, 2.2, and 2.3. The costs of PV panels and batteries are, respectively, equal to 1350$/kW$_p$ and 500$/kWh.

Table 2.1. Electricity tariffs.

Tariff Type	**Time (Hours)**	**Price ($\$/kWh$)**	
		Aalborg & Malaga	Boujdour
Peak	9-20	0.25	0.083
Off-peak	0-9, 20-24	0.23	0.077
Feed-in	0-24	0.1	0.033

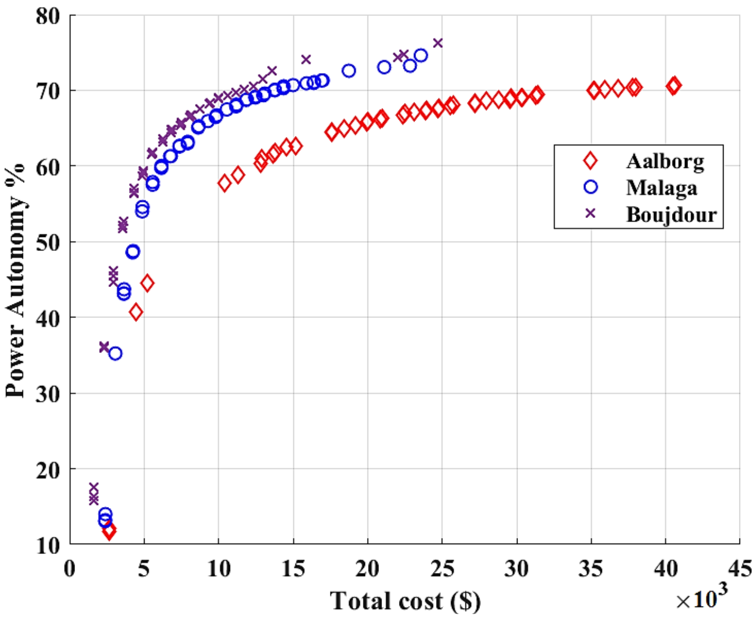
The Pareto-optimal front for different power autonomy factors for the three case studies for different levels of total costs for a PV-battery-powered base station in commercial and residential areas are shown in Figure 2.2. It is obvious from Figure 2.2, that the higher the total cost the higher the power autonomy factor, and vice versa. Based on Figure 2.2.a, to achieve the power autonomy factor of 70% in a commercial area in Aalborg, Malaga, and Boujdour, the total cost is 35000, 15000, and 12000 $, respectively. According to Figure 2.2.b. the maximum achievable power factor autonomy for Aalborg, Malaga, and Boujdour in a residential area is respectively 68%, 71%, and 73% and with the total cost equal to 35000, 24000, and 27700 $.

Table 2.2. Yearly rental costs of the base station sites.

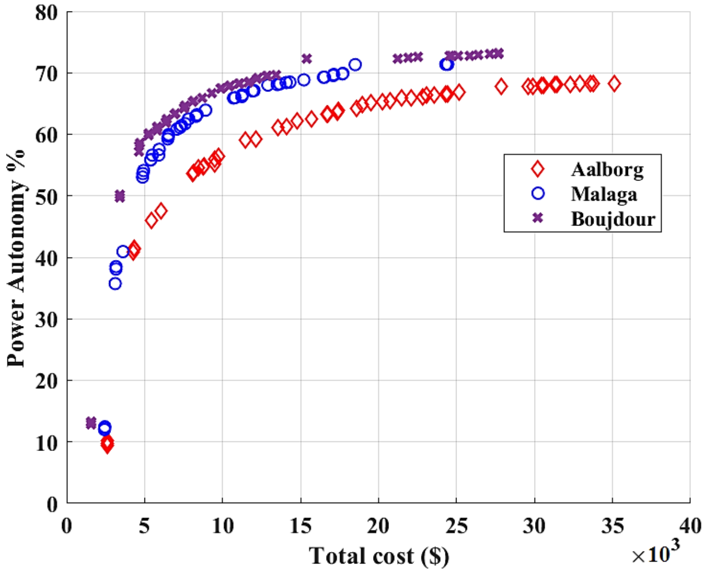
Rental Cost ($\$/m^2$)					
Aalborg		**Malaga**		**Boujdour**	
Residential	Commercial	Residential	Commercial	Residential	Commercial
100	200	50	100	33	66

Table 2.3. System variables and their ranges.

Variable	**Symbol**	**Unit**	**Range**
PV peak power	P_{PV}^{Peak}	kW_p	$(0 - 11.25)$
Azimuth angle	θ	degree	$(-90 - 90)$
Tilt angle	γ	degree	$(0 - 90)$
Battery capacity	B_{cap}	kWh	$(0 - 30)$
State of charge	SOC	%	$(10 - 90)$

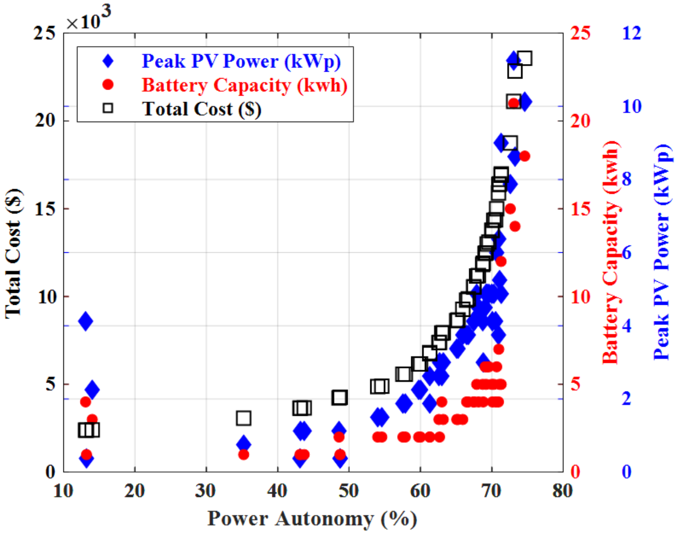


a. Commercial area.

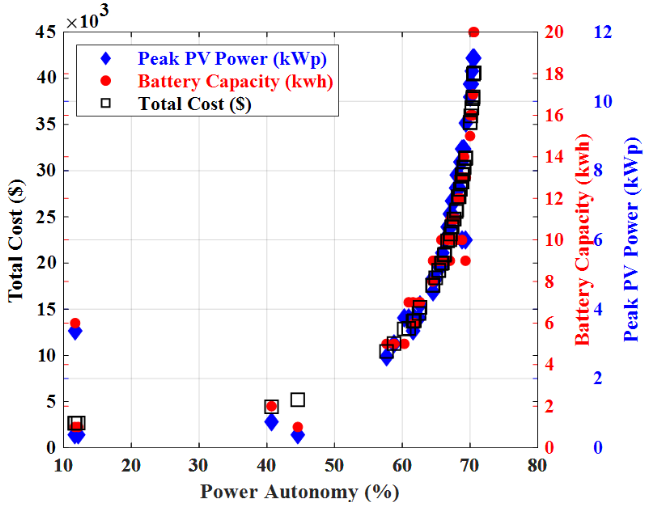


b. Residential area.

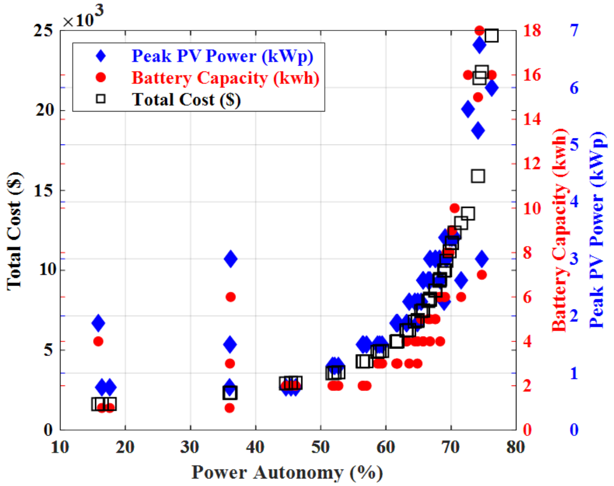
Figure. 2.2. Pareto-optimal front for different power autonomy factors for the three case studies for different levels of total costs for a PV-battery-powered base station in (a) commercial, and (b) residential areas.



a. Malaga.



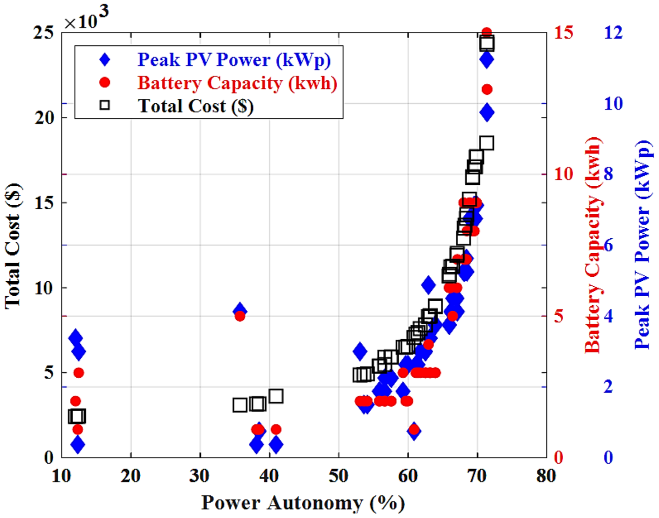
b. Aalborg.



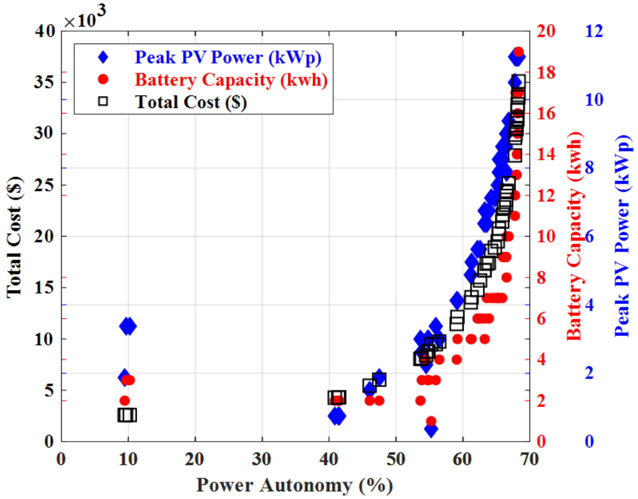
c. Boujdour.

Figure. 2.3. Total cost and power autonomy factor for a variety of PV panel installation areas and battery capacity values in a commercial area in (a) Malaga, (b) Aalborg, and (c) Boujdour.

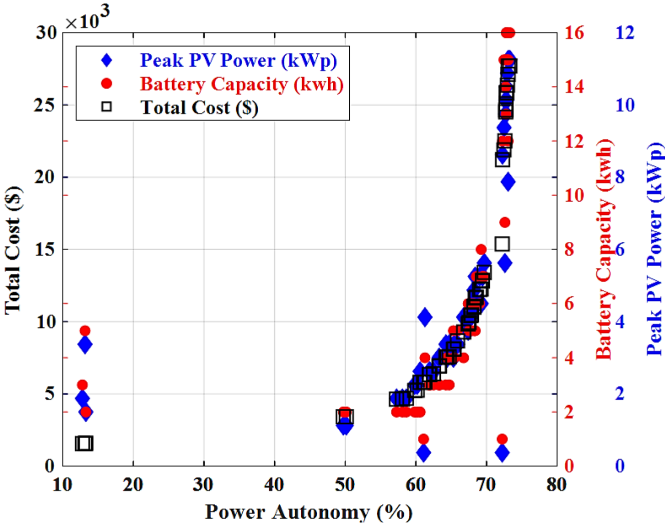
In Figure 2.3., the total cost and power autonomy factor for a variety of peak PV power and battery capacity values for Aalborg, Malaga, and Boujdour in a commercial area are shown. Based on Figure 2.3.b., to achieve 70% power autonomy, it is required to install a 4.9 kWp PV panel and a 15 kWh battery in Malaga, a 10.5 kW_p PV panel and a 15 kWh battery in Aalborg, and a 3.4 kW_p PV panel and a 9 kWh battery in Boujdour.



a. Malaga.



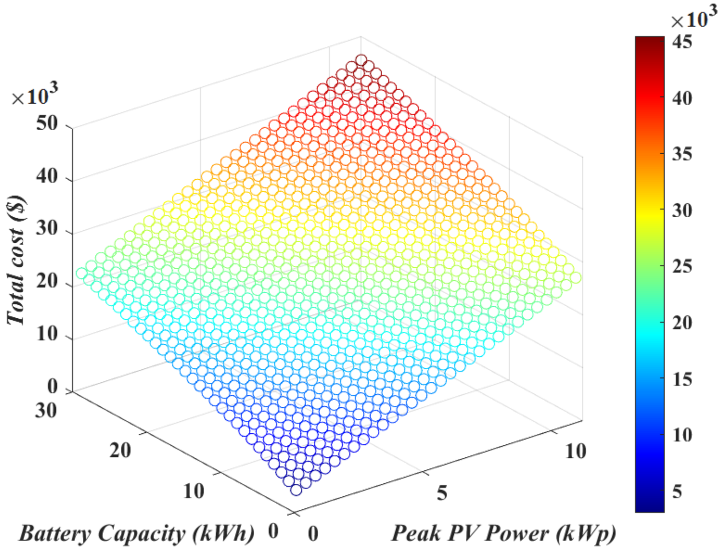
b. Aalborg.



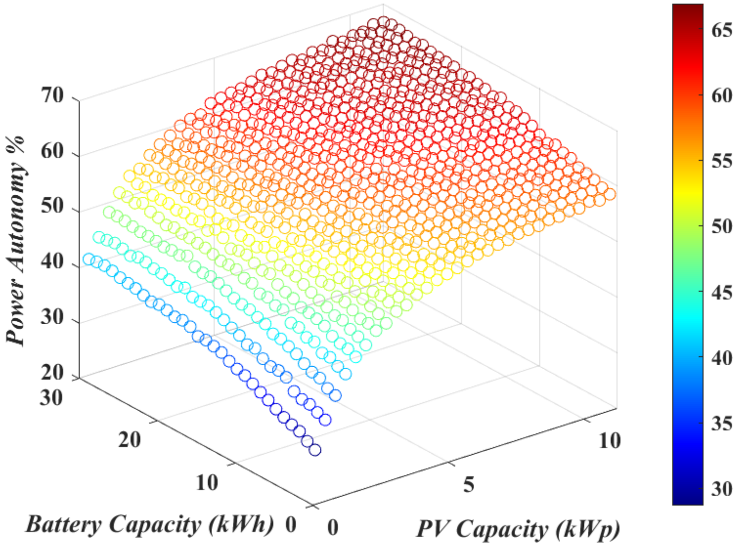
c. Boujdour.

Figure. 2.4. Total cost and power autonomy factor for a variety of PV panel installation areas and battery capacity values in a residential area in (a) Malaga, (b) Aalborg, and (c) Boujdour.

In Figure 2.4., the total cost and power autonomy factor for a variety of peak PV power and battery capacity values for Aalborg, Malaga, and Boujdour in a residential area are shown. Based on Figure 2.3.b., to achieve 68% power autonomy, it is required to install a 5.3 kW_p PV panel and a 9 kWh battery in Malaga, an 11.25 kW_p PV panel and a 19 kWh battery in Aalborg, and a 4.5 kW_p PV panel and a 5 kWh battery in Boujdour. The total cost for these installations will be 12900, 35000, and 10400 $, respectively for Malaga, Aalborg, and Boujdour.



a. Total cost.



b. Power autonomy factor.

Figure. 2.5. (a) Total cost, and (b) power autonomy factor for a variety of PV-battery system combinations to supply a commercial base station in Aalborg.

In Figure. 2.5. the annual total cost and the power autonomy factor for a commercial area in Aalborg are shown. Results are achieved for the range of PV peak power from 0 to 11.25 kW_p with an interval of 0.375 kW_p and the battery capacity from 0 kWh to 30 kWh. The azimuth and tilt angles of the PV panel are considered $-13^{\circ}$and 19°, respectively. It is observed that, since the two considered objectives, namely the total cost and the power autonomy factor conflict, the higher the former the higher will be the latter.

Another conclusion based on Figure 2. 5. is that when the battery capacity increases, installing a PV panel with a maximum peak power in a commercial area in Aalborg results in a higher total cost and the maximum power autonomy factor will not be enhanced.

2.4. SUMMARY AND CONCLUSIONS

This chapter presents an optimal approach for designing the PV-battery power supply systems of base stations in a grid-connected cellular telecommunication network. Two main considered objectives are minimizing the total cost and maximizing the power autonomy factor of the system while the constraints are satisfied. The spatial-temporal effect of the installation of the PV panels is investigated by applying the suggested approach to three different geographical locations. It can be concluded that to decide on the optimal PV-battery power supply system for base stations of cellular telecommunication networks the exact power generation of the power supply system and the consumption profiles of the base stations should be accessible. It is observed that to reach a power factor autonomy of 70% the total cost for Aalborg is three times that of Boujdour and two times that of Malaga. The results for achieving the highest economic design of the PV-battery system are dependent on the battery and PV panel technologies which affect the efficiency of the system.

CHAPTER 3. POWER MANAGEMENT AND SIZING OF PV-BATTERY SYSTEMS IN UAV-BASED TELECOMMUNICATION NETWORKS

This chapter presents an optimal approach for sizing the PV-battery power supply systems for powering UAV-based base stations in future cellular telecommunication networks. Two different scenarios, namely rural and urban areas are considered in this chapter. The suggested approach is described briefly in this chapter and a detailed investigation is presented in the publications J3, J4, and C4.

3.1. INTRODUCTION

To support Internet access for rural areas and regions without a reliable electricity grid and in conditions where the ground infrastructure is subject to damage by natural disasters, an alternative solution for mobile operators is drone-(UAV) based base stations (DBSs) to maintain coverage and connectivity. DBSs are also useful for temporary/unexpected high-traffic demand situations where infrastructures that have already been deployed become overloaded and require additional communication equipment to maintain the high quality-of-service (QoS) level.

In this chapter, an optimal framework for minimizing the cost of the PV-battery power supply for drone-based cellular networks in both rural and urban areas is proposed. First, the proposed approach is implemented in an off-grid cellular telecommunication network with DBSs that are powered by PV-battery systems-based recharging sites in a rural location. An optimal design of the PV-battery system is tested on three recharging stations for UAVs. The power consumption profiles of the recharging stations are derived from the results of [15]. The suggested approach is then applied to the UAV-assisted base stations in cellular telecommunication networks in urban areas.

3.2. OFF-GRID TELECOMMUNICATION NETWORKS WITH DRONE-BASED BASE STATIONS POWERED BY PV-BATTERY SYSTEMS

Fig. 3.1. shows the considered configuration of the off-grid UAV-aided cellular telecommunication network. Three recharging sites which are supplied with both the main electricity grid and PV-battery systems are considered in the configuration. Each UAV has an onboard battery to be able to take the required actions for providing

service to cellular telecommunication users and when this battery is discharged the UAV goes back to the recharging site to be charged. The same mathematical model for the PV-battery system as Chapter 2 is selected for the considered UAV-based telecommunication network. The detailed model of the PV-battery system of recharging sites is described in publication J3.

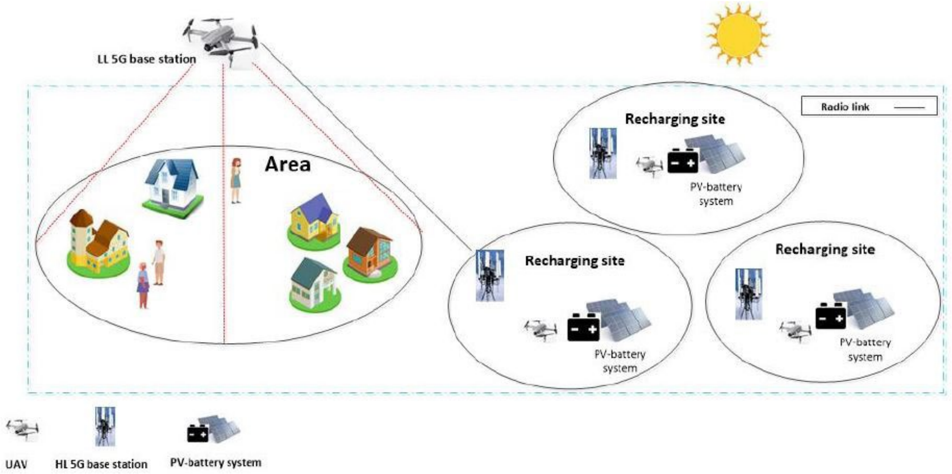


Fig. 3.1. Considered configuration of the off-grid UAV-aided cellular telecommunication network [J3].

UAVs can perform a set of actions, namely, staying, recharging, covering, and moving [33]. During the staying mode, UAVs do not consume any energy. To model the energy consumption of UAVs the mission planning of UAVs from [15] is considered and the energy consumption profile of each UAV in each recharging site is derived as follows. The PV-battery system provides the required energy for supplying the recharging stations.

The case study is a rural area with a population of 40000 [15]. As is observed in Fig. 3.2. there are eight zones (places to be covered by the UAVs) and three recharging sites in the location. Three places are both zones and recharging sites.

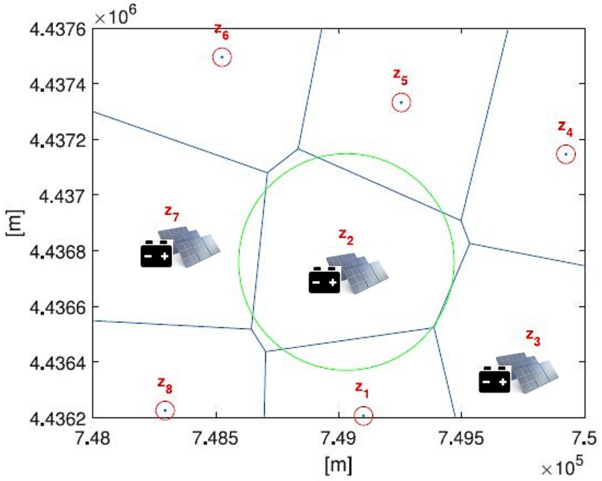
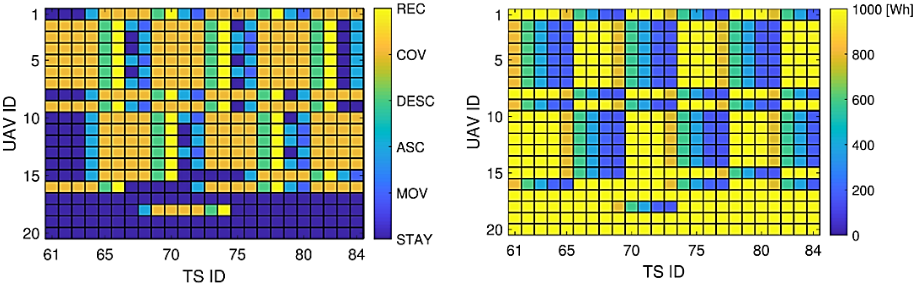


Fig. 3.2. Map of the studied scenario [15].

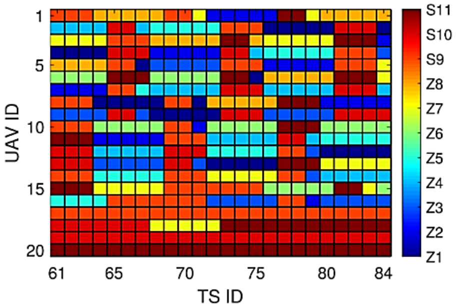
The first concern is "which UAV ID is recharging in which site and in which time slot during the horizon of study." The second concern is "what is the exact amount of energy level of each UAV ID when it arrives at each recharging site." Based on the above data the energy consumed in each time slot in each recharging site for the horizon of study is extracted.

To extract the above-mentioned information, based on Fig. 3.3. a. it can be concluded which UAV is recharging in which time slot. For example, in time slot 66, UAVs ID 2, 3, 4, 5, 6, 7, 9, and 16 are recharging in recharging sites. Then, from Fig.3.3. c. the sites in which these UAVs are recharging can be found (i.e., UAVs ID 3, 5, 7, and 16 are in recharging site 9; UAVs ID 2, 4, and 9 are in recharging site 10; UAV ID 6 is in recharging site 11). Tables 1 and 2, show that in each time slot which UAV is recharging in which site (sites 9, 10, and 11). Based on these data, for example, according to Table 2, in time slot 66, since UAVs ID 3, 5, 7, and 16 are recharging in site 9 the power which is consumed vs time slot in this site is 3200W (Fig. 3.4.). It is considered that each UAV requires 1000W to be charged when it is in recharging site (however, this is not a realistic assumption since when a UAV arrives at a recharging site the energy level of the UAV may not equal to zero). For other time slots and other sites, the same procedure is followed to achieve Fig. 3.4.



(a) Actions performed by each UAV

(b) Energy level of each UAV



(c) Positioning of each UAV.

Fig. 3.3. Actions, energy level, and positioning of each UAV [15].

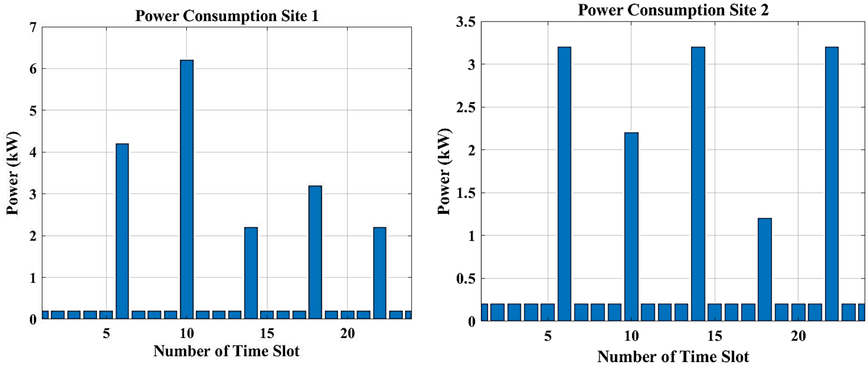
The considered objective function is minimizing the total cost of the PV-battery system of the recharging sites by optimizing the number of PV panels and batteries as follows, and the main technical constraint is the power balance constraint. The suggested framework for solving the optimization problem is shown in Fig. 3.5.

$$OF = \min\,(CAPEX + OPEX) \tag{3-1}$$

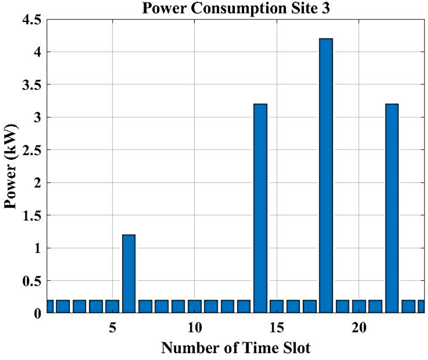
$$CAPEX = B_{cap}.Cost_{BAtt} + P_{PV}^{Peak} Cost_{PV} \tag{3-2}$$

$$OPEX = \sum_{t=1}^{H} OPEX_{Batt}^{t} \tag{3-3}$$

where $Cost_{BAtt}$, $Cost_{PV}$, H, and $OPEX_{Batt}^{t}$ are the battery unit cost in \$, the PV unit cost in \$/kW, the horizon of study, and the battery operational cost, respectively.



(a) Recharging site 1. (b) Recharging site 2.



(c) Recharging site 3.

Fig. 3.4. Extracted energy consumption profile for (a) recharging site 1, (b) recharging site 2, and (c) recharging site 3, vs the number of time slots [J3].

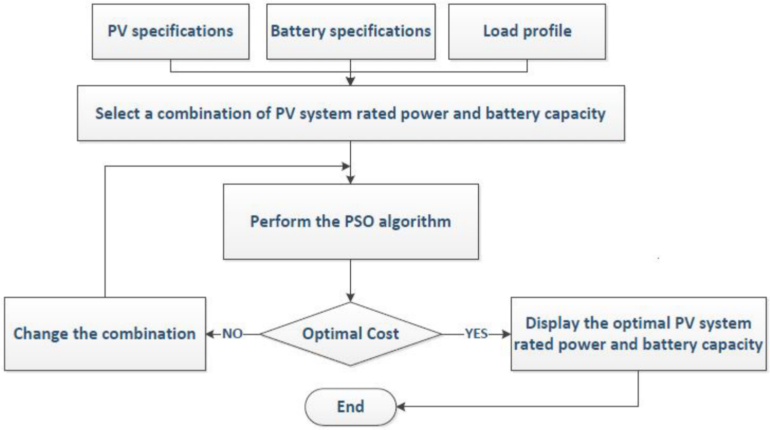
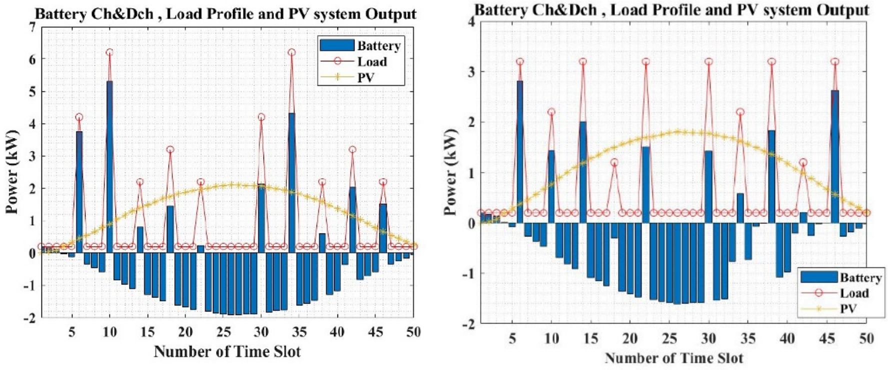


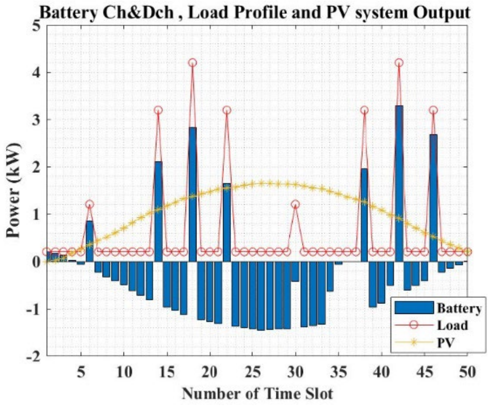
Fig. 3.5. Suggested framework for solving optimal economic PV-battery dimensioning of UAV recharging sites [J3]

Table 1. Time slots and location of UAVs' recharging modes

#UAV	REC TS	REC Site
UAV1	70, 78	**S3** (77, 78) / **S1** (69, 70)
UAV2	66, 74, 82	**S2** (65,66,81,82,83)/ **S1**(73,74,75)
UAV3	66, 74, 82	**S1** (65,66,67)/ **S3** (73, 74, 81, 82, 83)
UAV4	66, 74, 82	**S2** (65,66,67,73,74)/ **S1** (81,82,83)
UAV5	66, 74, 82	**S1** (65,66,73,74,75,81,82,83)
UAV6	66, 74, 82	**S3** (65,66,67,73,74,81,82,83)
UAV7	66, 74, 82	**S1** (65,66)/ **S2** (73,74,75,81,82,83)
UAV8	70, 78	**S1** (61,62,63,69,70)/ **S3** (77,78,79)
UAV9	66, 74, 82	**S2** (65,66,73,74,75,81,82,83,84)
UAV10	70, 78	**S1** (61,62,63,69,70)/ **S3** (77,78,79)
UAV11	70, 78	**S3** (61,62,63)/ **S9** (69,70,71)/ **S2** (77,78)
UAV12	70, 78	**S2** (61,62,63,69,70,71)/ **S1** (77,78)
UAV13	70, 78	**S2** (61,62,63,69,70)/ **S3** (77,78,79)
UAV14	70, 78	**S1** (61,62,63,69,70,71,77,78)
UAV15	70, 82	**S3** (61,62,63,81,82)/ **S1** (69,70,71,72,73,74,75)
UAV16	66, 78	**S1** (65,66,67,68,69,70,71,77,78)
UAV17	-	**S1**
UAV18	74	**S2** (61,62,63,64,65,66,67)/ **S3**(73→84)
UAV19	-	**S2**
UAV20	-	**S3**



(a) Recharging site 1. (b) Recharging site 2.



(c) Recharging site 3.

Fig. 3.6. Output power of the PV system, the battery charging/discharging power, and the load profile of recharging sites (a) 1, (b) 2, and (c) 3 [J3].

Based on the derived power consumption profile of Fig. 3.4. for the considered case study on the 24th of February the proposed framework is applied, and the following results are achieved [J3]. The complete range of systems variables is available in [J3].

Fig. 3.6. shows the resulting output power of the PV system, the battery charging/discharging power, and the load profile for the three recharging sites. According to this figure, it is observed that during the hours that the PV system cannot satisfy the load the battery is discharged to fulfill the demand.

Table 2. UAVs' recharging based on the number of sites and time slots

Site 1		Site 2		Site 3	
#TS	#UAV^{REC}	#TS	#UAV^{REC}	#TS	#UAV^{REC}
61		61		61	
62		62		62	
63		63		63	
64		64		64	
65		65		65	
66	3,5,7,16	66	2,4,9,	66	6
67		67		67	
68		68		68	
69		69		69	
70	1,8,10,11,14,15	70	12,13	70	
71		71		71	
72		72		72	
73		73		73	
74	2,5	74	4,7,9,	74	3,6,18
75		75		75	
76		76		76	
77		77		77	
78	12,14,16	78	11	78	1,8,10,13
79		79		79	
80		80		80	
81		81		81	
82	4,5	82	2,7,9	82	3,6,15
83		83		83	
84		84		84	

3.3. PV-POWERED BASE STATIONS EQUIPPED BY UAVS IN URBAN AREAS

In some temporary situations when the load demand increases unexpectedly (in big events such as football games, Olympic Games, or concerts,) and the existing telecommunication network cannot satisfy the QoS level DBSs are useful. It is specifically efficient from the economical point of view not to invest in ground-based infrastructure. Consequently, UAVs can support the ground base stations to provide the extra demand.

In this section, the power consumption of the UAVs' batteries is first estimated based on the mentioned method of Section 3.2, and the sensitivity analysis is then done to assess the effect of the PV-battery system dimensioning on a commercial urban area in Milano, Italy. The derived power consumption of batteries of UAVs is added to the load profile of the weekdays of the telecommunication network.

Fig. 3.7. compares the power consumption profiles of the telecommunication network with/without UAVs. The observed peaks in the power consumption profile of weekdays are related to the hours that the batteries of UAVs are charging.

A comparison of the total energy consumption of the base stations with and without the implementation of UAVs in the telecommunication network is shown in Fig. 3.8. According to this figure, the annual consumption grows 1.5 MWh when the UAVs are applied in the system.

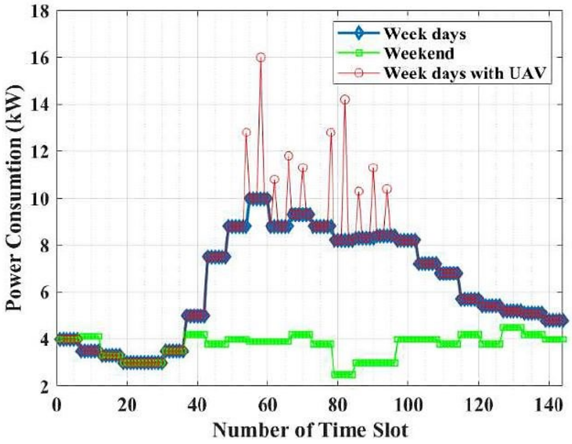


Fig. 3.7. power consumption profiles of the telecommunication network with/without UAVs [C4].

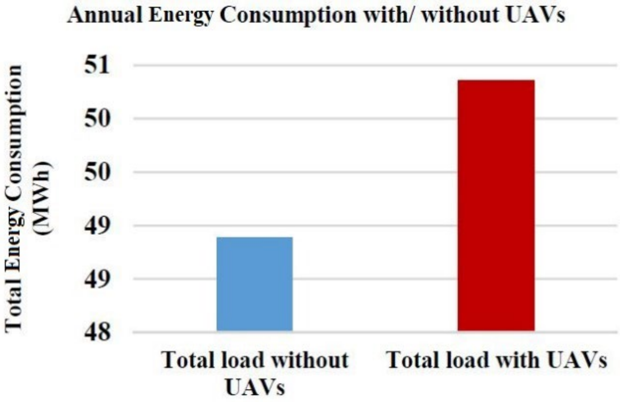


Fig. 3.8. Total yearly energy consumption of base stations with/without UAVs [C4].

Two different scenarios are considered to assess the impact of implementing PV systems and batteries on the UAV-assisted telecommunication network in the considered case study. Fig. 3.9. shows a comparison of the influence of applying different numbers of PV panels on the derived energy from the main electricity grid when there are only PV panels installed in the recharging sites.

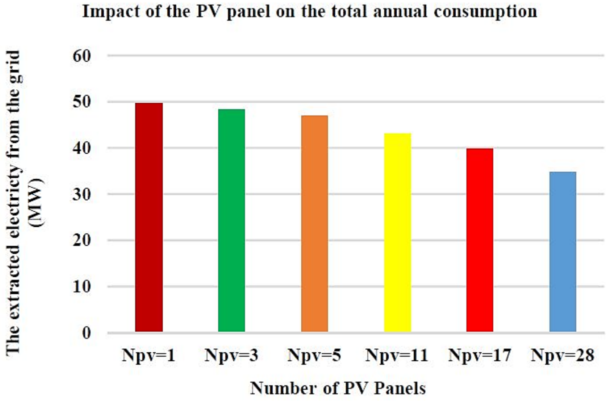


Fig. 3.9. Influence of applying different numbers of PV panels on the derived energy from the main electricity grid [C4].

In the second scenario, the influence of the incorporated PV-battery system in the recharging sites of UAVs is studied. When the rated power of PV panels is more than 3kW the batteries can store the extra PV power and this stored power can supply the load during high load demand hours. The influence of the different capacities and efficiencies of the battery on the derived energy from the electricity grid is compared in Figs. 3.10. and 3.11. According to Fig. 3.10. it is observed that (for a battery capacity of 50kWh) when the PV-battery system is implemented in the UAVs' recharging sites, the derived power from the electricity grid reduces respectively 16.7 MW and 1.1 MW compared to the case without any PV-battery system, and the case when only PV system is installed.

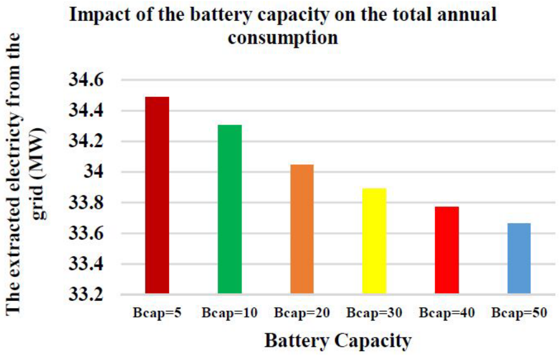


Fig. 3.10. Influence of different battery capacities on the derived power from the electricity grid [C4].

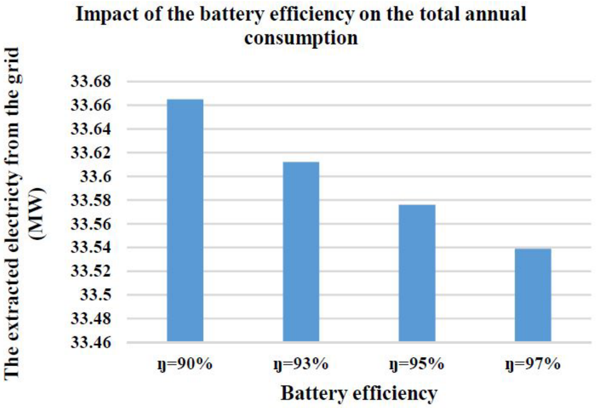


Fig. 3.11. Influence of different battery efficiencies on the derived power from the electricity grid [C4].

3.4. SUMMARY AND CONCLUSIONS

This chapter explains the power management and sizing of PV-battery systems in UAV-based telecommunication networks in both rural and urban areas. The objective is to minimize the total cost of the installed PV-battery systems in recharging sites of UAVs by optimizing the size of the system. A UAV-enabled cellular telecommunication network's power supply system must be optimized based on the power consumption profile of the UAVs and their mission planning, which differs significantly from conventional systems. Accordingly, the power consumption profile of a UAV-based cellular telecommunication network is derived based on the mission planning of UAVs. To minimize the total cost, including capital and operational expenditures, for UAV-enabled wireless networks in rural and urban areas, an optimal approach to sizing PV batteries is presented. For the case of urban areas, the optimal size of PV-battery system can be decided based on the sensitivity analysis. It can be concluded that the extracted power from the main electricity grid reduces significantly compared to the case without any PV-battery system, and the case when only PV system is installed.

CHAPTER 4. OPTIMAL POWER MANAGEMENT STRATEGY FOR RENEWABLE HYBRID ENERGY SYSTEMS

This chapter introduces an optimal strategy for the power management of microgrids as renewable hybrid energy systems (RHES). After determining the battery capacity and the size of PV panels as well as solving the optimal operation problem for each single RHES, an optimization framework for power management is extended to minimize OPEX and achieve coordinated operation of the cooperative multi-RHES considering the technical constraints. A detailed study of the suggested strategy is given in J5, C1, C2, and C3.

4.1. INTRODUCTION

Distributed generators (DGs) and the integration of renewable energy sources (RESs) into local distribution systems, in addition to DC power's advantages of decreasing power loss in transmission lines and controlling power flow, led to the reemergence of DC power [34, 35]. Combining AC and DC technologies in hybrid microgrids (MGs) facilitates integrating DC technologies into current AC systems [36]. In this configuration, both AC and DC networks are integrated into the same distribution network, which makes it possible to combine AC and DC distributed loads, storage units, and generators [37]. With this feature, future renewable sources or electric vehicles can be incorporated with minimal modifications to the current distribution network and costs can be reduced [38]. In hybrid MGs, AC and DC networks are connected through a bidirectional converter (BDC,) which allows power to flow between them and the power grid [34-38]. By linking AC and DC-powered appliances to the grid through these arrangements, fewer power electronic interfaces are necessary [34-38].

Considering the rapid development of MGs in distribution systems, the multi-microgrid (MMG) concept was proposed for the interaction and energy exchange among RHESs [39].

This chapter first studies the probabilistic optimal cost-efficient power management of a hybrid MG. Afterward, the proposed approach is extended to solve a multi-objective optimal probabilistic power management of MMGs to minimize the total cost and emission of the system. The sensitivity analysis is done to investigate the influence of different parameters on the MMG system operation.

4.2. OPTIMAL POWER MANAGEMENT OF HYBRID AC-DC MICROGRIDS

The considered structure of the hybrid AC-DC microgrid is shown in Fig. 4.1. A diesel generator (DE) unit, wind turbines (WT,) and AC loads are on the AC side while the DC side comprises a fuel cell (FC) unit, PVs, battery, and DC loads. A bidirectional converter connects the AC and DC sides of the hybrid MG. The considered objective is minimizing the following cost [C3]:

$$OF = min\left\{\sum_{t}^{T} Cost_{DE}^{t} + Cost_{FC}^{t}\right\} \tag{4-1}$$

where t and T are respectively the time slot and horizon of the study. $Cost_{DE}^{t}$and $Cost_{FC}^{t}$show the related costs to diesel generator and fuel cell (including the operational and start-up costs), respectively [C3].

Different technical constraints are considered in solving the optimal power management of the hybrid AC-DC MG including the constraint of the rate of production changes, the constraint of the minimum on/off time of units, battery limits, the power balance constraints in each DC, and AC sides of the hybrid MG. These constraints are completely discussed in [C3].

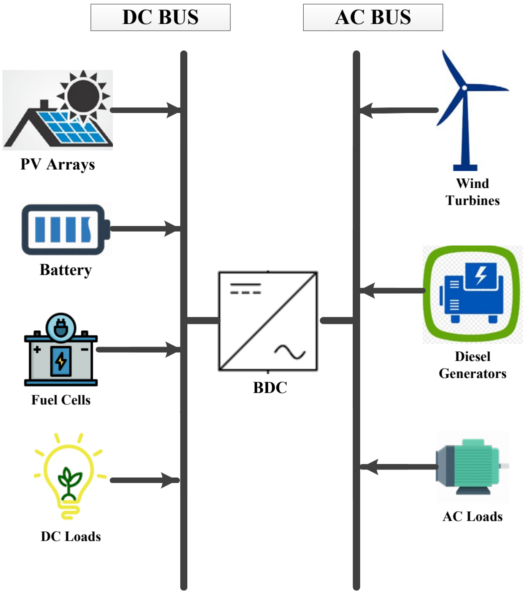


Fig. 4.1. Structure of the hybrid AC-DC microgrid [C3].

To solve the considered probabilistic optimal power management of the hybrid AC-DC MG the PSO-UT algorithm is suggested [C1, C3]. The parameters of the system are available in tables 4.1 to 4.4.

Table 4.1. Parameters of diesel generator unit

Unit	P_{Min} **(kW)**	P_{Max} **(kW)**	a ($\$/kWh^2$)	b ($\$/kWh$)	**c** *($)*	SUC *($)*	R^{up}/R^{down} *(kW)*	MUT/MDT **(h)**
Diesel generator	60	360	0.007	0.03	2.9	0.68	120	2

Table 4.2. Parameters of fuel cell unit

Unit	P_{Min} **(kW)**	P_{Max} **(kW)**	C_{NG} ($\$/m^3$)	Q_{LHV} (kWh/m^3)	**η** *(%)*	SUC *($)*	R^{up}/R^{down} *(kW)*	MUT/MDT **(h)**
Fuel cell	40	240	0.35	9.7	58	0.86	150	2

Table 4.3. Parameters of battery

Unit	$P_{Batt,Max}^{Ch/Dch}$ **(kW)**	$P_{Batt,Min}^{Ch/Dch}$ **(kW)**	$E_{Batt,Min}$ (kWh)	$E_{Batt,Max}$ (kWh)	η_{Batt} **(%)**
Battery	45	0	60	240	90

Table 4.4. Parameters of bidirectional converter

Unit	$P_{BDC,Max}(kW)$	$R^{up}/R^{down}(kW)$
Bidirectional converter	250	150

Two different scenarios, namely deterministic and probabilistic power management of a hybrid MG were investigated in [C3], however, the results of the probabilistic scenario are shown in this chapter.

To consider the impact of the uncertainties of AC and DC loads and the output power of PV and wind turbines on power management of a hybrid MG unscented transformation (UT) method is applied. It is assumed that the output power of renewable sources and the demanded loads adopt the normal distribution function. The mean value of the uncertain parameters is considered equal to their values in the deterministic scenario while the standard deviation is 10 % and there is a positive linear correlation among AC and DC loads. A review of the UT method is presented in [40].

Eight different scenarios of Table 4.5. are investigated and their operational costs are compared. It is observed from Table 4.5. that by increasing the output power of PV and WT units the operation cost decreases (Scenarios I and III.) It is also obvious that when the demanded load changes it has a significant impact on the operation cost of the MG. According to the comparison of the expected operation cost of the deterministic and probabilistic scenarios a standard deviation of 15 % is observed.

The results of solving the optimal probabilistic power management of AC and DC sides of the hybrid MG from averaging the eight scenarios are illustrated in Figs. 4.2. and 4.3.

Table 4.5. Considered solved scenarios by the UT method [C3]

Scenario	Operation cost ($)
The base case (deterministic)	965
Scenario I: increasing the output power of PV unit	949
Scenario II: decreasing the output power of PV unit	978
Scenario III: increasing the output power of WT unit	941
Scenario IV: decreasing the output power of WT unit	990
Scenario V: increasing the AC demanded load	1308
Scenario VI: decreasing the AC demanded load	704
Scenario VII: increasing the DC demanded load	1152
Scenario VIII: decreasing the DC demanded load	800
The mean value and standard deviation	974 ±144.7

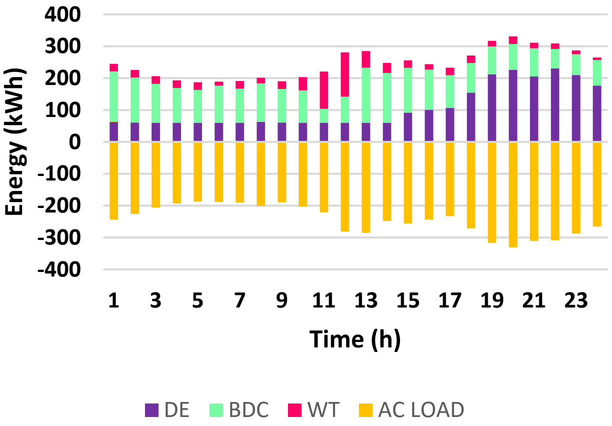


Fig. 4.2. Optimal power management of AC side of the hybrid AC-DC microgrid [C3].

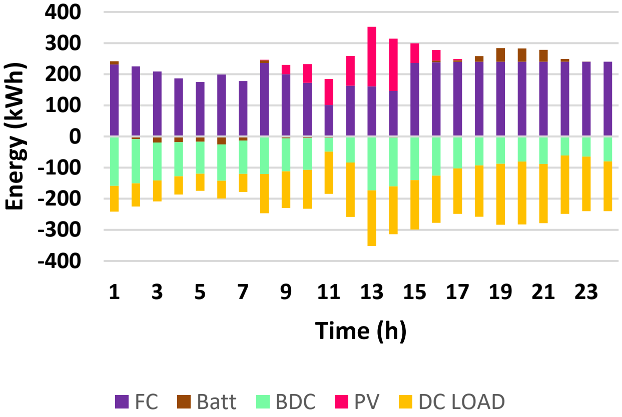


Fig. 4.3. Optimal power management of DC side of the hybrid AC-DC microgrid [C3].

4.3. OPTIMAL POWER MANAGEMENT OF MULTI-MICROGRID SYSTEMS

The studied structure of the on-grid multi microgrid system is shown in Fig. 4.4. Each MG comprises DEs, WTs, PV system, batteries, and local loads. The central energy management system (CEMS) is responsible to collect the data related to power consumption and generation and the state of the battery and to send the collected data to the dispatchable units (i.e., DEs.)

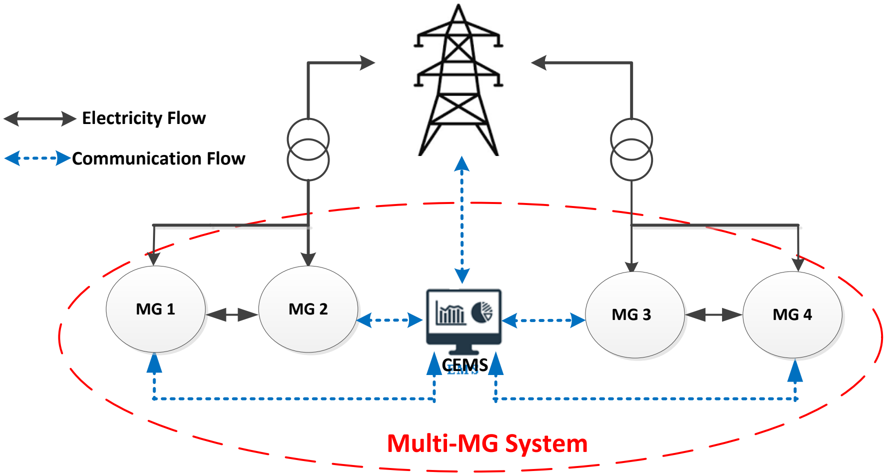


Fig. 4.4. Grid-connected multi microgrid system [C2].

Minimizing the operation cost and emission of the system are considered as the objectives as follows.

$$OF_1 = min\left(\sum_{n=1}^{N_p}\left\{\sum_{t=1}^{T}\left\{Cost_{DE}^{n,t} + P_{EX}^{n,t}B_{EX}^{t}\right\}\right\}\right) \tag{4-2}$$

$$OF_2 = min\left(\sum_{n=1}^{N_p}\left\{\sum_{t=1}^{T}\left\{P_{DE}^{n,t}E_{DE}^{t} + P_{EX}^{n,t}E_{EX}^{t}\right\}\right\}\right) \tag{4-3}$$

where T as the horizon of the operation is 24 hours, N_p is the number of PV panels. The hourly operation cost of diesel generators in \$ is $Cost_{DE}^{n,t}$. The shared power of the nth MG with the electricity grid in MW is represented by $P_{EX}^{n,t}$. The electricity price in \$/MWh is represented by B_{EX}^{t}.

The emission factor for each MWh of generated power of diesel generators in kg is shown by E_{DE}^{t}. The emission of one MWh of received power from the electricity grid in kg is represented by E_{EX}^{t}. The main considered technical constraints are the power balance and the power limit constraints [J5].

To analyze the influence of different parameters on the power management of MMG systems, PSO algorithm is applied while the deterministic scenario is considered [C2]. Results of the investigation of the influence of different battery efficiencies and maximum exchangeable power with the electricity grid on the optimal power management of MMG systems are shown in Figs. 4.5. and 4.6. A thorough study of the impact of the changes in the demanded load, the electricity price, the capacity of DE units, the maximum limit of the exchangeable power among MGs, and the rated power of renewable sources on the optimal power management of MMGs was carried out in [C2].

Fig. 4.5. shows the influence of the battery charging/discharging efficiency on the power management of the MMG system. According to Fig. 4.5. the increase of the battery efficiency results in a significant increase of the maximum achievable profit of the system.

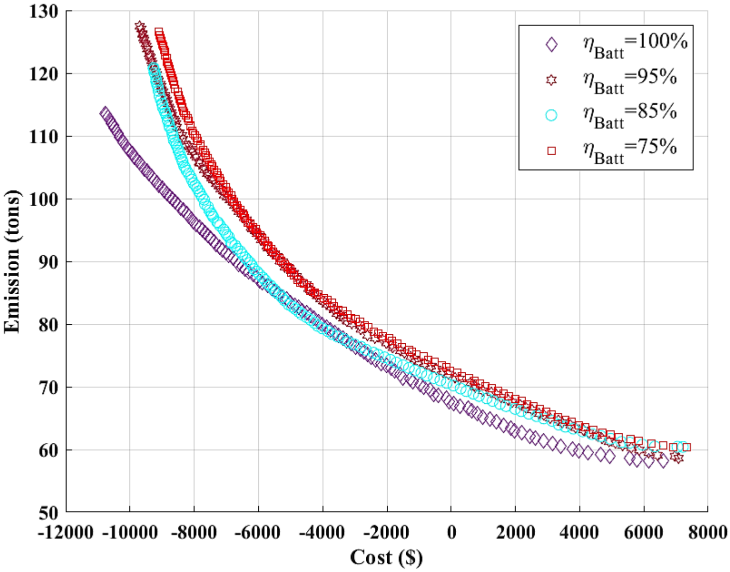


Fig. 4.5. Influence of different battery efficiencies on the optimal power management of MMGs [C2].

Fig. 4.6. shows the influence of the change in the maximum exchangeable power of MGs with the electricity grid on the optimal power management of MMGs. It is

observed that variations of +10% and +20% of the maximum exchangeable power, lead to an increase of 10% and 5% of the maximum achievable profit, respectively, while the variation of -10%, and -20% respectively lead to the reduction of 5% and 2% of the maximum achievable profit.

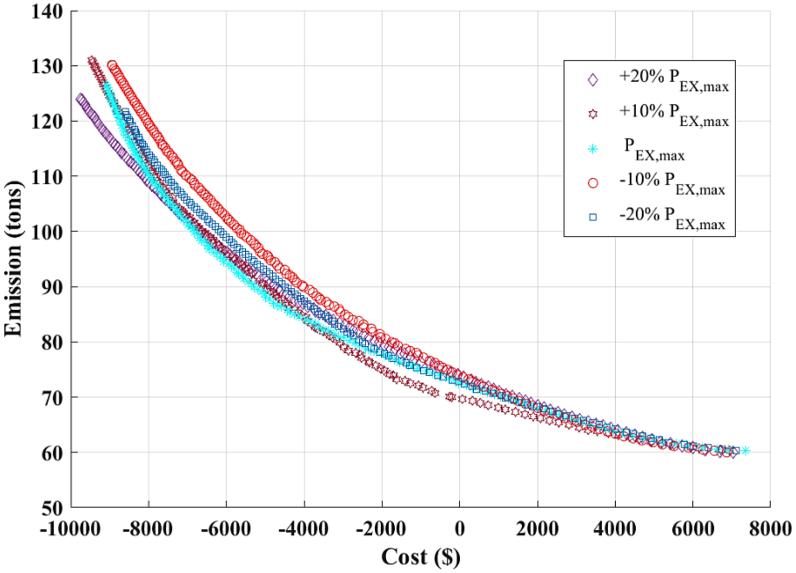


Fig. 4.6. Influence of changes in the maximum exchangeable power of MGs with the electricity grid on the optimal power management of MMGs [C2].

To solve the probabilistic optimal power management of MMG systems the multi-objective JAYA-UT algorithm is proposed. The flowchart of the suggested approach is shown in Fig. 4.7. while a detailed presentation of this method is discussed in [J5].

Two different scenarios, namely deterministic and probabilistic power management of an MMG system were studied in [J5] and detailed information of the considered case study and the parameters of the system are available in [J5]. Moreover, a thorough study of single objective power management of MMG systems was investigated and results were discussed in detail in [J5].

A comparison of the Pareto optimal solution of the multi-objective power management of a grid connected MMG system is shown in Fig. 4.8. It is shown that the impact of uncertainties on the operation cost of the system is more significant comparing to the emission. It is also observed that considering uncertainties on power management of MMG results in an increase of 23% of operation cost and 22% of emission.

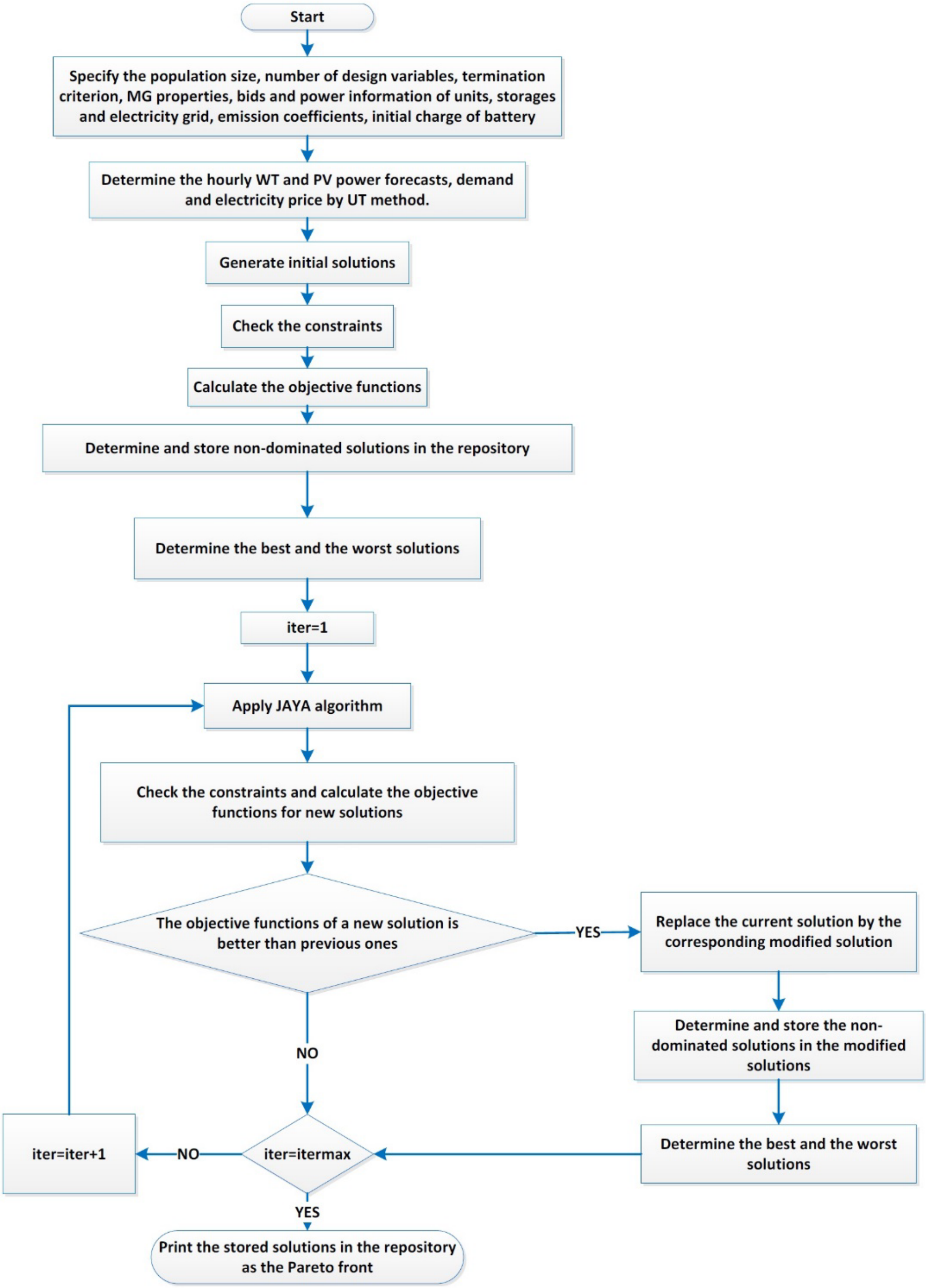


Fig. 4.7. Suggested UT-MJAYA for solving the probabilistic power management of MMG systems [J5].

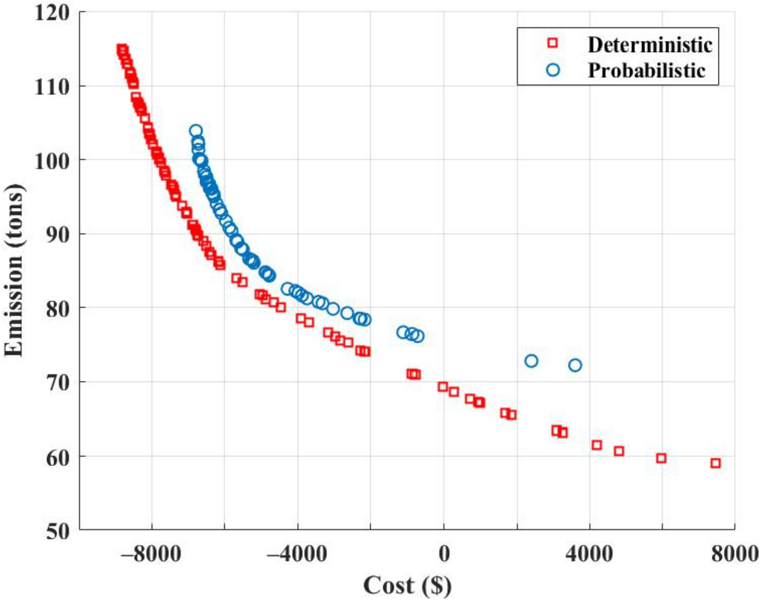


Fig. 4.8. Pareto optimal solutions of the multi-objective power management of a grid connected MMG system for deterministic and probabilistic scenarios [J5].

4.4. SUMMARY AND CONCLUSIONS

This chapter studies the optimal power management of renewable hybrid energy systems (RHESs). The objective functions are minimizing the operation cost and the emission. A single hybrid AC-DC MG is considered as the first case study and the probabilistic optimal power management of this system is solved by UT-PSO algorithm. It is observed that when the uncertainties of the variables including output power of RENSs, the load demand and the correlation among them are considered the results are more valid. The PSO algorithm is then applied to solve the deterministic optimal power management of multi-renewable hybrid energy systems (i.e., multi microgrids.) According to the sensitivity analysis of the parameters it is observed that the variation of different parameters has different influence on operation cost and emission. As an example, the variation of the capacity of RES units has considerable influence on the emission and it is why in the optimal power management of RHESs the main strategy is to take the more possible power from RESs. However, the variation of the demanded load has a considerable has a significant impact on cost and emission. To solve the probabilistic optimal power management of multi-renewable hybrid energy systems multi-objective JAYA-UT approach is suggested. Results show that the uncertainties have more impact on the operation cost of the system than on the emission.

CHAPTER 5. CONCLUSIONS AND FUTURE WORK

5.1. CONCLUSIONS

Next-generation cellular telecommunication networks require a higher density of base stations to satisfy the required latency and quality of service and mobile network operators (MNOs) must reduce their carbon footprints and energy consumption urgently. From the perspective of MNOs, this poses serious concerns about the sustainability and energy consumption of cellular telecommunication networks in the future. Currently, efforts are being made to reduce the electricity bills and carbon footprints of MNOs, such as powering base stations with photovoltaic (PV)-battery systems as a green and sustainable solution for next-generation cellular telecommunication networks.

This Ph.D. project carefully defines an accurate model for available PV output power generation estimation and realistic and case-specific scenarios combined with models of PV power generation and batteries for ground-based and drone-based base stations in future green next-generation cellular telecommunication networks. Efficient optimization frameworks are proposed to minimize the CAPEX and OPEX of the considered systems and techno-economic constraints are satisfied.

5.2. FUTURE WORK

Although using PV-battery systems reduces OPEX, it may increase CAPEX. Accordingly, there should be some initiatives to motivate MNOs to implement PV-battery systems as power supplies for base stations. Using retired batteries from electric vehicles (EVs) to power base stations in future telecommunication networks is a promising solution for disposing of massive amounts of batteries. The idea of repurposing the used batteries of EVs leads to a decrease in investment costs.

A second use of EV batteries in cellular telecommunication networks will have very impressive economic prospects since the technological level of batteries is improving, the application environment is maturing, and the process of dismantling and recovering batteries is improved. This will improve the efficiency of communication base station backup power services, as well as solve the problem of aged batteries from EVs. Cellular telecommunication networks will make a positive contribution to the promotion of EVs by using retired EV batteries.

Multiple base stations equipped with PV systems and battery units can participate in different demand response programs in active distribution networks (ADN), which is expected to be the best way to reduce the operation energy cost of base stations from MNOs and provide flexibility resources for the distribution system operator (DSOs).

It is anticipated that the increased use of base stations will lead to a more complex interaction between power distribution grids and next-generation telecommunication networks, including new markets for ancillary services. Increasing revenue streams for MNOs may be achieved by enabling base stations to participate in ancillary services markets, e.g., frequency reserves. But since the base stations belong to mobile network operators, it is difficult for the DSO to directly dispatch power to base stations to ensure the telecommunication quality service for telecom users and including user security and privacy leakage issues.

Nevertheless, some technical challenges need to be addressed first, such as optimizing base station portfolios to account for ancillary services markets, developing new coordination and operational schemes for a portfolio of base stations in next-generation cellular telecommunication networks, and increasing data exchange and interaction with DSOs and MNOs.

Due to the different solar irradiation and the distributions of telecommunication networks at different times and places, different level of flexibility appears in PV-battery-powered base stations in cellular telecommunication networks. Consequently, the power dispatch of these units will be difficult. Furthermore, if multiple base stations participate in different demand response programs (DRPs), the operational and maintenance costs of batteries increase which in turn decreases the participation enthusiasm of MNOs.

At the same time, the power demand of base stations in different places and at different times fluctuates considerably, and the uncertainty of the dispatchable capacity of the battery worsens due to the uncertainty of PV system generation and base station load. A major challenge will be to efficiently stimulate and measure the presence of base stations in DRPs. When multiple base stations are present in the DRPs, the batteries will over-discharge or the PV generation curtails due to the power imbalance between PV generation and power consumption of base stations. Furthermore, it will be more difficult to ensure the real-time energy balance because of the accurate prediction of PV generation and load demand and this leads to higher requirements on real-time power scheduling decisions.

The advances of PV-battery-powered base stations in future cellular telecommunication networks are relatively new, therefore, proposing an efficient optimal power dispatch of multiple PV-Battery-powered base stations participating in the DRPs is required.

According to the above-mentioned challenges, some suggestions for future work are summarized as the following:

1. Analysis of the performance status of retired EV batteries for powering base stations

The typical working conditions and application scenes of backup batteries in cellular telecommunication networks will be evaluated. Based on purchasing cost, installation and replacement cost, and electricity costs in the working process, a mathematical model will be developed for economic analysis of second-use EV batteries in base stations. Using the developed model, the economic impact of remaining cycle life on the operation and use of retired batteries as backup power supply systems for cellular networks will be explored.

2. How the energy coordination optimization of DSO and MNO results in a win-win agreement?

The DSO and the MNO are different entities, consequently designing a collaborative structure that guarantees both DSO and MNO will benefit through the optimization method is challenging. Additionally, a cooperative optimization scheme will be presented that can preserve the privacy and personal information of DSO and MNO.

3. Optimal dispatch strategy for multiple PV-Battery-powered base stations participating in the DRPs

Since the number of base stations is considerably high in next-generation telecommunication networks, the computational cost of co-optimizing with the DSO will be high for the MNO. In this regard, the power consumption profile of the base station and PV generation profile at the location of the base stations are identified in the first step. The objectives of power dispatch strategy optimization of base stations are the power balance between PV generated power and power consumption of base stations, through entirely using renewables which leads to the reduction of energy operational cost and maintaining the stability of the battery. When energy aggregators are considered carriers in the power-sharing scheme, base stations can coordinate with each other to engage in fulfilling power balance by simultaneously exporting and importing energy to and from energy aggregators. To propose an efficient online optimization algorithm for optimizing the energy sharing among base stations in real-time, the uncertain characteristics of the shared power of base stations should be considered.

LITERATURE LIST

1. M. F. Zia, E. Elbouchikhi, and M. Benbouzid, "Microgrids energy management systems: A critical review on methods, solutions, and prospects," Applied energy, vol. 222, pp. 1033-1055, 2018.
2. Han, D.; Li, S.; Peng, Y.; Chen, Z. Energy sharing-based energy and user joint allocation method in heterogeneous network. IEEE Access 2020, 8, 37077–37086.
3. H.-V. Tran, G. Kaddoum, P. D. Diamantoulakis, C. Abou-Rjeily, and G. K. Karagiannidis, "Ultrasmall cell networks with collaborative RF and lightwave power transfer," IEEE Transactions on Communications, vol. 67, pp. 6243-6255, 2019.
4. V. Chamola and B. Sikdar, "Solar powered cellular base stations: current scenario, issues and proposed solutions," IEEE Communications magazine, vol. 54, pp. 108-114, 2016.
5. M. A. Marsan, G. Bucalo, A. Di Caro, M. Meo, and Y. Zhang, "Towards zero grid electricity networking: Powering BSs with renewable energy sources," in 2013 IEEE international conference on communications workshops (ICC), 2013, pp. 596-601.
6. M. Meo, Y. Zhang, R. Gerboni, and M. A. Marsan, "Dimensioning the power supply of a LTE macro BS connected to a PV panel and the power grid," in 2015 IEEE International Conference on Communications (ICC), 2015, pp. 178-184.
7. F. Ahmed, M. Naeem, W. Ejaz, M. Iqbal, A. Anpalagan, and H. S. Kim, "Renewable energy assisted traffic aware cellular base station energy cooperation," Energies, vol. 11, p. 99, 2018.
8. M. H. Alsharif, J. Kim, and J. H. Kim, "Green and sustainable cellular base stations: An overview and future research directions," Energies, vol. 10, p. 587, 2017.
9. K. Kusakana and H. J. Vermaak, "Hybrid renewable power systems for mobile telephony base stations in developing countries," Renewable Energy, vol. 51, pp. 419-425, 2013.
10. A. M. Aris and B. Shabani, "Sustainable power supply solutions for off-grid base stations," Energies, vol. 8, pp. 10904-10941, 2015.
11. V. Khare, S. Nema, and P. Baredar, "Status of solar wind renewable energy in India," Renewable and Sustainable Energy Reviews, vol. 27, pp. 1-10, 2013.
12. J. Song, V. Krishnamurthy, A. Kwasinski, and R. Sharma, "Development of a Markov-chain-based energy storage model for power supply availability assessment of photovoltaic generation plants," IEEE Transactions on Sustainable Energy, vol. 4, pp. 491-500, 2012.
13. G. Leonardi, M. Meo, and M. A. Marsan, "Markovian models of solar power supply for a LTE macro BS," in 2016 IEEE International Conference on Communications (ICC), 2016, pp. 1-7. 15
14. V. Chamola and B. Sikdar, "Outage estimation for solar powered cellular base stations," in 2015 IEEE International Conference on Communications (ICC), 2015, pp. 172-1.
15. Galán-Jiménez, J.; Moguel, E.; García-Alonso, J.; Berrocal, J. Energy-efficient and solar powered mission planning of UAV swarms to reduce the coverage gap in rural areas: The 3D case. Ad Hoc Netw. 2021, 118, 102517.
16. Fletscher, L.; Suarez, L.; Grace, D.; Peroni, C.; Maestre, J. Energy-aware resource management in heterogeneous cellular networks with hybrid energy sources. IEEE Trans. Netw. Serv. Manag. 2019, 16, 279–293.
17. Amorosi, L.; Chiaraviglio, L.; Galan-Jimenez, J. Optimal energy management of UAV-based cellular networks powered by solar panels and batteries: Formulation and solutions. IEEE Access 2019, 7, 53698–53717.

18. L. Tang and H. Hu, "Multi-Objective Optimization of User Association in HetNets With Hybrid Power Supply," IEEE Transactions on Green Communications and Networking, vol. 3, pp. 933-941, 2019.
19. Á. F. Gambín, M. Scalabrin, and M. Rossi, "Online power management strategies for energy harvesting mobile networks," IEEE Transactions on Green Communications and Networking, vol. 3, pp. 721-738, 2019.
20. D. Benda, S. Sun, X. Chu, T. Q. Quek, and A. Buckley, "PV cell angle optimization for energy generation-consumption matching in a solar powered cellular network," IEEE Transactions on Green Communications and Networking, vol. 2, pp. 40-48, 2017.
21. D. Benda, S. Sun, X. Chu, A. Buckley, and T. Q. Quek, "PV cell orientation angles optimization for a base station equipped with several PV cells," IEEE Transactions on Green Communications and Networking, vol. 4, pp. 194-208, 2019.
22. D. Renga and M. Meo, "Dimensioning renewable energy systems to power mobile networks," IEEE Transactions on Green Communications and Networking, vol. 3, pp. 366-380, 2019.
23. M. A. de Souza, F. de Souza Farias, H. P. Kuribayashi, C. R. Francês, J. C. Costa, and D. L. Cardoso, "A Photovoltaic System for Heterogeneous Networks: a Technical, Economic and Environmental Analysis," Journal of Communication and Information Systems, vol. 35, pp. 90-102, 2020.
24. A. P. C. da Silva, D. Renga, M. Meo, and M. A. Marsan, "The impact of quantization on the design of solar power systems for cellular base stations," IEEE Transactions on Green Communications and Networking, vol. 2, pp. 260-274, 2017.
25. L. Chiaraviglio, L. Amorosi, N. Blefari-Melazzi, P. Dell'Olmo, A. L. Mastro, C. Natalino, et al., "Minimum Cost Design of Cellular Networks in Rural Areas With UAVs, Optical Rings, Solar Panels, and Batteries," IEEE Transactions on Green Communications and Networking, vol. 3, pp. 901-918, 2019.
26. R. Kaur, V. Krishnasamy, N. K. Kandasamy, and S. Kumar, "Discrete multiobjective grey wolf algorithm based optimal sizing and sensitivity analysis of PV-wind-battery system for rural telecom towers," IEEE Systems Journal, vol. 14, pp. 729-737, 2019.
27. S. Suman and S. De, "Low complexity dimensioning of sustainable solar-enabled systems: A case of base station," IEEE Transactions on Sustainable Computing, 2019.
28. A. Jahid, M. K. H. Monju, M. E. Hossain, and M. F. Hossain, "Renewable energy assisted cost aware sustainable off-grid base stations with energy cooperation," IEEE Access, vol. 6, pp. 60900-60920, 2018.
29. N. Piovesan, D. A. Temesgene, M. Miozzo, and P. Dini, "Joint load control and energy sharing for autonomous operation of 5G mobile networks in micro-grids," IEEE Access, vol. 7, pp. 31140-31150, 2019.
30. A. Jahid, M. S. Hossain, M. K. H. Monju, M. F. Rahman, and M. F. Hossain, "Techno-economic and energy efficiency analysis of optimal power supply solutions for green cellular base stations," IEEE Access, vol. 8, pp. 43776-43795, 2020.
31. A. Jahid, M. S. Islam, M. S. Hossain, M. E. Hossain, M. K. H. Monju, and M. F. Hossain, "Toward energy efficiency aware renewable energy management in green cellular networks with joint coordination," IEEE Access, vol. 7, pp. 75782-75797, 2019.
32. Da Silva, A.P.C.; Renga, D.; Meo, M.; Marsan, M.A. The impact of quantization on the design of solar power systems for cellular base stations. IEEE Trans. Green Commun. Netw. 2017, 2, 260–274.

33. Babu, N., Virgili, M., Al-jarrah, M., Jing, X., Alsusa, E., Popovski, P., ... & Papadias, C. B. (2022). Energy-Efficient Trajectory Design of a Multi-IRS Assisted Portable Access Point. IEEE Transactions on Vehicular Technology.
34. S. Ali, Z. Zheng, M. Aillerie, J.-P. Sawicki, M.-C. Péra, and D. Hissel, “A Review of DC Microgrid Energy Management Systems Dedicated to Residential Applications.” Energies, vol. 14, no. 14, p. 4308, 2021.
35. S. K. Sahoo, A. K. Sinha, and N. Kishore, "Control techniques in AC, DC, and hybrid AC–DC microgrid: a review," IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 6, pp. 738-759, 2017.
36. S. Bahramirad, Review of the AC/DC microgrid operation and control: Illinois Institute of Technology, 2016.
37. K. Gong, X. Wang, C. Jiang, M. Shahidehpour, X. Liu, and Z. Zhu, “Security-Constrained Optimal Sizing and Siting of BESS in Hybrid AC/DC Microgrid Considering Post-Contingency Corrective Rescheduling.” IEEE Transactions on Sustainable Energy, vol. 12, no. 4, pp. 2110-2122, 2021.
38. P. T. Baboli, M. Shahparasti, M. P. Moghaddam, M. R. Haghifam, and M. Mohamadian, "Energy management and operation modelling of hybrid AC–DC microgrid," IET Generation, Transmission & Distribution, vol. 8, pp. 1700-1711, 2014.
39. E. Taherian-Fard, T. Niknam, R. Sahebi, M. Javidsharifi, A. Kavousi-Fard, A., and J. Aghaei, “A Software Defined Networking Architecture for DDoS-Attack in the Storage of Multimicrogrids.” IEEE Access, 10, 83802-83812, 2022.
40. M. Javidsharifi, T. Niknam, J. Aghaei, M. Shafie-khah, and J. P. S. Catalao, “Probabilistic Model for Microgrids Optimal Energy Management Considering AC Network Constraints.” IEEE Systems Journal, vol. 14, no. 2, pp. 2703-2712, 2020.
41. A. Alsharoa, H. Ghazzai, A. Kadri, and A. E. Kamal, “Energy management in Cellular Hetnets Assisted by Solar Powered Drone Small Cells.” In 2017 IEEE Wireless Communications and Networking Conference (WCNC) (pp. 1-6). IEEE, 2017.

ISSN (online): 2446-1636
ISBN (online): 978-87-7573-760-4

AALBORG UNIVERSITY PRESS