PAINLESS

D3.1 – Energy models and optimisation frame-work: phase 1

Grant agreement no. 812991
H2020-MSCA-ITN-2018

ITN - Innovative Training Network

D3.1 – Energy models and optimisation frame-work: phase 1

WP 3 - Research Programme

Due date of deliverable: Month 18

Actual submission date: 20 / 03 / 2020

Start date of project: 01 / 10 / 2018   Duration: 48 months

Lead beneficiary for this deliverable: UCL

Last editor: Marco Virgili

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Dissemination Level		
PU	Public	✓
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

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History table

Version	Date	Released by	Comments
V1	09.03.2020	Marco Virgili, Mahshid Javidsharifi, Iman Valiulahi	Initial version
V2	11.03.2020	Christos Masouros	Review
V3	24.03.2020	Tamas Kerekes, Nithin Babu	Review
V4	25.03.2020	Pete James	Review

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Key word list

Energy models, Optimisation, 5G, Telecommunications, Energy storage, UAV, Energy autonomy, Energy harvesting

Definitions and acronyms

Acronyms	Definitions
AWGN	Additive white Gaussian noise
BS	Base Station
CB	Charging Base
DoD	Depth of Discharge
EH	Energy Harvesting
EMS	Energy Management System
ESR	Early Stage Researcher
ESS	Energy Storage System
GUI	Graphical User Interface
IoT	Internet of Things
MSL	Mean Sea Level
PAINLESS	Energy-autonomous portable access points for infrastructure-less networks
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
QoS	Quality of Service
SC	Supercapacitor
SCP	Sequential Convex Programming
SINR	Signal-to-interference-plus-noise ratio
SoC	State of Charge
UAV	Unmanned Aerial Vehicle

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1.   Introduction

This first (of two) phase of energy models and optimisation framework report is developed as part of the energy-autonomous portable access points for infrastructure-less networks (PAINLESS) project, which has received funding from the European Union, within the H2020 Marie Skłodowska-Curie Innovative Training Networks (ITNs) framework, under the 812991 Grant Agreement.

This report corresponds to Deliverable 3.1 of Work Package 3 (WP3) Research Programme, aiming at advertising PAINLESS breakthroughs with the public. More in detail, Deliverable 3.1 revolves around describing the energy models established in the first months of the project, that will provide a solid base for future developments on the path towards energy neutrality.
Energy neutrality for portable access points is an ambitious goal that could only be reached through several sub-goals, somehow intertwined:

1) Generating enough energy on-site to maximize energy autonomy from the power grid. The technology that will allow this is energy harvesting (EH) in its several declinations: photovoltaic modules, windmills, piezometric generators and more. Depending on the scenario, these could be installed directly on-board or serve as a recharging station. Our focus is on solar energy harvesting using photovoltaic modules coupled with an energy storage system.
2) Reducing the energy consumed by the supporting devices, especially in the case of energy-hungry ones, such as UAVs (Unmanned Aerial Vehicles). This can be accomplished by optimising the use of these devices, considering how different parameters (altitude, velocity, weight…) affect their energy consumption.
3) Providing a reliable source of electricity at any given time, to reduce the dependency from power oscillations of the primary energy source. This will be done by adopting Energy Storage Systems (ESS) with great enough capacity to make up for the aforementioned oscillations, while at the same time avoiding over-sizing, that would compromise the portability of the system. Depending on the scenario, such systems could differ in number and nature, thus requiring different models.
4) Joint optimization of the above energy aspects with communications operation, through balancing the energy consumed against the energy harvested and stored, and by developing energy-aware optimization of communications and UAV parameters (transmit power, UAV trajectory, UAV placement…) to maximise the energy autonomy of the communications Base Stations (BSs) from the power grid.

In Section 2, an overview over the general system of reference will be provided, so that the reader can get an idea of the context of application for the eventual PAINLESS outcomes. The final paragraph will also highlight the novelty of the work within PAINLESS.

Section 3 will give a brief description of the specific scenarios so far considered, narrowing the system to more targeted real-life applications. This will also give an idea of how broad the range of possibilities really is, once one starts matching all available technologies of energy harvesting, telecommunications, energy storage and other aspects.

Sections 4, 5 and 6 will focus on providing detailed explanations regarding all the models elaborated so far for energy harvesting, storage and balancing, respectively. A literature review of each topic will be displayed at the beginning of every section, highlighting the gaps PAINLESS aims to fill and then explaining how this is being done.

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Section 7 will analyse what still needs to be done in order to eventually accomplish the ambitious objectives established by PAINLESS and will describe the opportunities of improvement of the models, as well as their eventual applications and how they will contribute to PAINLESS.

Finally, Section 8 will draw some conclusions about the overall state of PAINLESS research on energy models, briefly synthesising this report.

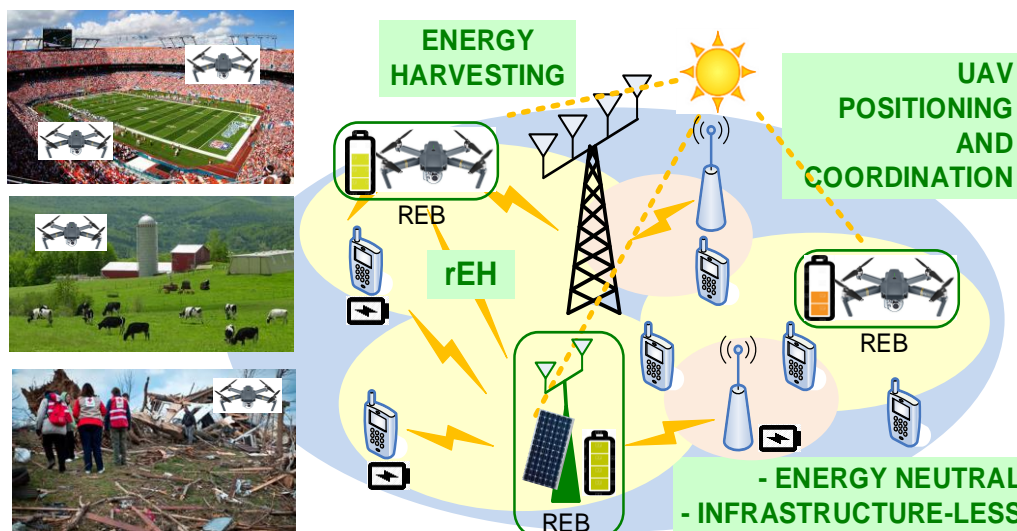## 2. System description

Fig. 1: A high-level diagram of the PAINLESS system model

The system under study cannot be described too specifically since several scenarios are considered, as exposed in Section 3. Nevertheless, a generic system can still be identified through the extended name of the project: energy-autonomous portable access points for infrastructure-less networks.
The core of this sentence is "networks", meaning that this system's main function is to create or expand a connectivity network, exploiting the 5G technology currently under deployment worldwide. This new standard is increasing both the quantity and the quality of data exchange, opening the path to several new mobile applications that were until now only possible with the use of fibre optics-based telecommunications.

The definition "infrastructure-less" is interconnected with the term "energy-autonomous", since connectivity cables are not the only infrastructure needed by these networks: they also need a source of energy. Energy is indeed one of the focal points of the PAINLESS framework, since the 5G telecommunication standard already exists, but its exploitation is limited by energy constraints. Energy-autonomy refers to the system output during grid-independent operation. For the purposes of PAINLESS this may be quantified by the amount of data (bits) that can be delivered per charge of the BSs, the lifetime of the grid-independent operation, and following the definition of new metrics such as energy generation vs. consumption, coverage vs. power, network performance over lifetime and operational cost vs. data rate is essential, to complement the current 5G metrics and promote energy-autonomous networks.

Energy-autonomy can be obtained by optimising three aspects, that will be extensively analysed in this report: energy harvesting, storage and balancing.

The term "portable" further specifies the system, although being a very relative term. Portability is the ability of the system to change its location, but this change of location could be a drop-and-forget

application, or only partially portable and still fall within the "portable" category. Two good examples of this are represented by the BS deployable via Unmanned Aerial Vehicle (UAV) and the UAV-based Base Station coupled with a (non-portable) recharging station, both mentioned in Section 3.

In brief, the system of reference is any configuration of access points that can provide a reliable mobile network, while managing the available energy in a way that makes them independent from the grid and needing as little control and maintenance as possible.

2.1. Novelty of the work in PAINLESS

An enormous number of studies were carried out regarding the 5G technology and its possible applications, but while these are getting more and more independent by the constraints imposed by data rates, the ones imposed by energy need remain. The novelty of PAINLESS stands in overcoming these obstacles, and doing it on three different, yet intertwined, levels:
1. converting the energy of the environment, may it be wind, sun, vibrations or even electromagnetic fields) into electricity (*energy harvesting*);
2. efficiently storing the energy produced to make up for any shortages or oscillations in the energy source, as well as improving the portability (*energy storage*);
3. optimising the energy consumption of both the access points and their auxiliary system, as well as "recycling" the data packages not needed to harvest more energy (*energy balancing*).

The intrinsic interdisciplinarity of such tasks makes the operation both innovative and challenging, which is why the PAINLESS consortium is composed by entities with different technical backgrounds, both from the private and the public sector.

3. Target scenarios

Within the system described in the previous section, several more specific scenarios can be modelled. These can be categorised for portability, energy source, size, location and many other parameters, and their number is only limited by technical and economic feasibility, as well as human imagination.
For convenience, the possible scenarios were split into two main groups: those that do and those that don't involve the use of UAVs.

3.1. UAV-based applications

This category includes the configurations with the highest mobility, as they can move three-dimensionally. This category can in turn be divided into several other sub-groups, depending on the flight mechanism (fixed or rotary wings), the UAV weight and dimensions, as well as the energy harvesting technologies.

A comprehensive description of the available UAV technologies and the advantages of having BS installed on them are described in [44]. In brief, the main advantages are the ability to adjust the altitude, to avoid obstacles and, consequently, to enhance the likelihood of establishing line-of-sight (LoS) communication links to ground users.
The main UAV types are listed in Fig. 2, but in this first-phase report, low altitude and light-weight models will be the main subject of study.
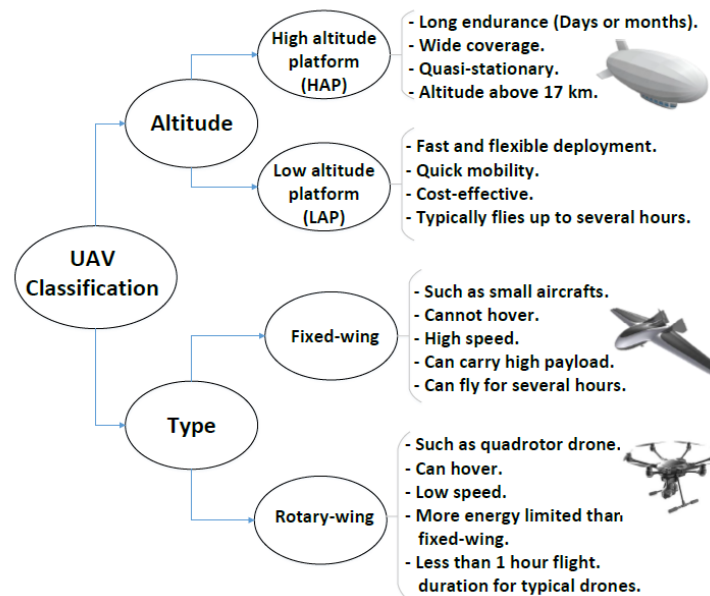
Fig. 2: UAV classification

It is stated in [44] that the most relevant uses for UAV based BSs are the complement of existing cellular systems and the use in areas where a regular connectivity infrastructure would be too hard or expensive to build, both of which fit perfectly within the scope of PAINLESS.

All this obviously comes at a cost, that is the elevated energy consumption they present, but this issue is exactly what PAINLESS is tackling.

The following sub-sections list some of the possible scenarios and their description.

3.1.1. PV recharging station

This scenario is depicted in Fig. 3 and involves two storage systems: one for the charging base (CB) and one for the UAV. The UAV can go back to the CB when not in use or when battery is low, where it is recharged by the PV battery, that is necessary to make the charging base always available and independent from the weather conditions. This in turn increases losses and costs but provides a wide range of manoeuvrability and convenience. The CB can also be a data transmitter, as there are no weight limits regarding the PV panels on the ground. The UAV can even be more than one, avoiding service interruption for recharge.

Single UAV   Multiple UAV

Fig. 3: PV-recharged UAV. Multiple UAVs can be used alternatively.

3.1.2. On-board PV

An alternative use of the PV technology is to mount it on-board of the UAV, although the increased area and weight make this practice most suitable to fixed wing models, as in Fig. 4. This option would allow for much longer autonomy, with the drawback of reduced mobility and quality of service, which would make it more suitable for wider and lower rate coverage for outdoor massive connectivity scenarios, providing more users with a weaker signal.

Fig. 4: On board PV solution

3.1.3. PV on BS (drop & forget)

A solution developed by one of our industrial partners (Nokia) is shown in Fig. 5 and involves the use of a UAV only for the deployment of a BS that comes with foldable PV modules. This is a peripheral UAV-based solution and lacks the manoeuvrability advantage of the BS. Nevertheless, the energy consumption is reduced to a minimum and the use of a UAV is still necessary in remote deployment areas where it is hard to get to.

Fig. 5: Drop and forget Base Station with built-in PV modules

3.2. Ground based applications

Fixed, off-the-grid solutions are the state-of-the-art commercial solution in remote areas without power grid availability. These typically involve large BSs powered by large PV panels and batteries, that are not easy to move, once installed. As our focus in PAINLESS is on portability and on-demand provision of connectivity in remote/emergency areas, the above solutions fall out of the scope of our study.

4. Energy Harvesting and Photovoltaic model

4.1. Background

The need to bring cellular network services to people that do not have access to a reliable power grid, as well as the carbon footprint of BS in cellular networks, result in various ambitions for "green" solutions from telecom providers, government agencies and researchers. On the other hand, in recent years the increase of traffic demand from mobile devices as well as the advent of cloud-based and IoT services raise the costs and greenhouse gas emissions.

Owing to the solar source decent availability worldwide, beside the considerable efficiency of commercial PV panels, solar power is assumed the most appropriate harvesting technology [1]. In 2001, solar harvesting to power BSs have been suggested for 2G technology [2]. Primary research was for rural scenarios where there is no power grid. However, during recent years PV power sources are practical also for urban areas due to the reduced power constraints of small BSs as well as the reduction of the costs of renewable energy technologies [1].

Solar-powered BSs can be particularly significant for regions that have poor grid connectivity while being rich in terms of solar resource [3]. Solar-powered BSs also present lower operation cost as compared to those using grid or conventional sources of energy.

On the other hand, a UAV can act as a flying BS characterized by a quick and dynamic deployment, which is extremely helpful for different scenarios. In public safety communication, for instance, where the ground infrastructure is subject to damage by natural disasters, an alternative solution for mobile operators is UAVs in order to maintain coverage and connectivity. In fact, due to their mobility, UAVs are more robust against sudden environmental changes [4]. UAVs are also useful for temporary/unexpected high-traffic demand situations where infrastructures that have already been deployed become overloaded and, hence, require additional communication equipment to maintain the high QoS level. For example, in such big events as football games, Olympic Games, or concerts, it is unfeasible from the economical perspective to invest on the ground infrastructure for a relatively short period of time [4].

A PV-powered BS is equipped mainly with PV panels, batteries and converters. Consequently, dimensioning of the PV panel as well as the battery is an important issue of research interest since under-dimensioning leads to frequent power outages. On the contrary, over-dimensioning leads to an unnecessary increase in capital cost. Given the number of interacting variables (power produced by the PV, power consumed by the BS, other endogenous variations…), the correct design of power electronic devices is paramount in the path to self-powered cellular communication networks [5].

4.2. State-of-the-art

Researches have been done concerning the possibility of powering BSs with solar energy in which the considered system is a BS paired with a PV panel and a battery for energy storage such that the BS can operate even when the PV panel is not producing energy [6, 7]. In [6], the authors study cellular access networks, which solely rely on renewable energy. Another configuration is adopted in [7], where PV panels and the main grid are mutually interconnected, making the whole system grid dependant. Authors in [8] suggest a traffic aware renewable energy assisted BS cooperation. The focus of some papers is on the overview of sustainable and green mobile network deployment [9-12], while some others [6,7, 13, 14] focus on modelling the behaviour of renewable-based BSs in order to dimension the system components correctly by understanding the system characteristics. [15, 12, 13] studied Markov models (a kind of stochastic models) to compute the BS outage probability when the cellular network is powered by solar energy. In [15] a discrete-time model of the battery charge is proposed which can be used to quantify the impact of system parameters (i.e. PV panel size, battery size, and harvested solar energy and load profiles) on the BS outage probability. However, no classification of the daily level of renewable energy production based on historical data is considered. In [13] two Markov chain models (mathematical systems used to describe random events) are portrayed. The first model is based on solar irradiation data in two consecutive days while the second one is based on solar irradiation data in triples of consecutive days. The objective of [13] is to expose the influence of correlation in weather conditions. A daily basis is considered for both solar energy generation and consumption. Furthermore, only the impact of different battery size on the system performance is studied. Authors in [5] consider the similar model as in [13], while they investigate the impact of three different quantization of weather characteristic, time slot duration, and battery capacity to analyse the performance of power system based on renewable energy for cellular networks. They conclude that by applying new generation of BS technology, a better performance will be achieved with half the solar panel size. Note that the case study of these researches is ground-based BSs. On the other hand, UAV-based BSs supplied by PV solar panels are investigated in [4].

Realistic, detailed and scenario-specific energy modelling for ICT has yet to be delivered. Current models of power management in ICT do not take power generation and storage into account, while the power consumption models that exist are either too generic and inaccurate, or simply centred around traditional macro BS operation, and very little is known about the UAV-based BSs. Realistic and case-specific models for power generation, storage and consumption, will be derived, and trade-off mechanism as well as the optimization framework that are essential for design of truly energy efficient ICT will be designed and formulated in this project.

4.3. Aims of PV modelling

The main objectives are:
1) To develop a comprehensive modelling of PV generation in order to supply the BS.
2) Sizing and dimensioning the Photovoltaic array and the capacity of the storage system according to the developed model.
3) To improve the suggested strategy in order to be implemented in both UAV and ground-based BSs.

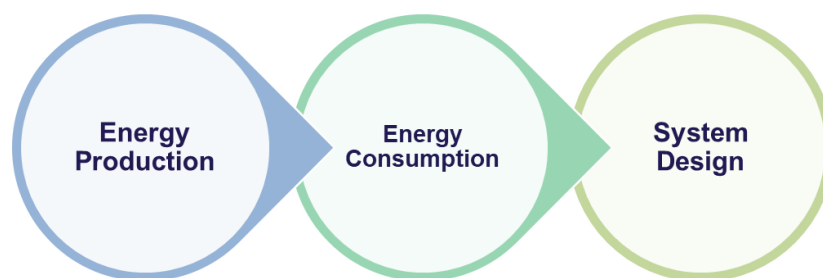Three different aspects can be considered in this phase of the project as Fig. 6.

Fig. 6: Different aspects of the project

According to the classification of the aspects to be considered in the project, in the first step the Energy production model is studied.

4.4. Energy Production model

The proposed PV-based system (see Fig. 7) consists of PV panels, storage device, and EMS. The on-board BS, UAV, and network users can be considered as the power consumers in the system. Two conditions can be assumed for the system; first, the power grid is accessible while in the other condition there is no access to the main grid, i.e. in rural areas. In order to demonstrate both these two conditions, the link between the main grid and the PV-based BS is illustrated with dashed lines in Fig. 7.
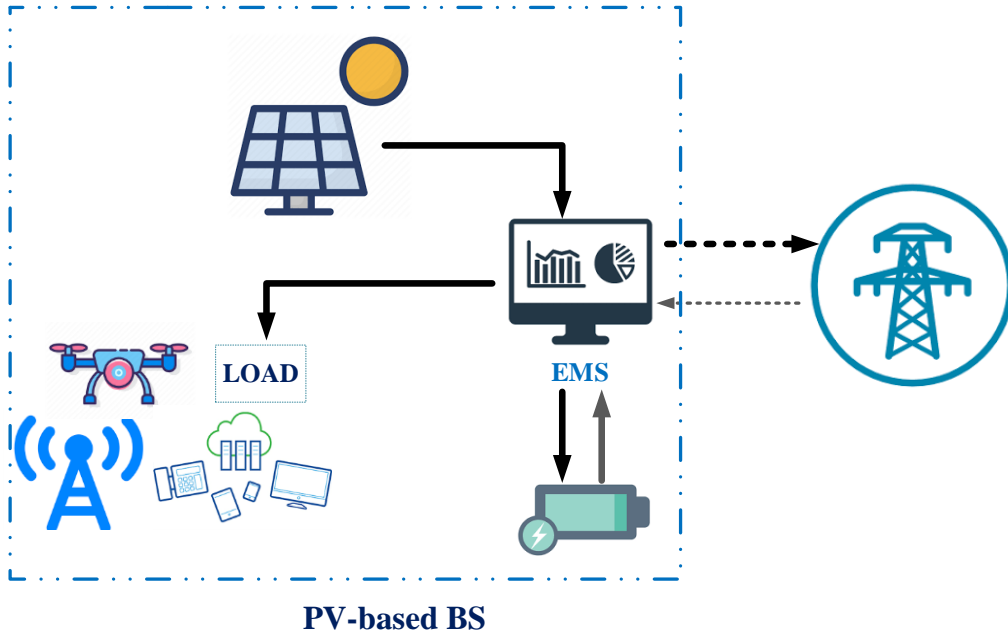
Fig. 7: Reference diagram for a PV-based BS

4.5. PAINLESS Novelty

According to Fig. 7, the focus of this section is on PV power production model. Several models have been proposed in the literature in order to estimate the output power of a solar PV system. Since the solar power generation in different geographical places depends on various parameters, including the solar irradiance, PV panels' installation angles as well as cell and ambient temperatures, the studied models are generated while considering some of these parameters [16]. The initial considered model in this project is based on the one proposed in [16] while some modifications are integrated into the model. When installing a PV panel, the optimized tilt and azimuth angles, γ and θ can guarantee the maximum output from the PV panels. A detailed research about installation angles of a PV panel is studied in [16]. The generated PV power is modelled as:

$$P_{PV} = I_t(\theta) \times N_{PV} \times \eta \tag{1}$$

where N_{PV} is the number of PV panels, η is the panel energy conversion efficiency. $I(\theta)$ is the received solar irradiance by the PV panel with Azimuth angle θ , which can be calculated as follows:

$$I(\theta) = I_b(\theta) + I_d(\theta) + I_g \tag{2}$$

where $I_b(\theta)$, $I_d(\theta)$, and I_g are the direct-beam, the sky-diffuse and the ground-reflected components, respectively. A comprehensive modelling of these components is investigated in [16].
In order to make the model more realistic, the panel temperature should be integrated to the model. The cell temperature is dependent on the ambient temperature and the total irradiation on the PV cell based on the nominal operating cell temperature (NOCT) [46].

$$P_{PV} = 0.16 \times I(\theta) \times (1 + P_{MAX}(T_C - 25)) \tag{3}$$

where P_{MAX} (%/°C) is the temperature coefficient, and T_C is the cell temperature which is defined as follows [46]:

$$T_c = T_a + [\frac{NOCT - 20}{800}] \times I(\theta) \tag{4}$$

where T_a is the ambient temperature.

The model developed by ESR #3 is shown in Fig. 8, where input data of the system are the tilt angles γ and θ, date and time, temperature, solar irradiance as well as the geographical parameters including the site's latitude and longitude, albedo and the hour angle ω.
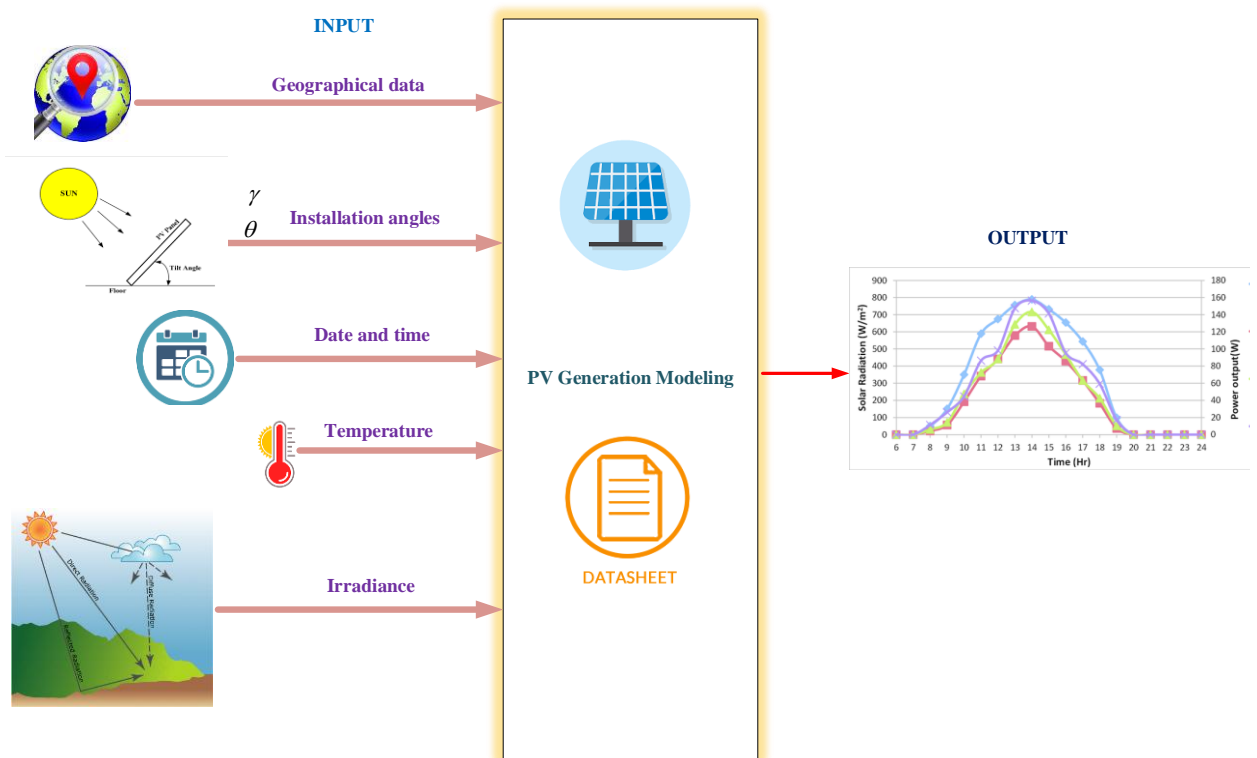

Fig. 8: The typical PV power production system

Based on the modified model, a GUI has been developed as is shown in Fig. 9. through which the input data for any case study can be given to the model and the PV output power is estimated for different locations. Different tilt and azimuth can be selected for any cases using the GUI in order to optimize the output solar power of the panel. Default optimal tilt angle for different locations is considered equal to the location latitude, while the azimuth angle value is selected such that the maximum PV output power profile is achieved [16].
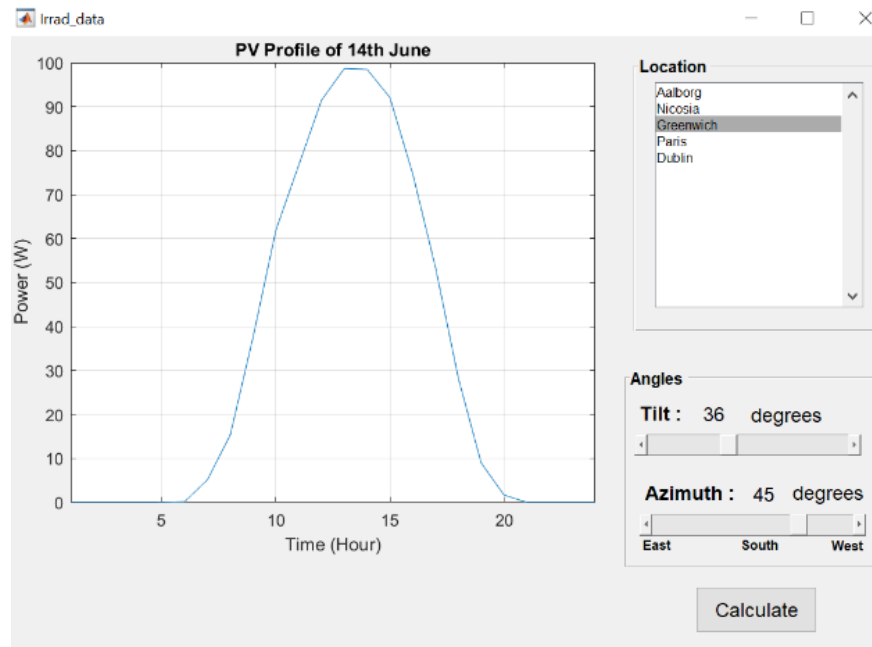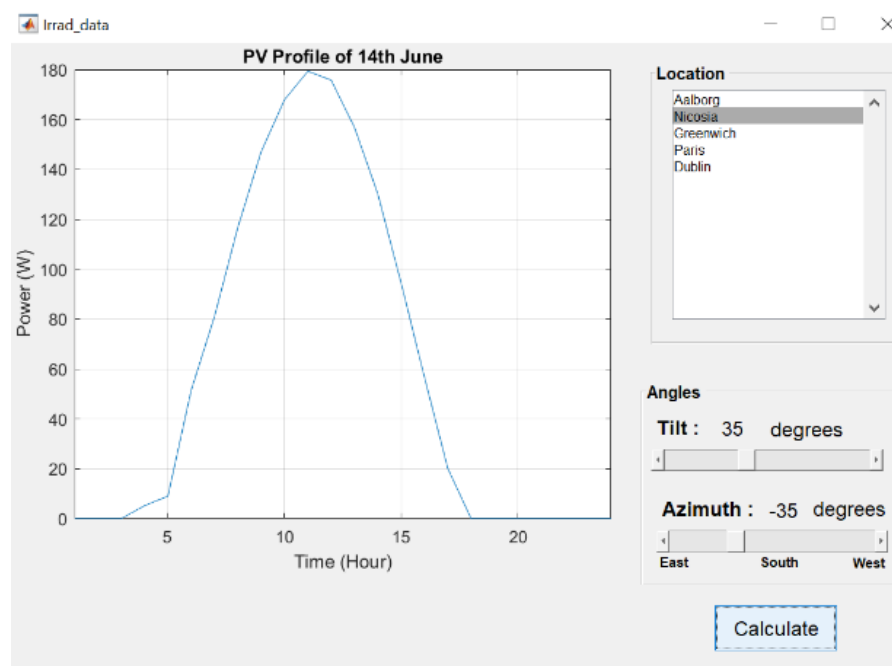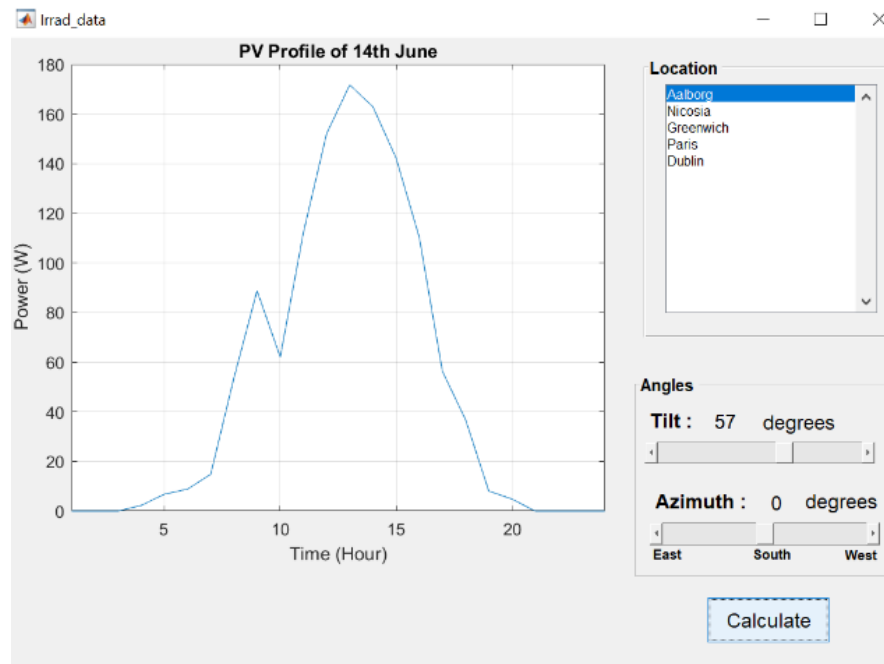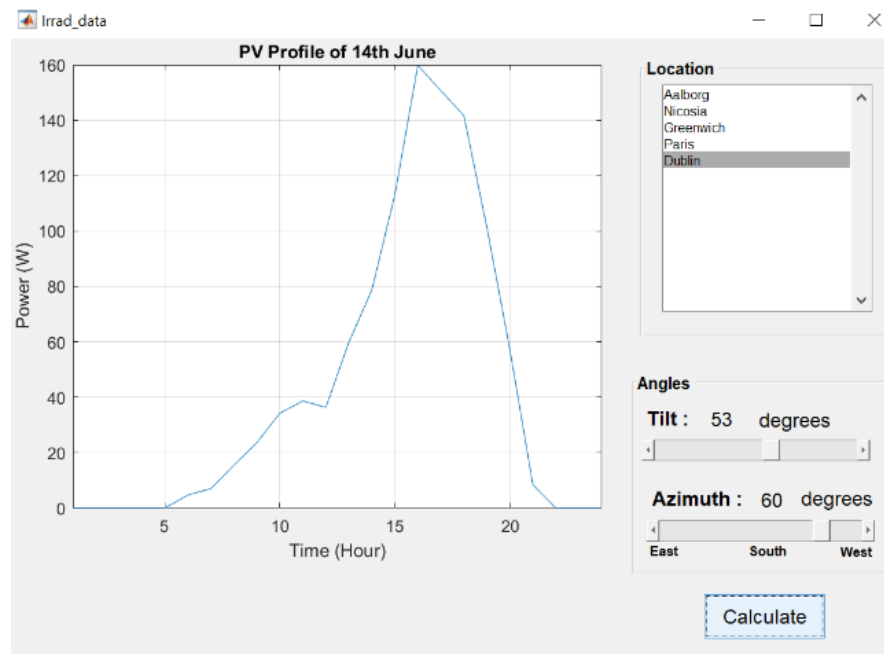
Fig.9. a

Fig.9. b

Fig.9. c

Fig.9. d

Fig. 9: A schematic of the provided GUI for (a) Greenwich, (b) Nicosia, (c) Aalborg, and (d) Dublin.

As a case study, the geographical data of city of Greenwich on 14th of June is given to the proposed model. These data are downloaded from PVGIS [17]. The data of a Canadian solar CS6K panel datasheet

is considered and simulations are done on a daily basis through MATLAB. When considering $\theta = 45°C$, the PV power production is compared with and without the temperature effect in Fig. 10.

The effect of different azimuth angles on the PV panel output power is compared in Fig. 11.
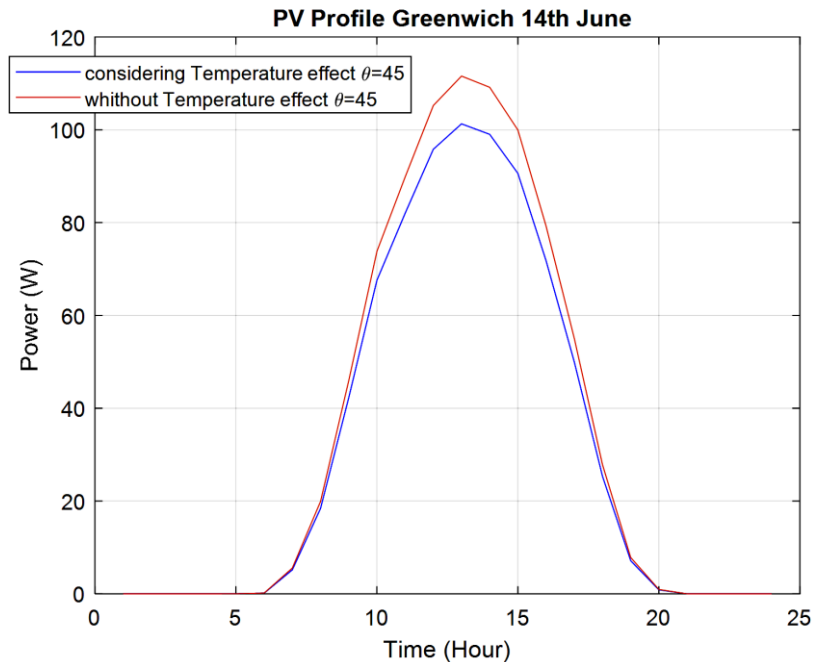

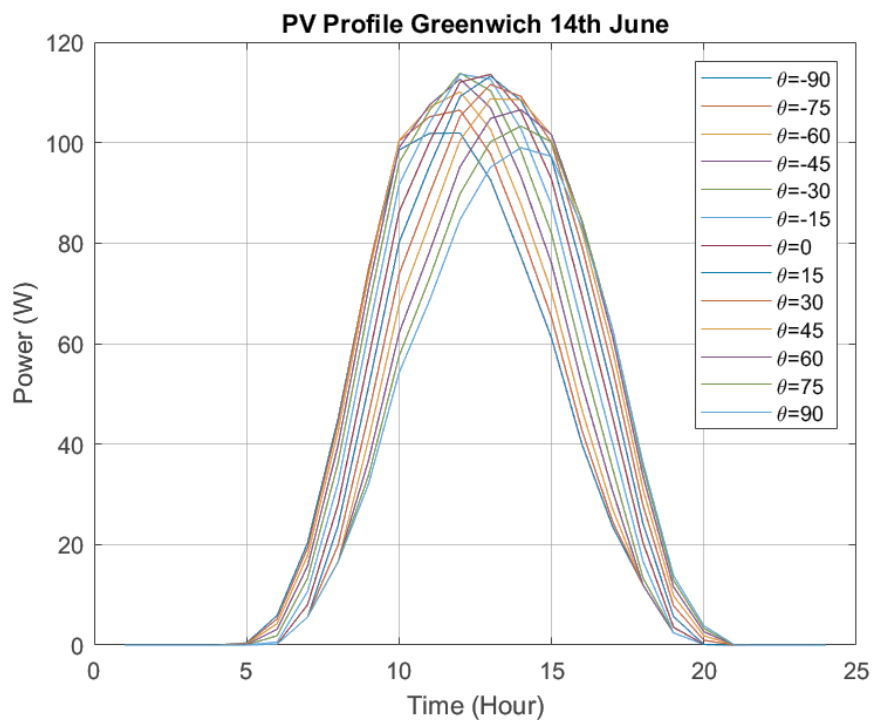Fig. 10: PV power production with and without temperature effect, both at θ = 45℃.

Fig. 11: PV power production for different Azimuth angles.

5. Energy storage model

Before analysing the energy storage aspect, it is necessary to include an overview on how the energy is used in a certain scenario, the one where UAVs recharge themselves at charging base and then exchange data while flying along a determined path. Sizing the battery of such devices is part of the scope of PAIN-LESS, but this can't be done without an extensive study and optimisation of the energy required by the system. The nature of this close relationship will be clear after reading the following paragraphs.

5.1. Literature review on UAV energy consumption models

Because of small UAVs' short history and mostly civil application, a widely valid flight model for such devices doesn't exist yet. Attempts to fill this gap in literature are being made, with various methods and outcomes. Among these, two main approaches can be pinpointed: empirical and analytical.

The empirical method consists of collecting experimental data on the UAV power consumption and then working out a mathematical model that is coherent with such data. Equations obtained this way are normally recognisable by the presence of many numeric factors and their main drawback is that they are very specific and heavily dependent on the data used to generate them, thus lacking generality. This means that an x model could only be applied to an x model of UAV (or to others of the same size/type) and only under the same conditions applied during the data collection. That is the case of the model developed in [20], where it was thoroughly observed how the power consumption changes as a function of several parameters, such as height, speed, payload, flight direction and so on. A regressive projection was then used to establish a general equation (5), that depends by all these parameters.

$$E = -278.695 + 8.195t_1 + 29.027t_2 - 0.432V^2 + 3.786V + 315D \qquad (5)$$
$$+ (4.917H + 275.204)t_3 + (0.311L + 1.735)t_3 + 308.709t_4$$
$$+ 68.956D_1$$

Where t_n is the time spent in a specific phase of flight, V is take-off speed, D is the distance of vertical flying upwards, H is the relative altitude of hovering and E is the total energy consumption. The downside of such model is that there is no guarantee on whether it can give reliable results when applied to different UAVs and different conditions from the ones used to develop it.

The other option is to use an analytical method, that is, putting together a series of existing mathematical models that best describe the target phenomenon. In the case of rotary-wing UAVs, the closest model for power consumption estimation is the helicopter flight model, that is treated in numerous articles and even textbooks. Obviously, helicopters are not the same as UAVs, but the rules of physics that allow them to fly are similar, making this a fair assumption, until the development of a custom analytic model. If the UAV is a fixed-wing model, the same thing can be done using an airplane model instead of a helicopter model. In both cases, the equations need to be adapted to the specific application, which is normally done by including some correcting factors, although this measure will hardly reach the accuracy of empirical models. This was done in [21] and [22] to optimise the path of, respectively, rotary and fixed-wing UAVs for telecommunications. These two models are summarised by two equations, one for fixed-wing (6) and one for rotary-wing (7) UAVs.

$$\bar{E}\big(q(t)\big) = \int_0^T \left[c_1 \|V(t)\|^3 + \frac{c_2}{\|V(t)\|} \left(1 + \frac{\|a(t)\|^2 - \frac{\left(a^T(t)V(t)\right)^2}{\|V(t)\|^2}}{g^2} \right) \right] dt + \frac{1}{2} m (\|V(T)\|^2 \\ - \|V(0)\|^2 \tag{6}$$

Where q is the path function, V is velocity, a is acceleration, c_1 and c_2 are coefficient that depend by the UAV geometry, t is the time variable, T is end time of the interval, m is the UAV mass and g the gravitational acceleration.

$$E(V) = T \left[P_0 \left(1 + \frac{3V}{U_{tip}^2} \right) + P_i \left(\sqrt{1 + \frac{V^4}{4v_0^4}} - \frac{V^2}{2v_0^2} \right)^{\frac{1}{2}} + \frac{1}{2} d_0 \rho s A V^3 \right] \tag{7}$$

Where T is total time, V is UAV velocity, U_{tip} is the rotor tip speed, v_0 is the mean rotor induced velocity in hover, P_0 and P_i are coefficient that depend by the UAV geometry, d_0 is the fuselage drag ratio, ρ is air density, s is rotor solidity and A the rotor disc area.

The problem with using equations (6) and (7) is mainly the lack of accuracy and testing, but also the type of data needed. As stated in [23], "manufacturers of commercial propeller do not provide detailed geometry information", forcing us to take approximate values, which in turn cause results to be even less accurate. A solution to this problem is to use momentum theory and approximate the propeller's shape to a disk [25] and match it with a regressive function that starts from (big) commercial motors and propellers. This method proved itself to be a decent approximation when compared to the results given by a professional UAV performance-evaluator [26]. Nonetheless, it still lacks proper comparison with real-life cases, as [26] is a simulation software itself.

Eventually, the selection of an empirical or analytical model comes down to a trade-off between practicality and accuracy. The ideal solution would be compromise between the two: adapting an analytic model to make it fit with empirically collected data. Such work would be of great interest for the scientific community and would open the path to new applications of UAVs, but it would require the access to several UAV models and enough time to gather and process consumption data. This is out of PAINLESS scope and will hence leave such task for the future. For the time being, the most practical approach was adopted: using the model used in [22], for both fixed and rotary-wing UAVs. This removed the constraints of environment and UAV selection, allowing to focus on the development of a sizing methodology for the energy storage system, as reported in detail in the next section.

5.2. PAINLESS novelty on UAV energy consumption models

There are different strategies to apply in order to reach PAINLESS objective of having energy autonomous telecommunication networks, but first it is necessary to know, or at least be able to forecast, how much energy such devices need. This information allows energy harvesting and energy storage systems to be designed properly, as well as simplifying the evaluation of impact for path optimisations.
During this first phase of the project, ESR #8 used existing power consumption models, refined them a little and put them in a wider iterative system, shown in Fig. 12, where the red circle highlights the central function of the flight model.

Without having to explain how the whole algorithm works, it is clear that this is the core of the calculations and it is repeated several times during the iterative cycle. This step calculates the energy consumed by the UAV using a specific flight model and data describing the UAV path and a few other important parameters, listed in the section "Input data".
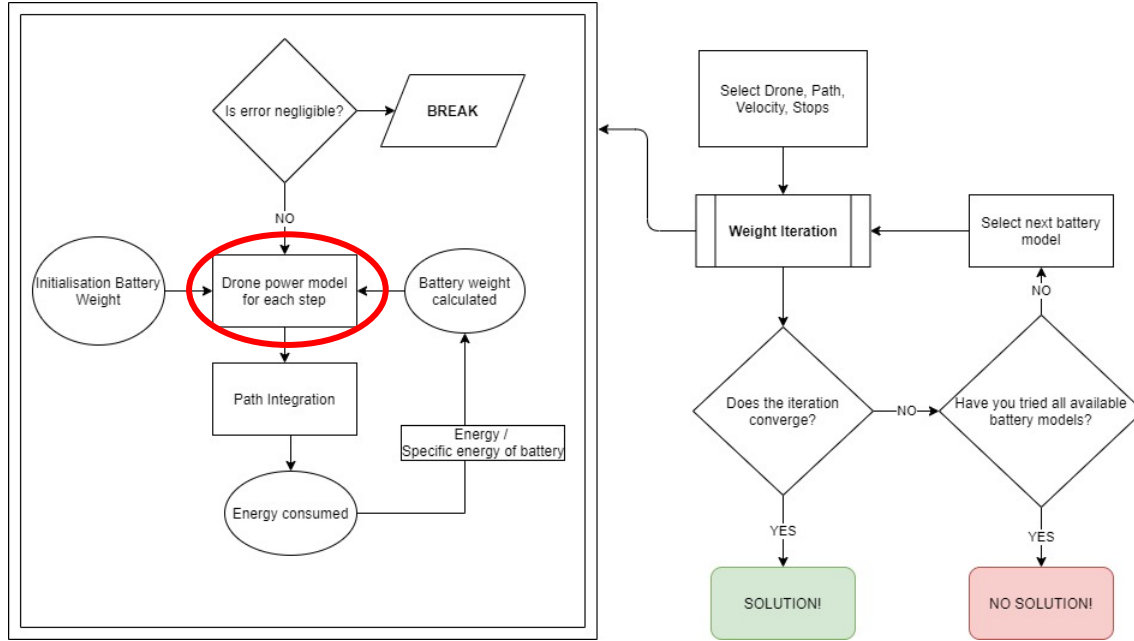

Fig. 12: Flow diagram of battery sizing algorithm

Simply by changing this block, the algorithm can work using several flight models, depending on the type of UAV selected, but the plan is to have at least two: a fixed and a rotary-wing model. As of today, for ease of testing and development of the application, only the latter model has been implemented and integrated, and it works as follows:

The model selected for the rotary-wing case is synthesised by Equation (7), best described in [22], that has the level of generalisation needed by our study. The problem of finding specific geometric data about the UAV (in order to calculate P_0 and P_i) remains, but tests have shown that the change of such parameters does not visibly affect the result, if the order of magnitude is respected. This model is very sensitive to velocity and time (V and T), but these are easier to evaluate.

Equation (7)'s accuracy was enhanced using a variable air density (ρ) that changes as a function of altitude, instead of being kept constant. The analytic relation is obtained in [24] and is the following:

$$\frac{P_{R2}}{P_{R1}} = \sqrt{\frac{\rho_1}{\rho_2}} \tag{8}$$

Where 1 and 2 represent two reference altitudes, P is the power consumed and ρ is the air density in kg/m^3. The air density and pressure at 0 Mean Sea Level (MSL) are taken, respectively, as 1.225 kg/m^3 and 101325 Pa (data taken from [27]), returning the following empirical relation between powers:

$$P2(\text{H}) = P1 \cdot \sqrt{\frac{1.225 \cdot 287 \cdot T[K]}{(101325(1 - 2.25577 \cdot 10^{-5} \cdot H)^{5.25588}}} \tag{9}$$

Where T is the air temperature, considered constant during the simulation, and H is the absolute altitude in metres to MSL. The assumption for this to be valid is that all other parameters stay the same, but this is not the case throughout the whole path. The solution to this is dividing the UAV path into several steps of time, small enough to be able to suppose an average velocity of the UAV and hence the time spent in each step. Furthermore, a series of intermediate "stops" are included to accommodate the typical tele-communication model of fly-hover-communicate, that is the application targeted by PAINLESS.

This concept of dividing the path into steps is better visualised in Fig. 13, although this doesn't represent the Z component of space (altitude).
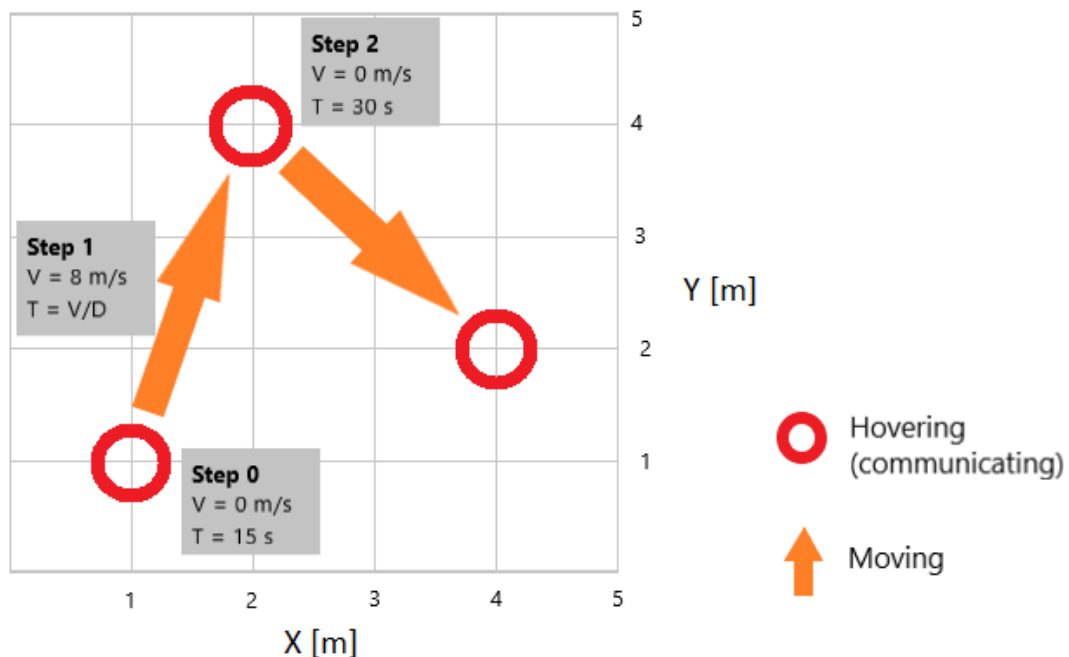

Fig. 13: UAV path sample

Once the energy spent in each step is calculated, all contributes are summed up to obtain the whole energy spent to have the UAV follow the path in question. In order make this model more realistic, electric losses were accounted for considering an efficiency of 0.85 (conservative assumption). At the moment no electronic configuration was implemented, but this parameter will be refined once more information will be available.

Because it will be powered by the same storage system, the Base Station consumption was also included in the calculation and can be entered by the user in the form of mean power in Watts. This is a good approximation, considering that the BS's maximum power is no more than 10 W [28], while even a small quadcopter needs at least 100 W to fly, so oscillations of the BS power consumption are negligible.

Input data

Calculations need data to be carried out and such data are provided by two sources: data regarding the UAV geometry are built-in with the code in sets that are selected depending on the UAV model picked by the user (Fig. 14 c). The available options are limited to one model so far, but the plan is to include more and even add the possibility for the user to manually contribute to the database.

All other necessary data need to be entered by the user via the interface, as in Fig. 14, although the implementation of an import system from .txt file is under development. These data are the ones related

to the path description (coordinates, velocity and so on) and to other parameters, such as Base Station weight and power consumption, reference altitude, number of stops.
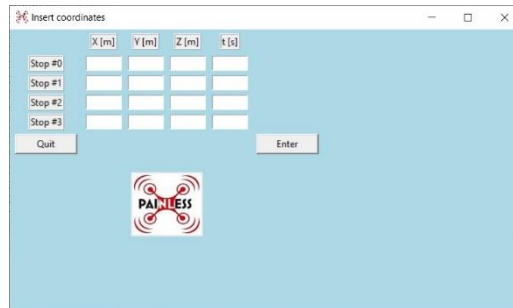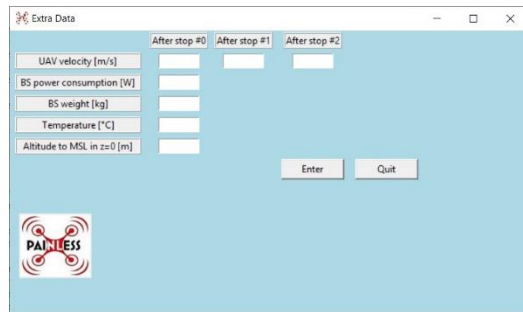

Fig. 14 a

Fig. 14 b

Fig. 14 c

Fig. 14 d

Fig. 14: Pages 1, 2, 3 and 4 of the GUI

It comes without saying that, if not necessary, the Base Station can be eliminated by selecting "0" both in the weight and the power consumption entries. Same goes with the stops: one can model a velocity variation by adding a stop with 0 seconds and change the velocity in the next interval.

The first part of section 5.4. will explain how the calculations are related to the storage system on board.

5.3. Literature review on Energy storage models

It is assumed that the solar energy is first used to power the BS, and the excess amounts of energy that are not immediately used for powering the BS are harvested into the storage (if there is still enough capacity) for future use. During the periods when no solar energy is being generated, e.g. during night or cloudy weather, or if the PV production is not sufficient to satisfy the BS demand, the stored energy can be used. In case the battery results empty, the required energy can be taken from the grid, if applicable [18] (Fig. 7).

Practically, in order to have a good match of the power consumption and generation profiles, two different approaches can be considered: installing a low capacity battery with optimized PV azimuth angle, or a high capacity battery without optimized angle. However, due to the short life time of batteries (3 - 9 years [19]) comparing to the warranty lifetimes of PVs (a 80% system performance warranty for around 20 years [19]), and since batteries are expensive (25-250e, 220e and 1500e per kWh for the battery types Lead-Acid, NaS and Li-Ion, respectively [19]), it is more effective to use small batteries while optimizing azimuth from economical and system lifetime points of view.

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D3.1 – Energy models and optimisation framework: phase 1

A comprehensive overview of the important battery parameters, including depth of discharge (DOD), state of charge (SOC) which affect the battery efficiency and lifetime are discussed in [18]. In order to provide a battery lifetime duration of up to 1000 cycles a maximum DOD ≤ 50-70% would be optimal, while values of DOD as high as 80% would reduce the service time to 50% [18]. In renewable powered systems, the charging and discharging currents are irregular, affecting the battery efficiency. From charge efficiency point of view, the best performance is achieved for SOC around 60%. While for SOC >80% (typically for batteries with DOD=50%), the efficiency reduces below 60%. It can be concluded that, while high SOC level decreases the battery aging and leads to the capacity loss process, it also reduces the efficiency which in turn leads to storage loss which wastes the energy significantly. This can considerably affect the battery and PV panel dimensioning [18].

Nonetheless, keeping a low DOD would negatively affect the UAV usage time and weight, so battery lifetime will not be strictly prioritised in this scenario.

The optimisation gets a bit trickier when considering an on-board harvesting system, like in [29] or in Section 6, as this would make the charging and discharging cycle happen more often, thus decreasing the battery life, although improving the overall energy balance. A possible solution to this would be the adoption of a hybrid system Supercapacitor/Battery [30]. A Supercapacitor allows to protect the battery from peaks of input and output power, improving both the device performance and the battery life span, but at the cost of extra weight, extra cost and a more complicated Energy Management System (EMS).

5.4. PAINLESS novelty on energy storage models

In the sections regarding the UAV power consumption model (5.2. and 5.3.), an element of equation (7) was overlooked: the weight. This is used to calculate the coefficient P_i, but it's not so easy to predict., as the energy consumption depends, among other things, by the weight itself. The total weight is constituted by fixed components (the UAV chassis, its electronics and the Base Station) and the battery weight, whose determination is the subject of this study. This generates a loop in which the battery size depends by the power consumption and the power consumption depends by the battery size.

This issue can be overcome by setting up an iterative method, as showed in Fig. 15: after collecting all the necessary data described in 5.3., an initialisation battery weight is used to calculate the total mass and, consequently, the total energy consumption, through the aforementioned discretisation of Equation (7). The total energy the battery should provide, comprehensive of electric losses and state of charge, is then divided by the energy density of the battery model selected (an insight on battery selection will be provided later in this section), as in Equation (10):

$$Battery\ weight = \frac{E_{consumed}\ [W]}{Energy\ density\ \left[\frac{W}{kg}\right]}\ [kg] \tag{10}$$

If the resulting weight is close enough (with a margin of error of 0.1%) to the initial guess, the loop breaks, and the solution is found. If not, the new weight is used to recalculate the energy consumption and so on, until either a solution is found, the weight becomes unrealistically large, or the number of iterations overcomes a certain threshold (set to 1000).

The latter two cases mean that, given the current data, the iteration diverges, thus there is no solution involving the selected battery model. This possibility is the reason why a broader loop is needed.
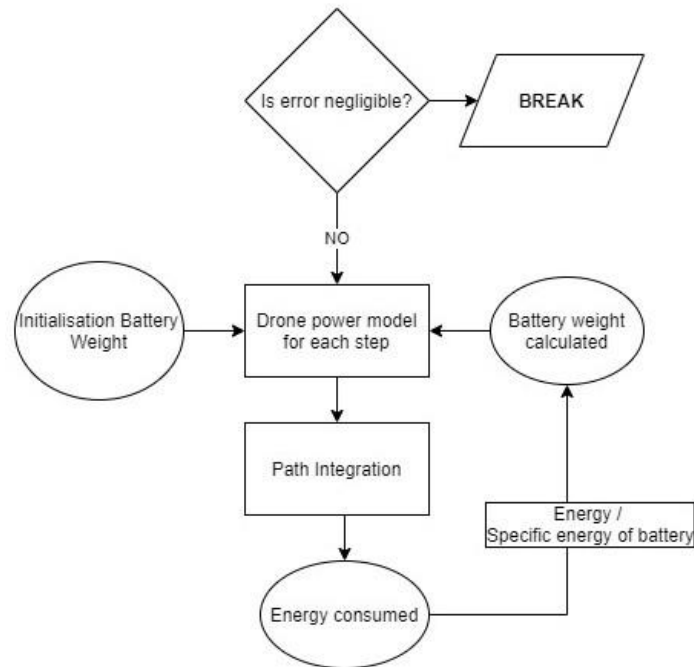

Fig. 15: Weight iteration

Normally, a higher price corresponds to higher performances and, more specifically, to a higher energy density, which means that more energy can be stored without adding extra weight. If data about several battery models are provided, these are sorted by the algorithm from the cheapest to the most expensive and then used one by one to try and get a solution from weight calculation, in a trial-and-error system that is described in Fig. 16.

This way, the cheapest battery model is selected first, the weight iteration initialised, and its results observed: if positive, the best available solution was found and there is no need to continue; if negative, the second cheapest battery model is selected and so on, until all models have been tried. This ensures that, if a solution is found, it involves the cheapest available model. If iterations keep diverging after all battery models were tried, it means that either all the battery models in the database have too poor performance, or the boundary conditions are unrealistic (UAVs weighing 10000 kg, flight times of 3 hours for a quadcopter…).

Hence, not only is the developed application a "battery sizing" tool, but a "battery selection" tool as well.
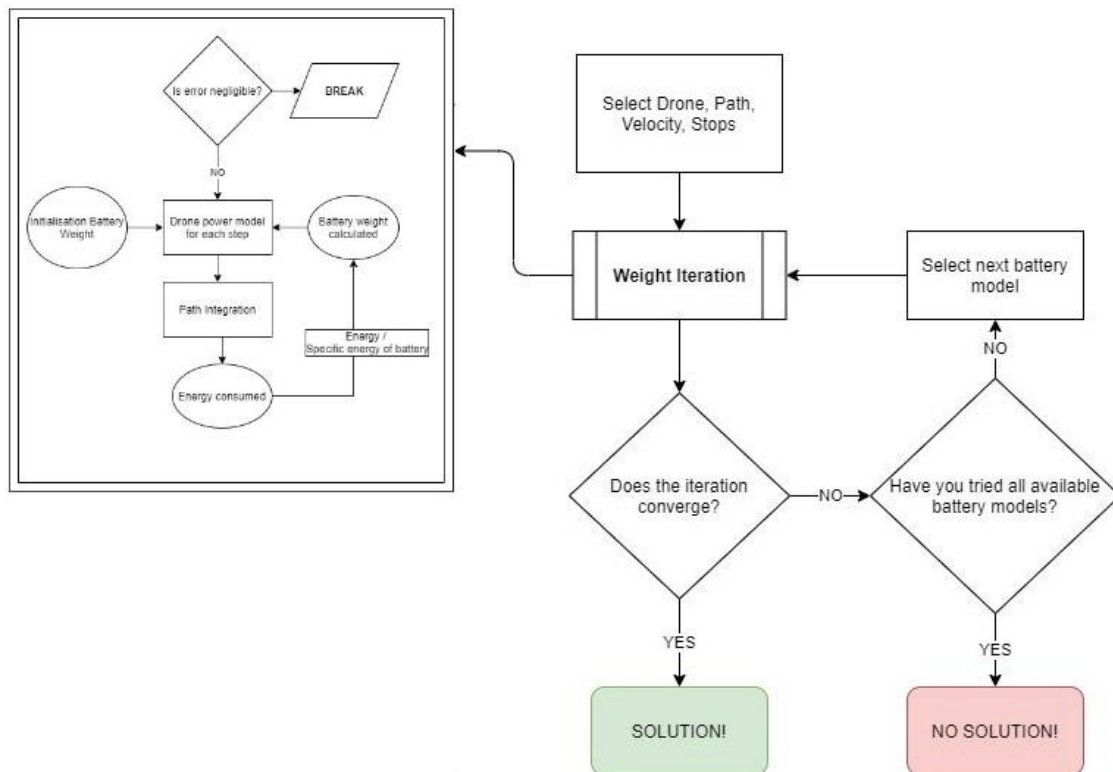
Fig. 16: Battery selection algorithm

Results

Once a solution is found, the application returns three windows: one showing a 3-D visualisation of the plot (Fig. 17 a), one showing the trend of power consumption versus time (Fig. 17 b) and one showing a resume of the results (Fig. 17 c), including number of iterations, battery model selected, battery weight, energy stored in the battery and total flight time.

Even though the input data used was a gross estimation that will be refined in the future, the first results the programme returned are realistic and can further improve when more accurate data will be provided.
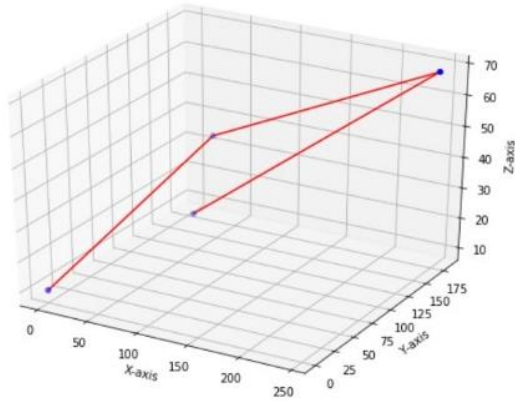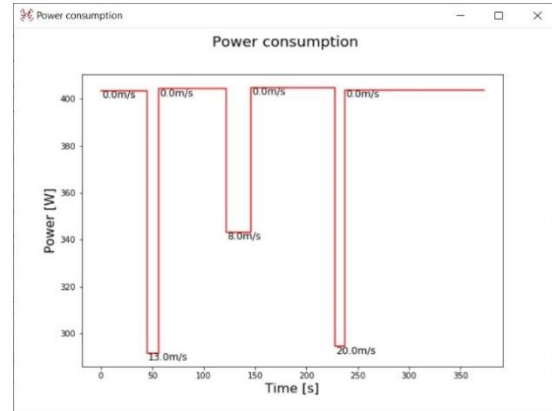
Fig. 17 a

Fig. 17 b

Fig. 17 c

Fig. 17: Path visualisation, Power vs time plot, Results summary

6. Energy balancing framework

6.1. Literature review
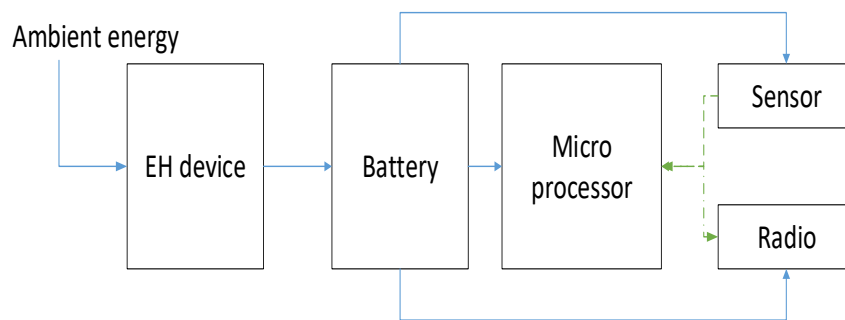

Fig _18_ .: Block diagram of a typical EH node. Solid and dash-dot lines indicate energy and data transfer, respectively [31].

Wireless networks often involve small battery-limited sensors and monitors. The constraints on the size and cost of sensors lead to corresponding limitations on the capacity and efficiency of the energy storage and communication performance. Traditional wireless networks are based on on-board bat-tery, whose aim is to minimize energy consumption. Therefore, prolonged communication services need frequent bat-tery replacement, increasing the maintenance cost. Energy harvesting (EH) based communication sys-tems, however, can be considered as a promising solution for the mentioned is-sues, as they can collect energy from the environment. In EH networks, the objective is to intellectual-ly manage the harvested energy to ensure uninterrupted operation. On the other hand, due to the fact that the ambient energy sources change constantly, the amount of harvested energy is limited. Hence, in the EH wireless nodes, it is necessary to strike a balance between the harvested and consumed energy in the battery to increase system performance.

Fig. 18 shows the block diagram of a typical EH communication node. Ambient energy is converted to electrical energy by EH device. The harvested energy is then stored in a storage element, which is typically a rechargeable battery. The storage element supports the energy which is needed for the micro-proces-sor, sensing and radio apparatus. With respect to the application, the sensor block might be used to collect and digitize the temperature, pressure, or motion data. The radio block is used to transfer and receive data.

In Fig. 19, $H(t)$ and $I(t)$ are used to denote the energy and data arrival rates to the corresponding buffers. The states of the energy and data buffers at time t are shown by $S(t)$ and $D(t)$, respectively. The finite capacity of data buffer and energy storage are d_{max} and E_{max}, respectively. An energy management policy means that the microprocessor needs to govern or decide to off or on the switches in Fig. 19 in each time t by optimizing a cost function. The optimal solution for this problem highly depends on the properties of $H(t)$, $I(t)$, and prior knowledge of the microprocessor about these functions. Two different scenarios, however, can be considered in practice. First, in the off-line policy, it is assumed that the exact values of $H(t)$ and $I(t)$ are available for the microprocessor in advance during the whole operation time. Second, in the online policy, the microprocessor only accesses the statistical information regarding $H(t)$ and $I(t)$.

Wireless communication with EH transmitter has recently gained significant research interests. In [32] and [33], under the hypothesis that the capacity of the battery is infinite or finite, system throughput maximization over a finite number of transmission epochs for both the off-line and online scenarios is investigated. In [34], the throughput maximization problem for the three-node relay channel in the deterministic EH scenario and the decode-and-forward (DF) relaying operation is studied. In references [35], [36], respectively, the capacities for the additive white Gaussian noise (AWGN) and fading channels with random EH sources are derived. It has been proven that by assuming an infinite energy storage constraint, one can obtain the same channel capacity with traditional constant power supplies. The optimal power allocation for outage probability minimization in point-to-point fading channels with the EH constraints and channel distribution information at the transmitter is studied in [37]. Using a dynamic programming framework, in [38], authors proposed the online optimal policy to control admissions into the data buffer. For point-to-point communication, in [39], energy management policies and some delay optimality properties are provided to stabilize the data queue in the data buffer. In [40], it has been shown that a variant of back pressure algorithm based on energy queues is optimal. The authors in [41] leveraged a geometric framework to obtain the optimal solution of EH communication system while minimizing the transmission completion time. In [42], an optimal power allocation that maximizes the system throughput in static channel for EH transmitter that has a finite battery is proposed. In [43], the authors provide optimal transmission policies by considering energy cost of the processing circuitry and transmission energy in the EH communication node. In section 6.2., a non-convex optimization is presented, which maximizes the system average throughput while considering the EH constraints.

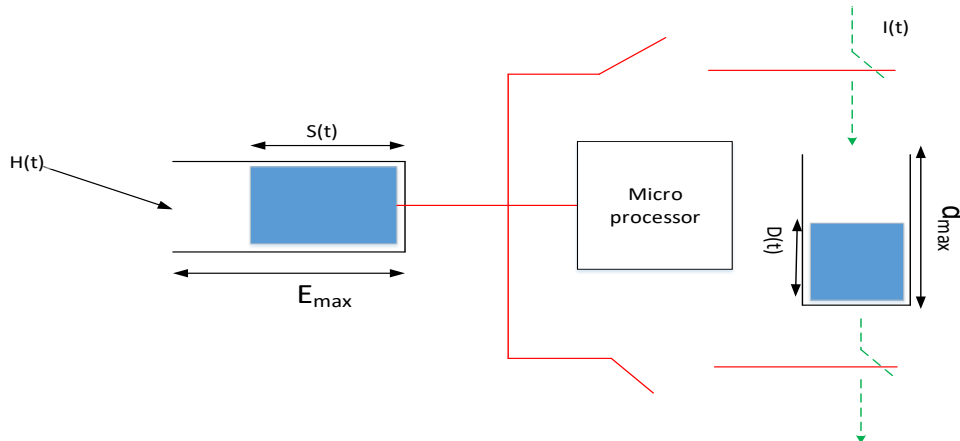**Fig. 19: A typical EH device with the energy and data buffers. Solid and dash-dot lines indicate energy and data transfer, respectively. Energy is harvested at rate $H(t)$ and stored in the buffer of capacity E_{max}. Input data is generated at rate $I(t)$ and stored in the buffer of capacity d_{max} [31].**
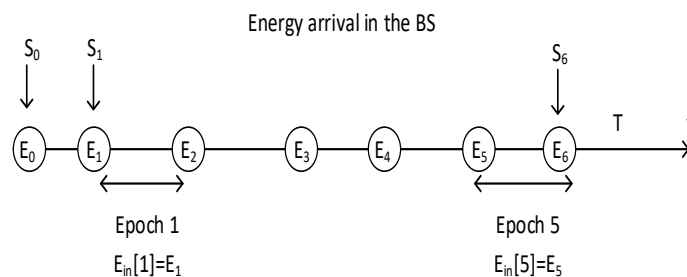
6.2. System Model and Problem Formulation

Fig. 20: Energies arrive at time instants s_k in amounts E_k [44].

As shown in Fig. 20, BS has an energy queue of finite capacity E_{max}. The available energy in the battery at time zero is E_0 and energy harvests from the environment at times $s_1, s_2, \dots$ in amounts $\{E_1, E_2, \dots\}$. Note that the energy might be collected from several different natural sources such as solar, indoor lighting, vibrational, thermal, biological, chemical, electromagnetic, etc. Moreover, the energy might come from man-made sources via wireless energy transfer, where energy is transferred from one node to another in a controlled manner. The time interval between two consecutive energy arrivals is called *epoch*. The epoch lengths are $l_i = s_i - s_{i-1}$ with $s_0 = 0$. Let us assume that $\mathcal{M} = \{1, 2, \dots, M\}$ and $\mathcal{N} = \{1, 2, \dots, N\}$ as the set of ground users and energy arrival, respectively. From Fig. 21, it can be seen that the base station (BS) needs to provide quality of service (QoS) requirements for M ground users. By assuming that the transmit power for *i*-th user in time slot *n* is $p_i[n]$ and BS transmit data for all users at *n*, the achievable data rate can be written as

$$R_i[n] = \log_2\left(1 + \frac{p_i[n]h_i}{\sum\limits_{j \neq i}^{M} p_j[n]h_i + \sigma^2}\right), \tag{11}$$

where hi is the channel between *i*-th user and BS and σ^2 is the power of the AWGN at *i*-th user. Note that and the term $\sum\limits_{j \neq i}^{M} p_j[n]h_i$ is caused because of co-channel interference of other users at *i*-th user.

Also, $\dfrac{p_i[n]h_i}{\sum\limits_{j \neq i}^{M} p_j[n]h_i + \sigma^2}$ is signal-to-interference-plus-noise ratio (SINR). Consequently, by defining

$$p := [p_1[1], p_2[1], \cdots, p_M[1], p_1[2], \cdots, p_M[N]]^T \tag{12}$$

as the transmit power vector, the average system throughput during transmission over all users is given by

$$R(p) = \frac{1}{M} \sum_{n=1}^{N} \sum_{i=1}^{M} \log_2\left(1 + \frac{p_i[n]h_i}{\sum\limits_{j \neq i}^{M} p_j[n]h_i + \sigma^2}\right). \tag{13}$$

The aim is to adapt transmission powers that maximize average system throughput while considering the available energy level. The energy consumed by the system must satisfy the causality constraints. Indeed, at any given time t, the total of energy consumed by the system up to time t needs to be less than or equal to the total amount of energy harvested up to time t. Therefore, the causality constraints can be written as

$$\sum_{n=1}^{k} (p_1[n] + \cdots + p_M[n])\ell_n \leq \sum_{n=1}^{k-1} E_n, \quad \forall k = 1, \cdots, N+1. \tag{14}$$

In practice, due to the fact that batteries have finite capacity, energy might be overflowed without using for data transmission. To avoid this issue, the following constraints are needed

$$\sum_{n=1}^{k} (p_1[n]+\cdots+p_M[n])\ell_n \leq \sum_{n=1}^{k-1} E_n, \quad \forall k=1,\cdots,N+1. \tag{15}$$

where states that the energy level in the battery never exceeds E_{max}. On the other hand, to achieve 100% coverage probability, communication services are provided for all ground users by the following constraint:

$$\log_2(1+\frac{p_i[n]h_i}{\sum_{j\neq i}^{M} p_j[n]h_i+\sigma^2}) \geq R_{req}, \quad \forall i \in \mathcal{M} \text{ and } n \in \mathcal{N}. \tag{16}$$
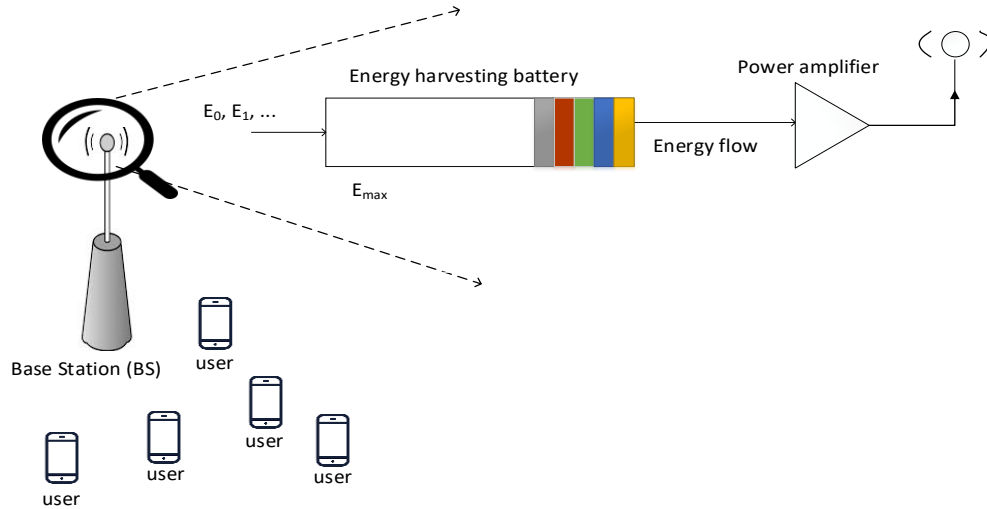
Fig*21*.: A hybrid energy harvesting base station (BS) for signal transmission.

To provide communication services for all ground users, in the following optimization problem, it is maximised the average system throughput subject to mentioned energy and communication constraints:

$$\max_{p} \frac{1}{M} \sum_{n=1}^{N} \sum_{i=1}^{M} \log_2(1+\frac{p_i[n]h_i}{\sum_{j\neq i}^{M} p_j[n]h_i+\sigma^2}) \tag{17}$$

$$C_1: \sum_{n=1}^{k} p_1[n]+\cdots+p_M[n])\ell_n \leq \sum_{n=1}^{k-1} E_n, \quad \forall k=1,\cdots,N \tag{18}$$

$$C_2: \sum_{n=1}^{k} E_n - \sum_{n=1}^{k} (p_1[n]+\cdots+p_M[n])\ell_n \geq E_{max}, \quad \forall k=1,\cdots,N \tag{19}$$

$$C_3 : \log_2\left(1 + \frac{p_i[n]h_i}{\sum\limits_{j \neq i}^{M} p_j[n]h_i + \sigma^2}\right) \geq R_{req}, \quad \forall i \in \mathcal{M} \text{ and } n \in \mathcal{N}. \tag{20}$$

The above problem is challenging to solve because the objective function and constraint C_3 are not convex respect to p. The problem would be more complicated when a specific energy model is considered, such as solar.

Due to the interference term in (17), the objective function does not fall in the class of convex optimization problem. Special tools are required to solve this kind of a non-convex optimization problem. Since we aim at an energy-efficient system, the techniques used for the optimization should be the least complex. One of the popularly used techniques to tackle this kind of non-convex optimization is the sequential convex programming (SCP) technique [45]. In SCP, instead of optimizing the non-convex objective functions/constraints, a sequence of convexly approximated problems, obtained through techniques like first-order Taylor approximation, is iteratively solved till the solution point converges to the Karush Kuhn Tucker point of the original non-convex problem.

7. Future plan

General plan

A Gantt chart is reported in Fig. 22, showing the past and future progression of the energy modelling and optimization sub-group of the PAINLESS Project.
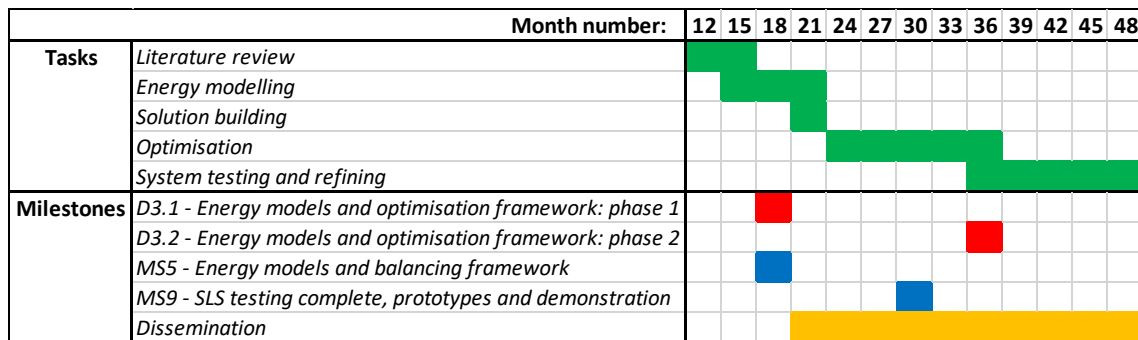
	Month number:	12	15	18	21	24	27	30	33	36	39	42	45	48
Tasks	*Literature review*	■	■											
	Energy modelling		■	■	■									
	Solution building				■	■								
	Optimisation						■	■	■	■				
	System testing and refining									■	■	■	■	■
Milestones	*D3.1 - Energy models and optimisation framework: phase 1*			■										
	D3.2 - Energy models and optimisation framework: phase 2									■				
	MS5 - Energy models and balancing framework			■										
	MS9 - SLS testing complete, prototypes and demonstration							■						
	Dissemination				■	■	■	■	■	■	■	■	■	■

Fig. 22: Gantt chart with tasks and milestones (red line represents current progress).

The upper side of the chart shows how the tasks were and will be handled on a time perspective, while the lower side summarises the main milestones and goals to be achieved. Months numbers start with 12, coherently with PAINLESS official time counting, according to which the current month is number 18 (March 2020).

The first 6 months were mostly dedicated to the literature review, on which basis the models described in the present report were developed.

From now on, these models will be further refined, while already sketching possible solutions, before tackling the actual Optimisation task, that consists of developing solutions and simulate their effectiveness. By the end of the optimisation phase, enough novel results should have been obtained and be ready for exposition in a joint dissemination activity. These should also comply with MS9 requirements. The next deliverable report (D3.2 – Energy models and optimisation framework: phase 2) will then summarise all

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D3.1 – Energy models and optimisation framework: phase 1

the progress carried out in the next 18 months, when the breakthroughs of PAINLESS will have taken shape and will possibly represent a significative impact on their research field.

At that point the last phase will start, during which empirical data will be collected through the construction and testing of prototypes, built on the basis of the theoretical results carried out. This will be facilitated by the secondments with PAINLESS industrial partners and will allow the ESRs to judge the accuracy of the models and solutions they will have developed, in order to adjust them accordingly.

Plans concerning each specific aspect of energy optimisation are reported in the following paragraphs.

PV Modelling

The proposed model of Fig. 7 is the primary model which is going to be improved in the future. In the improved model, the panel related parameters, including P_{max} and panel efficiency, should be added as input parameters. On the other hand, the power electronic interface efficiency is another input to be added. The storage device will also be integrated to the energy generation model and the performance of the EMS for fulfilling the energy balancing constraint will be investigated.

As is observed in Fig. 8, the location can be selected among some specific cities. However, the GUI interface can be improved to be more general in such a way that the users can put their own specification for the panel or the inverter, as well as the input geographical data (e.g. the solar irradiation or inputs for a year, the site's latitude and longitude, albedo). On the other hand, the output results of GUI can be plotted as solar irradiances, temperature as well as the PV output power such that the users can have a better understanding of the system under study.

In short, the future plan can be summarized as follows:

1. In order to make the suggested model more comprehensive, the power generation model should be extended while more details are considered.
2. Due to the inherent uncertain characteristic of the system, a proper approach should be proposed in order to consider the uncertainties in the parameters.
3. A new model of the storage device in order to consider the battery power constraints along with the battery SOC should be presented.

Battery Sizing Software

The battery sizeing software (called PainSizer by its developer) still needs a lot of work before being considered as a reliable tool and being made available to the public. Future versions are expected to present new features, more mathematical models, enhanced databases, improved graphics and a general debugging of the code.

Some examples of new features are the possibility of importing and/or exporting data files through external files, the manipulation of databases (adding, removing and modifying data) via user interface and, eventually, the extension of applicability to non-flying devices.

The new mathematical models will be added to account for fixed-wing UAV calculations, as well as offering alternative models taken from the scientific literature (and possibly original ones, too).

Databases are what make the difference in terms of accuracy of prediction, and an extra effort will be necessary to improve the reliability and variety of the current data. This is true both for battery and UAV data, that have been overlook so far, for the sake of method and code implementation. Innovative configurations will also be considered, as in hybrid storage systems with Supercapacitors or fuel cells.

Maintenance will also be necessary to make sure that new commercial products (e.g. new models of batteries or UAVs) will not make this software outdated, and therefore the ability of the user to access them will be a crucial asset.

An improved interface will make the software look more professional and be more profitable overall, by introducing scrolling windows, bigger font and reducing the weight of the memory occupation.

Once such changes will be implemented, the next phase of the project will be the application of the software to a real-life scenario: it will be used to size a battery to be be installed on a UAV prototype for real-life testing.

Energy Balancing

Despite these difficulties, in PAINLESS aims to find the optimal policy for problem (20). As mentioned, the objective function of the proposed problem (20) and constraint C_3 are non-convex, hence difficult to solve. This issue is tackled by taking advantage of two novel approaches. First, regarding the fact that the objective function of problem (20) can be written as a monotonically increasing function respect to SINR and the feasible set of the problem is a normal set, the goal is to obtain an optimal policy using the monotonic optimization technique. In the second approach, the non-convex functions of problem (20) are replaced with convex functions by applying the successive convex optimization technique.

Finally, the precise models of energy storage and harvesting developed in Section 6 will be incorporated into the proposed optimization problem (20).

8.   Conclusions

In this first phase of the "Energy modelling and optimization framework" within the PAINLESS project, the first part of the title ("modelling") was highlighted under the three main energy-related points of view: energy harvesting, energy storage and energy balancing. In other words, where to get the energy from, how to make it available at any time and how to manage it wisely. The only way to accomplish such an ambitious plan as designing energy-autonomous portable access points for infrastructure-less networks is to address all these three issues at the same time, seeking the best possible solution for each. Furthermore, each solution must be compatible with the others, making internal cooperation crucial. In fact, a good connection among all these research fields will trigger the multiplication factor for which the outcome of a work of ensemble is greater than the sum of each single piece of research. This is true for the energy modelling and optimisation sub-group and for the whole PAINLESS project as well.

The energy harvesting, storage and balancing aspects were described thoroughly in this report, including an overview on the most relevant related works found in literature and their mathematical formulation. Such models can still be refined and expanded, but the core content is there, ready to be used as a tool to test new solutions. This represents the first step of any good research, as it allows simulations to be carried out extensively and quickly, facilitating the achievement of new breakthroughs. Standing on stable and reliable foundations, the challenges ahead can be tackled with improved confidence and determination, on an open ground for the testing of novel ideas.

Part of these ideas were mentioned in the "Future Plan" section, but many more will surely come out in the future. The goal is to provide answers to both the individual and collective energy-related issues of the PAINLESS project by month 36, when phase 2 of the energy modelling and optimization is due. Eventually, the final efforts will be focused on real-life testing and empirical data collection. Data that would provide an evaluation of the actual potential of the proposed solutions, both technically and economically speaking.

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